N2 Opportunity Assessment

Low voltage network visibility and optimising DER hosting capacity

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What is RACE for 2030?

The Reliable Affordable Clean Energy for 2030 Cooperative Research Centre (RACE for 2030 CRC) is a 10-year, $350 million Australian research collaboration involving industry, research, government and other stakeholders. Its mission is to drive innovation for a secure, affordable, clean energy future. https://www.racefor2030.com.au

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Summary

S1: Introduction

> *There is only one boss. The customer. And [they] can fire everybody in the company from the chairman on down, simply by spending [their] money somewhere else.*
>
> –Sam Walton: Made in America, My Story, with J. Huey (1990)

More so than anywhere else in the world, Australia's electricity customers are choosing to spend their money on rooftop solar PV systems. There is a worrying trend in Australia, however, to limit or deny customers' PV connection, generation, and export due to the real and perceived limits of the low-voltage distribution network.

The limits placed on solar connections result from the fact that the electricity network has physical limits that, if breached, damage customer and network equipment and endanger safety. While these limits, also known as network PV hosting capacity, are knowable, they are for the most part unknown within the low-voltage distribution network. This lack of knowledge predisposes network businesses to act more conservatively than they might with greater awareness of the true limits. The result is lower overall utilisation of existing network infrastructure, greater costs, and reduced control by customers over their energy usage.

Table S- 1 DNSP LV network visibility (DNSPs surveyed by the AEMC and ENA in 2019)

DNSP		MV	LV		Behind meter		
		Zone substation feeder	Distribution transformer	LV feeder	Customer connection	Inverter exports	Customer consumption
SA	SA Power Networks	80%	3.4% ↑	↑	0.1% ↑	0.0%	
QLD	Energex	100%	40% ↑		1.5% ↑		
	Ergon Energy	95%	3.5% ↑				
WA	Western Power	100%	1.0% ↑	↑	5.0% ↑		
VIC	Citipower and Powercor	100%	99% ↑	99%	99%		
	United Energy	100%	100%	100%	100%		
	AusNet Services	100%	98%	98%	98%	↑	↑
	Jemena	100%	98%	98%	98%		
NSW/ACT	Ausgrid	100%	17% ↑	24% ↑	9.0% ↑	0.5%	0.5%
	Evoenergy	100%	3.0%	10% ↑	↑	3.3% ↑	3.3% ↑
	Endeavour Energy	95%	1.8%		15% ↑	0.05%	
	Essential Energy	85%	0.014% ↑		7.0% ↑	7.0%	

Bar and value indicate level of visibility; upward arrow indicates increasing trend. Source: image from AEMO, Renewable Integration Study Stage 1 Appendix A: High Penetrations of Distributed Solar PV, 2020. Derived from detailed DNSP responses to AEMC LV network visibility survey.

There is, of course, another path. Customers' solar, batteries, flexible appliances, and electric vehicles (collectively referred to as distributed energy resources – DER) can be effectively integrated into the distribution system. Through their intelligent operation, they can enable the network to host additional customer DER and provide a number of additional services to the wholesale market and the network. All of this can make total costs decrease throughout the network – for those customers with DER and those without it.

Navigating towards this preferred path requires more effectively exploiting the networks' limits, though, as mentioned above, the networks' limits are generally unknown. While the invisibility of network limits may seem surprising, the reality is, grid operators have never before needed to know the status of the low-voltage network in hourly or even daily timeframes.

A one directional electricity grid – with power coming from a few, large, faraway power plants – delivered affordable and reliable energy through a 'set and forget' design. Such a grid can be well designed largely through effective planning, and relatively static customer behaviour enabled planning to work off reliable assumptions. Technology, specifically low-cost solar panels, changed all that.

Roughly one in four Australian households have solar today, and all signs indicate that customer adoption of solar is still accelerating. Add batteries and electric vehicles – whose widespread adoption has not yet been proven but can reasonably be assumed – and you have a very dynamic grid, with significant amounts of power coming from what was previously the "end of the line," and an increasingly large range of behaviour from customers. In short, the grid now changes so much, so quickly, that relying almost exclusively on planning and a "set and forget" design is no longer fit for purpose.

The clear alternative is to improve and increasingly rely on operations – that is, actively managing the grid in short timeframes (making regular changes to settings at least daily or weekly, if not every hour or every minute). Dynamic operations and management rely on data and reasonable visibility of the grid's status, and the primary challenge with increasing visibility of the low-voltage network is cost.

Australia's distribution system's total length is roughly 850,000 km – a length longer than a roundtrip to the moon.[1] Exhaustively monitoring it is simply not an option. Even adding a modest amount of visibility has proven challenging. One reason for this challenge is that network business' proposals to improve visibility typically rely on estimating the benefits from greater DER integration (which the visibility will enable). Estimating those benefits effectively, however, itself requires improved visibility. Networks struggle to credibly claim the benefits of increasing PV hosting capacity when they are unable to accurately identify the existing hosting capacity of a network. In other words, networks find themselves in a circular argument in which they lack the visibility to justify investments in additional visibility.

[1] Mission Innovation, Smart Grids Innovation Challenge Country Report 2019: https://www.mi-ic1smartgrids.net/wp-content/plugins/dms/pages/file_retrieve.php?obj_id=154

By adopting their draft determination on “access, pricing and incentive arrangements for DER”, the AEMC will encourage and facilitate network provision of export services to customers. The rule change would also encourage greater awareness of network limits and constraints, though demonstrating that the benefits of greater network visibility outweigh the costs of data collection may remain challenging. One potential way to address the challenge is to have DER provide a wider variety of benefits to the grid – not simply benefits to the wholesale energy market, but benefits to the transmission and distribution networks, like deferring or avoiding upgrades and managing voltage. These greater services would increase the value of DER, and thereby make initiatives to improve DER integration simpler to approve. But of course, making the provision of grid services commonplace from DER is itself a challenge that likewise requires better data and improved communication of that data to the wide variety of actors that engage with DER.

This report is the output of a project focused on these interlinked challenges and opportunities – providing low-cost visibility of the low-voltage network, assessing and communicating the grid’s limits, and mainstreaming customer DER network support – and developing a research roadmap to navigate them. The purposes of the project and this report are to help align industry stakeholders on the current challenges and issues related to network visibility and DER hosting capacity utilisation, and to identify a research roadmap that can help the RACE for 2030 CRC (and others) guide research in this topic.

S2: Industry Capability Review

S2a: Low Voltage Network Visibility Capability Review

Real-time visibility of network conditions at the low-voltage (LV) end of the grid is critical to the operation and planning of a highly decentralised power system. LV visibility enables the efficient management of network capacity to support the integration of large numbers of DER in the LV distribution network, and the delivery of DER services to consumers, networks and markets in a decarbonised economy.

LV visibility is instrumental to inform key network decisions across multiple timescales ranging from seconds to days for various use cases such as network state estimation and contingency management, DER balancing and dispatch, market services, constraint management, and planning.

Stakeholders – including network businesses – generally acknowledge that in Australia, low-voltage networks are characterised by low levels of visibility. Low visibility results from limited access to and existence of network data; in addition to wide discrepancies in smart meter data between networks, most networks have incomplete, unverified network connectivity models. Indeed, many networks have conflicting network models in use themselves, with variations between the data in GIS systems and in distribution management systems. Smart meter data, even where it does exist, may not include the necessary communications infrastructure to provide it at the latency required for certain use cases. The lack of LV visibility can result in uncertainty in network operation and planning decisions, leading to conservative capacity management practices and inefficient utilisation of DER and network infrastructure. As a result, customers become more likely to experience more stringent constraints to DER connectivity and operation than necessary.

Our industry capability review and engagement with stakeholders reveal three primary monitoring technologies with the clearest opportunities to improve LV visibility: smart meters, phasor measurement units, and customer energy monitoring and management systems.

- Smart meters, although still at relatively low levels of penetration in most networks, have immediate potential to improve LV visibility at relatively low cost with direct benefits to both customers and networks.
- Phasor Measurement Units (PMUs), an emerging advanced monitoring technology in Australian distribution networks, can offer the highest quality of data for network use cases.
- Customer energy monitoring and management systems, which have greatly evolved in recent years following advances in smart inverters and home automation, open new opportunities to leverage LV data. Data from solar and battery inverters as well as home energy management systems can be utilised to enhance LV visibility, while enabling customers to manage their electricity consumption and match it with their electricity generation and storage preferences.

Network use cases for LV data can be clustered in three broad application categories: network maintenance, operation and planning. Applications in network maintenance can leverage LV data to improve inspection and monitoring of network asset conditions and ensure compliance. Applications in network operation can use LV data to improve network performance and capacity management. Network planning applications can use LV data to forecast future network conditions and required investments and benefit customers by supporting integration of behind-the-meter DERs more accurately. All use cases can directly benefit DER owners by increasing the utilisation of DERs (and/or their data) and benefit all network consumers by increasing network utilisation.

LV visibility can be increased by installing new measurement devices or by procuring data from proprietary sources, including leveraging data from existing monitoring infrastructure (smart meters and energy monitoring systems). The latter in combination with selective network monitoring and modelling can lead to cost-effective solutions to increase LV visibility, depending on the data requirements of the target use case.

However, data sourced from a diversity of systems and tools, such as GIS, DER registers, smart meters and network models, also present challenges. Inconsistency in data formats and the lack of transparency of closed-source models and data impose barriers to the development of standard processes, technologies and policy required to accelerate the industry transformation to provide reliable, affordable, clean energy envisioned by RACE for 2030.

The review of industry capability and use cases for network data and models identifies gaps and challenges summarised in the following priority areas:

- Barriers to data quality, consistency and integration,
- Limitations in data granularity and accuracy,
- Cybersecurity vulnerabilities,
- Locational prioritisation of network monitors,
- Data procurement costs, and
- Barriers to transparent network and load models.

Recommended opportunities for further research to improve LV visibility include:

1. Developing accurate network models: Many use cases rely on network models, and new methods should be developed to extract accurate network models with minimum data requirements. An interesting avenue for future work is to identify the minimum required information of network models for different use cases. The selective use of smart meter data to develop and validate accurate models for LV networks is another interesting direction to explore.

2. Leveraging smart meters: While smart meters are arguably a first resort to improve network visibility, their deployment at scale in Australian networks is slow due to technical, regulatory, economic and public trust barriers. A key research direction involves the study of the minimum number of meters, the accessibility of their data, their location on the network, and the type and granularity of data required per LV data use cases.

3. Leveraging emerging monitoring technologies: In light of recent technological advances, several products have been developed for DER and customer energy monitoring and management. These products collect different data and use different formats to store data. These variations create interface challenges when data is provided by multiple third parties in different formats and qualities. In addition, trust concerns related to customer and device level data need to be considered. The value of having additional device-level metering should be evaluated against using additional channels utilised in the smart meters. A direction for future work is the development of technical standards to ensure that data is provided in more consistent, trusted and versatile formats. Recently, a group of leading technology providers and other stakeholders developed the DER Visibility and Monitoring Best Practice Guide. This voluntary code details what static and dynamic data should be collected by DERs to deliver the maximum benefit for all energy consumers. An important research direction is to determine how data is made available using large-scale trials and demonstrating effective data provision, utilisation and management.

4. Validating and adopting more open approaches to models and data: given that the network is shared infrastructure providing an essential public service with monopoly

protection, stakeholders see value in increasing the public release of network model and dataset benchmarks, such as those developed by the National LV Feeder Taxonomy Study. Open-source data and models can foster collaboration and higher quality solutions, reducing duplication of work, increasing trust and credibility, and enabling more transparent and informed policy development.

S2b: Assessing DER Hosting Capacity Capability Review

Network hosting capacity refers to the amount of DER that can be accommodated by a distribution network (or part of it) without adversely impacting power quality or reliability for normal operation at any point in time and at a given location under existing control configurations and infrastructure. Hosting capacity assessments can be conducted to measure either the amount of energy consumption (i.e. load) or export that a given network segment can accommodate. Hosting capacity assessments vary by technology – a different assessment is required to determine PV hosting capacity compared to battery hosting capacity. The accurate assessment of network hosting capacity is becoming a foundational enabler for system planning and operation as network processes change with the increase of DER.

Hosting capacity is dynamic in nature and can change depending on the weather and the behaviour of customers and their devices. Hosting capacity can also change due to various control approaches taken by network managers. Therefore, matching the physical hosting capacity with the flexible operation and/or interconnection of DERs is an alternative to traditional distribution upgrades. To meet the ongoing customer demand for DER connection, DNSPs need to know and effectively communicate the physical hosting capacity of their networks.

A hosting capacity assessment is at core a power system simulation study in which DER are increased on a network model until the network's technical limits are reached. The quality of the network model and data used in such studies are central to the accuracy of the assessment, which is affected by modelling and data errors and uncertainty. The intended use case is a key driver of the assessment, as it guides the selection of relevant impact factors – model inputs and associated assumptions underlying the calculation, such as network configuration, voltage regulation assumptions, thermal limits and target DER portfolio.

Best practise involves the following steps for the assessment of hosting capacity:

1. Establish a relevant stakeholder process,
2. Select and define the target use cases for the hosting capacity assessment,
3. Identify criteria to guide the implementation of the hosting capacity assessment,
4. Identify the network representation approach,
5. Develop a hosting capacity assessment methodology (or methodologies) and

6. Validate the results of the hosting capacity assessment over time against real data.

Poor access to LV network data and the lack of accurate network models increase uncertainty in hosting capacity assessments, leading to conservative operation and planning decisions.

The method selected to assess hosting capacity depends on the use case, data availability and model accuracy. Therefore, different methods can be used by different DNSPs. However, the lack of common service standards, or a common way for DNSPs to express and report on hosting capacity, can impact on the development of business cases and stakeholder decisions on DER integration, and the opportunity to connect DERs.

As a result, the equitable access of customer DER to network resources remains an open challenge due to several factors, including the inherent locational diversity of DER connections. Indeed, dynamic operating envelopes, an approach increasingly gaining favour in Australia as a cost-effective approach to integrating DER, rely on a regularly calculated hosting capacity assessment to identify the network operating envelope, and yet there is no clarity on what data and assumptions should be used and which ones are most critical to define accurate and equitable limits on customer DER. Both the ESB Data Strategy Consultation Report and the AER's Value of DER Methodology study underline the importance and value of consistency and guidance (potentially from the AER) on methodologies for calculating hosting capacity.

To address current gaps and challenges in the assessment of hosting capacity, further research is recommended in the following topics:

- Impact factors: Impact factors are data and assumptions used as inputs into hosting capacity assessments, including assumptions about network configuration, voltage regulation, customer and load behaviour, DER installation and inverter setting assumptions. Decisions on which impact factors to use significantly influence the assessed hosting capacity of a distribution network but modelling all potential impact factors is extremely difficult and computationally intensive. Further research is needed to define the most significant impact factors for each hosting capacity application use case.

- Optimal mix of data and models: Data requirements vary for different hosting capacity use cases, and network-wide monitoring can be expensive. Further research is required to evaluate data and model requirements to represent LV networks with the highest accuracy commensurate with the target use case for the hosting capacity assessment.

- Analysis framework: State estimation methods can be very effective to model networks with incomplete datasets. Further research is required to assess optimal mixes of data and models, and the importance of phase imbalance, data granularity and uncertainty per hosting capacity use case.

- Hosting capacity calculation methods: Hosting capacity methods differ in input data, accuracy, computation time, consideration of uncertainties, time resolution, and models used. Further investigation needs to be carried out to confirm that the available hosting capacity calculation methods are fit for purpose for the relevant use cases and impact factors. Further investigation is also warranted to ensure an appropriate way to measure and communicate the level of hosting capacity performance that a DNSP is providing to its customers within a nationally consistent approach as contemplated by the access and pricing rule change.

- Application use cases: Existing research and technology developments rely on hosting capacity assessments largely focused on solar PV hosting capacity. The assessment of combined hosting capacity for multiple DER technologies requires cross-evaluation of impacts of one technology on the other's hosting capacity. A proposed direction for research is to investigate hosting capacity under coordinated management of DER (e.g., batteries and EVs) and cost-reflective pricing on underlying load profiles. The equity of the control scheme and the fair distribution of capacity among customers needs to be considered in addition to the calculation of hosting capacity, as the calculation of hosting capacity itself depends upon the control scheme used or assumed.

S2c: Data Access and Mapping Capability Review

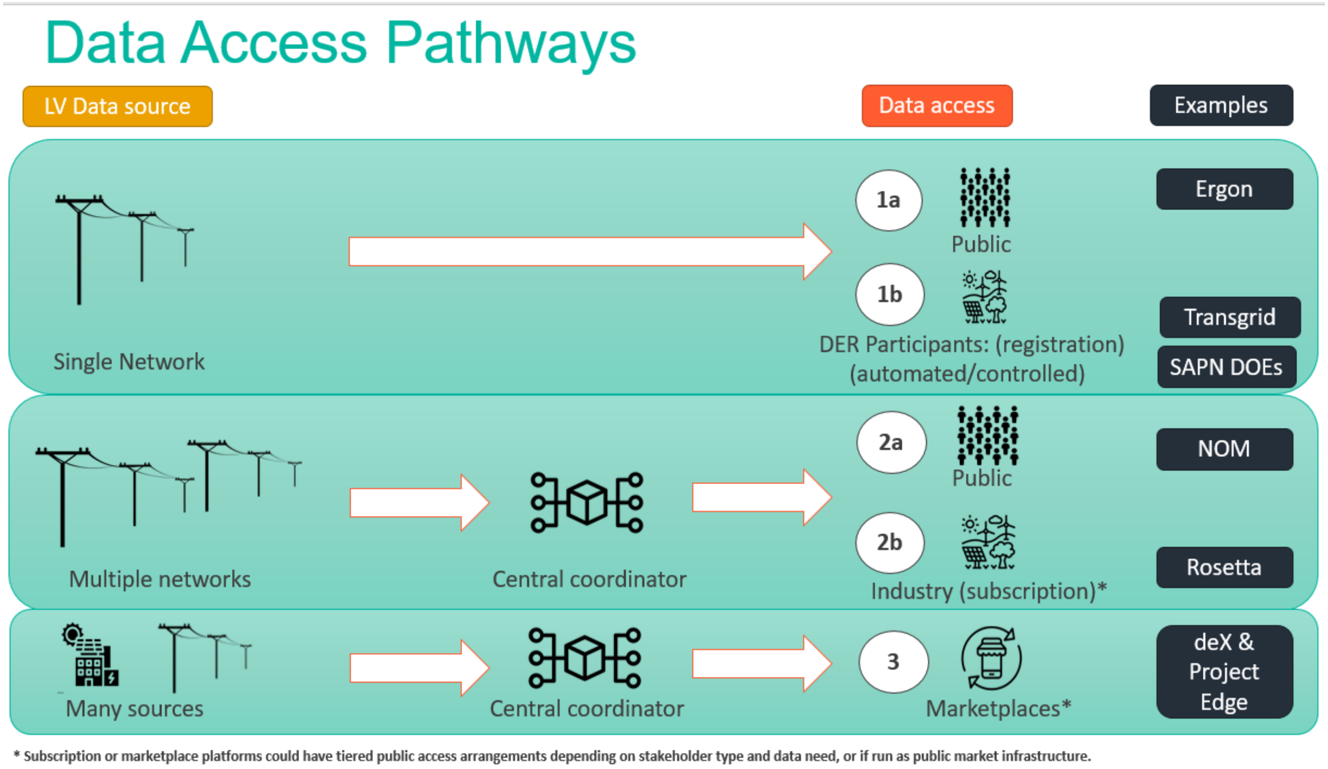
The transition to a decarbonised, smart and increasingly decentralised energy system will see the emergence of new capabilities to enhance DER hosting capacity and operate LV networks. This will increasingly involve participation of parties outside network businesses, from small DER prosumers to large retailers, aggregators and technology suppliers acting as agents or conduits. Therefore, external data access is critical to effectively communicate and facilitate information on LV network characteristics, conditions and emerging needs to address LV network challenges and create new opportunities to unlock DER value. Data access and transparency is also a vital enabler for trust between customers, networks, regulators and third parties. While mapping hosting capacity is the primary form of external data access application, the scope of this review has been broadened to a range of use cases, and other forms of access like APIs.

With the exception of smart metering jurisdictions (Vic, WA), current levels of LV visibility in Australian networks are low, and the primary focus of LV data usage has been *internal* to networks. As such, the use of LV data access and mapping techniques is in an early stage in Australia. While the potential for external LV data access appears high, the value proposition for publishing LV data needs to be better established. Furthermore, the level of coordination across industry parties to effectively communicate LV data and deploy mapping solutions remains unclear.

Through a capability review and engagement with stakeholders and subject matter experts, relevant aspects of LV data access and mapping are identified, including pathways for LV data access, key strategic considerations, lessons learnt from local and international precedents, and standing barriers and opportunities.

Existing initiatives have explored alternatives in how users can access network data. Factors that lead to different pathways include (i) LV data sources, (ii) how data is managed and processed, and (iii) the level and type of data access required. The figure below identifies three main pathways.

Figure S-1 Three Primary Data Access Pathways



To assess which data pathways are likely or useful for the industry more broadly, specific use cases are assessed against the strength of the need for i) *cross-jurisdictional coordination* (to provide consistency and market efficiency), ii) *external mapping* access (to enable each data use case, such as US-style hosting capacity map applications) and iii) contractual *transactions* if these require data to realise the DER or LV network value, as publishing to an actionable marketplace may negate the need for other "viewing only" data access platforms . This assessment revealed that:

- Regulators have relatively limited direct use cases requiring mapping, but a high need for cross-jurisdictional consistency. However, ensuring trust between consumers, commercial participants, networks and market operators is vital to the regulator's role, particularly in the context of hosting capacity calculation methodologies. Trust is unlikely to be achieved without a reasonable degree of data transparency, even if regulatory functions can largely be undertaken from consistently reported data.

- As network conditions and needs at the LV level become more operationally dynamic and move from the realm of 'planning' to 'operation', the need for data availability, analysis and action becomes far more granular, time critical and potentially automated. Such use cases are digital infrastructure intensive, which lends itself to common market tools and frameworks.

- Where multiple value streams and use cases can be harnessed within the same data access/provision infrastructure, this will strengthen and accelerate the case for external LV data presentation.

While the shape of future distribution services markets is uncertain, DER flexibility can be seen as a valuable system resource that may provide opportunities to alleviate emerging network investment. Networks that develop the data systems and capability to curate and release LV data in a form consistent with other jurisdictions will position themselves to capture the value of emerging use cases. As such, a 'no regrets' research program should aid in developing:

1. A shared understanding of the common raw and processed data outputs required for different use cases to meet the range of stakeholder expectations. A particular gap is EV data use cases.
2. Collaborative digital and data infrastructure, systems and processes to support implementation of LV data that help to 'stack' value from a range of use cases and achieve cross-jurisdictional consistency of data provision and processing, and can integrate with private or public marketplace developments.
3. Capability within networks to connect the planning and operational functions through spatial network models and data management.

S2d: Mainstreaming DER Network Support

DER devices can provide network support by shaping their operation to network conditions to improve power quality, security and reliability, contributing to improved utilisation of network hosting capacity.

Drawing on findings from industry reports and stakeholder interviews, mainstreaming DER network support can be advanced through the following enabling objectives:

1. Identify the best combinations of network and non-network options to provide network support and optimise utilisation of hosting capacity.
2. Outline how the process for evaluating DER-based options for providing distribution network support can be standardised to improve DER device standards and compliance.
3. Support data sharing between networks, DERs, and third parties.
4. Improve customer engagement through education and the development of new products and services.

Combined network and non-network solution mixes are likely to vary with network location, PV penetration level and feeder type. However, research categorising fit-for-purpose approaches in representative benchmark cases will advance the most effective avenues for trials and development. Recommended research opportunities include:

- Assessing combinations of network and non-network forecasting and control solutions to optimise DER hosting capacity across representative benchmark network cases.

- Assessing opportunities for mainstreaming network support services from flexible loads (e.g., air conditioning, hot water systems, pool pumps) in combination with current priority DER (PV and battery systems).

- Assessing potential impacts to the network of synchronised responses of large fleets of DER, e.g., to sudden market or grid contingency events.

- Investigating the interaction between cost-reflective network pricing and non-network solutions across different use-cases.

- Investigating the relative merits of structured 'bulk' procurement of network support services.

A standardised process for evaluating options for DER network support should stem from collaborative assessments, accurate models and data, and clear guidance from regulators. Recommended research advancing these objectives include:

- Comprehensive cost-benefit analysis considering all DER value streams quantifying implications from customer and network perspectives.

- Analysis of customer equity aspects of DER hosting capacity allocation and network services, including impacts and limitations arising due to network location. For example, the analysis can quantify how Volt-Watt/VAR automatic inverter responses affect customers at different network locations.

DER monitoring devices can be leveraged to provide valuable LV data to increase network visibility to support network operation and planning, contributing to improve the assessment of hosting capacity and dynamic operating envelopes. Data challenges ensue as DER data streams become integral parts of networks digital infrastructure.

Transparent processes on how DER data and services are managed can improve customer understanding of the benefits of DER participation and improve customer engagement.

Recommended research opportunities in these areas include:

- Surveying options for secure, automated data platforms that can integrate large volumes of DER data while preserving customer privacy.

- Progressing the objectives of the DER Visibility and Monitoring Best Practice guide by piloting the provision and use of a standardised set of solar PV and battery (and/or other DER) timeseries data and data management processes. Such research can assist the API task force in developing a standard API for DER communications and inform a NEM-wide standardised DER data collection and management process.
- Surveying customers to assess their perception of the most equitable ways to manage network hosting capacity.

S3: Research Roadmap

The overarching aim of this theme is to help customers connect and operate DER in ways that make financial and common sense to them by improving network and DER visibility. This research roadmap takes a phased approach to achieve a series of intermediate milestones to help the six research priorities deliver on this aim. The Research Roadmap table below highlights the milestones for each research priority across three timeframes.

Table S-3 Research Roadmap

Research Priorities	Milestones		
	2023	2025	2030
Data Acquisition	• Definition of "right data" for use cases (RQ1) • Protocols for interoperability & information exchange (RQ7)	• Low-cost technology to provide right data mainstreamed (RQ7)	• Data release framework operationalised (who, what, when) (RQ1,RQ7, RQ11)
Data Processing & Access	• Standardised definition of Hosting Capacity – inputs & outputs (RQ3, RQ12)	• Common digital infrastructure for LV data access use cases (RQ7) • HC calculation framework and tools facilitate transparency (RQ3, RQ12)	All stakeholder types have ready access to granular data required to execute role in DER (RQ7, RQ3)
	• DER processing platforms / LV network model development (RQ1, RQ3)		• LV network models have 3rd party access for solution development (RQ7, RQ3)
	• Integration of spatial data for network operations (RQ1)		
Decision Support Tools	• Capacity allocation use cases & value proposition for customers articulated and communicated (RQ2, RQ3) • Standardised assessment methodologies for non-network options to provide network support that address customer equity and other considerations (RQ1, RQ2, RQ3)	• Tools for connecting medium term use cases (RQ1, RQ2, RQ3) • Methods and tools for rapid risk-based decision making in spatial LV network planning (RQ1, RQ2, RQ3)	
Market Integration	• Data value proposition for different use cases (RQ9, RQ1)	• Business models / marketplace integration for data services (RQ9, RQ1)	• LV data feeds unified transaction platforms and settlement procedures for LV solutions (RQ8, RQ1)
	• Appropriate pricing structure and signalling mechanisms for different use cases (RQ9)	• DER Customers can equitably participate in wholesale and network markets (RQ8, RQ4, RQ5)	• Solutions to LV network issues are tailored to time and location (RQ2, RQ8)
	• Business case for flexible DER products / Better return on investment for customers (RQ5, RQ9)		• Established market for DER services (RQ5, RQ8,RQ9)
Customer Engagement	• Customer education / awareness programs (RQ5)	• Strategies to enable equitable customer access to network resources (RQ4)	
Policy Support	• DER device standards / settings (RQ10) • Technology Standards (RQ6)	• Safe integration of DER to electricity system to manage non-compliance (RQ6, RQ10)	• Compliance ecosystem for DER devices (RQ10)

S3.1 Recommendations

The research roadmap above identifies broad milestones that the research program should meet to enable reliable, affordable, clean energy by 2030. Given the rapid transition in the industry, identifying a detailed, prescriptive research program that spans the next ten years is inadvisable and prone to large errors. Nevertheless, some critical actions can be identified now that are important to achieving the program's broad aims. These were developed through industry consultations that focussed on prioritising research questions and workshopping project ideas industry was interested in resourcing.

A primary focus of Theme N2 is improved visibility of LV networks which will enable network companies to better plan their resources, allow more DER integration at the customer-level, and improve network utilisation. There are strong interdependencies in the first three research priorities identified. Better planning and decision-making require better tools and methodologies to assess hosting capacity and network constraints, which in turn require appropriate network models and the 'right data' for different use cases. The critical actions identified below align with this narrative:

1. Understanding the data landscape
    a. Exploring effective ways of showcasing and sharing information
    b. Developing rules for governing data
2. Developing tools and models for efficient and equitable network planning
3. Exploring integrated approaches to using DER to provide network services
    a. Identifying value of DER services for networks and customers

Prioritising investment in projects that address these three high-level opportunities is recommended, but there are notable limitations to this list. Despite the research highlighting the significance of issues relating to the market, customer behaviour and policy support, these were absent from the stakeholders' list of prioritised research projects. These research topics should not be ignored but may be better prioritised within other RACE themes. Given the interdependencies and overlap of opportunities regarding market structure, policy, and customers being explored by other RACE themes, a key role for RACE will be integrating lessons across its four different programs.

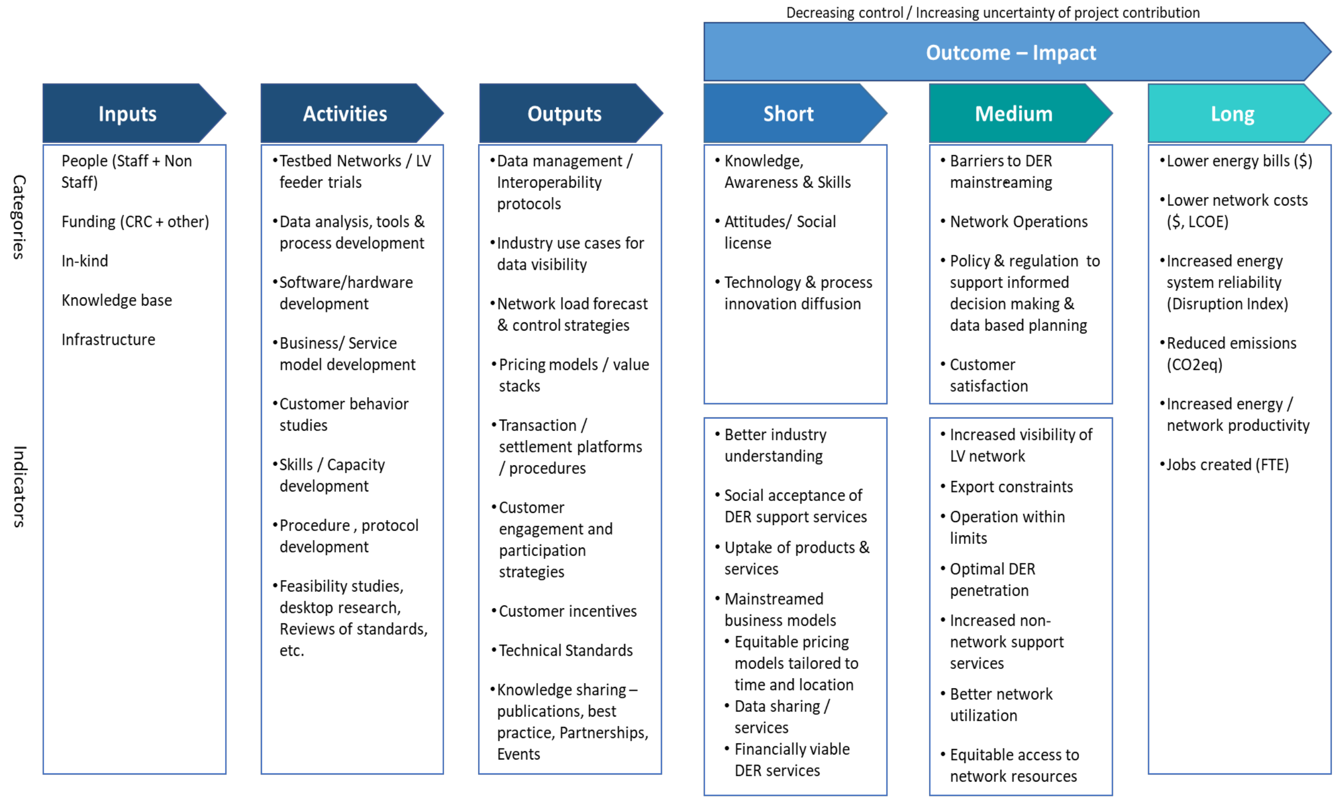
S3.2 Impact Planning

The impact framework is an essential component of RACE for 2030 as it enables each of its four program themes to strategically plan their research. It also provides the opportunity for those proposing projects under the themes to consider their pathway to impact early in the design phase and enable them to then demonstrate their impact over time.

The theory of impact for Theme N2 follows a familiar chain, from inputs (time, funds, people, etc.) and activities to outputs, outcomes, and impact. For projects funded by RACE for 2030, resources (e.g. grant funds and time) are used as inputs to support various project activities (e.g. software development, demonstration projects, and desktop studies). The effectiveness of these activities depends on knowledge and technology diffusion – the reach of the knowledge sharing activities or the uptake of the newly developed product. This diffusion will seed new ideas among stakeholders and enable industry development, such as implementing new practices or reducing barriers to mainstreaming DER. These new practices, in turn, can lead to wider societal impacts, such as reduced greenhouse gas emissions.

Figure S-2 provides additional detail on the impact framework and applies it specifically to this research topic. The figure also identifies indicators that can be evaluated at each stage of the chain.

Figure S-2 Impact framework for Theme N2: LV Network Visibility and Optimising Hosting Capacity



S4: Economic Potential Analysis

This section provides a preliminary analysis of the value of the potential impacts of research into optimising hosting capacity for DER. This is a broad and complex question, so we have deliberately sought to keep the scope narrow. The analysis leverages existing models and datasets to identify the costs and benefits across different scenarios.

A definitive cost-benefit analysis is not possible and outside the scope of this report; we seek rather to provide an indicative range, compare that range with other estimates and understand which drivers and uncertainties are most impactful.

Rooftop solar PV is the most widespread and affordable DER technology and its capacity continues to grow strongly. Given the existing and continued large scale deployment of rooftop solar, it is a key focus of the analysis. We have also assessed vehicle-to-grid batteries as the next highest value opportunity for value to be gained from improved hosting capacity.

Broadly speaking, the methodology of the study is to determine the DER energy or capacity that is being limited by existing or expected hosting capacity constraints and what value they would have for the electricity system if they were no longer constrained.

No new estimates of the costs of increasing hosting capacity are presented in this report. However, we have included some data and insights from existing studies. We also use existing studies to check the plausibility of the updated benefits estimates.

S4.1: Analysis of rooftop solar PV and hosting capacity

The level of projected PV curtailment is shown for Central and High DER AEMO scenarios. The level of curtailment can be a significant source of lost electricity, for example up to 9% of NEM operational demand by 2050.

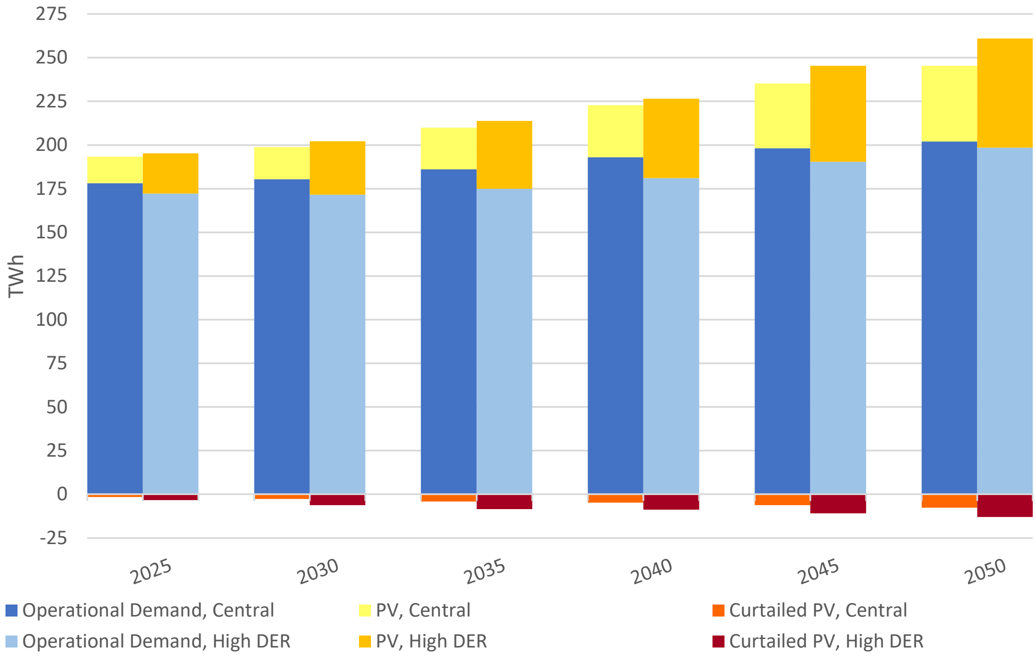


Figure S-3 Projected total demand in the NEM broken down into operational demand and solar PV generation. The curtailed PV amount is shown for full curtailment and median demand.

The method for calculating the benefits of avoided rooftop solar PV curtailment for the generation sector focuses on half hourly generation prices at the time of the curtailment event are used to estimate value. The results of the projected range for the value of curtailed rooftop solar PV generation under the AEMO Central and High DER scenarios are shown in Figure 7. The value represents the discounted sum of avoided generation sector short run marginal costs between 2025 and 2050 (on the basis that the outcomes of hosting capacity research begins to be felt in the market from 2025 and provides ongoing benefits).

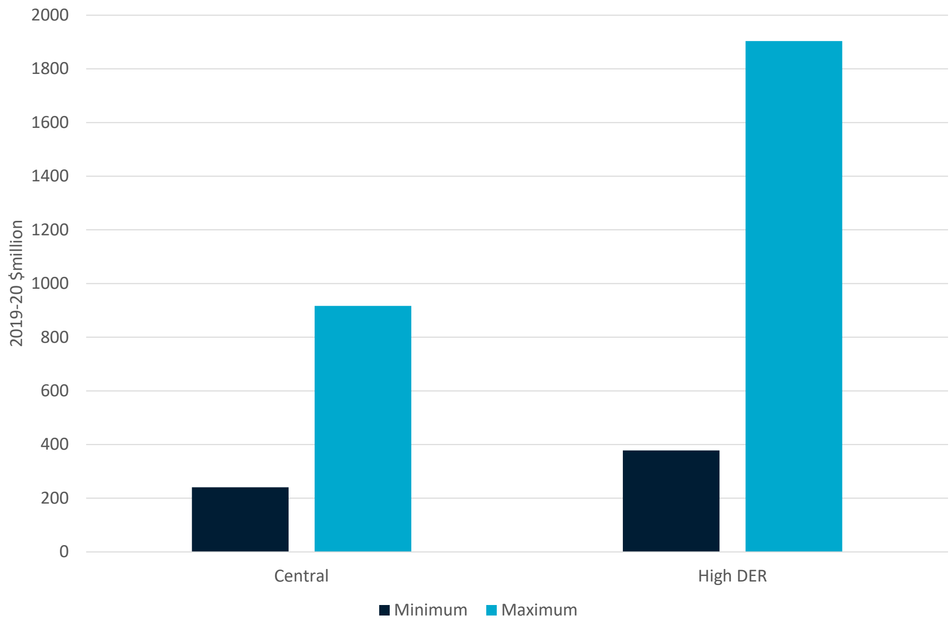


Figure S-4 Projected range for the value of curtailed rooftop solar PV generation in the NEM under the AEMO Central and High DER scenarios

S4.2 Analysis of vehicle to grid and hosting capacity

The avoided total costs method is used to determine which large-scale battery costs are avoided by allowing the full power capacity of V2G participating electric vehicles to perform similar services to large-scale batteries. Based on the assumptions used for the analysis (which are discussed in the full report) the increased storage capacity available from increasing hosting capacity available to V2G participants is 6.8GW by 2050. Summing up the discounted values to 2050, we find the benefit of increased hosting capacity through avoided large-scale battery costs is $2.3 billion. While this seems a large number, we would generally expect to spend between $500 and $1000 billion on new electricity generation and storage infrastructure between 2020 and 2050. Based on AEMO's published 2020 ISP modelling of the Step Change scenario, the system will require 23.3 GW of storage by 2042. Using Graham et al (2020) data, the cost of installing this storage capacity is estimated to be around $26 billion (undiscounted).

The major risk to realising the V2G benefits is that, given the slow start to electric vehicle uptake in Australia and accelerating deployment of renewables, substantial quantities of large-scale battery storage may be constructed before V2G may begin to compete as an alternative source of storage. Roll out of bidirectional capable chargers may also be delayed as well as the vehicles. Should this be the case we also considered a case where only half the vehicles were available in which case the benefit is reduced to $1.2 billion.

S4.3 Literature on costs of increasing hosting capacity

The cost of increasing hosting capacity can encompass many activities from expanding distribution infrastructure to managing existing resources in a way which increases the scope of existing infrastructure to accommodate DER operation. Management itself can be achieved through various levels of intervention from standards and incentives through to direct control.

To understand what this range of costs might look like Graham et al. (2019) [1] reviewed studies by SAPN (2019) [2] and Baringa Partners (2019) [3]. It also included AEMO's organisational running costs as a ballpark estimate of the cost of running an additional Australian electricity market institution. The SAPN study represents an example of the simpler approach of dynamically signalling network constraints. The costs in that study only relate to South Australia but were scaled up to national levels for comparison purposes. The Baringa Partners study was commissioned by the UK Open Energy Networks project and has been adjusted for currency differences and UK electricity system scale.

Graham et al (2019) [1] concluded that, based solely on these available data, a reasonable estimate of the cost of DER integration for an Australia-sized electricity generation system might be $600 million to 2030 and $1 billion to 2050 on an NPV basis.

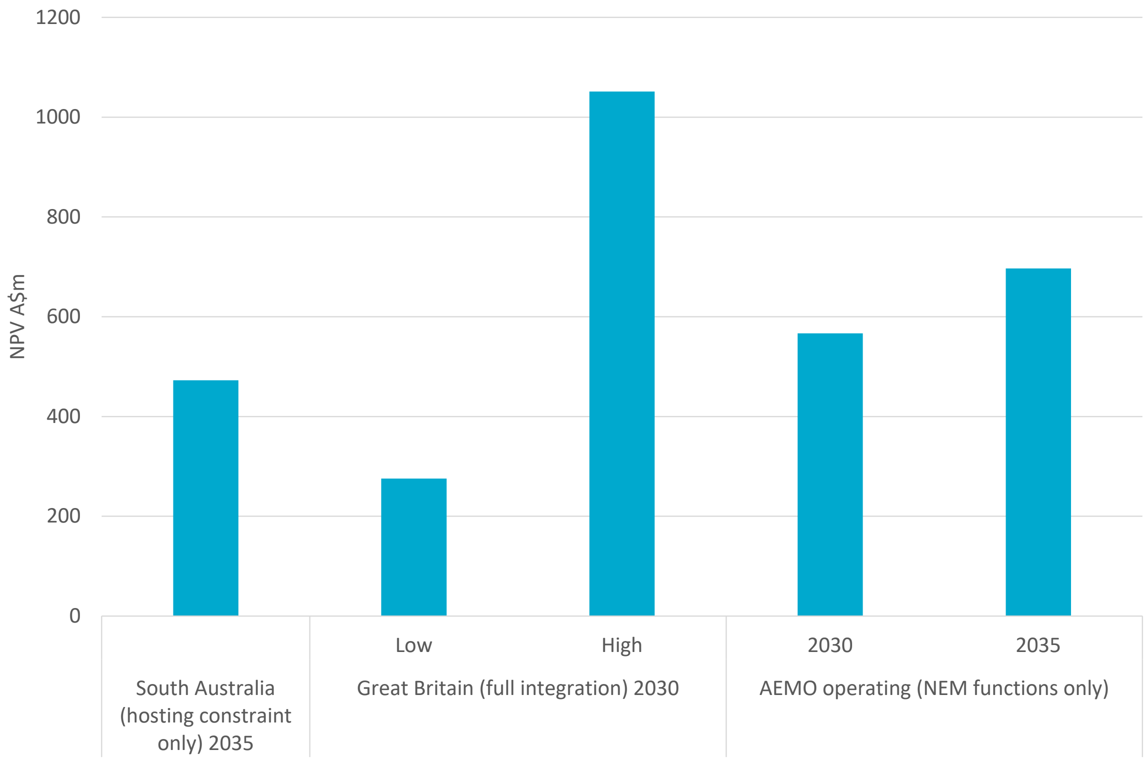


Figure S-5 Estimates of the cost of DER integration (partial or full) to 2030 or 2035 normalised to an Australian-sized electricity generation system.

S4.4 Net benefits of increased hosting capacity

Table S-3 Summary of estimated cost and benefits of increasing hosting capacity

Study	Costs	Benefits	Comments
Current study	-	$1.7b to $5.1b	Two DER technologies, generation sector only to 2050
Graham et al. 2019	$1.0b	$2.0b to $30.0b	All technologies, all sectors to 2050. From basic to high level of DER management
Baringa Partners 2020	$3.0b to $4.2b	$3.0b to $7.8b	All technologies, all sectors to 2039. High level of DER management

This analysis was designed to be a targeted update of key opportunities for benefits for increased hosting capacity. The narrowness of the scope has meant there is more work to do in terms of a definitive answer on this topic. However, even were the scope broader there are range of uncertainties and practical limits to overcome. We highlight that it is difficult to understand how big the current problem of rooftop solar PV outages is due to lack of low voltage network visibility and confidentiality of customer data. There is a circular problem in that a lack of network visibility leads to opaque benefits for optimising DER integration, which leads to continued low funding to increase network visibility required to accurately assess benefits and identify the value of DER integration.

Some suggested priorities for future work include:

- Coverage of more technologies than rooftop solar PV and V2G batteries
- Updated estimates for network sector benefits (this study only provided new insights for generation sector benefits)
- Further exploration of the driving factors of overvoltage on system strength curtailment to better understand the range of results
- Gathering of data on the prevalence of current settings and future intentions around connection curtailment and regulatory constraints
- Understanding the range of inverter disconnection events to better quantify the level of curtailment, full or partial and length of time.

1 Introduction

There is only one boss. The customer. And [they] can fire everybody in the company from the chairman on down, simply by spending [their] money somewhere else.

–Sam Walton: Made in America, My Story, with J. Huey (1990)

More so than anywhere else in the world, Australia's electricity customers are choosing to spend their money on rooftop solar PV systems. There is a worrying trend in Australia, however, to limit customers' PV connection, generation, and export due to the real and perceived limits of the low-voltage distribution network.

The limits placed on solar connections result from the fact that the electricity network has physical limits that, if breached, damage customer and network equipment and endanger safety. While these limits, also known as network hosting capacity, are knowable, they are for the most part unknown within the low-voltage distribution network. This lack of knowledge predisposes network businesses to act more conservatively than they would with greater awareness of the true limits. The result is a lower overall utilisation of existing network infrastructure, greater costs, and reduced control by customers over their energy usage.

Table 1-1--DNSP LV network visibility (DNSPs surveyed by the AEMC and ENA in 2019)

DNSP		MV	LV		Behind meter		
		Zone substation feeder	Distribution transformer	LV feeder	Customer connection	Inverter exports	Customer consumption
SA	SA Power Networks	80%	3.4% ↑	↑	0.1% ↑	0.0%	
QLD	Energex	100%	40% ↑		1.5% ↑		
QLD	Ergon Energy	95%	3.5% ↑				
WA	Western Power	100%	1.0% ↑	↑	5.0% ↑		
VIC	Citipower and Powercor	100%	99% ↑	99%	99%		
VIC	United Energy	100%	100%	100%	100%		
VIC	AusNet Services	100%	98%	98%	98%	↑	↑
VIC	Jemena	100%	98%	98%	98%		
NSW/ACT	Ausgrid	100%	17% ↑	24% ↑	9.0% ↑	0.5%	0.5%
NSW/ACT	Evoenergy	100%	3.0%	10% ↑	↑	3.3% ↑	3.3% ↑
NSW/ACT	Endeavour Energy	95%	1.8%		15% ↑	0.05%	
NSW/ACT	Essential Energy	85%	0.014% ↑		7.0% ↑	7.0%	

Bar and value indicate level of visibility; upward arrow indicates increasing trend. Source: image from AEMO, Renewable Integration Study Stage 1 Appendix A: High Penetrations of Distributed Solar PV, 2020. Derived from detailed DNSP responses to AEMC LV network visibility survey.

There is, of course, another path. Customers' solar, batteries, flexible appliances, and electric vehicles (collectively referred to as distributed energy resources – DER) can be effectively integrated into the distribution system. Through their intelligent operation, they can actually enable the network to host additional customer DER and provide a number of additional services to the wholesale market and the network. All of this can make total costs decrease throughout the network – for those customers with DER and those without it.

Navigating towards this preferred path requires more effectively exploiting the networks' limits, though, as mentioned above, the networks limits are unknown. While the invisibility of network limits may seem surprising, the reality is, networks have never before needed to know their status in short term timeframes.

A one directional electricity grid – with power coming from a few, large, faraway power plants – delivered affordable and reliable energy through a 'set and forget' design. Such a grid can be well designed largely through effective planning, and relatively static customer behaviour enabled planning to work off reliable assumptions. Technology, specifically low-cost solar panels, changed all that.

Roughly one in four Australian households have solar today, and all signs indicate that customer adoption of solar is still accelerating. Add batteries and electric vehicles – whose widespread adoption has not yet been proven but can reasonably be assumed – and you have a very dynamic grid, with significant amounts of power coming from what was previously the "end of the line," and an increasingly large range of behaviour from customers. In short, the grid now changes so much, so quickly, that relying almost exclusively on planning and a "set and forget" design is no longer fit for purpose.

The clear alternative to relying on planning to ensure a reliable and affordable grid is to improve and increasingly rely on operations – that is, actively managing the grid in short time frames (making regular changes to settings at least daily or weekly, if not every hour or every minute). Dynamic operations and management rely on measurement and data and increased visibility.

The primary challenge with increasing visibility of the low-voltage network is the cost. Australia's distribution system's total length is roughly 850,000 km – a length longer than a roundtrip to the moon.[2] Exhaustively monitoring it is simply not an option. Even adding a modest amount of visibility has proven challenging. A reason for this challenge is that network businesses proposals to improve visibility typically rely on estimating the benefits from greater DER integration (which the visibility will enable). Estimating those benefits effectively, however, itself requires improved visibility. Networks struggle to credibly claim the benefits of increasing PV hosting capacity when they are unable to accurately identify the existing hosting capacity of their system. In other words, networks find themselves in a circular argument in which they lack the visibility to justify investments in additional visibility.

By adopting their draft determination on "access, pricing and incentive arrangements for DER", the AEMC will encourage and facilitate networks actively providing export services to customers. This rule change would also encourage greater awareness of network limits and

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[2] Mission Innovation, Smart Grids Innovation Challenge Country Report 2019: https://www.mi-ic1smartgrids.net/wp-content/plugins/dms/pages/file_retrieve.php?obj_id=154

constraints, though demonstrating that the benefits of greater network visibility outweigh the costs of data collection will likely remain challenging.   One potential way to address this challenge is to have DER provide a wider variety of benefits to the grid – not simply benefits to the wholesale energy market, but benefits to the transmission and distribution networks, like deferring or avoiding upgrades and managing voltage. These greater services would increase the value of DER, and thereby make initiatives to improve DER integration simpler to approve. But of course, making the provision of grid services commonplace from DER is itself a challenge that likewise requires better data and improved communication of that data to the wide variety of actors that engage with DER.

This report is the output of a project focused on these interlinked challenges and opportunities – providing low-cost visibility of the low-voltage network, assessing and communicating the grid's limits, and mainstreaming customer DER network support – and developing a research roadmap to navigate them. The purposes of the project and this report are to help align industry stakeholders on the current challenges and issues related to network visibility and DER hosting capacity utilisation, and to identify a research roadmap that can help the RACE for 2030 CRC (and others) guide research in this topic area.

The immediate next section summarises our overall methodology for conducting this study. After that an extended section focused on the existing state of the industry's capability in addressing these topics follows, with sub-sections focused on four sub-topics (visibility, assessing hosting capacity; data mapping; and mainstreaming DER network support). We progress then to an identification of barriers to solving industry challenges and a list of research questions. Finally, we conclude with an economic potential assessment that provides a rough, but indicative value of effectively optimising DER hosting capacity in Australia between 2025 and 2050.

2 Methodology

This Opportunity Assessment focuses on the interconnected problems of network visibility and hosting capacity. This report is the manifestation of a project that has involved significant iteration, feedback, commentary and thought from the authors along with a broader member of stakeholders, who are largely (though not entirely) represented by the Project Steering Committee and the Industry Reference Group (IRG).

The three main outputs of this project are a research roadmap, an impact framework, and a set of key performance indicators to track progress within this theme during the remainder of the RACE for 2030 CRC. This section describes the roadmap for developing the roadmap and the other outputs.

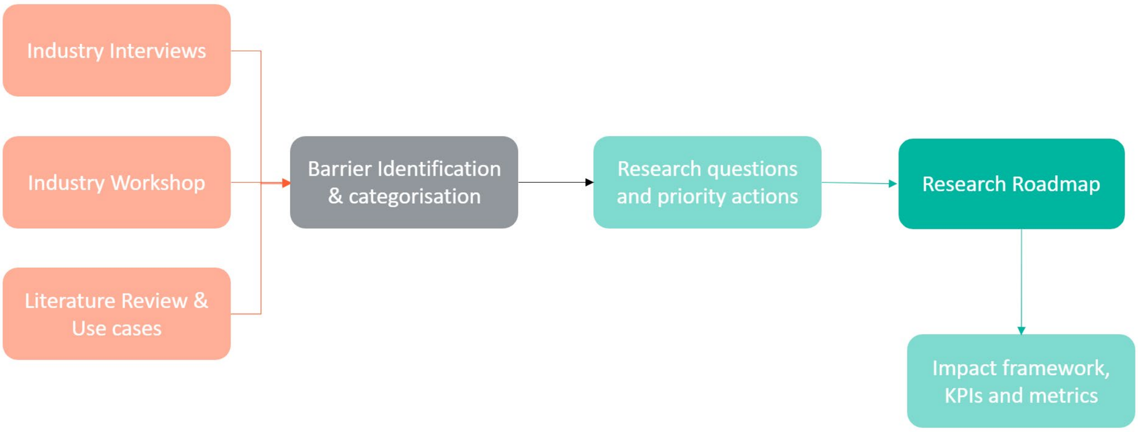


Figure 2-1 -- A Roadmap to Develop a Research Roadmap

The research roadmap as such is a list of milestones – specific deliverables we recommend be completed in the next three, five, or ten years to address a set of research questions and research priorities. To arrive at these research questions and priorities, we started by scanning the landscape and understanding the problem space. We conducted a series of more than twenty-five interviews with industry stakeholders and held a dedicated workshop with the IRG to identify and clarify industry barriers. We also conducted a thorough review of existing industry capability – and that review is documented in the next section of this report.

By combining this review of industry capability with stakeholder interviews and workshops, we developed an exhaustive list of barriers. To address these barriers, we developed a long list of research questions, that we summarised to a shorter list of twelve. We workshopped these research questions with the project steering committee, to better understand key industry and research priorities. The six identified research priorities form the essential framing element of the roadmap. The roadmap, along with a couple of antecedent impact frameworks, were used to design an impact framework for this topic. The framework includes short- and medium-term outcomes, against which a list of key performance indicators, and metrics to measure them, were developed.

3 Low Voltage Network Visibility

3.1 Review scope

Historically, distribution networks have been designed on a 'fit and forget' basis with an adequate safety margin for its anticipated loading level and power flows. Hence, DNSPs have undertaken limited monitoring of the LV networks because it was not necessary for them to know exactly what was happening on the network all the time. Conventionally, lack of real-time visibility of LV distribution networks has been justified by the presence of unidirectional power flow from transmission grids to distribution networks and economic issues. For such a configuration, the peak load profile and fault current levels are the main design and operation factors, and grid operators do not require detailed data beyond the transmission connection points. Unidirectional power flow combined with accurate forecasts of customer load gave grid operators a fairly good overview about the operating state of distribution networks.

However, increasing DER integration at the customer level can cause a range of challenges for existing networks, including reserve power flows and power quality issues. Addressing these challenges requires improved visibility of LV networks. Improving the visibility of LV networks through the deployment of smart meters, for example, can facilitate the management of changes occurring at the customer level due to DER deployment. Improved network visibility enables DNSPs to better establish their hosting capacity and make more informed investment decisions for the benefit of consumers.

The main barrier to improving LV network visibility is the limited availability of measurement data from distribution networks: an insufficient number of points are metered, and the measurements taken tend to be inadequate. Grid digitisation, enabled by recent technology advances, is the key enabler to improve network visibility. Technologies that capture new network information can provide important data on what is happening in the network. The provided data improves the efficiency of network management and operations for a more affordable, reliable, and safe electricity supply. This section covers some pertinent aspects of LV network visibility, including enabling technologies, use cases and key barriers and challenges. In particular, data requirements for different use cases are identified and the technologies that can be employed for data collection are reviewed. Key barriers and limitations are highlighted, and some recommendations are given for the future works.

3.2 Data sources and monitoring technologies

3.2.1 Data sources

In order to collect data from LV networks, various options and sources can be employed. Some options require installation of new devices or procurement of data from proprietary sources, while there are some options that leverage existing equipment and data sources. The latter is likely to have a lower cost. Hence, instead of network wide monitoring, combinations of data sampling and network modelling can be used as a cost-effective solution. The AEMC's "Integrating distributed energy resources for the grid of the future" identifies the following as potential sources of information:

- **DER register:** provides static data on the DER systems connected to the NEM. The data on each installation includes the installed capacity, and the make and model of inverter used for the DER system.
- **Smart meter data:** allows consumers and market participants to see both incoming and outgoing flows of electricity. Smart meters are already capable of providing a large amount of information about voltage, consumption and exports.
- **Consumer data right for energy:** consumers could access relevant NMI standing data fields and DER register information, that could help them to understand and manage their DER usage.
- **Inverter data:** smart inverters can provide information that is not obtainable from smart meters. For example, smart inverters can provide information on power produced, even where that power is consumed on the premises.
- **Data on DNSP monitoring and investments dealing with DER:** DNSPs make some of their information available either through regulatory planning reports, including distribution annual planning reports (DAPR) in which DNSPs are required to publish their forecasts of maximum demands for relevant network assets, the constraints they have identified based on these forecasts, and their investment options.
- **ARENA projects:** The Australian Renewable Energy Agency (ARENA) has supported several integration studies by DNSPs, universities and other interested parties developing new ways of using DER in the distribution networks. Information on and data from the projects are published as part of ARENA's Knowledge Bank.

3.2.2 Data requirements

As discussed in more detail below, data requirements vary for different use cases and hence, a range of various technologies can be employed to obtain the data. In general, use cases focused on network monitoring require data from power quality monitors, smart meters, and smart inverters. This data can be collected from different systems and tools, such as GIS, a DER register, smart meters and power flow models. Data from network sensors and smart meters are the minimum requirement for dynamic voltage control. In case of hosting capacity calculation, most of the approaches require a network model, which can be obtained using network asset information, GIS data, data from network sensors and AMI data, smart meter data, and estimated load data.

3.2.3 Monitoring technologies

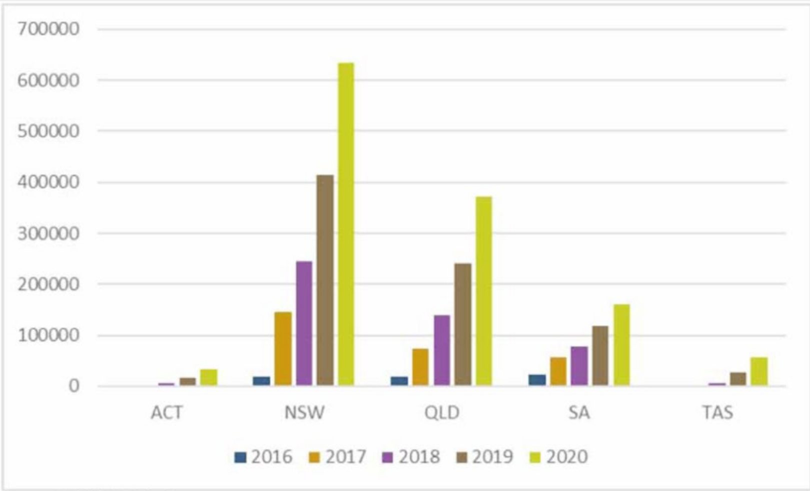
Smart meters

Smart meters are one of the monitoring technologies with the most immediate potential for improvements to network visibility bringing benefits to both customers and network operators. They can facilitate increased flexibility of tariff options by allowing implementation of cost-reflective pricing that better reflects the value of electricity supplied, when it is supplied, and reward consumers for changing their consumption. Smart meters provide customers with:

- More granular information and price signals to enable them to actively manage their energy profile.
- Different tariff structures which provide the opportunity to implement more cost reflective pricing.
- Access to new products and services e.g., live data monitoring, and load management.
- Better services from retailers and network providers.

At the same time, network operators can use data from smart meters to improve visibility of their networks. Without smart meter data, network providers today rely on manually obtained data to plan the network, which leads to inefficient outcomes and ultimately higher costs to customers. Indeed, limited access to real-time data obliges network providers to take more conservative approaches, which in turn, reduces the hosting capacity of the network, and consequently customers likely experience significantly more solar constraints than necessary.

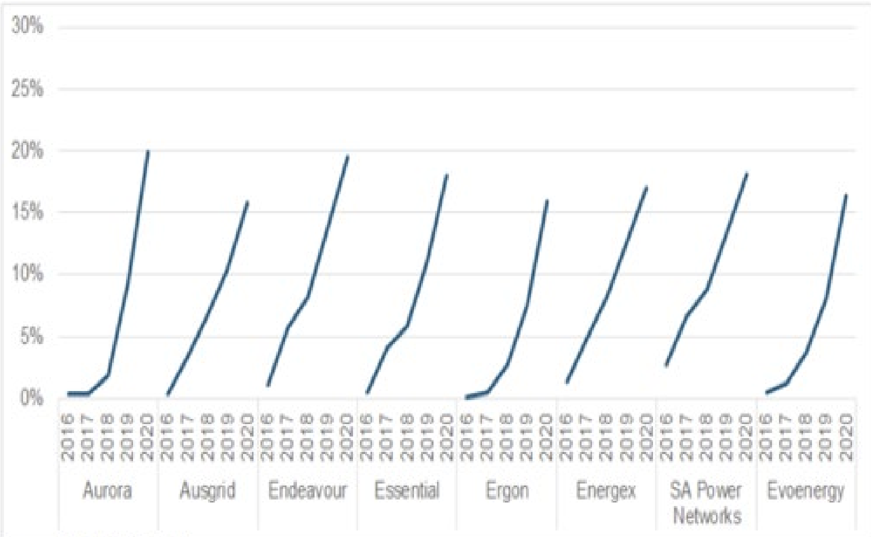
A review conducted by Australian Energy Market Commission (AEMC) in December 2020 concluded that the penetration of smart meters has increased in the past 2 years, reaching 1.04 million (17.4% penetration) in all states excluding Victoria. The total number of smart meters installed in each state is illustrated in figure 1. NSW has highest number of smart meters installed; on the other hand, Tasmania has the highest penetration reaching 20%.



Source: AEMO (MSATS data)
Note: Data in this chart shows smart meters for small customers only.

Figure 3-1 - Smart meter penetration in each state [4]

Furthermore, smart meter penetration differs between DNSPs. As shown in figure 2, compared to other DNSPs, Ausgrid and Ergon have the lowest percentage of smart meters in their network. It is essential to understand the drivers for smart meter installation. According to AER, between 2019-2020 it was found that there are four reasons for installing smart meters. Customer requests is the key driver followed by new connection**,** with new meter deployment (retailer-led) being the least category.



Source: AEMO (MSATS data)
Note: Data in this chart shows smart meters for small customers only.

Figure 3-2- Percentage of smart meter penetration in each DNSP [4]

Apart from Australia, smart meters are being deployed worldwide including in the United Kingdom, European Union (EU), New Zealand, Canada, China, and parts of America. The current state of the market for smart meters is reported in [4] as follows:

- **United Kingdom:** one of the key drivers for smart meter roll out is providing flexibility for ways gas and electricity customers can participate in the market.

- **European Union (EU):** finds in necessary to deploy smart meters to support their smart gid development. It has high penetration percentage of 99 and 98% in Italy and Finland, respectively.
- **New Zealand:** roll out depends on customer benefits, primarily increased accuracy in billing and forecasting. As of 30 September 2020, 89% of residential connections have been installed with smart meters.
- **Canada:** smart meters are viewed as primary components in renewable investment, increase in decentralised renewable energy and smart grid technologies deployment. With 82% of the electricity meters being smart meters.

Phasor Measurement Units (PMUs)

Phasor Measurement Units (PMUs) are a promising metering technology for power networks. In simple words, a PMU is a measurement device, capable of measuring the synchronised voltage and current phasors in power systems. A distinct peculiarity of PMUs over other metering devices used in power networks is that the measurements are time-stamped and synchronised to the coordinated universal time reference. Having a common time-reference allows PMUs to define “phasors” and compare them in different locations in a power grid, because the instantaneous phase of a given stationary sinusoidal signal cannot be defined unless it is referenced to a common value. Therefore, “synchrophasors”, which are phasors calculated at different locations all using a common time reference, can be obtained from PMUs. Availability of the synchrophasors in power networks can provide frequent and accurate snapshots of the status of the electrical grid, enabling development of advanced processes such as state estimation, which is crucial for network operation.

Traditionally, state estimation has been performed by the supervisory control and data acquisition (SCADA) system with a refresh rate in the range of few tens of seconds (or even minutes). Having high refresh rate synchrophasors can significantly improve classical state estimation processes, enabling the implementation of novel real-time management, control, and protection functionalities leading to optimal, affordable and efficient operation of the electrical grid, enhancement of the security of supply, and prevention of blackouts.

PMUs were originally studied and deployed in large transmission networks, and one of their primary applications have been in the context of Wide Area Measurement System (WAMS). In this context, PMUs have various applications such as power swing detection, stability enhancement, real-time congestion management, disturbance management, and adaptive protection.

The use of PMUs and WAMS in distribution networks is becoming an emerging research topic. Compared to transmission networks, the phase angle displacements between grid nodes in distribution systems are extremely small. As a consequence, PMUs dedicated to distribution networks require higher measurement accuracy. In addition, measurements in distribution networks are more contaminated with measurement noise, harmonics, and non-predictable dynamics due to the presence of DERs and power electronic converters. This measurement noise makes it challenging to provide high accuracy synchrophasor estimation in the presence of interfering signals. A further challenge is related to the cost of PMUs, which can limit wide roll out of these advanced monitoring devices.

Having said that, compared to legacy technologies that are designed to monitor specific grid conditions and limited applications or uses, PMUs collect a wide set of grid condition data from many locations, which can be used for a broader and evolving set of use cases and applications. This enables development of advanced applications including [5]:

- State or condition monitoring of the distribution system.
- Monitoring and analysis of customer-owned, behind-the-meter distributed generation and energy storage devices, enabling better forecasting and integration of those devices.
- Measurement and verification of customers' energy efficiency, demand response and load management activities (subject to appropriate privacy protections).
- Monitoring and analysis of significant end-user loads (for example, clusters of electric vehicle chargers).
- Identification of asset and equipment problems, including detection and advance warning of equipment operational issues and failures.
- Fault detection (including high-impedance faults), location and event forensics.
- Anomaly detection, including potential cyber-intrusions.
- Detection of previously unknown dynamic events (for example, control instabilities or oscillations) that are not recognizable with traditional monitoring.

A summary of PMU data applications and the data requirement is presented in Tables 3-1 and 3-2 [6]

Table 3-1- Applications using synchrophasors and the data requirement.

Application	Measurement Quantities	Time Resolution	Accuracy	Latency & Continuity
Voltage profile and variability	Voltage magnitudes critical, voltage phase angle useful for tap change detection	1 sec or better resolution is useful, synchronisation between & among measurement locations essential	Absolute accuracy of 0.5% is adequate	Retain complete history
Awareness of real-time loads	Current magnitudes very useful, voltage phase angle can be proxy for current if network impedances are	1 cycle or better resolution reveals transient behaviours, full time domain characterisation to 30kHz sampling of	Absolute 0.5% error likely adequate	Operationally relevant latency on the order of 1 sec

	known, current phase angle useful for P,Q decomposition & reverse power flow	interest to reveal harmonics		
Outage management	Voltage and current magnitudes	1 sec likely adequate	1% error likely adequate	1 sec latency likely adequate
System frequency & oscillation detection	Voltage phase angle essential	1 cycle or better & synchronisation essential	Change in time, not absolutely accuracy of interest, 1% error adequate of stable	Retain complete history, latency requirement may vary, sub-second critical information protection
Island detection; microgrid islanding & resynchronisation	Voltage phase angle essential	1 cycle or better	Insensitive to magnitude error, phase angle error stable to 0.01	Continuous monitoring, sub-second latency critical if informing protection
Distribution state estimation and topology detection	Voltage phasors, sensitive to placement and number of sensors, network model and load data important	Synchronisation critical	Absolute accuracy on the order of 0.0001 pu, requires correction for transducer errors	Operationally relevant latency on the order of 1sec
Topology detection based on source impedance	Voltage and current phasors	1 Cycle or better & synchronisation critical	Changes in time, not absolute accuracy of interest, 0.5% error adequate if stable	Operationally relevant latency on the order of 1 sec
Phase identification	Voltage phase angles essential	1 sec or better for time series approach, synchronisation critical	Absolute accuracy of phase angle on the order of 1 likely adequate	No particular need for latency or continuity
Model validation for line segment impedances	Voltage & current phasors	synchronisation critical	Absolute accuracy of all phasors is limiting factor, as good as 0.0001 pu for shorter segments	No particular need for latency or continuity
DER characterisation, transformer, generator and load models	Voltage and current phasors	1 cycle or better reveals dynamic behaviours: synchronisation between primary & secondary side	Change in time, not absolute accuracy of interest, 0.5% error adequate if stable	No particular need for latency or continuity

		of transformer critical		
Event detection and classification	Voltage and current magnitudes adequate for most events, phase angles useful	1 cycle or better, synchronisation critical	Changes in time, not absolute accuracy of interest, 0.5% error adequate if stable	Continuous monitoring, operationally relevant latency on the order of 1 sec
Fault location	Voltage & current phasors	1 cycle or better, synchronisation critical	Absolute accuracy of all phasors is limiting factor	Continuous monitoring, operationally relevant latency on the order of 1 sec
Phasor-based control	Voltage phasors	1 cycle or better	Absolute accuracy critical for steady-state optimisation, but stable errors acceptable for disturbance rejection	Continuous monitoring, latency critical

Table 3-2- advantages of using high-resolution voltage angle measurements compared to conventional techniques [7]

Application	**Competing conventional methods**	**Likely advantage of voltage angles**	**Likely technical challenges**
Unintentional island detection	Automatic Transfer Switch	faster, greater sensitivity and selectivity	communication latency
Oscillation detection	-	Unique and crucial	Potential Transformer and Current Transformer errors
Reverse power flow detection	Line sensors, directional relays	may extrapolate to locations not directly monitored	PMU placement
Fault location	various	better accuracy using voltage phasor values	Communication latency
High-impedance fault detection	various, difficult	better sensitivity and selectivity using voltage phasor values	Communication latency
Topology detection	direct SCADA on switches	fewer measurement points, higher accuracy using timeseries phasor data	PMU placement
State estimation	computation based on V mag measurements	linear state estimation, higher accuracy	PMU placement

Load and DG characterization	limited observation with PQ instruments	uniquely capture dynamic behaviours	data mining, proximity to subject

Other DER and LV Network Visibility Technologies

In light of recent technological advances, several products have been developed for customer and behind-the-meter assets energy monitoring and management. These technological advances including smart inverters, home automation technologies, and integrated energy management components can be utilised at the customer premises or at different locations of the network. They can enhance the network visibility, while enabling customers to manage their electricity consumption and match it with their electricity generation and storage preferences. Increase in deployment of these smart devices enhances grid stability and reliability by enabling real-time action of smart customers in response to grid operator requests (e.g., through demand response). Indeed, these technologies provide information about customer load and DER data, which in turn improves network visibility. In Table 3-3, a list of different technologies that can be used to improve DER and network visibility is provided, in which for each product the main features are highlighted:

Table 3-3- Products that can be utilised for DER and LV network visibility

Product	Company	Features
The Solar Smart Monitor	Solar analytics	Solar Analytics communicates with all inverters through Solar Smart Monitor. Features include 5 Second Live data, 3G/4G multi band communications, measures up to six sub-circuits and provides Class 1 equivalent accuracy. It also collects data from the inverter and inverter consumption meter.
Auditor 6M	Wattwatchers	Provides real-time energy monitor leveraging cellular communications. Up to 6 channels of measurement. Revenue-grade (Class 1 accuracy). Suitable for single, two and three phase applications.
Edge’s eSensor	EDGE ELECTRONS	Edge’s eSensor is an intelligent and compact power quality monitor, which uses software-driven technology for network control.
Droplet	switchDin	Droplets are generalised distributed energy resource (DER) controllers, which can be used as energy management systems for homes & businesses, battery energy storage system controllers, microgrid controllers, managed DER controllers, AS4755 DRED controllers and DER system aggregators. Each Droplet-equipped site or device can operate autonomously or in coordination with other Droplets via Stormcloud, our cloud-based management platform.
HomeKit	GOODWE	GoodWe HomeKit is a solution designed to monitor load energy consumption in real time, 24 hours a day. It

		consists of a smart meter and a Wi-Fi / LAN communication module. It can be applied to grid-connected systems with inverters of any brand or even systems without PV and it is a key component in keeping load consumption records. With 60-second update frequency, data is transmitted by Wi-Fi / LAN and stored on the cloud.
blue'Log X-Series	meteocontrol	The blue'Log X-Series records all relevant system data, provides various interfaces and functionality for power plant control and thus enables grid-compliant feed-in for PV systems.
Envoy	ENPHASE	The Envoy delivers performance data from microinverters to the Web and carries system updates from the Web to microinverters. It provides the real-time, module-level performance data to monitor the system or fleet from any web-connected device.
GridEyE	DepSys	A platform combining hardware and software components to produce and leverage real-time data. GridEye helps to operate, monitor, analyse, automate and optimise any power distribution grid.
GridGem	ArgandSolutions	An integrated control and monitoring solution to solve the problems faced within the renewables, energy storage and / or buildings markets. GridGEM's core competence is constraints management and real-time monitoring.
Ubi™ Energy Management Platform	mondo	It provides near real-time energy monitoring, single or aggregated multi-site data, downloadable historic data to see trends, financial and sustainability reporting, optimises solar and batteries.
dex	GreenSync	Provides Visibility of DER, including standing data (nameplate) and near real-time telemetry. Mapping DER to the network model, providing critical insights into DER behaviour and their impact on the grid, leading to increased network reliability, improved compliance and better network planning decisions.
The kWatch®	Flow Power	The kWatch® Intelligent Controller has the ability for near-real time information collection from meters and delivery (via portal and app) to enable participants to make educated decisions about energy usage. Real-time and near real-time visibility of customer loads in response to DR activations and market signals. Ability to measure and observe individual asset behaviour within the customer site.
Node 1	Indra	Indra's node#1 (domo and industrial) based on the Intel® IoT Gateway design acts as the datalogger for every data sent from/to the devices, with the ability to speak the main protocols out there.

Sensor® IQ Intelligent Breaker System	ETC	- Synchronise 1 min data across all their smart meters - Delivers switching with data reporting for one-, two-, and three-pole circuits - Offers total system power control and can combine lighting, video projection and audio systems with its built-in sequencer and available isolated ground bar
Powerpal Energy Monitor & Phone App	REDUCTION REVOLUTION	- Measures whole property's electricity usage and provides easy access to this data on the phone. - Gives clear and detailed insights into the electricity consumption - Powerpal uses an optical sensor which attaches to the front face of the electricity meter. It then sends this data directly to the smartphone.
VisNet Hub	EA Technology	- The real-time monitoring device that operates in low voltage distribution substations providing valuable insight into substation efficiency and optimisation. - Checks voltage and current data on every LV feeder giving insight about load, faults and condition information across the network. - Provides comprehensive network visibility with its capability to monitor 6 feeders and communicate via GPRS
Gridsight		AI-generated, real-time network models that are 95% accurate by combining machine learning algorithms with smart meter & IOT data.
GridQube	DSSE and CCO software suites	Distribution System State Estimation and Capacity Constrained Optimisation engines for MV and LV networks. GridQube DSSE uses a three-phase network model to integrate available measurement data from SCADA, LV measurements and Smart Meters. GridQube CCO is a general-purpose optimisation suite allowing specification of technical and operational constraints throughout the modelled network.

3.3 Use cases

3.3.1 Key application use cases

The collected data from LV network can be employed for different use cases. As recommended in [8], use cases can be categorised under three key applications: network maintenance, operation and planning. Network maintenance use cases leverage data to improve the inspection and monitoring of network asset conditions and ensure compliance. Example of network maintenance use cases include:

- **Advanced condition monitoring:** Monitoring and diagnosing asset conditions, allowing for improved and optimised inspection and maintenance strategies.
- **Risk-based maintenance optimisation:** Optimising asset maintenance and replacement strategies and improving network reliability

- **Neutral integrity monitoring:** Identifying or predicting neutral integrity failures to reduce customer shock risks
- **Bushfire risk management:** Assessing the network-related bushfire risk based on fault ignition likelihood and consequences.

The other application of LV network data is for network operation. Network operation use cases leverage data to manage network availability and performance. These use cases include:

- **Fault identification:** Identifying faults to enable faster maintenance responses
- **Demand response/management:** Reducing or shifting customer load with non-network solutions
- **Power quality monitoring:** Monitoring quality of supply to improve safety, reliability and visibility of system strength
- **DER coordination:** Providing signals for the aggregated operation of DER to support local network conditions
- **Dynamic voltage control:** Dynamically controlling voltage within the nominal range through smart meters

Use cases that fall under network planning leverage data to forecast future network operating conditions more accurately. Two main use cases under this category are:

- **LV network modelling:** Using AMI data to model LV network behaviour and aid in forecasting, connection approvals and DER integration.
- **Load modelling:** Leveraging data from AMI and other resources to accurately model loads in distribution system for performing time-series analysis.
- **Long-term DER hosting capacity improvement:** Understanding the impact of DER to manage load and defer network augmentation investment

Table 3-4 Provides a summary of data requirements for some exemplary use cases.

Table 3-4- Key application and use cases of LV network data

Key Application	Example Use case	Parameters required (at NMI)	Measure interval	Data resources	Update rate
Network maintenance	DER compliance	Active/Reactive Power generated, Voltage	5-10 min	DNSP/smart meters	Monthly
	Constraint reporting	Capacity, Voltage Active/Reactive Power generated and consumed	10 min	DER register/smart meters/DNSP	Weekly/ Monthly
Network operation	Network state estimation	Voltage (assumes voltage and current available at substation)	5-10 min	DNSP/smart meters/inverters	Real time (could be monthly)

	Fault identification	Voltage and current	1-5 min	DNSP/smart meters/inverter	Real time
	Constraint management	Capacity, Voltage Active/Reactive Power generated and consumed	10s – 5 min	DNSP/smart meters/DER register	Real time
	Orchestrating DER	Capacity, Voltage Active/Reactive Power generated and consumed	10s – 5 min	DNSP/smart meters/DER register	Real time
Network planning	DER hosting capacity	Voltage, Active/Reactive Power generated and consumed	5 min	DNSP/smart meters/DER register	Monthly

3.3.2 Exemplary use cases

In recent years, several projects have been developed to investigate different use cases relevant to network visibility and DER integration, and this section provides a review of such projects. These projects are examples of network operation and network planning use cases. In these projects data is used to enable better management of generation and demand and support the further integration of intermittent renewables and DER, either through the identification and dynamic response to power quality issues or the coordination of DER to relieve local network constraints. Each project is an example of application of data and analytics to improve network visibility and facilitate DER integration. These projects are investigated to answer three essential questions:

- What data is required as the input?
- What are the employed technologies to collect the required data?
- What are the key findings and limitation in each project?

More details about these projects can be found in Appendix 1.

3.4 Lessons learnt

3.4.1 Best practices

In summary, improving LV network visibility requires data collection from different sources in LV networks and appropriate tools to analyse the data. The DER Visibility and Monitoring Best Practice Guide (the Guide) [9] developed by the DER industry specifies the data requirement to improve network visibility and to enable the transition of the electricity network to a high penetration DER grid. The required data can be classified as either static data, which is data related to the DER system that does not change frequently, or dynamic data that changes frequently depending on the system and grid operating conditions. As discussed in Section 3.3, different practices employ various options and sources to collect the required data. Some options require installation of new sensors or procurement of data from proprietary sources. These options are able to provide a high level of network visibility. Some other practices leverage existing equipment and data sources. Instead of network-wide monitoring, these practices employ a combination of data sampling and network modelling as a cost-effective solution to improve network visibility.

3.4.2 Standing challenges and barriers

While data can play a vital role in improving network visibility, there are several key gaps and challenges in employing network data and modelling the network for different use cases:

- ***Data quality, consistency and integration:*** Data quality issues can be caused due to reliance on third-party data or use of manual or paper-based processes. Also, inconsistency in the format of data provided by different third parties and delays in data collection and processing can make it difficult to implement use cases that require real-time information. In addition, trust concerns related to customer and DER level data needs to be considered.
- ***Data granularity and accuracy:*** While AMI provides a new level of visibility to distribution system loads, it comes at a cost. Large volumes of AMI data must be effectively recorded, communicated, stored and processed for applications in distribution planning and operations. The volume of AMI is directly proportional to the time granularity at which the data is recorded and stored. While lower time granularities result in less burdensome data management, lower time granularities also provide less detailed view of the network.
- ***Cybersecurity*:** Increase in the deployment of data from different sources increases the involvement of third-party systems, and hence, new capabilities to manage cybersecurity threats are increasingly required.
- ***Location of smart meters:*** Smart meters are not always located in the areas where visibility is most needed, and their deployment can be sporadic. The sporadic deployment of smart meters obliges DNSPs to rely on cellular communications, instead of mesh communication networks, which can sometimes be unreliable.
- ***Data procurement costs:*** Cost of procuring smart meter data can prevent implementation of use cases at-scale.
- ***Network and load modelling:*** The employed methods for load and generation modelling would have an influence in the accuracy of the hosting capacity calculation. A study by EPRI [10] shows that modelling loads directly with their AMI active and reactive power recordings is likely to result in lower hosting capacity values. These hosting capacities might be up to 40% lower than hosting capacities obtained with conventional utility load modelling methods.

3.4.3 Opportunities for further work

The review and assessment carried out within this report indicate that there are many opportunities for future work to develop new models for improving network visibility. Based on the identified barriers and challenges in this report, some of the directions for future works can be regarded as follows:

- **Network modelling:** As many use cases rely on network models, new methods should be developed to extract accurate network models with minimum data requirements. An interesting avenue for future work is to identify the minimum required information of network models for different use cases.
- **Smart meters:** While it is acknowledged that smart meters are a key enabler in improving network visibility, their integration in the power systems is delayed due to several barriers. Future works need to be done to investigate what is the minimum number of meters, their location on the circuit, the type and granularity of data for different use cases?
- **Emerging technologies:** As stated above, several products have been developed in recent years that can be employed to enhance network visibility. These products collect different data and use different formats to store data. This can create interface challenges when data is provided by multiple third parties in different formats and qualities. A direction for future works is to develop technical standards that are required to ensure that data is provided in a consistent and useable format. The value of having additional device-level metering should be evaluated against using additional channels utilised in the smart meters.

4 Industry Capability Review: Assessing DER hosting capacity

4.1 Review scope

DERs such as rooftop solar PV units, battery storage, thermal energy storage, electric vehicles and chargers, smart meters, and home energy management technologies are emerging in an unprecedented way that is expected to increase and estimated to contribute 45 percent of Australia's electricity generation capacity by 2050. In general, this growth is driven by customers; present network limits may constrain DER exporting and importing capabilities. At the same time, the capacity of networks to connect increasing levels of DER – their DER hosting capacity – is increasingly limited without significant improvements in monitoring and control functionalities.

The accurate assessment of network hosting capacity is a foundational enabler of a range of transformational activities outlined in the Electricity Network Transformation Roadmap [11] to address the technical challenges introduced by growing levels of DER.

The Electric Power Research Institute (EPRI) provides the following definition for DER hosting capacity:

Hosting capacity

The amount of DER that can be accommodated by the distribution network (or part of it) without adversely impacting its power quality or reliability for normal operation at any point in time and at a given location under existing control configurations and without requiring infrastructure upgrades.

This section summarises foundational work by EPRI and Energy Networks Australia (ENA) on the assessment of hosting capacity, and reviews hosting capacity analyses underlying Australian network studies and trials, their main use cases, including the estimation of dynamic operating envelopes. It also identifies best practices, standing challenges and barriers, and opportunities for further work to address them.

4.2 Hosting Capacity Analysis

4.2.1 Impact factors

Hosting capacity is a multi-dimensional problem driven by the specific DER as well as the grid itself. As noted in [12], while significant attention has been focused on various methods for calculating hosting capacity, the most important aspect may be the specific inputs and assumptions that drive the hosting capacity calculation. The hosting capacity calculated for a grid highly depends on the impact various different inputs or assumptions may have – and it is not practical or possible to consider all plausible assumptions or inputs entirely. The impact of these factors can vary on the hosting capacity results, sometimes opposing and other times complementing each other. The selection of the input assumptions and their associated impacts can influence the network hosting capacity results for various utility and stakeholder applications. (See Tables in Appendix 2.)

Feeder Metrics: Voltage, thermal, protection, and reliability are the issues for which hosting capacity is ultimately defined. However, all these feeder metrics are not affected by all the DER and grid impact factors. The range of applied impact factors can change depending on the considered feeder metrics. Hosting capacity can be assessed for each of these feeder metrics independently to provide visibility into each metric contribution. Most important in applying the results from a hosting capacity study is to access each metric's hosting capacity. The feeder metrics mapped to the impact factors to determine hosting capacity boundary conditions recommended by EPRI [13] are presented in Table A 2-1 in the **Appendix**.

The accuracy of a hosting capacity calculation increases with the number of impact factors considered. However, consideration of multiple impact factors increases the computational burden and complexity in assessing hosting capacity. Utilizing particular grid and DER assumptions, boundary cases can be identified that calculate the minimum and maximum hosting capacities without needing the execution of repetitive cases. Identifying the lowest (worst-case) and highest (best-case) hosting capacities is essential for assisting with interconnection requests and informing DER installers and project developers. A summary of the impact factors, and their relative ranking as recommended by EPRI [14] is provided in Table 2-1 in **Appendix 2**.

In Australia, Energeia [15] recommended several impact factors and their related metrics to calculate the hosting capacity as (i) power quality (i.e., over-voltage, under-voltage, flicker, and total harmonic distortion), (ii) reliability (i.e., thermal overload, safety protection, mal-operation, and islanding), (iii) system security (i.e., disturbance ride-through, and under frequency load shedding), and (iv) cost/efficiency (i.e., phase imbalance, and forecasting error). The effect of miscoordination of protection devices on hosting capacity has not been analysed thoroughly. However, based on the reviewed national projects, it noticed that some or all of the following impact factors are used to calculate the hosting capacity such as configuration, voltage regulation, thermal limits, connected load, connected DER, control-managed, DER portfolio, DER location-site specific, and/or time (see Table 4-4-4). In addition, Horizon Power in [16] used more specific impact factors, such as the output fluctuation factor, diversity factor, and other appropriate factors for time intervals, to determine the hosting capacity.

4.2.2 Optimal mix of data and models

To perform hosting capacity across an entire LV distribution network system, a large amount of validated data is required. Missing and/or inaccurate grid data is a significant concern to utilities undertaking hosting capacity analyses. Unlike some conventional planning studies, hosting capacity assessment and the interconnection review process requires a higher degree of grid model accuracy in connectivity information and electrical parameter data. Besides, rectifying data quality and completeness issues can be highly time-consuming and expensive for DNSPs. Capturing the needed datasets for network segments composed of hundreds to thousands of customers, devices, and characteristics that are dynamic in time is not trivial.

There is a need to validate existing data and gather new, previously untracked data based on the significant impact factors for a use case. Multiple source systems like Geographic Information Systems (GIS), Customer Information Systems (CIS), Asset Management Systems, and engineering design tools are involved in data collection and gathering processes. A wide range of techniques is employed, including correlating information from disparate repositories, searching paper records, leveraging validation algorithms, and performing extensive field surveys. After gathering and validating data, one of the critical challenges is to convert data to the planning tool format while ensuring consistency and accuracy of data. A certain level of manual support is needed to complete this process. Achieving a grid model with the requisite level of data integrity and completeness is often a multi-year, multi-tens-of-million-dollar process.

The lack of visibility of the LV network is a primary concern for most of DNSPs in Australia, as it affects the accuracy of representing the network segments and may lead to over- or under-estimate the hosting capacity. For instance, some assumptions are considered to represent the network, such as neglecting the phase imbalance effects. Therefore, an optimal mix between the data and model should be considered to model the behaviour of the network as accurate as possible considering trade-off between accuracy and cost. Interestingly, with nearly 100% smart meter penetration level in Victoria, a supervised (i.e., gradient decent) univariate regression model based on smart-meter driven approach that represents the DER hosting capacity estimation model for the analysed LV network is proposed by [17]. However, the accuracy of the smart meter-driven approach depends on the volume of smart meter data as more data helps to capture the variance of a larger sample of network conditions (i.e., voltage vs active power). This approach is not suitable for planning studies that involve testing various network solutions that change the fundamentals of the feeder. Therefore, it is recommended to build explicit models (i.e., model-based approach) for the components, which consider phase imbalance, to be able to apply “what-if” scenarios and avoid over or under investment due to inaccurate quantification of hosting capacity.

The **model-based approach** contains explicit electrical models of the corresponding components in the distribution network (i.e., bus, branch, loads, generators, DERs, shunts, etc.), including the network topology and parameters. The explicit electrical models should be characterized to allow running power flow simulations using a software package for different demand/generation scenarios, or “what if” scenarios. This approach is the most used modelling approach by DNSPs in Australia and worldwide for designing, planning, and improving the distribution network. However, this approach is limited for the HV networks and critical demand/generation scenarios.

The **smart meter-driven approach** could be a promising alternative to model-based approaches that can save both time and effort in assessing hosting capacity [17]. Unlike a model-based approach, the smart meter-driven approach does not require explicit electrical models, i.e., does not require power flow simulations, rather it uses only historical smart meter data.

Here, the advantages and disadvantages of network representation approaches can be summarized as shown Table 4-1.

Table 4-1. Advantages and disadvantages of LV modelling approaches

Model	Advantages	Disadvantages
Model-Based Approach	• It is adaptable, network elements and participants can be added, removed or changed. • Control techniques can be implemented and tested through simulations.	• It is typically limited to HV feeders and to critical demand/generation scenarios. • Model simplifications arising from lack of critical visibility or network information can lead to grossly incorrect estimates of hosting capacity.
Smart Meter-Driven Approach	• It does not require explicit electrical models, i.e., does not	• Impractical for networks without high penetration of smart meters

	require power flow simulations, only historical smart meter data. • It can save time and effort in the assessment of new connection requests.	

4.2.3 Analysis framework

Hosting capacity can be assessed on two main analysis frameworks based on the availability of the data and the optimal mix of data and models, namely steady-state analysis, and time-series analysis [18]. The **steady-state analysis** for hosting capacity assessment is conducted for two base-feeder load levels: the daytime minimum and daytime maximum load, while absolute maximum and absolute minimum loads can be considered if the daytime load levels are not known. These load levels are utilised to derive a bounding worst-case response for extreme conditions for the DER varying from zero to full output. The steady-state analysis procedure involves: (i) solve the power flow with DER output set to zero, (ii) lock all regulator and capacitor switches at their present state, and (iii) solve the power flow with DER producing maximum power.

The **time-series analysis** is conducted for demand/generation coincident scenarios based on time-of-day. Basically, a day of time dependent load can be selected for the maximum load and a day for the minimum load. Each of these days should be evaluated by considering highly variable and non-variable DER output. The load and DER resemble scenarios can be selected from the steady-state analysis results based on monitoring criteria impact. The main objectives of the time series analysis are: (i) determine feeder response from actual load and DER data, (ii) compare time-series response to that indicated with the steady-state analysis, and (iii) determine DER influence on control elements.

An unbalanced three-phase power flow simulation should be run considering changing the demand and generation profiles within a time (i.e., hourly or less) and across various seasons. Therefore, time-series simulation can be carried out to consider the time variations of the profiles based on time-series data (i.e., load profiles, DER profiles, meteorological variables, etc.) with adequate granularity. Determining the adequacy of data granularity (i.e., at least 30-minute resolution) depends on a trade-off between capturing time-dependent aspects, the corresponding computation time, and available historical data [19]–[21]. In practice, the minimum resolution can be defined based on the available timeframe of the data from historical smart meter data, SCADA measurements, and meteorological data.

To calculate hosting capacity based on a model-based approach, the planning standards and guidelines for a distribution network should be defined (i.e., voltage limits, rated capacity of assets, etc.). Then, power flow and/or state estimation can be conducted by including the demand/DERs scenarios of interest. Here, hosting capacity should be calculated by keeping some critical parameters (i.e., voltages, thermal limits, etc.) within pre-specified limits.

Power flow aims to obtain the voltage magnitudes and angles at all nodes, and the currents flow in all branches by giving the topology and components of the network and set points of connected loads and generators. Here, unbalanced power flow is the basis of distribution network analysis. Typically, the power flow can be represented by bus injection models or DistFlow equations [21].

State estimation (SE) is a decision support tool that uses the network state information for better-informed decision processes and the development and implementation of active control strategies.

The main concept of SE is to estimate states of the network (e.g., voltage, active and reactive power) that are not measured. In practice, one estimates the network's state by minimizing the weighted least squares of the difference between the measurement and variable values. If the problem is well formulated, then Gauss-Newton algorithms can find a solution efficiently. To formulate the problem well, accurate models for the electrical distribution networks are required. Distribution system state estimation (DSSE) has been proposed to handle the unbalanced systems recently applied in [22] summarized in **Appendix 2**.

In Australia, most of the electricity distribution networks are radial (no 'loops' in the distribution network). Typically, the nodal power injections and branch power flow in a network are considered as constant real and reactive power over the time interval (typically 5 or 30 minutes) [19]–[21]. Here, the power flow and state estimation should consider two main constraints (i.e., voltage and thermal constraints) and the existing active energy management strategies (i.e., volt/var, volt/watt, etc.).

Based on the reviewed projects, most typically use balanced power flow to calculate hosting capacity, which neglects the phase imbalance that may lead to over- or under-estimating the hosting capacity results and the ability of the network to accommodate DERs. One of the projects developed unbalanced distribution system state estimation (DSSE) technique to calculate the hosting capacity [22]. The state estimation technique needs less input quantities than that required in power flow. However, it is sensitive to the accuracy of the data, with particular high non-linearity in the data increases the risk of numerical instability in the solution finding process. Both power flow and state estimation need explicit models for the network components, including phase imbalance effects to calculate hosting capacity accurately.

Active network management strategies can be defined for both voltage and thermal constraints using centralized, decentralized, and distributed techniques [21]. It is worthy of mentioning that the concepts of hosting capacity and active network management strategies are often profoundly related. An active network management strategy often implicitly or explicitly determines the DER hosting capacity achieved within a given distribution network segment. Active network management strategies focus on providing setpoint control for DER by determining the exact value of the DER output that will best allow some operational objective to be achieved.

4.2.4 Hosting Capacity Calculation Methods

There are several hosting capacity methodologies under development and more likely on the horizon. For ease of discussion, we have focused on four primary methodological categories recommended and discussed by EPRI: stochastic, streamlined, iterative, and hybrid. These methods are briefly summarized in the main body of the report with illustrating their accuracy and comparison for assessing hosting capacity based on distribution feeder and DER evaluation criteria. For more details, the reader can be referred to [14]. Additionally, a capacity constraint-based method can be used to approximate hosting capacity, which can be a useful if only approximate or estimated data is available for many measurements critical for assessing hosting capacity.

Stochastic Methods

This method starts with a model of the existing distribution system, performing a baseline power flow analysis of the existing system and gradually increasing the penetration level of DERs on a feeder for varying sizes and random locations to evaluate any adverse effects arises for different scenarios that results in hosting capacity range. Assumptions such as DERs with similar characteristics, sizes and locations are considered in this method. It can handle larger, three-phase, and behind-the-meter DER systems and calculate the range of possible impacts by the DER locations and sizes at future penetration levels. This method requires significant executing time and is computationally intensive. Stochastic methods can be an effective approach to develop research tools, but it is not recommended for applications beyond that, such as interconnection studies. This is because of such methods are not effective at capturing full range of distributed DER impacts (e.g., locations), applicable to specific impact factors only and difficult to consider range of possible DER and grid scenarios.

Streamlined Methods

Instead of direct modelling, a set of simplified algorithms are applied for each power system limitation (typically: thermal, safety/reliability, power quality/ voltage, and protection) to approximate the DER capacity limit at nodes across the distribution circuit. Time series data are acquired by leveraging smart meter data to capture daily changes in load, DER, and regulation equipment and observe their impacts on hosting capacity. Some assumptions, such as all existing DER have a fixed output and do not contribute to voltage changes, might overestimate hosting capacity in some cases. This method provides time-based hosting capacity with a faster computation capability that enables analysis of additional scenarios such as DER forecasts, reconfiguration, smart inverter settings, DER mitigation strategies, etc. As a new technique in calculating hosting capacity, many stakeholders are still struggling to understand it. In addition, it uses non-standard distribution modelling data and lacks accuracy.

Iterative Methods

The iterative method essentially increases the DER iteratively at each node on the distribution system until a violation occurs. Power flow simulations are performed to determine the maximum level of DER hosting capacity at different independent locations without exceeding thermal and voltage limits. Besides, a protection analysis is also performed to evaluate the protection criteria and determine the hosting capacity to each node without hindering the protection devices' ability to detect fault conditions. The iterative method is also sometimes referred to as the detailed method. Systems "as is" and "what-if" scenarios, such as DER forecasts, reconfiguration, smart inverter settings, DER mitigation strategies, etc., are limited due to the computation burden. In this method, vendors implement the same processes, and existing DER is assumed not to contribute to voltage deviation that might lead to overestimating the hosting capacity in some cases. The method resembles the similar concept of executing an interconnection study where the DER impacts are determined using the distribution planning software and requires significant time, data, and computational cycles to complete, which is similar to the stochastic-based approach.

Hybrid Methods

Hybrid methods can be considered an alternative to overcome the computation burden of stochastic and iterative methods. The Distribution Resource Integration and Value Estimation (DRIVE) tool is one example that has been developed by adding new capabilities, improving overall accuracy, and increasing efficiency based on the needs of several DNSPs worldwide. Unlike the iterative method, hybrid methods no longer meticulously iterate through penetration levels to find a hosting capacity solution. Instead, educated penetration increments are used to easily speed up the analysis. These educated penetration increments are a key difference between iterative and hybrid methods. Since the hybrid methods are a newly developed distribution analysis technique, it is not easily understood by all stakeholders.

Capacity Constraint-Based Method

Capacity constraint-based methods utilise power flow analysis capabilities to approximate the set of DER, and other network loads and generation units, operational set points that do not violate a defined list of technical and operational constraints. These Capacity Constraints are typically represented as a list of inequality constraints on the decision variables that can be used in standard optimisation frameworks or analysed using geometric approaches. In most cases these Capacity Constraint analysis is performed considering a base case load flow which can be derived from forecasts or from State Estimation systems. This type of methods decouples the optimisation (e.g. a capacity allocation) problem from the underlying power flow problem and is standard practice in most electricity markets, including the National Electricity Market.

Supervised univariate regression model (SURM)

The obtained new dataset containing maximum voltage and aggregated power is used to train a supervised (i.e., gradient decent) univariate regression model that represents the DER hosting capacity estimation model for the analysed LV network. As a first step to develop this model, all the customers' daily smart meter data in a LV network are collected by leveraging the smart meter database. In the next step, smart meter data are analysed and cleaned from missing and inconsistent values. A new and clean dataset is obtained which contains the maximum voltage and the corresponding aggregated power for each day.

The main idea of reviewing the above-mentioned hosting capacity assessment methods is to show the accuracy of each method. The question is which method should be used when, and which method is the most applicable. Choosing a hosting capacity method heavily depends on the objective of a particular study. A comparison has been carried out in California [23] as part of the Demo projects to evaluate the accuracies of these methods. It is noted that the iterative method produces accurate results. However, it is not necessarily true that the iterative method should be used as a benchmark or reference for other calculation methods. The accuracy of hosting capacity assessment methods should be compared based on the results that can be obtained considering all the impact factors, regardless of the method. The impact factors can affect the accuracy of the hosting capacity results.

Most projects that calculate hosting capacity in Australia do not clearly mention the use of any of the EPRI recommended hosting capacity calculation methods. However, the projects that used PowerFactory and OpenDSS software utilised DRIVE method. In addition, capacity-constraint based methods are used to approximate the hosting capacity in three national projects [11,21,22]. Also, a new hosting capacity calculation method has been proposed in [17], which is called "supervised univariate regression model". This method is carried out based on a smart meter-driven approach. This framework required a high penetration of smart meters data. Further investigation needs to be carried out in this context to validate EPRI and the University of Melbourne recommended hosting capacity calculation methods for several use cases and based on their significant impact factors.

4.2.5 Simulation Tools

Several simulation tools are available in the market to analyse the electrical distribution network. The tools can conduct balanced and unbalanced power flow and balanced and unbalanced state estimation under fundamental frequency and harmonics cases. Some software tools are capable of conducting short-circuit calculations (steady state). Few tools can be used for electromechanical and electromagnetic transient power flow. Here, some tools can do more than one of the analyses as mentioned above. The tools can be categorized as commercial and open-source software. Here, the comparison between the available simulation tools according to each one's capability is listed in Table 4-2.

Table 4-2. Available tools can be used as an engine to calculate the hosting capacity.

Tools	Balanced PF	Unbalanced PF	Balanced OPF	Unbalanced OPF	Balanced SE	Unbalanced SE	electromagnetic transient PF	electromechanical transient PF	Short circuit
Commercial									
PowerFactory	✓	✓	✓	X	✓	✓	✓	✓	✓
PSS/Sincal	✓	✓ (3-wire & 3-phase)	X	X	X	X	X	X	X
PSCAD	✓	X	X	X	X	X	✓ (3-wire)	X	X
PSS/E	✓	X	✓	X	X	X	X	✓ (3-wire)	✓
Open Source									
PandaPower	✓	✓	✓	X	✓	X	X	X	✓
OpenDSS	✓	✓	X	X	X	X	X	✓	✓
PowerModelsDistribution	✓	✓	✓	✓	X	X	X	X	X
Open-DSOPF	✓	✓	✓	✓	X	X	X	✓	✓

In Australia, the available commercial tools in use are PowerFactory, PSS/Sincal, PSCAD, and PSS/E. Here, PSCAD and PSS/E are in use by AEMO, and PSS/Sincal and PowerFactory are in use by most of the country's DNSPs. In comparison, the open-source tools are OpenDSS, and PandaPower. Among the open-source simulation tools, PandaPower is the most used in Australia. However, PandaPower does not support distribution network contexts in its current version. Besides, OpenDSS has been used to carry out an industrial research project by the University of Melbourne [17].

4.3 Use cases

The key application use cases of hosting capacity – extracted from reviewing relevant national and international projects – are as follows:

- **Connect new customer PV and batteries exporting DER.** Enable customers and their agents to connect a reasonable amount of solar, batteries at their premise at a reasonable cost. Customers clearly understand long-term value proposition of export.
- **Enable cost-effective distribution planning.** Improve annual and five-year network planning exercises to fully leverage customer DER.

- **Connect new EV and load.** Enable customers and their agents to connect reasonable amounts of new devices with certainty about any/all limits on their import capabilities.
- **Inform customers of real-time network conditions.** Identify and communicate dynamic operating envelopes.
- **Procure DER to provide network services.** Use customer devices to increase hosting capacity, avoid/defer network investment.
- **Provide better managing power transfer stability limits.** Enable dynamic DER export limits to better manage voltage and thermal constraints (e.g., DOEs).
- **Illuminate cost as a function of penetration level to all parties** (currently may be borne by a single parties), for example utilities, DER developers, customers, etc.
- **Active energy management strategies** (i.e., volt/var, volt/watt, etc.).

4.4 Dynamic Operating Envelopes

An operating envelope can be defined as the DER or connection point behaviour that can be accommodated in a distribution network (or part of it) before reaching physical or operational limits. Accordingly, a dynamic operating envelope (DOE) allocates individual or aggregate DER or connection points to the available hosting capacity in a distribution network (or part of it) at a given time interval. Typically, a DOE aims to provide upper and lower bounds for either individual DER assets or a connection point in importing or exporting power in a given time interval. Therefore, the relationship between the hosting capacity and operating envelopes can be extended beyond the operational time-domain into more extended network planning time domains [19]–[21]. However, time-series hosting capacity can be considered as the keystone for DOE, which is not to say that time-series hosting capacity and DOE are identical. To distinguish them, time-series hosting capacity provides the available capacity that allows the network to accommodate DER without introducing any negative impacts, but it does not limit the import and export limits for each DER, and it does not provide the proper active management settings that the DER should follow. However, DOE aims to incorporate the calculated time-series hosting capacity to manage the DER imports and export limits and their proper active management setting to efficiently use the available hosting capacity by securing the maximum benefit for the customers and DNSPs.

It should be realized that DOE aims to provide a range of DER or connection point behaviours to ensure that physical and operational limits are not exceeded and should not be used to provide pseudo-set-point control. This range can be referred to as nodal limits on real and reactive power injection or demand. Therefore, the dynamic operating envelopes effectively represent the translation of physical and operational voltage and thermal constraints into nodal real and reactive limits for each participating node for a given distribution network segment. However, if more fine-grained, DER or connection set-point control is required (i.e., for network services, augmentation deferment, etc.), appropriate economic or market-based incentives should be used.

4.4.1 Calculation and Implementation

The high-level approach for the calculation of a DOE in each time interval as follows (order is important) has been proposed by ANU in the evolve project [21]:

- Calculate available hosting capacity.
- Allocate available hosting capacity to individual or aggregate connection points or DER.

- DER and connection point behaviour (including participating in markets for energy and ancillary services) is maintained within operating envelopes.
- Physical and operational limits of distribution networks are not breached.

The suggested framework is deployed into cloud infrastructure and integrated with both DNSP and aggregator systems, which is an open-source technology framework [21]. It ingests the relevant network and DER data, making them available for analysis in a standards-based form. The calculation and publication of operating envelopes are implemented as a series of software modules and algorithms within the evolving framework.

As the first step indicates, DOEs can be considered a particular application or type of hosting capacity analysis. At the very least, DOEs depend upon hosting capacity calculation and the considerations and challenges in accurately assessing hosting capacity noted in **Section 4.2** likewise impact the calculation of DOEs. Indeed, given the dynamic nature of DOEs, the data and computational challenges of accurately calculating hosting capacity likely become more significant.

4.4.2 Benefits and challenges

There are several benefits of operating envelopes at the current maturity levels of DER deployed within the electricity system:

- Operating envelopes can address multiple use cases, including challenges currently being faced in electricity distribution networks and at the whole system level.
- Once calculated, operating envelopes promise to be simple to implement across various DER assets and do not require the use of sophisticated local control and optimization systems. This can increase adoption and compliance from the variety of DER assets installed in Australian distribution networks.
- Operating envelopes can be deployed progressively into different segments of a distribution network as they are needed.

Even DOEs are showing promising results to allow the distribution networks to accommodate more DERs and manage their import and export limits effectively. However, DOEs have some challenges:

- Estimating the accurate hosting capacity results and their proper implementation in a use case.
- Sharing the path of privacy and exporting and importing limits between customers and DNSPs or vice versa, which may lead for more concern by DNSPs to consider cyber security issues.
- Developing a secure and reliable platform which requires additional infrastructure (i.e., hardware and software), which add more costs.
- Responding to the DOE can be affected by the immature technology, absent of standards and the technical ability for consumer systems.
- DOEs may not provide a sufficient incentive to change consumer behaviour to effectively augment the capacity of the network to host DER, and so additional approaches are likely required.

4.4.3 Applications

The bi-directionally defined operating envelopes have the potential to achieve multiple operational goals for network operators. Some of the remarkable applications of DOEs are detailed below.

- **Managing Solar Generation (Export)**
  The peak solar generation is only likely to breach physical or operational limits when the underlying demand is low and when solar generation is at its peak. An operating envelope helps in this instance by signalling the need for a reduced generation or for an overall reduction in export from a customer connection point.
- **EV Charging (Import)**
  In the near future, electric cars could cause significant consequences to the correlated charging of electric vehicles in the evening. Like solar generation, the dynamic operating envelope would provide a clear signal to customers to defer or reduce EV charging power to avoid breaching voltage or thermal constraints.
- **DER Market Participation (Both Import and Export)**
  One of the critical use cases of the dynamic operating envelopes is that the additional network capacity can be used by DER assets to participate in markets for energy and ancillary services. DER assets' participation will be limited by the operating envelope boundaries, which will ensure safe and secure operating limits of the electricity distribution network. For this reason, an operating envelope time interval should be aligned with the time interval of the market.
- **Using Operating Envelopes to Maintain System Security**
  There is emerging interest in using operating envelopes to maintain systems' security limits during periods of high solar generation. The reduction in minimum demand in the grid will require solutions that may include solar curtailment, which could be accomplished using operating envelopes. Better managing of power transfer stability limits is anticipated as one of the operating envelope-use cases in the coming decade.
- **Dynamic line rating assessment**
  Adjusting line ratings to reflect environmental conditions at a point in time (such as temperature) to maximise load or generation while maintaining safety and reliability.

4.5 Australian practices

Growing DER penetration in Australia, forecasted by AEMO to contribute 13-22% of the annual National Electricity Market (NEM) energy needs by 2040 [5], has attracted Australia's energy governance bodies to improve the network visibility and manage growing DER penetration. PV systems are the main contributor to the DER growth; however, storage batteries are showing significant contribution in SA. Therefore, AEMO recommended several technical requirements to integrate and manage the existing and/or new DER [24]. These recommendations are: (i) updating DER inverter standards, (ii) ensuring visibility of LV networks to support decision-making, and (iii) improving understanding of DER behaviour during power quality disturbances. Most of the DERs are integrated into the LV networks; therefore, Energy Networks Australia (ENA) and AEMO are carried out Open Energy Networks (OpEN) project to study the voltage limits challenges in LV networks with incorporating the feedbacks from the stack holders on the best integration of DERs. OpEN recommended to use real-time monitoring in order to improve the network visibility, and support the

DER integration by establishing national guidelines for DER operating envelopes [25]. In 2019, Australian Energy Market Commission (AEMC) published several recommendation for DNSPs to overcome the challenges of integrating DERs, which causing power quality issues as DER penetration increases [26]. These challenges are: (i) lack of visibility of LV networks, (ii) inadequate technical standards and compliance, and (iii) an industry-wide lack of cost-reflective pricing.

Furthermore, several completed and ongoing projects are focusing on proposing and evaluating several options for managing LV networks as DER penetration level increases. Here, ARENA Networks Renewed project is evaluating several solutions to increase electricity supply quality and reliability using smart inverters and battery storage [27]. In addition, there are multiple virtual power plant (VPP) pilots and trials occurring, which include assessing VPPs' potential for network management. Moreover, a list of Australian projects, which are related to assess the hosting capacity are summarised in Table 4-3 and Table 4-4-4.

Table 4-3. **Data, models, analysis engines, analysis frame works, methods and software for Australian hosting capacity assessment projects**

	Project	Data		Representation approaches		Analysis Frameworks								Tools
		Network data	Smart metering data	Model-Based Approach	Smart Meter-Driven Approach	Power Flow	State Estimation	Stochastic	Streamlined	Iterative	Hybrid	Capacity Constraint-based method	SURM	
1	Advanced planning of PV-rich distribution networks (2019-2021) [17]	✓	✓	✓	✓	✓ (Unbalanced)	X	X	X	X	✓	X	✓	OpenDSS
2	Distributed Energy Resources Hosting Capacity Study (2018-2020) [28]	✓	✓	✓	X	✓ (Balanced)	X	X	X	✓	X	X	X	PandaPower
3	Dynamic Limits DER Feasibility Study (2018-2020) [19]	✓	X	✓	X	✓ (Unbalanced)	X	X	X	✓	X	X	X	Python load flow program
4	Jemena DER Hosting Capacity Project (2019-present) [29]	✓	✓	✓	X	✓ (Unbalanced)	X	X	X	✓	X	X	X	N/A
5	SA power networks: Advanced VPP grid integration (2019-present) [20]	✓	✓	✓	X	✓ (N/A)	X	X	X	?	?	X	X	N/A
6	evolve DER Project (2019-2020) [21]	✓	✓	✓	X	✓ (N/A)	X	X	X	✓	X	X	X	N/A

7	Horizon Power Carnarvon DER Trials (2017-2020) [16]	✓	✓	✓	X	✓ (Balanced)	X	X	X	X	✓	X	X	PowerFactory
8	Increasing Visibility of Distribution Networks (2017-2019) [22]	✓	✓	✓	X	X	✓ (Unbalanced)	X	X	X	X	✓	X	SEI PV Analysis Tool
9	Expanded Network Visibility Initiative ENVI (since 2019) [21]	✓	✓	✓	X	✓ (Unbalanced)	✓ (Unbalanced)	X	X	X	X	✓	X	Proprietary
10	Project SHIELD (2020 - present) [30]	✓	✓	✓	X	✓ (Unbalanced)	✓ (Unbalanced)	X	X	X	X	✓	X	Proprietary

Table 4-4-4. Impact factors for the Australian hosting capacity assessment projects

	Project	Impact Factors
1	Advanced planning of PV-rich distribution networks (2019-2021) [17]	Configuration, voltage regulation, thermal limits, connected load, connected DER, control-managed, DER portfolio, DER location-site specific, and time
2	Distributed Energy Resources Hosting Capacity Study (2018-2020) [28]	Voltage regulation (over/under voltage, voltage sags/swells), connected load, connected DER, control-managed, DER portfolio, thermal limits, and time
3	Dynamic Limits DER Feasibility Study (2018-2020) [19]	Voltage regulation (over/under voltage), thermal limits, connected load, connected DER, control-managed, time, DER portfolio, and time
4	Jemena DER Hosting Capacity Project (2019-present) [29]	Configuration, voltage regulation, thermal limits, connected load, connected DER, control-managed, DER portfolio, DER location-site specific, time
5	SA power networks: Advanced VPP grid integration (2019-present) [20]	Voltage regulation, thermal limits, connected load, connected DER, DER portfolio, DER location-site specific, and time
6	evolve DER Project (2019-2020) [9]	Configuration, voltage regulation, thermal limits, connected load, connected DER, DER portfolio, control-managed, DER location-site specific, and time
7	Horizon Power Carnarvon DER Trials (2017-2020) [16]	Output fluctuation factor, diversity factor, and other appropriate factors for time intervals

8	Increasing Visibility of Distribution Networks (2017-2019) [10]	Voltage regulation, thermal limits, connected load, connected DER, DER portfolio, control-managed, DER location-site specific, and time
9	Expanded Network Visibility Initiative (ENVI) (Since 2019) [21]	Voltage regulation, thermal limits, connected load, connected DER, DER portfolio, control-managed, DER location-site specific, and time
10	Project SHIELD (2020 - present) [30]	Voltage regulation, thermal limits, connected load, connected DER, DER portfolio, control-managed, DER location-site specific, and time

4.6 Lessons learnt

Several recommendations for calculating the hosting capacity are extracted from the national and international projects, which are listed as below:

Impact factors

Based on EPRI [13], [14], following key recommendations on impact factors can be considered while assessing hosting capacity:

- DER impacts should be considered to design and study the realistic, worst-case conditions to ensure adverse impacts to reliability.
- The hosting capacity should consider the worst-case and best-case conditions to understand the upper and lower limits that should drive decision making.
- Considerable work and research are needed to evolve the data requirements, methods for assessment, and tools to evaluate probabilistic (risk-based) methods to enable better quantification of the hosting capacity upper and lower boundary conditions and evaluate the risk of such conditions.
- EPRI recommends carefully considering impact factors while deriving practical applications for the results of a hosting capacity study.
- It is also critical to understand how those impact factors are, or could be, considered in the applied hosting capacity method.

Optimal mix of data and models

Assumptions around voltage regulation, future load profiles, DER profiles and characteristics, phasing, etc. are necessary due to the uncertainties in underlying data, and 100% accurate hosting capacity is not feasible. However, assumptions and understanding their implications can result in a precious outcome.

- **Model-based approach**
  The recommendation of this approach based on the project that carried out by the University of Melbourne [17] are as follows:
  - **HV Feeder Selection.** DNSPs can reduce the modelling efforts, and time by selecting the HV feeders properly (significantly affecting the hosting capacity assessment). This selection should consider several characteristics such as feeder type (i.e., rural, urban, etc.), topology, length, number of customers, number of installed DERs, etc. Here, applying extreme cases aims to investigate a potential solution's viability; thus, that solution is likely applicable (and might perform even better) in milder cases.
  - **Explicitly Model LV Feeders.** DNSPs should consider the integrated HV-LV feeder models with detailed modelling for the LV feeders down to household connection points in calculating hosting capacity. This is essential to fully consider the voltage-related control actions from the controllable devices to quantify voltage issues and their effects on hosting capacity assessment.
  - **Cater for Uncertainties.** DNSPs should consider the uncertainties related to future DERs location, size, and meteorological and demand profiles to the extent that is possible.
- **Smart meter-driven approach**
  The recommendation of this approach based on the project that carried out by the University of Melbourne [17] are as follows:

- **Run Trials on Actual Distribution Transformers.** DNSPs with available smart meter data should run trials of the smart-meter driven approach and compare the results with their existing DER hosting capacity assessments.
- **Use Data that Covers a Minimum DER Penetration Increase.** For DNSPs to successfully use the proposed smart meter-driven approach, it is recommended to use the historical data that cover a period where a minimum increase of DER penetration occurs, i.e., 30% for distribution transformers in urban HV feeders and 20% for those in rural HV feeders.
- **Other Considerations.** Changes is the voltage level due to the tap changing in the zone substation's OLTC actions can slightly reduce the accuracy of the DER hosting capacity estimations. Furthermore, the accuracy of the prediction limits also reduces because of the OLTC actions that can create voltage spikes and become outliers.

Analysis framework

DNSPs should carry out time-series simulations to reflect the time-dependent aspects of demand/generation and controllable devices in calculating hosting capacity. This enables a more accurate assessment of voltages and power flows regarding time variation and control device actions to support realistic dynamic "boundary conditions" [19]–[21].

Hosting capacity calculation methods

Based on EPRI [14], [31], the recommendations for each hosting capacity calculation method are summarised as below:

- **Stochastic Method**
    - This method does not guide DER developers or DNSPs engineers on location specific DER impacts.
    - The detailed implementation of this method is not easily repeated or replicated to entire distribution systems, and the analysis can take hours to days to evaluate a single feeder.
    - This method can be very effective for research purposes, but it is not recommended for any extended application exceeding that.
    - The method is implemented uniquely for individual distribution planning tools.
- **Streamlined Method**
    - Developing the agnostic (non-specific DER) hosting capacity is a unique aspect of the approach that enables the rigorous hosting capacity assessments to be performed upfront while allowing the actual DER-specific results to be derived offline, but the process needs further validation. The streamlined method results should be compared with results from other methods to gain confidence in the accuracy.
    - The streamlined approach can be implemented in multiple time periods to derive a time-based hosting capacity.
    - Further consideration should be given to the impact of the input load forecasts as slight variations in the shape of the load (and existing DER) forecast can significantly impact DER-specific hosting capacities.
    - The method can be implemented independent of distribution planning tools.
- **Iterative Method**
    - The simulation time to perform the iterative analysis increases with the feeder numbers and additional impact factors.
    - Limiting the cases, locations, and scenarios considered or making the analysis more efficient can reduce the computational burden.

    - An agnostic hosting capacity analysis in the iterative method enables performing the rigorous hosting capacity assessments upfront, while allowing the actual DER-specific results to be derived offline. Further validation of this process is needed.
    - Further analysis on the impact of slight variations to input loads, DER profile assumptions, and load forecasts on the time-based hosting capacity results are recommended.
    - Further assessments of the input time-series data and the validation of simulation results through actual field verification are recommended.
    - The method can be implemented uniquely for individual distribution planning tools.
- **Hybrid Method**
    - This method strikes a balance between computational efficiency and method accuracy by leveraging lessons learned from iterative and streamlined methods.
    - This method can be implemented independent of distribution planning tools and data.
    - This method can be extended to evaluate various scenarios like grid conditions and smart inverter impacts because of the computational efficiency.

Simulation tools

- DRIVE is a standalone tool that does the hosting capacity analysis, which can interface with any vendor tool. Currently it is interfaced with Cyme, Synergi, PowerFactory, DEW, Sinapsis, DSS, and Windmil. However, other simulation tools need a top-up tool to calculate the hosting capacity.
- Other promising open access simulation tools such as PowerModelsDistribution and Open-DSOPF can be used to perform unbalanced optimal power flow.

4.7 Best practices

The end-use application for which one is calculating hosting capacity should drive the consideration of which calculation method to use. Therefore, the judgment on selecting the impact factors, models, frameworks, methods, and tools should be carried out based on 1) whether the appropriate factors are considered the specific end-use application and 2) the effectiveness (or lack thereof) of the underlying data and models in reflecting real-world conditions. With any modelling and simulation effort, reasonable assumptions have to be made, as a 100% accurate model is unrealistic.

Based on the reviewed projects and with significant input borrowed from [23], the key process steps for assessing hosting capacity based on the best practices are as follows:

1. Establish a stakeholder process to work with networks and other interested stakeholders to select, refine and implement the hosting capacity assessment to meet the near and long-term goals.
2. Select and define the use cases for the hosting capacity assessment with diverse stakeholders' input. These use cases should guide the development of network representations, hosting capacity calculating methodology, and its implementation. There are two primary use cases: (i) interconnection and planning; (ii) and a complementary function of optimizing the locational benefits of DERs.
3. Identify criteria to guide the implementation of the hosting capacity assessment. The established stakeholder process identifies and answers key questions regarding the scope, duration, and other key elements of the use cases to identify the essential impact factors.

4. Identify the network representation approach based on the identified impact factors and the available data for a use case.
5. Develop a hosting capacity assessment methodology (or methodologies) that can handle the use cases with the related impact factors, available data, and the model assumptions, which aim to provide clear and specific guidance and ensuring that the methodologies, assumptions, and results are transparent and informative to all involved stakeholders and end-users.
6. Validate the results of the hosting capacity assessment over time. Validating the results in the real-world is helpful and recommended to improve accuracy and functionality over time. Transparency in the methodology and assumptions and ready access to hosting capacity assessment results will ensure that they can be easily validated and any problems with the methodology identified and resolved.

4.8 Standing challenges and barriers

Based on the reviewed national and international projects, assessing hosting capacity is constrained by the limitations of:

Impact factors

- Consideration of multiple impact factors increases the computational burden and complexity in assessing hosting capacity.
- Lack of information and studies for selecting the significant impact factors and their feeder metrics for a hosting capacity use case.

Optimal mix of data and models

- The lack of visibility of the LV network data (i.e., smart meter data) and network information (i.e., network connectivity and impedances) is a primary concern for most of DNSPs in Australia, as it affects the accuracy of representing the network segments and may lead to over- or under-estimate the hosting capacity.
- MV and LV network model simplifications arising from limited access to data and network information, such as neglecting the phase imbalance effects can lead to grossly inaccurate hosting capacity estimates.
- New network representation approaches are considered to overcome the lack of network information such as smart-meter driven approach. However, the accuracy of such approach depends on the volume of smart meter data as more data helps to capture the variance of a larger sample of network conditions (i.e., voltage vs active power). Moreover, it is not suitable for planning studies (i.e., “what-if” scenarios) that involve testing various network solutions that change the fundamentals of the feeder.
- The existing Network Opportunity Maps are not clear understanding of the existing export limit and current hosting capacity results, which will be gradually improved by increasing smart meter penetration.
- DNSPs have a lack understanding of their own network assets in real-time and the ability to manage those assets to increase higher DER penetration levels.

Analysis framework

- Balanced power flow and/or state estimation simulation will not be able to accurately reflect the changing demand and generation profiles within a time (i.e., hourly or less) and across various seasons in each phase, which may lead to over- or under-estimation of the hosting capacity result and the ability of the network to accommodate DERs.

- The state estimation technique needs less input quantities than that required in power flow. However, it is sensitive to the accuracy of the data, with particular high non-linearity in the data increases the risk of numerical instability in the solution finding process.
- Consideration short or high-resolution data granularity leads to more accurate hosting capacity results. However, it increases the computational burden and complexity in assessing hosting capacity.

Hosting capacity calculation methods

- There is no common hosting capacity method between DNSPs in Australia. Therefore, stakeholders have poor knowledge in understanding the hosting capacity limit, and how that can affect DER integration business cases and the ability of customers to connect and export DERs.
- Choosing a hosting capacity method for a use case is challenging, which heavily depends on the objective of a particular study.

Simulation tools

- The choice of the tools depends on several factors, for example, objective of the study, availability of the data and cost of the tool.
- The lack of consistency in analysing hosting capacity. DNSPs can use any planning tool based on the availability of the data, models and impact factors to evaluate the state of the network. However, a consistent method to analysis and report the hosting capacity should be common for all the DNSPs in Australia (e.g., DRIVE is regularly used by American DNSPs).

Application use cases

- Limited visibility and inability to manage DER limit hosting capacity and constrain the export capacity that can be safely released to DER.
- Costs and benefits of coordinated aggregation of electric vehicle (EV) chargers are not well understood. The potential to increase hosting capacity by combining traditional network voltage control approaches (i.e., OLTC transformers), strategically located sensors, and inverter volt-var, volt-watt functions, while practical, is not fully quantified.
- The equitable access of network resources to consumers DER remains an open challenge with static or dynamic operating envelopes due to unavoidable locational diversity of DER connections.

4.9 Opportunities for future work

The recommended future works to overcome most of the challenges and barriers of assessing hosting capacity are as follows:

I**mpact factors**

- **Develop a roadmap to link the use cases with their significant impact factors.** Although various impact factors significantly influence the hosting capacity of a distribution network, modelling all impact factors are extremely difficult. Further research is needed to define the most significant impact factors and their feeder metrics for each hosting capacity application use case. As the accuracy of a hosting capacity calculation increases with the number of impact factors considered, trade-off between accuracy of hosting capacity results, the corresponding computation time, and available data.

Optimal mix of data and models

- **Build a wide range of LV networks representations.** Data requirement for different use cases of hosting capacity can vary and network-wide monitoring could be expensive. Further research and investment are required to accurately represent the behaviours of LV networks considering the optimal mix of data and models as a trade-off between accuracy and cost.
- **Build integrated HV-LV feeder models.** Addressing both levels in a coordinated way will likely allow the best results on these long HV feeders. Further analyses could be undertaken that explore the use of HV and LV mitigation measures in combination with detailed modelling for the LV feeders down to household connection points.
- **Develop a mix data-model approach.** Further research to select the best combination of data, and network modelling to have sufficient visibility for various use cases.

Analysis framework

- **Develop state estimation models.** When required data is not available, state estimation method is used to model the network. Further research to improve the performance of state estimation models based on the optimal mix of data and models considering the phase imbalance effects and data uncertainty, which may or may not be combined with power flow models, is required.

Hosting capacity calculation methods

- **Validate the available hosting capacity calculation methods.** Hosting capacity methods differ in the input data, accuracy, computation time, consideration of uncertainties, consideration of the time-related influence and the models used. Further investigation needs to be carried out to validate EPRI and the University of Melbourne recommended hosting capacity calculation methods for several use cases and based on their significant impact factors. The accuracy of hosting capacity assessment methods should be compared based on the results that can be obtained considering all the impact factors, regardless of the method.

Application use cases

- **The effects of a fleet of behind-the-meter batteries.** Fleet of behind-the-meter batteries could be able to mitigate the power quality issues. Further projects could be applied to investigate the effects of behind the meter batteries on hosting capacity results by incorporate coordinated management.
- **Electric vehicles (EVs).** EVs can essentially be considered large flexible loads that are intermittently connected to the grid. Further analysis to study the positive and negative impacts of EVs on hosting capacity results could be explored.
- **Develop a crystal-clear hosting capacity allocation strategy for DERs** that will address the system's security, consumer preference and equity issues. Develop use cases for dynamic operating envelope (DOE) that will consider a wide range of new technologies including EVs, demand side management.

- **Control methods for hosting capacity**. What are the criteria to choose the proper control method for managing hosting capacity limits? How to calculate the cost/benefit of a hosting capacity control scheme? Is it cost/benefit to network, customer, or a balance of both?

4.10 Conclusions

In summary, DNSPs should keep in mind key considerations to efficiently implement hosting capacity assessment. As there is no common hosting capacity calculation methodology in Australia, and there are several drawbacks for each methodology; therefore, further investigation should be taken to gain familiarity and understanding of the different HCA methodologies, their function, their capabilities, and their limitations based on each use case. Here, some important questions should be answered before spending time and resources on widespread implementation of HCA methodologies are “what an HCA can do?” and “what is the capability of an HCA to meet an identified objective of a use case?”. Accordingly, consistent HCA methodologies among DNSPs in Australia will allow for peer learning and experience exchange which will help to the accuracy and functionality of the HCA methodologies over time. The consistent HCA methodologies should be able to be implemented on different types of DERs to useful over time, which may allow to identify opportunities to expand hosting capacity.

One of the main concerns for DNSPs is data sharing to shape the behaviour of the networks which is keystone of calculating hosting capacity accurately. Data collection will help DNSPs and customers for better capturing the diverse value streams of DERs. Some of the issues that may raise, which should be considered by DNSPs, are customer confidentiality, access permission, and cyber security. In addition, DNSPs should consider balancing grid optimization, transparency and competition, consumer protections and grid security.

As DNSPs and other stakeholders are interested to build roadmap of the electrical grid in Australia for future planning to quantify the challenges and opportunities, the HCA methodology will be a formative tool. Furthermore, DNSPs should look for more robust DER forecasting methodologies, which should be implemented to ensure providing greater granularity and accuracy of the HCA methodologies.

5 LV Data Access and Mapping

5.1 Review scope

As our energy sector undergoes a transition to a decarbonised and decentralised system, it is increasingly important to harness the full potential of LV data. Effectively leveraging LV data can enable new capability to enhance DER hosting capacity, as well as efficiently managing and operating LV networks. In this context, LV data access and mapping represent key tools to communicate and facilitate information on LV network conditions to parties outside network businesses that are affected by or involved in developing solutions for LV issues. Data access and transparency is also a vital enabler for trust between customers, networks, regulators and third parties. “Mapping hosting capacity” as appears in the N2 brief has been more broadly interpreted by the research team to encompass the following scope:

Scope of LV Data Access and Mapping

The availability and presentation of LV data (obtained via the means outlined in the N2a sub-theme) to supply applications or use cases that require participation, knowledge or buy-in of stakeholders outside the network business.

Given this definition, *LV data access* and *mapping* also considers*:*

1. Use cases beyond hosting capacity, as this is only one of a series of identified opportunities.
2. Different types of data access and presentation beyond mapping. Given the inherently granular-spatial nature of LV data, data presentation often most usefully takes the form of map visualisations. This is particularly relevant as maps commonly empower smaller, less sophisticated users and prosumers who are important in realising DER value. As such, mapping is explicitly considered throughout this analysis, however, other forms of data access are also considered where appropriate, such as API data release without visualisation.

Despite the importance of external data access and mapping for the future grid, so far this has only been explored in Australia in a very limited way. The value proposition for publishing LV data for potential use cases has not yet been systematically quantified. Additionally, the level of cross-industry coordination required to deploy coherent and transparent maps remains unclear.

Against this background, this chapter reviews pertinent aspects of LV data access and mapping, including pathways for how that data reaches users, key strategic considerations, lesson learned from exemplar mapping practices, and standing barriers and opportunities.

5.2 Data access pathways

A future electricity system will require integrating and unlocking the benefits of DER in a timely manner [32]. The importance of developing systems to provide LV data access and mapping to expand the DER integration process has been emphasised in a range of other reports, as outlined by the ESB ([32], page 111).

Currently, the primary industry focus regarding LV network visibility is sourcing, and to a lesser extent processing, data to inform the operational and planning needs of the distribution businesses (DNSPs). In most instances, the data custodian is the DNSP, with limited or no access by other parties [32]. In Australia, the industry is only beginning to grapple with LV data applications and access requirements of external parties to aid in developing efficient solutions that improve network operations, planning, or regulation. Industry interviews for this Opportunity Assessment revealed a strong desire amongst a range of stakeholders for increased levels of data access and transparency for several reasons, such as:

- market operators needing to understand better where and how their functions account for or resolve lower level network constraints.
- retailers and DER (or non-network) service providers needing to understand where and how their products or projects account for network constraints or provide network solutions.
- renewable energy and DER project proponents and asset managers who need to know what can be connected to the network and where cost implications exist.

- broader transparency and oversight of what is happening on the LV system to underpin fair and equitable network policy setting, regulation and customer understanding of network access and associated limitations.
- the *coordination and integration* of efforts across network jurisdictions ensures that DER markets develop with limited friction and optimal equity levels.

While LV data mapping is in an early stage, there are a range of existing platforms or initiatives that help to demonstrate the strategic choices that need to be made in implementing and developing mapping tools. These existing initiatives have some differences in the LV data sources, how the data is managed and processed, and the level and type of permission access (public or private access). Specifically, three main pathways that have been demonstrated to date:

- **Pathway 1**: A single network is in charge of managing and publishing its own network data. LV data access can be either through fully public and free access channels (1a; e.g. Ergon) or via a minor application process (1b) such as online registration (e.g. Transgrid) or direct automated/controlled data exchange (e.g. SA Power Networks Dynamic Operating Envelopes or DOEs).

- **Pathway 2**: This pathway involves a third-party entity that plays the role of a central coordinator, as data comes from multiple network sources, and coordinated in a single location. Examples of this pathway include public free access such as the Network Opportunity Maps (2a), and subscription access such as the Rosetta network map (2b).

- **Pathway 3**: This pathway also incorporates a central coordinator for data collection and management of multiple network data. However, unlike Pathway 2, data is sourced from non-network sources: customer devices, retailers or DER third parties, making use of monitoring assets already deployed within the grid. As this is a complex and costly undertaking, it is also linked to a transaction platform that allows DER transactions to take place, and marketplaces to develop (such as deX: Decentralised Energy Exchange, or Project Edge). This might incorporate not only information/data flows, but also financial flows, control or price signals.

Other permutations are possible but are less likely or common.

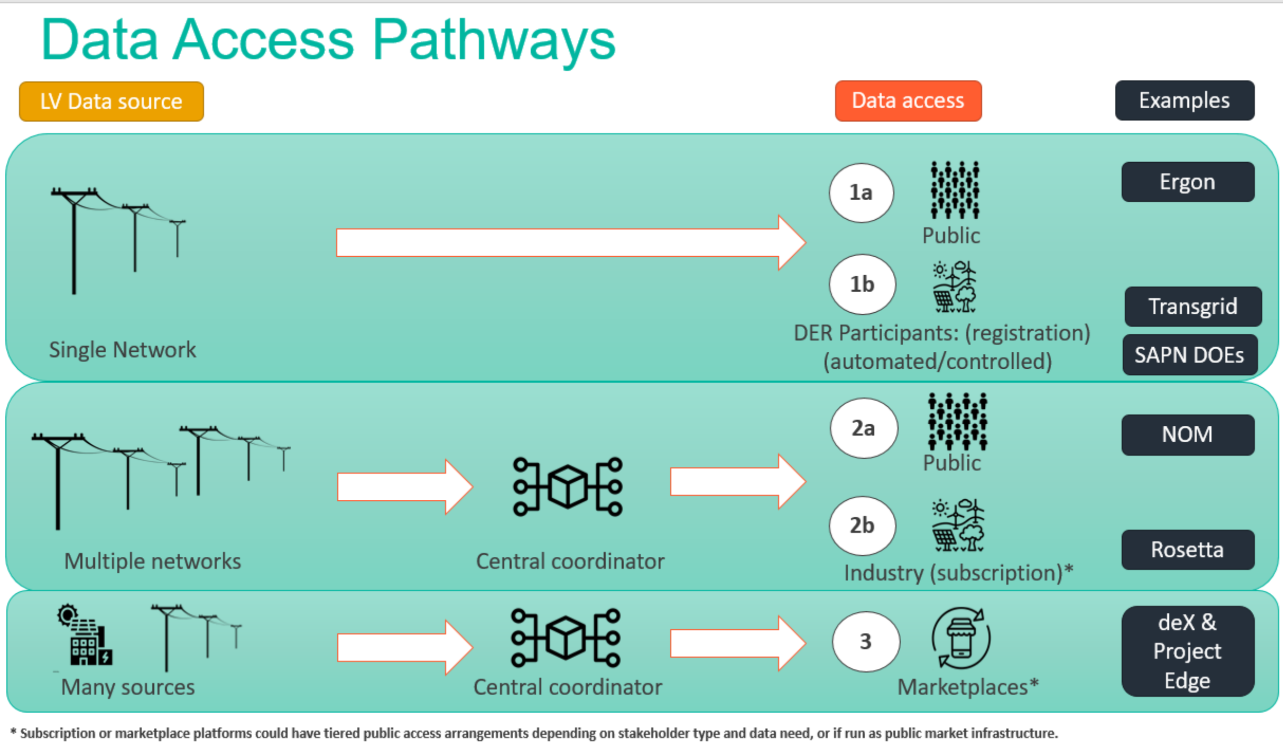


Figure 5-1: Data pathways according to data source and audience or use case

Certain use cases lend themselves to one pathway more than another. For example, DER procurement to provide network services might require two-way data flow for needs and offers, and an ultimately a contractual transaction. Pathway 3 might be the ultimate outcome for this use case. In contrast, detailed solar PV hosting capacity calculations might follow Pathway 1, or Pathway 2 if coordination is achievable. Each Pathway presents different advantages and disadvantages, as summarised in Table 5-51**Error! Reference source not found.** below.

It is worth noting that the central coordinator's role might be accommodated within potential emerging market frameworks to efficiently operate DER [33]. The joint AEMO and Energy Networks Australia Open Energy Networks (OpEN) project defines four potential market frameworks:

- *Single Integrated Platform* (SIP), which considers the expanded role for AEMO as a single centralised platform for dispatching and managing distribution and transmission energy resources.
- *Two-step Tier* (TST), in which there is a layered distribution level platform interface operated by the local distribution network and an interface between the distribution network's platform and AEMO.
- *Independent Distribution System Operator* (IDSP), which envisages independent distribution system operators optimising DER dispatch within distribution network technical limits; and
- Hybrid, in which DNSPs would manage and communicate distribution network constraints via aggregators, retailers and AEMO. Also, AEMO would manage a market platform that

optimises all DER bids for wholesale electricity and system support services. In this way, this framework addresses some limitations and concerns of the other frameworks.

In general, these frameworks consider the expansion of the wholesale market responsibilities and/or incorporate the participation of new or reframed entities, such as distribution market operators (DMOs) and distribution system operators (DSO). Key responsibilities of these new roles would require network visibility capabilities to manage network constraints, facilitate DER network services and ensure DER participation in the electricity market. The DMO and DSO may play a data coordinator role to optimise the provision of services from DER and guarantee the operation within network constraints.

The OpEN cost-benefit assessment [34] concluded that all four market frameworks could deliver net benefits under high DER penetration scenarios. However, costs for consumers are greater than benefits in low DER scenarios. It suggests that given that the benefits of deploying these market frameworks are dependent on DER deployment rates, there is no need to adopt any of the frameworks in the near term. However, there are key capabilities that should be developed within the near future, including better network visibility and data access [33]. Also, it was concluded that the Hybrid framework is a pragmatic solution that can bring the best of TST and SIP frameworks and avoid some of their weaknesses. Nevertheless, more detailed and clear definitions of roles and responsibilities is required. Consequently, OpEN concluded to test a range of hybrid models in a series of trials to explore frameworks that take a form closer to the SIP and others closer to the TST.

ESB recently conducted an extension analysis of OpEN market frameworks to examine the projected benefits that result from updated DER forecast trajectories [35]. ESB identified that long-term value for customers could be capture through tariffs and procurement options for DER services, which might be harmonised with the data access pathways discussed above. Specifically, ESB discussed the following four approaches:

1. *Structured procurement (manual)*, which is built on the RIT-D process and accepts bids from multiple parties in a more consistent and timely manner.
2. *Structured procurement with digital platforms*, which envisages marketplaces (such as Pathway 3) with simple auction mechanisms that operate alongside tariffs structures and ongoing enhancements.
3. *Retailer portfolio level tariff charges*, in which retailers at the portfolio level are charged for network access, and network charges can be optimised within their portfolio.
4. *Dynamic price signals per network element (real-time distribution market)*, which could be coupled with market mechanisms to provide congestion pricing and network access allocation for new and existing DER owners.

Each of these market designs implies a higher degree of consistency across network jurisdictions. Approaches 1 and 3 may have a better match Data Pathway 2, while Approaches 2 and 4 may match Data Pathway 3.

Table 5-5-1: Advantages and disadvantages/challenges of data pathways

	Advantages	Disadvantages
Pathway 1	• Low barriers to individual action might facilitate quick implementation by first movers. • No regulation required to initiate.	• Unlikely to be the most efficient option if all DNSPs take this pathway separately. • Harder to ultimately achieve Pathway 3 if this is required for key use cases. • No coordination between networks limits the efficiency of future market operation.
Pathway 2	• Standardisation of processes and procedures achieves greater market-wide data consistency. • Better experience for users than Pathway 1. • Cost-efficiency in platform delivery and achieving standardisation of calculations.	• Differences in data access and maturity of analytical capability could slow implementation or create 'lowest common denominator' effect. • Central coordination may be harder to fund than Pathways with agreement across multiple organisations. • Regulation required to achieve data consistency.
Pathway 3	• Two-way data flow provides value add to allow transactions where needed to integrate third parties more deeply into network processes.	• Much more complex technically to integrate more data sources. • Less likely to have fully free and open data access compared to other Pathways so may not fit all use cases. • Coordinator role tends toward core market infrastructure which are traditionally run by market bodies, not private entities. • Data privacy and security more challenging.

5.3 Key Considerations for Data Pathways & Access Formats

Determining what data pathways and access formats suit **specific LV data use cases** – and thereby the direction of industry approach more broadly – can be informed by consideration of the need for three high-level features, outlined below: (i) *cross-jurisdictional coordination*, (ii) *external mapping* , and (iii) *transactions*.

5.3.1 Cross-jurisdictional Coordination Need

Given the multiple sources of LV network data, it is normal to find differences across jurisdictions. In fact, there are already differences in the maturity of data use cases [8][34]. For example, some applications require smart meter data whose availability differs between jurisdictions. As data can be provided by multiple sources, a coordinator can be required to integrate different data systems. However, integrating data systems can be challenging due to the increasing volume, variety of formats and qualities. When cross-jurisdictional coordination is required, technical standards may be necessary to provide consistent and usable data.

As presented in Pathway 1, individual deployment of mapping by each network jurisdiction might accelerate data release but may reduce data consistency and potential for efficient solution provision for parties operating across jurisdictions. This was a key observation of the UK's Energy System Catapult, that proliferation of multiple standalone platforms might difficult the data access, bringing confusion and complexity [36]. Alternatively, data access and mapping activities can be done through a central coordinator, as considered in Pathway 2 and 3. Cross-jurisdictional coordination leads to data standardisation and greater system-wide visibility, facilitating DER integration and coordination activities [33].

Users in the mid-scale (1-5MW) solar supply chain in the US reported high value in cross-jurisdictional consistency to enable efficient operation of market players across borders [37].

5.3.2 External Mapping Need

Not all use cases require data to be visualised or seen by all parties. Each use can be analysed from this perspective to determine whether there is an inherent need for external mapping.

Level and type of data release

A key consideration is the level and type of data release necessary to meet the stakeholder objectives. In other words, "what specific data is needed for this use case, and what form should it be in? Does it need to be seen (spatially)? Connected to real-time decision making? Or both?" Key issues in this regard include:

- Sophistication of key user types: more distributed and smaller scale players (potentially down to DER prosumers) are generally less sophisticated, without dedicated staff or mapping tools, and will require a greater level of curation to make data useable and valuable. For example, calculated hosting capacity values are particularly valuable to less sophisticated parties, while more specialised or large entities with dedicated electrical engineers on staff may be better able to engage with LV issues and solutions if accurate LV asset models are provided as downloadable GIS files [37]. Data release can vary from 'unprocessed' LV data (limited examples to date) to carefully curated applications that require post-processing tasks and data-driven capabilities, which is the approach taken in most US hosting capacity map applications [12].
- Volume/frequency of data: this might dictate whether 'live' APIs are more suitable that sporadically curated outputs, or how data is fed to mapping platforms. Such APIs may be a good option for data access with very granular timesteps, such as more operational

network applications, and where users are relatively sophisticated. Data can also be disclosed in different ways, and could include mapping tools, or merely raw data access through APIs without visualisation features.

Data access permission/rights

Depending on who needs the to see the data, it can be made available in different ways [36]:

Open access: Data is made available for all to use and distribute with no restrictions.

Public access: Data is made publicly available but with some restrictions on usage.

Shared access: Data is made available to a limited group of participants, possibly with some restrictions on usage.

Closed access: Data is only available within a single organisation.

In some use cases, open or public access is warranted as electricity customers are a key user; while in other instances shared access may be more appropriate where industry parties are acting on behalf of the end user, such as DER aggregators.

Thus, depending on the answers to the questions “what specific data is needed for this use case?” and “who needs to access it?”, a substantive need for external mapping may or may not exist.

Cybersecurity limitations and privacy concerns

Data privacy and cybersecurity remain central and growing concerns [32]. Data privacy and cybersecurity are potential systematic issues that might inhibit LV data release. Releasing and using LV data needs to comply with consumer privacy requirements. Enhanced legal and regulatory frameworks are likely required to ensure safe and secure data access services can occur. This is increasingly relevant in the emerging energy transition scenarios as DER owners will play a more active role in the energy system. This may mean that different LV data types carry different privacy and security requirements and thus a nuanced, ‘tiered’ approach is required to enable the most open access possible.

5.3.3 Transaction Need

Some mapping initiatives may require additional capabilities to realise the value from data access. In addition to the network LV data, other information and financial flows can be involved. In particular, this consideration is important for mapping cases that require active participation or exchange of contracts, active control or dynamic price or operating signals. In fact, harnessing the inherent flexibility of DER requires demand-side participation, which will involve control and energy price signals to some extent [33]. Thus, it is important to consider whether publishing to an actionable marketplace is an important step, as this may negate the need for other “viewing only” data access platforms.

5.4 Use Case Analysis

The key considerations described above can be analysed based on the use case application, as shown in Table 5-2 below. For example, the process of setting standards on devices such as inverters, requires cross-jurisdictional coordination to guarantee consistency and fairness across the network service territories, but does not necessarily require direct transaction to take place. On the other hand, procurement of DER network services requires consistency, mapping and transactions. The connection of exporting DER or EVs carries high priority for public access mapping as end customers need to see the data, but cross-jurisdictional coordination may be less relevant if the bulk of users are primarily interested in connecting DER in a highly specific locale.

Thus, judgements on the key aspects of different use cases will dictate the appropriateness of market infrastructure for communicating LV data. The key takeaways from the analysis of Table 5-2 below are:

- Regulators have relatively limited direct use cases requiring mapping, but a high need for cross-jurisdictional consistency. However, ensuring trust between consumers, commercial participants, networks and market operators is vital to the regulator's role, particularly in the context of hosting capacity calculation methodologies. Trust and is unlikely to be achieved without a reasonable degree of data transparency, even if regulatory functions can largely be undertaken from consistently reported numerical data.
- The historical needs for network data visualisation have focussed on efficient network planning, which benefits from cross-jurisdictional consistency but is not bound by it. However, as network conditions and needs at the LV level become more operationally dynamic and move from the realm of 'planning' to 'operation', the need for data availability, analysis and action becomes far more granular, time critical and potentially automated. Such use cases are digital infrastructure intensive, which lends itself to common market tools or frameworks. At least parts of these functions are beginning to be undertaken within third party marketplaces, however, as noted in the OPeN, it is currently unclear what direction the roles of market coordinator will take and to what extent will contract or subsume private activity.
- Where multiple value streams can be harnessed within the same data access/provision infrastructure, this will strengthen and accelerate the case for external LV data presentation. Synergies may well exist between compelling territory-specific use cases for mapping that require open or public access data – like DER or EV connections – and other use cases that require cross-jurisdictional consistency.
- It seems reasonable to expect that networks that develop the data systems and capability to curate and release LV data in a form that is consistent with other jurisdictions will put themselves in a good position to capture the value of emerging use cases, irrespective of the future market form.

A series of conclusions are developed from this analysis below.

Table 5-2: LV Data Use Cases

Realm	Use case	Description	Key User Groups	Cross-jurisdictional consistency need	Mapping need	Transaction need
Planning	**Enable cost-effective distribution planning**	Improve annual and five-year network planning exercises to fully leverage customer DER (incl. forecasting DER impacts; incremental DM/non-network investment)	Network, DER/DM participants, Market operator, Regulators	Medium-High	High	Potential
Connections	**Connect new customer PV and batteries (exporting DER)**	Enable customers and their agents to connect a reasonable amount of solar, batteries at their premise at a reasonable cost. Customers clearly understand long-term value proposition of export.	Network, Customers, DER participants	Low-Med	High	Potential
	Connect new EV and load	Enable customers and their agents to connect reasonable amounts of new devices with certainty about any/all limits on their import capabilities	Network, Customers, DER participants	Low	High	Potential
Connections, Regulation	**Set connection standards on devices, inverters**	Set fair, cost-effective & nationally consistent inverter settings	Networks, Regulators, DER participants, Consumer reps	High	Medium	No
Regulation	**DER Market efficiency (future)**	Assess how well DER markets are delivering on desired objectives re: customer choice, system performance, reliability, and environment.	Networks, Regulators, Govt	High	Low	No
Planning, Operations	**Procure DER / Demand Management to provide network services**	Use customer devices to increase hosting capacity, address constriant to avoid/defer network investment	Network, DER/DM participants	High	High	Yes
Operations	**Inform DER participants & networks of "real-time" network/DER conditions & implications**	Identify and communicate dynamic operating envelopes	Networks, DER participants	Low	High	Potential
	Monitor and verify DER market transactions	Provide data required for DER to demonstrate participation in the wholesale (and network) energy market	Market operator, networks, DER participants	High	Low	Yes
	Network fault detection	Use better information to improve quality and reliability of supply	Networks	Low	Internal only	No
	Monitor DER standards compliance	Ensure that DER is installed according to standards set at time of installation	Networks, Regulators, DER participants	Low	Internal only	Potential
Planning	**Design smart tariffs**	Establish tariffs that are cost-reflective, equitable, and understandable by customers	Networks, Retailers, DER participants	Medium	Low	No

5.5 Precedents

This section covers the lessons learnt from data access and mapping precedents both locally and internationally.

5.5.1 Local precedents

Table 5-3 summarises network mapping precedents in Australia, albeit not with a focus on Low Voltage, as this is currently scarce. Each precedent has been classified based on the three data pathways described previously.

The most common examples follow Pathway 1 (own mapping platforms) as this is generally easiest for businesses to contract and manage and no external coordination is required. A number of examples of Pathway 2 exist which offer users cross-jurisdictional consistency, but face challenges of finding agreeing and maintaining common data standards over time and as such may be supported by regulation in the right circumstances. These platforms have been popular with the renewable energy industry who develop projects across a number of network jurisdictions. Examples of Pathway 3 are emerging as powerful new platforms given the transaction capability and tend to be accessible only behind registration of paywall, depending on the user type.

In summary, networks are currently focused on LV data sources and processing with a narrow focus on outward presentation. Some mapping is increasingly granular to 11 or 6.6 kV, but this is primarily for infrastructure location use cases and rarely include data on network conditions. Limited evidence of public LV data release was found, primarily being confined to innovation projects or registration-based marketplaces such as Evolve and deX.

5.5.2 International precedents

Similar to the local situation, LV data mapping tools are still in an early stage internationally, and a systematic approach for LV data mapping is still lacking. In Europe, legislation and data privacy and security concerns have imposed LV data release restrictions.

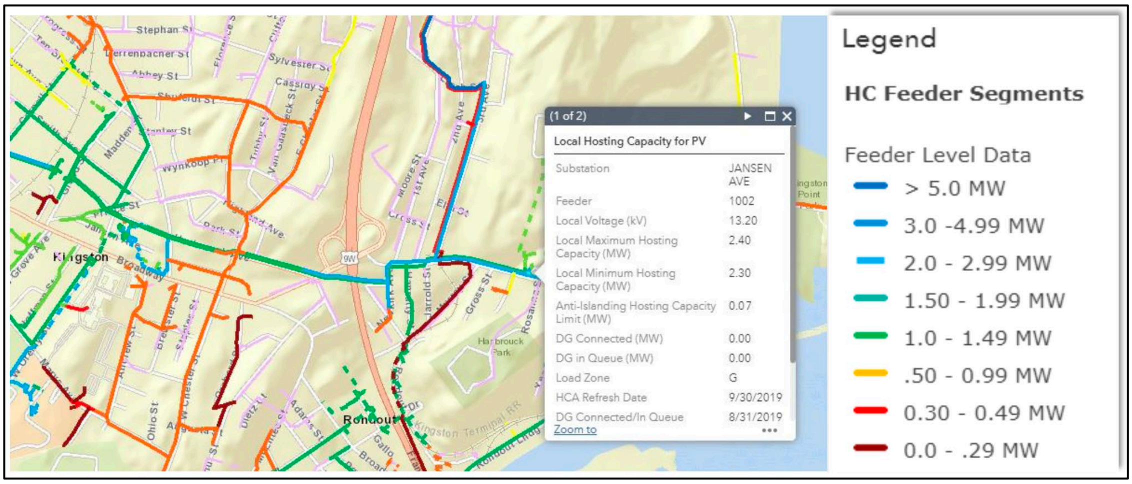
The US, however, has made headway in hosting capacity maps in the past few years, as summarised in Table 5-4 below [38]. According to EPRI [39] several patterns are evident:

1. Medium voltage feeder level hosting capacity maps are most common. Low voltage hosting capacity is not common as LV data like load is not public, although voltages, aggregate load, etc. has been made public in some jurisdictions. The amount of connected generation and queued generation is often disclosed and updated frequently.
2. Maps are specific to a given technology application, and are almost exclusively for solar PV, as per the example shown in Figure 5-2 below.
3. While maps are produced for external users, much of the value derived by maps is for internal network use cases like planning and operations. There is still some issues with interpretation and trust in mapped data, as renewable energy developers are not always

sure how to interpret the outputs or assume the results are not updated or good enough and they will need to go through regular detailed connection review anyway.

4. The lowest frequency of data update is annual, however monthly is common for certain data parameters such as the scale of existing connection applications under consideration, with many networks targeting ongoing ‘live’ data updates. Hosting capacity is precalculated and updated periodically, however triggers to recalculate differ by utility, and transparency of calculation methodology is currently lacking. More sophisticated users with electrical modelling capability may find publicly available load flow models of distribution assets overview as or more useful than infrequently updated pre-calculated hosting capacity outputs in the context of assessing new connection costs [37].
5. Map data generally has downloadable spreadsheet or results components, as this is a common request from users.
6. The mapping tools have generally been developed through different staged approaches, starting with simple tools, with plans to evolve towards more complex versions with new capabilities, such as dynamic and forecast hosting capacity maps, or a more sophisticated data portal that collects and combines ‘non-wires alternatives’, outages and climate risks on maps to help identify potential project sites as the case of the Massachusetts System Data portal.
7. Mapping platforms tend to be single utility (following Pathway 1), but collaboration on map methods and outputs is common. This is perhaps a reflection of the huge number of network businesses in the US, and the impossibility of full cross-jurisdictional consistency.
8. Hosting capacity maps make the process of connection assessment more efficient by saving time and cost on both sides, as renewable energy developers have the information available online and there is no need to contact utilities and request the data via request forms. Nevertheless, further work is required to assess whether the time and expense of creating and maintaining hosting capacity maps justify these time savings.

Figure 5-2 Example of heat maps of the gross hosting capacity by feeder calculated for large centralised solar PV



Additionally, some early EV connection capacity maps have been developed in the UK to communicate the capacity available in local areas for residential scale connections, while these are also under discussion in New York [40]. There are also UK mapping initiates for marketplaces (i.e., Pathway 3), such as Cornwall Local Energy Market and Piclo Flex, which provide participants with a platform to buy and sell energy and flexibility to the grid and participate in the wholesale market [41].

5.5.3 Costs & maintenance

The publishing of such data does represent a substantial undertaking for network businesses in the US. On the positive side, it drives the need for better network models from which everyone benefits, however the additional work to create and update maps can be substantial.

In terms of funding, most US utilities have built and maintained their hosting capacity maps funded through the rate base. Network models have been updated through routine long-term network planning studies, as they service several use cases, not just hosting capacity, so the business case rationale is quite broad.

For an individual network, EPRI notes that developing a roadmap for hosting capacity mapping typically takes around 3-4 months, and initial implementation tends to run over a few years, however this depends on the network's starting point. There is a huge range of costs according to the size of territory, the complexity of proposed maps and starting point of data sources, systems and network models. While it is important to note that these examples cannot be compared as 'like for like', some rough example cost data points for hosting capacity maps are:

- At the high end, in 2017 a California utility costed $2-8m USD to initially develop hosting capacity for 4500 circuits and $1-5m to maintain the map.
- In the mid-range, a smaller utility with a better starting point costed $280K USD p.a. to maintain maps.

At the low end, Eversource costed $300K USD to develop a map and $20K/a ongoing for software contracts.

Table 5-3 Summary of Australian network mapping precedents

Type	Use case	Examples	Max granularity	Platform	Coverage	What's common	Access
Pathway 1	Reg reporting	Endeavour; Ausnet	Mostly Zone Sub; some Dx feeder	ESRI; Google	Single network	N/A	Public (free)
	New load connection capacity	Endeavour; Western Power	Heatmap (11kV); HV Distn	Google; ESRI			Public (free)
	Demand Mgmt	Ergon Energy		ESRI			Public (free)
	New RE connections	Transgrid; Western Power	Region; Zone Sub	Google; ESRI			Public (registration)
Pathway 2	Demand Mgmt/Investments	Network Opportunity Maps	Mostly Zone Sub; some 22/11 feeder	National Map (open source)	NEM	data/calc/output	Public (free)
	RE Connections		22kV feeders			calc options/output	Public (free)
	EV infrastructure devt		11kV feeders (NSW only)			data	Public (free)
	Infrastructure locations/ RE connections	Rosetta Network Map	Mostly 66/22; some to 6.6kV	Google	NEM,NT,WA	data type	Subscription
	Investments						Subscription
	Market communication	AEMO	Transmission	Mapbox (open source)	NEM		Public (free)
	Dynamic Operating Envelopes	Evolve Project	LV (NSW, Vic)	React (open source)	Partner networks (4)	data/calc/output	TBD
Pathway 3	LV Operational Visibility	deX	DER portfolio		Partner networks (3)	data/calc/output	Subscription
	DER Control & Markets					data/calc/output	Subscription

Table 5-4 Summary of US distribution network hosting capacity map precedents

Utility	Reg. Req't?	Update Frequency	Map Info Features	Granularity	Additional Maps in Portal	Potential Future Enhancements	
						Near-term	Longer-term
Con Edison	Yes	Annual	Max/min load duration curves & forecasts; aggregated substation data (e.g. DER online)	Primary circuit (radial); Building level (network)	NWA[1], LSRV[2]; insights for EV charging stations	Energy storage; EV charging	PV+storage, other DERs; forecasted HC; dynamic HC
Eversource Energy (CT)	No*	Quarterly, moving to monthly	Feeder voltage; substation info; bulk circuit name; bulk substation info; feeder location HC capacity; DER capacity (online & queued)	Primary circuit	None	Wire size; voltage regulators	Additional technical details, including those more typical of FERC SGIP pre-app report
Orange & Rockland	Yes	Monthly	Max/min hosting capacity; queued & connected generation; local voltage; substation details; load zone	Primary circuit, and initial sub-circuit differences	NWA[1] RFPs; LSRV[2] maps	Increased refresh frequency; energy storage, EV charging	PV+storage; other DERs; upstream substation/bank level constraints; forecasted HC; dynamic HC
Pepco Holdings	Yes**	As needed, per ≥500 kW change on feeder	Operating voltage; total active & queued generation; total allowable PV (kW); max allowable capacity for a generator	Primary circuit	Heat Map; Restricted Circuit Map	Improved data quality; EV charging locations	ADMS adoption impact
Southern California Edison	Yes	Monthly	Steady-state voltage, voltage fluctuation, both generation and load; protection; thermal, both generation and load	Primary circuit (line segment)	LNBA[3] results; GNA DX report[4]; RAM circuits[5]; 10-year DER growth scenarios; load by customer class	Transfer map data to interconnection portal	Dynamic hosting capacity

Notes: [1] NWA = Non-Wires Alternative. [2] LSRV = Locational System Relief Value. [3] LNBA = Locational Net Benefit Analysis. [4] GNA = Grid Needs Assessment.
*[5] RAM = Renewable Auction Mechanism. * Eversource requested regulator approval to invest in maps, which the regulator agreed to in a 2017 ruling. ** Launched hosting capacity maps prior to regulatory requirement.*

Source: Integrating Hosting Capacity Analysis into the Utility Interconnection Technical Review Process (3002018644), EPRI, 2020

5.6 Standing challenges and barriers

A wide range of barriers to achieving the desired benefits associated with LV Visibility and hosting capacity optimisation were identified through interviews and a workshop with the Industry Reference Group. Those outlined in Table 5-5 are considered to be either an impediment to or can be overcome by data access and mapping.

Table 5-5 Barriers of relevance to data access and mapping

Category	Barrier	Relevance to data access & mapping
Data	D2. Data storage and processing platforms	The industry currently lacks data storage and processing platforms tailored for storing, analysing and sharing LV data. New capabilities may also be required for central data coordinators (Pathways 2 and 3).
	D3. Data security and interoperability	Needs to be considered and overcome for any data access and mapping strategy. Cyber security limitations – particularly driven by a lack of clarity and conservatism surrounding government restrictions on what data businesses can share – are hampering the potential for effective data access. The lack of a clear legal framework for managing cybersecurity and privacy concerns is already presenting challenges.
Information & Knowledge	I1. Analytical skills	Mapping platforms require new or more robust capabilities and tools for spatial data management and analysis [8].
	I2. Fit for purpose network models.	As network data becomes more granular in time and space to address LV issues, decision making complexity balloons surrounding spatial data analysis methods, and greater sophistication is required.
	I3. Sophisticated network planning methodologies.	
Regulatory	R1. Data Access & Ownership	The source and ownership or access right to data a substantial impediment to the ability to collate and share consistent LV data. Privacy concerns may limit mapping and data release strategies.
	R3. Common definitions and calculation frameworks	Collaboration on mapping calculation approaches and outputs is required to achieve fair customer outcomes across jurisdictions.

Network cultural	N3. Standardised approaches across networks	A collaborative data access and mapping strategy can proactively address inevitable data or more methodical standardisation issues.
	N4. Co-ordination and engagement	
Customer Behaviour	C1. Equitable access of consumer DER to network resources	From a customer perspective, there is an unresolved tension about who can access new grid connection capacity for DER or EVs, which may be aided by data transparency & mapping.
	C2. Consumer engagement in decision making & communication	Consumer buy-in and trust more broadly is also strongly tied to data transparency.
Market	M2. Network business case and value calculation	A trust deficit regarding network investments can be addressed through consistent and open data provision.
	M3. Customer incentives	The lack of end user engagement in LV solutions is likely to require engagement via data, either directly or via third party representatives (e.g. retailers or aggregators).

5.6.1 Active industry processes addressing barriers

A number of existing industry processes are already in train working on many of the above challenges and barriers. The ESB is currently developing an implementation plan for its data strategy [ref:005ESB] and has framed its response around three key actions: working groups to i) address LV reporting to provide transparency for DER investors and planners, ii) research impacts of current voltage levels; and iii) reviewing needs regarding building analytical capability in LV data and modelling. ESB recognises the need for cost-benefit studies to assess the most useful and cost-effective form to release LV data.

The Distributed Energy Integration Program (DEIP) also convenes working groups including the Dynamic Operating Envelopes Workstream, the EV Data Availability and residential connections taskforces, and the DER Standards, Data and Interoperability Working Group. These working groups have identified needs such as governance around customer data sharing, including LV data, DER operational, registration, and compliance data. Also, confidential data privacy was identified as a concern [42]. In [43] ARENA recognises an institutional barrier related to the lack of standards. Apart from the DER Register, no current standards specify what DER-related data should be collected and how it should be stored, or industry agreement on those matters. This lack of standardisation also applies to mapping and data release capabilities but appears not to have been identified as an industry gap to date.

5.7 Conclusions

Future research directions are outlined in the Roadmap. However, by way of summary, if we review the Australian needs in light of international experiences, and account for the likely strong interaction of post 2025 market design and OPeN processes on data coordination roles, we suggest that a ‘no regrets’ research program should aid in developing:

- A shared understanding of the common raw and processed data outputs required for different use cases to meet stakeholder expectations, accommodating the diversity of data sources outlined above. Where this involves data from customer-owned devices (such as in a marketplace bringing together DER operational data) clarity of data access and privacy rights and consent processes will be a critical consideration.

- Collaborative digital and data infrastructure, systems and processes to support implementation of common LV data that helps to ’stack’ value from a range of use cases and achieve cross-jurisdictional consistency of LV data provision and processing, and can integrate with private or public marketplace developments.

- Capability within networks to connect the planning and operational functions through spatial network models and data management.

6 Mainstreaming customer DER network support

6.1 Review scope

This section is framed around one question: How can customer DER be mainstreamed to provide network support and increase hosting capacity?

6.1.1 What is DER network support?

One definition of customer DER network support is given in the DER Technology Integration report by farrierswier and GridWise energy solutions [44] "The ability of DER devices to respond to power system disturbances in a manner that (1) limits or prevents any adverse impacts caused by the DER themselves and (2) provides additional grid support that benefits overall grid security and reliability". A problem with this definition is that DER's ability to provide grid support doesn't occur just in response to power system disturbances. These services also occur indirectly, when DER is used to maximise self-consumption for example. Customer DER network support can also be preventative, avoiding resource adequacy issues, when DER is used to provide demand response. This broadens the above definition to:

DER network support

The ability of DER devices to (1) limit or prevent any adverse impacts caused by the DER themselves and (2) provide additional grid support that benefits overall grid security and reliability.

6.1.2 What is Mainstreaming DER network support?

Mainstreaming DER is defined by the Networks Renewed ARENA project[3] as

Mainstreaming DER network support

A vision of the market conditions that will exist if customer-owned DERs are able to contribute network support services for a clean, reliable, affordable, and equitable energy future

A subsequent pathway for DER-based network support services to be commercially ready – or mainstreamed – was laid out in the Networks Renewed ARENA project

This pathway and findings from industry reports and IRG feedback indicate that mainstreaming DER to provide network support and optimise hosting capacity can be achieved through five related, but distinct enabling objectives:

[3] https://arena.gov.au/projects/networks-renewed/

1. identify the best combinations of network and non-network options to provide network support and optimise utilisation of hosting capacity
2. outline how the process for evaluating DER-based options for providing distribution network support can be standardised
3. improve DER device standards and compliance
4. provision data sharing between networks, DERs, and third parties
5. improve customer engagement through education and the development of new products and services.

The content in each section of this chapter is associated with an enabling objective, where industry reports relevant to the topic are reviewed, and findings identified, which relate to the enabling objective. In most cases, associated insights are also drawn from the IRG interviews. Key findings are then derived from the identified findings. A review of academic papers, however, is not included. It is therefore recommended that a thorough review of the academic literature be undertaken as part of any project related to the findings posed in this section.

6.2 Assessment of DER Integration Techniques (DERITs)

This section reviewed industry reports investigating network and non-network options to provide network support and increase hosting capacity to identify key findings related to enabling objective 1: "identify the best combinations of network and non-network options to provide network support and optimise utilisation of hosting capacity"

Enabling objective 1 addresses the scope opportunity given by the RACE2030 committee:

RACE2030 N2c opportunity

"What are the best combinations of network and non-network options for DER hosting capacity (e.g., Load management, smart charging, battery + transformer tap changers + PV inverter reactive power control)?"

Where "best" is interpreted as the combination of network and non-network options which provides the most increase in DER hosting capacity for the lowest cost. Network and non-network (customer DER based) options designed to provide network support and increase DER hosting capacity are referred to as DER integration techniques, or DERITs. The types of DERITs reviewed are given in Table 6-6-1.

To identify the best combinations of DERITs, the review focused on findings associated with:

- Reduction in voltage excursion and impact on load profiles
- Increase in PV hosting capacity
- Cost-benefit

- Efficacy generally for different feeder types and DER (primarily solar PV) penetration levels

Category	Type	Description
Network-side DERITs	Conventional	Adjustment of LV off-load tap transformers, the addition of more taps for LV transformers, adjustment of the on-load tap changer (OLTC) in zone substation transformers, augmentation
	Advanced	LV OLTC transformers with adaptive Control, Low Voltage Regulator (LVR)
Customer-side DERITs	Passive	PV inverter Volt-Watt/Var response and Dynamic Operating Envelopes (DOEs). DOEs set limits on real power export from DER.
	Un-orchestrated DER	Where solar PV and batteries are managed to maximise self-consumption or household savings. This process can be optimised through smart controls.
	Orchestrated DER	Where a fleet of household DER is managed to provide benefits to all fleet participants as well as network support.
	Demand side management (DSM)	Where flexible loads (air conditioning, electric hot water systems) are controlled to provide Demand Response (DR). DSM can also be included in an orchestrated or un-orchestrated DER DERIT.
	Cost reflective tariffs	Cost reflective tariffs are designed to incentivise customers to shift their consumption away from periods of high demand (in the case of SAPNs solar sponge, it's to shift consumption to periods of high solar PV export).

Table 6-6-1 Description of DER integration techniques (DERITs)

6.2.1 Key findings

Existing industry practice avoids easy comparison of results or drawing significant conclusions about any given DERIT or combination of DERITs. Indeed, the clearest finding from a review of industry examples is that the best combination of network and non-network options to use to provide distribution network services vary. “Best” also isn’t defined, but presumably would be the DERIT which provides the biggest increase in hosting capacity for the least cost, a kW/$ metric.

- The best combination of network and non-network options varies. Different DERITs worked better on some feeder types than others, and some worked well for low PV penetrations but not for high.
- Network-side DERITs, even advanced techniques like OLTC and LVR, while effective at low PV penetration levels and for all feeder types, tend to lose their effectiveness (in terms of increasing hosting capacity, alleviating congestion, and mitigating voltage excursion) with increasing PV penetration levels. It is recommended that customer-side DERITs are explored in combination with network-side.
- Implementing Volt-Watt/Var voltage response had the highest net-benefit at low PV penetration levels; transformer upgrade/reconductoring in combination with Volt-Watt/Var resulted in the highest net-benefit for higher PV penetration and longer feeders.
- PV + smart battery did well in cases with higher PV penetration levels. It resulted in negligible curtailment, and when combined with lowered LV transformer taps and augmentation of congested assets, 100% PV penetration could be achieved for all feeder types. It was also found to be the most cost-effective approach.
- Augmentation (to a pre-determined limit) only increased hosting capacity for certain feeder types, was expensive, and customer-side DERITs were required to reach higher PV penetration levels.

PV + smart battery is shown to be a low cost (to the network) DERIT which increased hosting capacity regardless of PV penetration and feeder type. PV + battery systems with no smart controller showed no increase in hosting capacity and didn't help to mitigate congestion or voltage excursion.

The review suggests that networks should utilise existing assets and consider network-side DERITs first before adopting more complicated ones.

- DNSPs should adopt intelligent approaches that exploit the existing flexibility provided by OLTCs at zone substations, adjust the off-load tap changer position of LV transformers and/or the voltage target at zone substations to lower customer voltages first, before implementing other network or customer DERITs.
- An increased 'buck' tap range of an off-load tap changer can have a much more beneficial impact on voltage than an increase of the transformer's rating and/or reconductoring of the LV network.
- LV transformers were most likely to experience congestion first due to excessive PV export, before conductors – increasing the capacity of LV transformers would therefore have the greatest return in terms of increasing PV hosting capacity.

- As part of a DNSP's normal transformer replacement activities, additional negative taps and transformers targeting the updated regulated voltage levels should be installed in all cases.

According to the 2019 consultation paper on 'Smart' Demand Response Capabilities for Selected Appliances (Smart DR) by the Department of Environment and Energy (DEE) [45], controllable loads have the significant potential to contribute towards load smoothing. Despite this, none of the studies reviewed included controllable flexible loads as part of an orchestrated or un-orchestrated DERIT, only solar PV and batteries. While there are DR projects currently underway, they are primarily focused on providing resource adequacy. Aside from the ARENA sponsored Rheem project[4], which uses electric hot water heaters, and for which no knowledge sharing reports have yet been published, there is a paucity of customer-side DERIT projects which consider flexible loads in combination with solar PV and/or battery.

There has been no research comparing orchestrated customer DER versus un-orchestrated. Referring to the findings from the AEMO Virtual Power Plant Demonstrations (AEMO VPP) project [46], and the AGL South Australian VPP (AGL SA VPP) project [47], VPP participants provide benefits to the network (network support) when operating in self-consumption or energy arbitrage mode. These modes equate to the PV + smart battery DERIT, and don't require a household to be part of a VPP to implement.

Cost-reflective tariffs are designed to incentivise customers to shift their consumption from periods of high demand to periods of low (or periods of high PV export as is the case for the SAPN solar sponge tariff). If customers successfully adopt such tariffs, their change in behaviour would smooth out household load profiles and inherently increase hosting capacity. Unfortunately, there is insufficient evidence to draw conclusions on the efficacy of cost-reflective tariffs for providing distribution network support. Generally, consumers find cost-reflective tariffs less attractive and prefer less complex, more familiar tariffs, such as flat rate tariffs. In Australia, retailers often absorb network tariffs and the end customers actual costs do not reflective the network tariff, independent of specific network tariff design.

Orchestrated DER

- VPP participants are able to respond to both FCAS and energy market price signals, where VPP participants would discharge during low frequency events and charge during high frequency events. But generally, the primary driver of VPP charging/discharging behaviour appears to be optimising self-consumption.
- VPPs demonstrated the potential to accurately forecast wholesale energy prices, resulting in pre-charging in anticipation of discharging during a forecasted high-price event, and pre-discharging in anticipation of a forecasted low-price event.

[4] https://arena.gov.au/news/storing-excess-solar-from-the-grid-using-hot-water-systems/

- VPP participants benefit through energy arbitrage, with participants savings and return on investment (NPV) increasing with increasing export limits**.** VPP participants also see benefits through FCAS participation.
- VPPs at scale have the potential to provide generation capacity during periods of low generation reserves, provide demand to offset low minimum demand periods and contribute to peak demand reduction. Providing such services leads to reduced wholesale prices for all customers and reduced renewable energy curtailment.
- VPP revenue is strongly correlated to FCAS. As a result, if revenue is the objective, a VPP will prioritise FCAS participation at the expense of other value streams. There is a risk that this behaviour may result in a negative impact on the network.

The ESB also realises the importance that the operation of DERITs ensures system security and doesn't jeopardise it.

ESB Post-2025 Review

Technical integration of DER is needed to ensure that a reliable and secure system continues; arrangements need to support service providers to interact with the wider systems and wholesale market.

Reforms must ensure that integrating flexible DER and demand-based assets into the market at all levels, be done safely and effectively.

- As VPPs grow in size and become more numerous, they will play an increasingly important role in the power system. According to AEMO, to ensure their efficient integration into the power system and to avoid jeopardising the security of it, VPPs will need to be visible (submission of near real-time operational data), forecastable, and dispatchable.

6.2.2 Network-side DERITs

All the findings in this section are taken from the Advanced Planning of PV-Rich Distribution Networks (PV-Rich) project[5] and the Future Grid for Distributed Energy (Future Grid) project[6], unless otherwise specified.

The PV-Rich project developed analytical techniques to assess residential solar PV hosting capacity of electricity distribution networks by leveraging existing network and customer data. The Future Grid project assessed potential mitigation options, based on analysis of implementation cost vs benefit.

[5] https://arena.gov.au/projects/advanced-planning-of-pv-rich-distribution-networks-study/

[6] https://arena.gov.au/knowledge-bank/future-grid-for-distributed-energy/

Tap changing (conventional)

Adjusting LV off-load tap changers (OLTC) down to allow more head room for PV export was only effective in mitigating voltage issues for urban and short rural feeders; the mitigation was limited for longer feeders. Longer feeders tend to experience larger voltage excursion, and LV transformers don't have the tap capability to offset the voltage rise. However, an advantage to this technique is that is significantly reduces real power PV curtailment. Another finding was that adjusting the OLTC voltage target at the zone substation (i.e. reducing the voltage at the MV side of the LV transformers) in combination with adjustment of LV off-load tap changers showed slightly higher benefits to simply adjusting off-load tap changers alone.

Augmentation (conventional)

LV transformers are most likely to experience congestion due to excessive PV export, increasing the capacity of LV transformers (within pre-determined augmentation limits) would therefore have the greatest return in terms of increasing PV hosting capacity. Interestingly, LV conductors didn't experience congestion, which is likely due to voltage limits curtailing PV export before thermal constraints are experienced.

Transformer upgrade/reconductoring, OLTC and LVR (advanced)

Transformer upgrade/reconductoring, OLTC and LVR were effective at improving power quality performance at lower levels of PV penetration. LV OLTC-fitted transformers combined with adjusted LV transformer off-load taps and network augmentation was effective at mitigating all voltage issues in both urban and rural feeders. Voltages were always maintained within regulation limits. As per the other network-based techniques, there is negligible curtailment – even at 100% PV penetration. For long rural feeders with SWER lines, where adjusting the LV transformer off-load taps alone didn't maintain voltages within regulation limits, adding LV OLTC-fitted transformers rectified this. However, a significant number of transformers did need to upgrade to OLTC however – a cost consideration. It was also found that an increased 'buck' tap range of an off-load tap changer had an improved impact on voltage than an increase of the transformer's rating and/or reconductoring of the LV network.

The Future Grid report goes on to recommend that as part of a DNSP's normal transformer replacement activities, additional negative taps and transformers targeting the updated regulated voltage levels should be installed in all cases.

Voltage management in the MV network (advanced)

Adjusting the OLTC voltage target at the zone substation (followed by the adjustment of off-load tap changers) only gave slightly higher benefits over adjusting LV transformer off-load tap changers alone. The Future Grid report recommends further analysis on this type of approach to explore the use of HV and LV mitigation measures in combination.

6.2.3 Customer-side DERITs

Volt-Watt/Var functions (passive)

Simulations found that Volt-Watt and Volt-Var voltage response, with Volt-Var prioritised, was highly effective at limiting voltage issues for both urban and rural feeders. Importantly, real power curtailment was minimal with the total amount of energy curtailed always below 2% at 100% PV penetration. The study also found that Volt-Var can require significant import of reactive power, increasing loading on cables and transformers, and raise concerns around power factor and voltage management in the MV network (which is in opposition to LV management via Volt-Var).

Dynamic operating envelopes (DOEs) (passive)

DOEs have only recently been implemented by SAPN (where they are labelled “Dynamic Export Limits”) on a trial basis to manage excess solar PV export, and the impact/effectiveness has yet to be established. The method given in an analysis of SAPN’s Tesla VPP project[7] may be similar to the one implemented for the state-wide roll-out of DOEs. The method used 5-min power measurements from each VPP participant and was found to have significant potential. That potential has resulted in ARENA developing a DOE Working Group in its Distribution Energy Integration Program and several newer ARENA projects, such as Project Symphony in WA and Project EDGE in Victoria, considering or incorporating DOEs in their program design. The outcomes of implementing DOEs on network performance and customer feedback are still unknown with significant additional analysis required before widespread adoption would be justified. Importantly, there are no established methodologies for measuring DOEs, and the ones which have been established cannot be easily reviewed or verified to determine their overall effectiveness at better utilising network capacity. SAPN’s approach, which relies upon a few archetypal network models to underline the calculation of a DOE at every part of the network may significantly underestimate the network’s hosting capacity. Additional research is required to identify how best to calculate DOEs and balance the cost of additional network visibility to develop more accurate DOEs against the benefits of increasing hosting capacity and less regularly curtailing solar (and other DER) export.

PV + dumb battery (unorchestrated DER)

PV + battery in the home with no smart controller showed no increase in hosting capacity and didn’t help to mitigate congestion or voltage excursion. The lack of control meant that batteries would reach capacity before the midday solar peak and therefore couldn’t soak excess PV generation at this time. Capacity is reached prematurely due to low consumption in the evenings resulting in batteries not being fully discharged overnight, and low consumption in the mornings resulting in excess PV export prematurely charging batteries

[7] https://arena.gov.au/assets/2021/01/analysis-of-the-vpp-dynamic-network-constraint-management.pdf

to full before daytime solar peak. While PV + dumb battery brought no significant benefits to the network, it did reduce grid imports by up to 80%, reducing electricity bills. Interestingly, despite the reduction in grid imports, curtailment levels were unaffected, confirming that PV + dumb battery doesn't reduce solar soaking during peak PV export times.

PV + smart battery (unorchestrated DER)

While PV + dumb battery is dumb, PV +smart battery is smart, and when combined with augmentation (within limits), helped to increase hosting capacity to 100% regardless of penetration and type of feeder It also reduced asset utilisation, alleviating congestion, and helped to mitigate voltage excursion. All these benefits are achieved without any curtailment. This is made possible by the smart controller – which manages the battery state of charge over the whole PV generation period, significantly reducing export. A similar result is found in the AGL South Australian VPP project [48], where the aggregate load profile of a fleet of households (unorchestrated) with PV + smart battery is shown to smooth significantly.

Tariffs

The 2020 Energy Networks Australia (ENA) Open Energy Networks (ENA OpEN) report [33] claims that new tariffs should be offered which incentivise prosumers to self-consume their solar PV generation, charge batteries or shift load during periods of low demand, and discharge batteries and export solar PV generation (sun permitting) during periods of high demand. The tariff suggested in the ENA OpEN report is cost reflective, and reliant on a change in customer consumption behaviour. The desired change in behaviour would smooth out household load profiles, reducing infrastructure utilisation and voltage excursion, and inherently provide network support. But, unfortunately, according to the CSIRO report "Australian Consumers' Likely Response to Cost-Reflective Electricity Pricing" by Stenner et al [49] "Consumers find all forms of cost-reflective pricing significantly less attractive than traditional flat rate tariffs". The assumption is that customers will respond "rationally" to price signals and shift their consumption accordingly, but there is insufficient evidence confirming whether this is the case. According to Stenner et al, customers prefer simpler, more familiar tariffs. Flat rate tariffs rank well, more complex tariffs, such as cost-reflective, rank poorly.

One issue with the impact of tariff reform is that retailers often absorb network tariffs and do not pass through the full cost signal to their customers. To help address this issue, AGL has proposed trialling a "bulk wholesale network tariff model," in which networks charge retailers for their customers use of the distribution network based on "the total load profile of all the retailer's customers in a distribution network region…aggregated to a feeder, transformer, or local network level". The envisaged benefit of such an approach is that it would enable retailers to reduce network costs through the development of smart energy usage programs that still maintain a level of simplicity in customer billing.

Virtual Power Plants (orchestrated DER)

In the AEMO VPP project [50], it was found that VPP participants demonstrated their ability to respond to both FCAS and energy market price signals. Operationally, regarding FCAS, VPP participants would discharge during low frequency events and charge during high frequency events. VPPs also demonstrated the benefits of accurate forecasting, pre-charging in anticipation of discharging during a forecasted high-price event, and pre-discharging in anticipation of a forecasted low-price event. But generally, the primary driver of VPP charging/discharging behaviour appeared to be optimising self-consumption.

In some cases, network congestion (voltage) can limit VPPs from providing dispatch (discharging batteries), as discovered in the AGL SA VPP project [47], where breach of local voltage levels limited the dispatch performance of the overall fleet. This occurred more regularly during times of high solar export (as expected).

The positives associated with VPPs are raised in the AEMO VPP project [50], where AEMO found that VPPs at scale have the potential to provide generation capacity during periods of low generation reserves and also to provide demand to offset low minimum demand periods. This will occur naturally in response to energy price signals, where they take advantage of high prices (by discharging) during high demand/price periods and low prices (by charging) during low demand/price periods. Coincidently, this also happens when operating in self-consumption mode. This type of participation can provide the following benefits to the network:

- benefit all electricity consumers by creating competition in these markets to reduce prices and if scaled up enough displace/defer the need for more expensive large-scale generation assets.
- lessen the duration and magnitude of the negative spot price period.
- reduce curtailment of variable renewable energy and reducing the need for ramping large thermal units.
- assist with the management of peak demand and prices on extreme days.

There are, however, potential negative impacts of VPPs on the network. According to the AEMO VPP project [51], VPP revenue is strongly correlated to FCAS, how many FCAS markets the VPP participates in, and the overall responsiveness of the VPP to price signals. As a result, if revenue is the objective, a VPP will prioritise FCAS participation at the expense of other value streams, including energy price arbitrage which produces more local network benefits. While FCAS itself is a beneficial network service, there is a risk that this the overall impact of VPP participation in FCAS is negative for the network compared to its other behaviour.

Poor network outcomes can also result from bad battery control, where batteries reach capacity too early and are unable to absorb solar export during middle of the day, also suggested by the PV-Rich project [52]. Poor network outcomes can also result from simultaneous ramping up or down of exported power from an entire VPP in response to market signals if not scheduled. Stakeholders also expressed concern during IRG meetings regarding the risk unregulated large scale VPPs posed to network security.

- *Stakeholders are concerned about the risks integrating large scale fleets of solar PV might pose for system security. One stakeholder asked, "What are the power quality implications for fleets of DER exporting en masse in response to wholesale price signals?"*

As VPPs grow in size and become more numerous, they will play an increasingly important role in the power system. According to AEMO, to ensure their efficient integration into, and to avoid jeopardising the security of the power system, VPPs will need to be:

- Visible - submission of near real-time operational data so AEMO is aware of how VPPs are responding to market signals
- Forecastable – either through AEMO improving their forecasting capabilities to predict VPPs' operational behaviour, or through forecasts provided by VPPs themselves
- Dispatchable – with VPPs participating in central dispatch as a form of scheduled resource

It is important that the forecasting and control methodology implemented by VPPs to control the charging/discharging of fleets of batteries doesn't compromise power system reliability.

On forecasting, the AEMO VPP project [46] found that while improvements are still needed, VPPs demonstrated the potential to accurately forecast their performance. Producing accurate VPP forecasts, which includes a large quantity of DER, dynamic in nature, is challenging. However, AEMO expects forecasting "performance to improve with greater diversity of resources through additional installations and increased experience.". Accurate forecasting will be an important capability for VPP market participation in the future. According to another report from the AEMO VPP project [51], VPPs that prioritise their DER fleet for participation in FCAS are harder to forecast. AEMO expects VPPs assist the grid where required. To ensure this, the forecasting and control methodology of VPPs will require careful planning and likely additional regulation.

6.2.4 DERIT cost-effectiveness

In the Future Grid project, two value streams were used in the economic evaluation: the value of the additional PV generation enabled by mitigation measures compared to a baseline scenario without mitigation measures, and the marginal cost of mitigation measures. Implementing Volt-Watt/Var was found to have the highest cost net-benefit for achieving low PV penetration levels (< 25%), but with increasing PV penetration transformer upgrade/reconductoring resulted in the highest cost net-benefit. This was due to the increase in curtailment (interpreted as lost generation) which came from Volt-Watt/Var at higher penetrations.

The PV-Rich project [12] cost-benefit analysis considers CapEx and OpEx of assets, and unserved generation due to PV curtailment. It then calculates the NPV to give 60% and 100% hosting capacity. Interestingly, in contrast to Future Grid, PV-Rich found that augmentation only increased hosting capacity for certain feeder types, was expensive, and that customer based DER integration techniques were required (in combination with augmentation) to reach higher PV penetration levels. The reason for this could be inputs (data and models), difference in classification of feeder types between the two networks, or method, or a combination of all three. PV-rich also found that PV + smart battery + augmentation was the most cost-effective solution for achieving 60% hosting capacity for non-rural feeders, and Volt-Watt/Var + augmentation for rural feeders. PV + smart battery + augmentation was found to be the most cost-effective solution for achieving 100% hosting capacity for all feeder types.

6.3 Standardised process for evaluating DER-based options

Findings from reviewing reports for Section 6.2 revealed that different methods were used to assess the network support provided by a DERIT. The aim of this section is to identify findings on how to develop a standardised process for incorporating DER based options in DNSP revenue proposals. This aim is aligned with enabling objective 2: "outline how the DNSP process for evaluating DER-based options for providing distribution network support can be standardised".

The first finding from Section 6.2.1 points out existing industry practice avoids easy comparison of results or drawing significant conclusions about any given DERIT or combination of DERITs, and that the best combination of network and non-network options to provide distribution network services vary. Data sources and network models input into DERIT assessments also varied, with two out of the three projects assessed being forced to rely on simulated data. There is currently no standard way for evaluating these approaches for either technical impact or cost-effectiveness.

There was also significant feedback from the IRG related to network expenditure proposals. With the one IRG member pointing out that:

- *some DNSPs are engaged with the process (of incorporating DER into their revenue proposals) and some aren't, and that DNSPs need to get better at articulating/describing their revenue proposals as it relates to DER to get investment approval.*

Unfortunately, no IRG members advised on how to "get better," and many admitted to not knowing how to achieve (adequate) LV visibility cost-effectively, possibly acknowledging the difficulty of the task. One IRG member noted that

- *each DNSP has their own approach and suggests standardising processes related to DER.*

One network freely admitted during interviews to the difficulty of incorporating DER into their revenue proposals. Also expressed by a network was the challenge of calculating a hosting capacity limit or determining the best solution to manage hosting capacity.

- *It's difficult to decide on a hosting capacity limit, as there are so many viable options. It's easy to set a limit based on simple technical/fundamental data, but more difficult to decide upon the "best" solution. How is "best" determined? What's the correct balance between network cost-benefit and customer satisfaction?*

All of the above information supports the need to standardise the process for how DNSPs evaluate DER-based options for providing distribution network support.

6.3.1 Key findings

DERIT assessments need to be precise. According to findings in Section 6.2.1, different DERITs worked better on some feeder types than others. This indicates that, ideally, in each instance that a DER integration assessment is undertaken, it be done with as much precision possible. This means accurate models and historic load and generation profiles. Using "archetypal" feeder models and estimations of load and generation profiles may result in an incorrect assessment, costing the network and the customer.

A standardised method for how DNSPs evaluate DER-based options for providing distribution network support should be reached collaboratively, involving all industry stakeholders.

As recommended by the 2020 report "Value of Distributed Energy Resources: Methodology Study" (VDER) by CSIRO and Cutler Merz [53], the AER should prepare a practice guide for DNSPs setting out a principle-based approach to preparing business cases for DER integration. A list of input assumptions, required for a DERIT assessment, updated regularly, should also be provided.

The cost-benefit analysis needs to be reliable, consistent, and comprehensive, ideally considering all DER value streams. This analysis will also need to strike a balance between customer and network needs, as the two can sometimes be in conflict.

The customer needs to be given due consideration when assessing a DERIT, especially when allocating hosting capacity, which needs to be equitable. Curtailment (especially when unfair) is an impact on customers and is the type of impact that needs to be incorporated into a standardised DERIT assessment. It may be that a DERIT can't be implemented unless a thorough customer cost-benefit has been implemented, and meets certain requirements, measured using standard "customer metrics".

Industry consultation required

A consistent refrain heard during IRG interviews and meetings was that industry consultation be part of due process before implementation of DER-based operational changes:

- *The industry is fragmented, with inadequate collaboration across the industry and jurisdictions in terms of how to move things (regulation/operation/standards) forward to transition towards the future grid. The process should be: Policies -> principles -> standards/solutions (which are then trialled/tested/developed).*
- *The discussion on how to prepare for the energy transition is being driven by networks. The operational changes/solutions implemented by DNSPs are in response to their immediate concerns (reverse power flows, high voltages etc.) and without consultation with other industry stakeholders. Stakeholders would like to see more consultation before operational changes are implemented.*

Cost-benefit analysis' varied

In the Future Grid report [54], the cost-benefit analysis compared the value of additional PV generation enabled by each mitigation measure against the annualised cost to implement. Two value streams were used in the economic evaluation: the value of the additional PV generation enabled by mitigation measures compared to a baseline scenario without mitigation measures, and the marginal cost of mitigation measures.

The PV-Rich project [55] cost-benefit analysis takes into account CapEx and OpEx of assets, and unserved generation due to PV curtailment. It then calculates the NPV to give 60% and 100% hosting capacity. This study considers the cost of solutions and unserved PV generation.

The CSIRO report on the SAPN and Tesla Advanced VPP Grid Integration project[8] "Analysis of the VPP dynamic network constraint management" by O'Neil et al [56] did an in depth customer cost-benefit study, where the NPV for each household with a VPP was calculated. Findings show that VPP participants benefit through energy arbitrage, with participants savings increasing with increasing export limits, up to $423/year on average for a 10-kW export limit. Due to data limitations, the report did not evaluate the overall benefits of the VPP Grid Integration approach to all customers (including those without VPPs or DER).

The methods used to assess the cost-benefit of a DERIT in the three studies referenced are inconsistent in terms of calculating cost-benefit to the network or the customer. They were also limited by only evaluating a few DER value streams – though typically the DER in these trials themselves only had a few value streams available to them. See Table 6-6-2 for a list of all DER value streams.

Benefit type	Value stream
Wholesale market	Avoided marginal generator SRMC

[8] https://arena.gov.au/projects/advanced-vpp-grid-integration/

	Avoided generation capacity investment
	Essential System Services
Network	Avoided/deferred transmission augmentation
	Avoided/deferred distribution augmentation
	Distribution network reliability
	Avoided replacement / asset derating
	Avoided transmission losses
	Avoided distribution losses
Environment	Avoided greenhouse gas emissions
	Reduced health impacts of air pollution
Customer	Change in DER Investment Costs
	Electricity bill management
	Willingness to pay for other perceived benefits (e.g., self-reliance, feel good factor, sense of contribution)

Table 6-6-2 List of DER value streams VDER [53]

Accurate network models needed

The Future Grid report [54] recommends that DNSPs “build power flow models for a wide range of LV”. It was found that “…the 10 LV network examples used in their study were not fully representative of the full population of LV networks.”. This is understandable as the diversity of LV arrangements is substantial. They go on to say that “The creation of an expanded set of example LV networks would allow a more accurate extrapolation to the entire distribution network”. This recommendation is also made in the PV-Rich project [55], where DNSPs should “Explicitly Model LV Feeders” and consider the use of integrated HV-LV feeder models down to customer connection points. They claim this “is necessary to fully capture the response of voltage-related control actions from residential PV systems as well as network elements and, hence, correctly quantify voltage rise issues and benefits from potential solutions.”

Quality/resolution of data

The analysis in the PV-Rich project [52] was undertaken at 30-min intervals (as was Future Grid project [54]). This resolution is too low to capture PV generation variability due to transient clouds. A repeat of the study at a higher time resolution may produce different results in regard to voltages and control cycles for LV OLTC transformers, which in turn impacts transformer maintenance costs.

The Future Grid project [54] was the only one which used real-world data, taking advantage of extensive AMI data sets. Thirty-minute data was available for most customers. This allowed them to avoid over-simplifying assumptions about customer load. By contrast, O'Neil et al [56] estimated benefits to VPP participants using simulated load profiles and PV generation for 1000 VPP sites. The PV-Rich project [52], due to limited access to smart meter data, were forced to generate P, Q and V data points for each customer from a much smaller real-world data set consisting of 30-min P and Q values. The reference data pool was used to run unbalanced, 30-min resolution, time-series, three-phase four-wire power flows for a large number of load and generation profiles to generate the corresponding P, Q and V data used for the study.

AER to give guidance

The VDER report [53] looks at DER value streams and gives a number of recommendations to the AER and AEMC to assist the development and analysis of a business case for a DER-related expenditure. It recommends that the AER prepare a practice guide setting out a principle-based approach to preparing business cases for DER integration. It is advised that at a minimum the practice guide should include:

- the types of DER benefits which may be included,
- how wholesale market benefits should be calculated,
- the preconditions under which network benefits may be included,
- a comprehensive base case, the source of key input assumptions, and
- how the business case should be reported
- consider equity when determining hosting capacity

Balancing network and customer needs

In the PV-Rich project [57], it was found that Volt-Watt response alone (with no Volt-Var) results in significant real power curtailment. Findings for Volt-Watt were similar in the Future Grid report [54], finding that while it was effective at maintaining voltage within regulation limits, it resulted in large amounts of curtailment. In comparison, a key advantage of network DERITs is they don't result in customer PV system curtailment. Volt-Watt/Var is an example of a passive DERIT which provides benefits to the network but not to the customer. However, importantly, it does allow for more customers to actually install a PV system in the first place. This highlights the concern around equitable curtailment is relevant (See Section 6.4.1). And while Volt-Watt/Var may be good for the network but bad for (certain) customers, the reverse can be true in the case for PV + dumb battery and orchestrated DER which responds to price signals, where they provide a benefit to the customer but can be bad for the network.

Customer consideration and equitable access to hosting capacity

Lack of customer consideration when making decisions around operational changes was raised by one member of the IRG. It was also suggested that solar PV control strategies shouldn't be implemented unless an appropriate customer cost-benefit analysis was undertaken.

- *There isn't enough consideration of customers and customer value when the decisions are made around operational changes. Households should expect some kind of certainty around expected returns on their investment in solar PV. Also, control strategies for solar PV shouldn't be implemented without a cost-benefit analysis for both customers and the network*

The need to consider equity when allocating hosting capacity is recommended to the AEMC (and DNSPs) in VDER [53]. The was also raised by members of the IRG:

- *Hosting capacity needs to be properly assessed, and once assessed, an agreement needs to be reached on how that capacity is allocated fairly among customers.*
- *The equity of the control scheme important. And to give an example of how hosting capacity increases can impact customers: "One solution doubles the number of solar PV systems a feeder can handle without breaching a "hosting capacity limit" but each solar PV system suffers 5% increase in curtailment".*

The concern around how fairly Volt-Watt/Var distributes curtailment is presented as a finding in Section 6.4.1, thus Volt-Watt/Var may come under scrutiny if equitable access to hosting capacity is to be considered when assessing a DERIT. Depending on the implementation choices, geographically biasing curtailment could also result from DOEs.

6.4 DER device standards and compliance.

According to 2017 report "Electricity Network Transformation Roadmap" (ENTR) by CSIRO [58], there are a number of critical gaps in standards required to enable mainstreaming of customer DER. These include gaps in areas such as interoperability and communications protocols. It also recommends that open standards be established to ensure secure system operation, management, and exchange of information with DER. This section reviews industry reports to identify these critical gaps. Also included is a review of two key DER standards, AS4777 and AS4755, and whether they are appropriately designed to facilitate DER integration as it relates to future network and customer needs.

System operators have expressed concern about the risk of distributed solar PV on system security and the need to know how solar PV fleets respond during contingency events. Networks have also talked about the need for solar PV inverters to be compliant, so they respond to control signals as expected. IRG members have commented in similar terms:

- *We are concerned about the risk of integration of, and system dependence on, large scale fleets of solar PV on system security. System operators need to know how solar PV fleets respond during contingency events. If they don't know settings, it's harder* *to know the impact (how solar PV inverters will respond) of contingency events. Knowledge of potential lost generation (from solar PV) is required to then know what reserves are required to return the system to stability.*

- *Networks want to improve installer compliance. They need solar PV systems to be compliant, so systems respond to control signals (using DOEs) as expected. If a sufficient number of solar PV systems aren't compliant then the constraints (cable/SS thermal levels, voltage) which were used to set the DOE can potentially be breached*

In the Horizon Power Distributed Energy Resources (DER) Carnarvon Trials (HP Carnarvon Trials) [59], it is claimed that correct solar PV inverter settings become more critical as they play an increasingly important role as "first responder" to power quality excursion events and ensuring network stability generally.

This suggests the need to understand PV inverter settings, including the potential level of non-compliance, and how fleets of solar PV might respond to contingency events and to control signals from a DNSP, VPP or any controlling entity. Industry reports and were reviewed to identify findings related to the effect of PV inverter settings and non-compliance. Findings are presented in this section.

6.4.1 Key findings

Recommended changes to standards include: New inverter standards (e.g. voltage ride-through) around response to grid-disturbances, mandating that batteries have smart controllers, and a regular compliance check of DER.

It is recommended that Volt-Watt/Var be reviewed to determine how it can (more) fairly distribute curtailment, and to assess the impact excessive import of reactive power has on the MV grid. It is also recommended that DRM be reviewed to determine whether it will remain valid (or how it could be changed to improve its validity) if IEEE2030.5 and/or OpenADR communication standards are included.

Many major inverter brands demonstrated non-compliance to simulated grid disturbances and measures are required to improve compliance. Measures are also needed to ensure inverters are correctly configured, but it's unclear how to effectively achieve this.

The extent of non-compliance, either due to incorrect inverter settings or firmware, in PV inverters is unknown, therefore the response of fleets of PV inverters to contingency events is also unknown. As pointed out by Stringer et al, the response of PV inverters (in terms of change in MW) is large. This therefore puts system security at risk if the response of PV inverters to contingency events can't be predicted and prepared for.

It is necessary for AEMO to know the extent of non-compliance, in aggregate, but identifying compliance using conventional means (physically checking, by either the owner or an electrician) would need to occur through appropriate sampling. What are the best processes to estimate DER compliance reliably, quickly, and cheaply?

Standards

In the 2020 report "Renewable Integration Study: Stage1" (RIS) AEMO [60] expresses concern about the impact on system security due to non-compliance of distributed solar PV (DPV) and recommend new inverter standards (voltage ride-through for example) around response to grid-disturbances.

The PV-Rich project [55] recommends that DNSPs push for network-friendly (smart) battery connection standards now to enable residential batteries to more effectively reduce grid exports from PV generation, assisting mitigation of voltage and congestion issues. This recommendation comes from their finding that PV + dumb batteries provide little in terms of network benefit. The new standard would also prevent poorly controlled batteries, operating in unison en masse, threatening power system security.

The recently updated AS/NZS4777.2:2020 Standard incorporates recommendations put forward by AEMO in alignment with best international practice. Tests for low-voltage ride-through capabilities uplifted in the AS/NZS4777.2:2020 Standard have been initiated [61]. Research is needed to assess impact of Volt-Watt/VAR automatic inverter responses on the customer (curtailment), including excessive reactive power absorption raised in Sections 6.2.1 and 6.3.1.

COAG are currently in the process of deciding whether AS4755 (in its current form) should be mandated or not. There are a number of opponents to mandating AS4755[9][10], who claim that the standard (the hardwired DRM component) is outdated and should be updated to align better with international standards (IEEE 2030.5, OpenADR). AS4755 is also currently under review[11] (draft was due at the end of 2020), with changes expected to bring it more in line with international standards, incorporating IEEE 2030.5 and/or OpenADR[12] communications protocols for implementing control. These changes may address the recommended changes raised in the ENTR and by OEN but are unlikely to address regular compliance checks, as implemented by Tesla for their batteries during the AEMO VPP trial (AEMO VPP project [46]) and requirements that batteries have smart controllers. The VPP enablement requirement found in most Australian state incentives for batteries, however, may help practically require all batteries to have smart controllers.

There is an assumption that API connectivity will replace "outdated" Demand Response Management (DRM), but this may not necessarily be the case. Work by Yildiz as part of the CRC-Project "Integrated Smart Home Energy Management Technologies"[13] found that local control using DRM may be necessary to control power diverted from battery or solar PV

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[9] https://www.energycouncil.com.au/media/17233/20190923-aec-smart-appliance-review-final.pdf

[10] https://www.energyrating.gov.au/sites/default/files/documents/Dr%20Martin%20Gill_0.pdf

[11] https://aemo.com.au/en/initiatives/major-programs/nem-distributed-energy-resources-der-program/standards-and-connections/as-4755-demand-response-standard

[12] https://www.openadr.org/assets/docs/openadr_der_factsheet_pdfx4.pdf

[13] https://www.researchgate.net/project/CRC-P-Integrated-Smart-Home-Energy-Management-Technologies

inverters to flexible loads at high frequency, as the latency is too high when controlling through the cloud. DRM is also brand agnostic, a key advantage for aggregators, when orchestrating different brands of DER. Could DRM be improved with an increase in control resolution? From ~25% to 10% for example?

Findings from both the Future Grid report [54] and the PV-Rich project [57] show that while Volt-Watt/Var is effective, it has drawbacks. When Volt-Watt is prioritised, while very effective at maintaining voltage within regulation limits, large amounts of curtailment can result. When Volt-Var is prioritised, Volt-Watt/Var was highly effective at limiting voltage issues for both urban and rural feeders, with minimal real power curtailment, even at 100% PV penetration. It does however require significant import of reactive power, increasing loading on cables and transformers, raising concerns around power factor and voltage management in the MV network. And according to Heslop et al, Volt-Watt/Var does unfairly allocate curtailment, where households further away from the distribution transformer are more heavily curtailed. Heslop et al also find that curtailment is significantly more equitable when Volt-Watt/Var parameters are tuned according to distance from the distribution transformer.

Compliance

The UNSW project "Addressing Barriers to Efficient Renewable Integration" [14] bench tests the response of a range of PV and storage inverters to disturbances of different kinds on the network. Results show that knowledge of PV inverter response to grid disturbances will not just be poor due to incorrect settings, but also non-compliance. Many major brands demonstrated non-compliance to simulated grid disturbances. UNSW found that inverters can "suddenly cease to deliver power or disconnect from the grid due to the action of certain type of disturbances, identified as phase-angle jumps, short duration voltage sags and rate of change of frequency….These behaviours are a threat for the stability of power systems with high PV penetration, as large amounts of PV generation can suddenly be removed due to grid disturbances."

In the Carnarvon Trials [62], Horizon Power found that it was difficult to reliably link contingency events (both voltage and frequency) in the microgrid to large scale simultaneous solar PV inverter tripping, and simultaneous inverter tripping caused the largest power changes on the Carnarvon microgrid. If the case of the Carnarvon microgrid were also the case for the NEM, then insufficient knowledge of inverter settings means:

- The industry can't build reliable models for predicting the response of solar PV inverters during contingency events.
- The industry can't reliably predict how solar PV will respond during contingency events.

[14] https://arena.gov.au/projects/addressing-barriers-efficient-renewable-integration/

- The industry can’t set reserve requirements accurately and efficiently.

The behaviour of DPV, and therefore the effect of DPV inverter settings, in response to major power system voltage disturbances were analysed in a key study by Stringer et al [63]. Following a major voltage disturbance event in South Australia, DPV generation reduced by 45%, constituting approximately 10% of regional demand at the time. And this is not a worst-case scenario, which would occur at midday or during a period of low demand. If DPV were scaled to 2035 levels, the response would constitute 29% of total demand or ~536 MW. This is the kind of response that AEMO is blind to and have difficulty planning for due to not knowing the inverter settings. Stringer et al recommend the need for a study to “analyse actual operational data in order to capture legacy issues (for instance systems installed under superseded connection standards), the diversity of installed inverter models, and the complexity of events within the low voltage network”

6.5 Data sharing between networks, DERs, and third parties

Enabling objective 4 “provision data sharing between networks, DERs, and third parties” represents a vision where a standardised process for receiving, transferring DER data exists. A vision that includes DER data platforms integrated with comprehensive network information (topology models) and made accessible to all industry stakeholders to facilitate the mainstreaming of customer DER to provide network support. There are a number of existing industry reports showing support for this vision, albeit expressed differently, including from the ENA [33], the ESB [32], the CEC [64], and AEMO[60]. Recommendations to achieve this DER data vision include improvements in DER data communications standards, API development and standardisation, increase in hardware capabilities from technology providers, development of digital infrastructure for DER data management, automation, and transactions, regulation reform, cybersecurity, and progress on legal aspects related to DER data ownership and sharing.

6.5.1 Key findings

It will be necessary to build robust DER data platforms that can support large volumes of DER data effectively, which are predominantly automated, and have the computing capacity to manage the large number of load flow simulations required to determine hosting capacity and dynamic operating envelopes. DER operations will require reliable and fast communications infrastructure (3G/4G/5G).

The quality of data coming from smart meters is variable and needs to be in formats and volumes required to meet various use cases. Unconstrained access to smart meter data is also required to meet user needs, but access is currently restricted, and the various reasons for this need to be addressed. In the process of ensuring effective access to customer DER data, customer rights will need to be protected.

This section draws on IRG feedback and reviews several important trials to identify key findings on data sharing. Trials reviewed include: The AEMO Virtual Power Plant

Demonstrations[15], AGL Virtual Power Plant project[16], SAPN Advanced VPP grid integration project[17], and the Greensync Distributed Energy Exchange (deX) program[18].

Other industry activities

Other projects/working groups currently underway, and from which important findings are expected include: The ARENA DER Integration and Automation project, The DER Standards, Data, and Interoperability Working Group (SDIWG), The ARENA My Energy Marketplace project lead by WattWatchers, and the ARENA SHIELD project. Descriptions of each project are given in the Appendix.

It is necessary to build robust DER data platforms that can support large volumes of DER data. As volumes increase so do API response times, leading to degradation of services, unsatisfactory user experience and the potential to cause timeouts and network errors. Onboarding and data integrity checking processes need to be automated in order to reduce resources, speed up the process, and remove human error.

Operations wise, systems will need to have the computing capacity to manage the large number of load flow simulations required to determine hosting capacity and dynamic operating envelopes.

Tools are required which will automate the process of collecting GIS/CIS/ADMS data about the network, leading this information into load flow analysis software, and then incorporating load flow results into operational tools (such as ADMS).

A couple of IRG members mentioned the challenges associated with building a robust DER data platform:

- *Dealing with the huge amounts of AMI data is a challenge and improvements are ongoing in the areas of model refinement, remove manual handling of incoming data, automatic data error checking and make their models more resilient to data errors.*
- *A lot of computing power is needed to ingest large datasets and perform operations on them (load flow simulations for determining DOEs) quickly.*

And according to another IRG member, Victorian DNSPs developed DER platforms to ingest and process AMI data:

- *Access to smart meter data has enabled Victorian DNSPs to use AMI data to assist in managing their networks, and Victorian DNSPs have therefore developed their DER/LV data processing and analysis platforms/procedures and built capability to handle large amounts of information into their businesses.*

[15] https://arena.gov.au/knowledge-bank/?keywords=AEMO+Virtual+Power+Plant+Demonstrations

[16] https://arena.gov.au/projects/agl-virtual-power-plant/

[17] https://arena.gov.au/projects/advanced-vpp-grid-integration/

[18] https://arena.gov.au/projects/decentralised-energy-exchange/

The quality of communications infrastructure is going to be an issue**.** All projects aside from the AGL trial experienced issues with poor uptime and limited bandwidth. DER operations requires reliable and fast communications infrastructure (e.g. 3G/4G/5G).

The quality of data coming from smart meters is variable**.** According to the Carnarvon Trials, [59] and [62], Horizon Power found that the Advanced Metering Infrastructure (AMI) "was unable to deliver the required timestamping or synchronisation of data acquisition at the required resolution". It was difficult to conduct useful analysis using unsynchronised AMI data, and Horizon Power were forced to invest in software and technology to improve data acquisition through the AMI to then be able to effectively analyse the AMI data.

Access to smart meter data in the format and volume required to meet vendor and networks use cases is currently limited, for various reasons (see IRG comments below). These reasons need to be addressed to allow smart meter data to meet user needs.

- *One technology vendor observed that access to DER data is difficult because of a low penetration of smart meters and business constraints between DNSPs/Service providers/Retailers in regard to how data can be shared.*
- *One network thought the metering contestability framework should be revised to improve smart meter data access.*
- *There are two main challenges associated with smart meter data; one around the quality and volume of smart meter data being able to meet the use case needs of networks, and the other around costs. Cost models still aren't mature with metering companies still working out what to charge DNSPs for their data.*

In the process of ensuring effective access to customer DER data, customer rights will need to be protected. One IRG consumer advocate thinks rights agreements between consumers and whoever is managing their data will be an issue, asking:

- *How will metering companies and technology providers engage with consumers? How is the LV data is going to be used?*

A reform recommendation from the ESB P2025 report also stresses the importance of customer protections:

ESB Post-2025 Review

Reforms must ensure that they manage risks to customers through the right protections, no matter how customers choose to use or receive energy, or their level of engagement. Also recommended is a risk assessment tool that helps to assess whether customer protections may be needed with the expansion of new forms of energy services,

The Australian Competition and Consumer Commission (ACCC) has been assigned the lead role in rulemaking, consumer education and enforcement for the Consumer Data Right

(CDR) in energy[19]. A CDR for energy data is likely to result in better data sharing between networks, DERs, and third parties. According to the ACCC, "The CDR is a competition and consumer reform which will allow consumers to require a company such as their energy retailer to share their data with an accredited service provider such as a comparison site to get more tailored, competitive services. Consumers will need to consent and authorise their data to be shared under the CDR.", where "The ability to securely share energy data with trusted parties will promote competition between energy service providers, leading to better prices and more innovation of products and services."

6.6 Customer engagement

Customers, as prosumers, own the DER to be integrated and will be a more active stakeholder in the future electricity system. Therefore, to mainstream customer DER for network support, the industry will need customers to be informed, engaged, and incentivised to participate. As an example of the type of information required to be communicated to customers, suggested by an IRG member, are the network services required and how participation in network services will help the network:

- *For DER to be able to provide a credible solution (to provide network support), good information on the service required and its value to the network needs to be broadcast to incentivise participation.*

The importance of customers being informed and educated (in an increasingly complex electricity system) is stressed in ENTR [58] and recommends that information and education be provided through digital information channels, and that decision-making tools need to be developed and deployed for effective customer support. The IRG is also aware of the need to educate customers, where one IRG representative pointed out that:

- *there is a customer impact to DER integration and the industry needs to assist customers to better understand the operational and financial aspects of integrating DER. They give hosting capacity as an example: "How do you explain network capacity to consumers? How do you explain why capacity is different at different points in the network?"*

Any product (hardware or software) which controls or facilitates control of a DER device (solar PV inverter, battery, or flexible load) could be considered a customer DER product. A customer DER service utilises customer DER and customer DER products to provide a service; either to the network, the customer, or both.

The main product option is solar PV + battery. Green Energy Markets, in a report commissioned by AEMO in 2020[20], projected the installed capacity of residential batteries to

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[19] https://www.accc.gov.au/focus-areas/consumer-data-right-cdr/cdr-in-the-energy-sector

[20] https://aemo.com.au/-/media/files/electricity/nem/planning_and_forecasting/inputs-assumptions-methodologies/2020/green-energy-markets-der-forecast-report.pdf?la=en

grow from ~ 1 GWh today to 5 GWh, and this is for the BAU case which uses existing policies, and assumes a slow change towards TOU tariffs and deployment of VPPs up until 2030. So, a 5-fold increase in installed battery capacity over the next 10- years is projected for households with only a "slow" change in incentives – sounds like solar PV over the last 10 years, without a generous FiT. The assumption of slow growth in VPPs means the majority of solar + battery systems will be maximising self-consumption. Increased self-consumption (as shown in the AEMO VPP trials) smooths out the load profile, reducing power import/export and voltage excursion, and therefore indirectly provides network support. So, the solar + battery product, if not right now, will be mainstreaming network support by 2030. This leaves the other customer DER product, flexible loads (with or without solar), as the next customer DER product to be mainstreamed.

Is there a need for solar + flexible loads?

According to Green Energy Markets, the total installed capacity of residential solar PV (< 10 kW) is expected to be 25 GW by 2030, and according to AEMO's projections, residential demand will be around 100 GWh/day, with a large proportion of this occurring in the evening, but 25 GWh can be used as a conservative estimate. Assuming 5 hours (again, conservative for most of Australia) of sunshine hours/day, means 125 GWh/day of solar PV generation. So, 5 GWh of battery storage can only do so much to reduce daytime solar PV export, and reduce evening peak demand.

The manner in which flexible load products can provide network support is the same as solar + battery, by smoothing out the residential load profile. This can be achieved through load shifting, which reduces peak demand and solar soak (their solar PV energy and others), or through demand response. They can also be used to firm (offset the variability of) PV generation by modulating the consumption of the flexible load to follow the variability of irradiance.[21]

Flexible loads considered are electric hot water (EHW) systems and air-conditioning (A/C) units. Both make a up a significant portion of residential energy consumption, and both are contributors to peak demand.

Note: While this section does have a focus on solar PV + flexible loads, the majority of the findings apply to all customer DER products and services, not just those which incorporate flexible load.

This section reviews industry reports and draws on IRG feedback to identify barriers to achieving customer engagement related to customer education and communication and customer DER products and services.

6.6.1 Key findings

Customers' understanding of network operation and customer DER products are poor. To be engaged, particularly to continue participation beyond the onboarding process,

[21] https://ieeexplore.ieee.org/document/9084100

customers need some understanding of network operation, especially the benefits that can come from customer DER products (orchestrated or otherwise) which provide network support. The financial benefits especially need to be well understood.

Installers are an integral part of the customer engagement process. Horizon Power, SAPN, GreenSync, state governments and many others see installers as an important medium through which to communicate with customers.

It is recommended that information on the benefits of their participation in a DER service (savings, $C0_2$ reduction, etc.) be provided to customers on an ongoing basis. And to err on the side of more (information), than less

There have been a number of A/C trials conducted in the NEM over the last 10 years, all making important findings, and yet there is still a low penetration of AS4755 compliant A/C units and (aside from Energex) there is still negligible available DR capacity.

Cost-reflective tariffs are seen as a way to incentivise customers to change their consumption behaviour and smooth out residential load profiles. Customer acceptance of cost-reflective tariffs is generally poor but improves dramatically when some kind of additional incentive is included, like a free “automation device” (customer DER product).

The upfront costs of DER products are often prohibitive and is the main deterrent to purchase. As it may be difficult to reduce these upfront costs, better returns through participation in DER services are necessary to make purchasing a DER product financially viable.

DNSPs are encouraged to share their network information, which would bring industry wide benefits, including to the networks themselves. A key benefit is that 3rd parties (vendors, retailers, aggregators, universities, commercial innovators) would then be able to access it and offer innovative and desirable customer DER services which meet both the needs of network and customer.

A major barrier to implementing residential DR solutions by retailers and aggregators was a lack of consistency in technology standards, making aggregation difficult. Lack of standardisation undermines economies of scale, increases costs, and risks for appliance manufacturers and deters potential DR service providers. If standardisation of DER data formats were achieved, and there was a consistency of data provided by DER, then technology vendors could build functionality that was brand agnostic, drastically reducing costs, development time, and software complexity.

Education and communication

According to findings from the HP Carnarvon Trials [59], few customers taking part in various Horizon Power trials understood batteries and how they work with solar PV systems. This is complicated by the premium FiT currently offered in WA; when this FiT is withdrawn, customers will more clearly see the benefit of batteries and self-consumption. Also, the AEMO VPP project [50] found that to foster customer engagement (and therefore participation), a certain level of understanding of VPP operation by participants was necessary as part of the onboarding process for AEMOs VPP trials. The aggregator Intelligent Automation in the 2020 report “Demand response in the National Electricity Market” (DR in the NEM) by Energy Synapse [65] said customers didn’t know what demand response was and that a low understanding of demand response was seen to make an investment decision on a DER product more challenging. A need for greater education in the sector was identified by Energy Synapse. The 2020 report “Smart Home Energy Management Systems User Needs” by Roberts [66] presented similar findings following a survey of households who already owned DER technology and products, where “despite cost-saving being a significant motivator, consumers rarely quantify the energy or financial benefits of their demand reduction and load-shifting behaviours.”

Findings from the HP Carnarvon Trials [59] also show that the industry needs to invest effort into installer education with respect to inverter settings. Horizon Power see installers as an important medium to communicate to customers that being able to export energy is an opportunity not an unconditional right, and that at times network conditions will prevent that opportunity. This is echoed in the deX “Consumer insights report” by GreenSync in 2019 [67], where Greensync learnt that “early engagement with installers is important and appreciated, which can result in better industry advocacy for deX long-term, while delivering a more seamless experience for customers and increasing respect and loyalty for Enphase.” According to Greensync “installers are vital to deX's long-term success as they have the direct relationship with customers”. Installers helped to explain deX and provide context to customers. Networks also tend to work through installers and retailers to communicate technical requirements of the network connection. Indeed, some networks provide installers with information to pass on to customers, and then survey customers directly to learn whether the knowledge they gained of their connection agreement met their expectations. Several networks also run working groups and/or engage with the Clean Energy Council to effectively liaise the solar installer and solar owner community.

According to “Virtual Power Plant Consumer Insights Interim” report by CSBA and commissioned by AEMO as part of their VPP trials [68], customers ongoing satisfaction with VPPs continues with ongoing communications after on-boarding, as customers want to understand the financial, environmental and community benefits of their participation in the VPP. Referring again to deX consumer insights report [67], GreenSync also found more information helped, where improved messaging around a point where customers became disengaged during the registration process helped to reduce dropouts.

Customer DER products and services

Referring to a report on A/C DR trials conducted in the NEM[22], there have been a number of A/C DR trials conducted in the NEM in the last 10 years. Key findings from the report are that compliance of A/C units with AC4755 is low, the cost of making them compliant is high, and participation in trials is low. Finally, determining the change in A/C consumption during

[22] https://www.researchgate.net/publication/350487842_A_review_of_air-conditioning_trials_in_the_NEM

a DR event was difficult. Despite these trials, there is still low penetration of AS4755 compliant A/C units and (aside from Energex), there is still negligible exploited DR capacity from A/C units.

According to the Smart DR report by the DEE [45], cost-reflective tariffs should play a role in incentivising the uptake of customer DER products. This assumes a change in behaviour, represented by the customer buying a customer DER product to better take advantage of the cost-reflective tariff. But as discussed earlier ("tariffs" under section 6.2.3), according to Stenner et al [49], there is insufficient evidence that this would be the case. Interestingly, it was found by Stenner et al that when a customer DER product (or "automation" device as it's called) was included free as part of signing up to a cost-reflective tariff, acceptance of the cost-reflective tariff increased significantly, almost to a level rivalling the flat rate tariff, which was most favoured.

According to a report by Energy Synapse [65], in the opinion of aggregators and retailers, the main barrier to uptake of DR products was high technology costs coupled with low revenue certainty. Not being able to participate in the Wholesale Demand Response Market (WDRM), an example of low revenue certainty, restricts the viability of DR. These survey results are confirmed in a report on solar pre-cooling[23], which found that the average annual savings from solar pre-cooling were only $25/year. Also, a report by Yildiz[24] found that the purchase of a solar to hot water diverter had at least a 5-year payback. Flow Power in an interview with ecogeneration[25] also points out how expensive customer DER products are. To make an investment in customer DER products financially viable, assuming the high upfront cost remains, revenue from these products by providing customer DER services needs to improve. This can be achieved through the WDRM and through new innovative and desirable services offered by vendors, retailers, aggregators etc.

Flexible load products.

According to Solar Quotes, there are only five products available for diverting solar to your EHW system (AWS, Catchpower, Fronius, MYPV, and Solar Edge). For a single-phase unit, the price ranges from $850 to $1700. For products which divert solar to A/C, there are even less. Options are Paladin and Sensibo. SwitchDIN does have the capacity to divert power to both, as well as batteries.

Unsurprisingly, the report by Energy Synapse [65] indicates that the residential sector's inability to participate in the WDRM reduces the financial viability of purchasing a customer DER product to participate in DR. This is echoed by Enel X, Energy Synapse and Flow Power

[23] https://www.researchgate.net/publication/349806389_Analysis_on_the_potential_of_solar_pre-cooling

[24] https://www.researchgate.net/publication/342622384_Control_of_Electric_Hot_Water_Heating_Systems_for_improvement_of_PV_self-consumption

[25]

in the same interview with ecogeneration[33], who consider residential participation in the WDRM will be very positive for DR and therefore the uptake of customer DER products.

The ESB P2025 report also supports the residential sector participating in wholesale markets.

ESB Post-2025 Review

…traditional electricity supply model and are now evolving to support customers and unlock value for them from being flexible with their demand and DER. Where retailers and aggregators can access wholesale markets on behalf of individual customers, this flexibility can be harnessed to deliver services that support the wholesale market as well as providing services to networks.…

And that customers should be rewarded for their flexible demand, enabling access to products and services that innovation offers.

…Initial reforms to focus on rewarding customers for their flexible demand and increasing value to the system from flexible resources. Customers should benefit from potential revenue streams where flexibility in their energy use can be offered (through a retailer or aggregator) to the wholesale market or through network services.

There are expected industry wide benefits which come from DNSPs sharing their network information, including to the networks themselves. A key benefit is that 3rd parties (vendors, retailers, aggregators, universities, commercial innovators) would then be able to access it and offer innovative and desirable customer DER services which meet both the needs of network and customer, relieving DNSPs of this enormous task. It is anticipated that the availability of new services would lead to the development of new products to meet these service needs and improve the financial viability of purchasing customer DER products through increased revenue from participating in these services.

The following “expectation” taken from the ESB P2025 report is aligned with the above finding

ESB Post 2025 Review

… as the penetration of DER increases, distribution networks must actively manage and procure services to keep their network operational and stable. Similarly, retailers may now offer customers many different products ranging from traditional power supply to energy saving services. These changes are all about delivering greater value to customers…

Reforms also to focus on changes needed to make it easier for innovative new retailers and service providers to enter the market enabling customers to benefit from greater choice and competition. This does not mean small customers will have to do more in the market. Customers will continue to interface with retailers and aggregators, but retailers and aggregators will have new opportunities to engage in the market and offer different choices to customers.

There was a lot of valuable IRG feedback on the topic of sharing network information, which is summarised below:

- *Networks should be more open to sharing the knowledge they have of their LV networks. Network data could be used to help explain hosting capacity to customers and tell them the hosting capacity of their section of network, leading to tools which help customers make informed investment decisions on DER investment decisions, and also on what network services they can effectively provide.*
- *Networks should share their DER data network information so other parties are able to access it and offer/design solutions, so it's not just the networks developing DER integration solutions.*
- *A new business model (offered by retailers/aggregators/VPP operators) is emerging which facilitates the participation of distributed DER in the NEM. These businesses are reliant on sufficient hosting capacity to allow their assets to export and are pushing networks to reliably maintain this sufficient level of hosting capacity now and in the future, so they have certainty in their investment/service.*
- *Solutions providers would be able to offer better/more services and value to customers and DNSPs if they had access to network models. One example: They could manage a fleet of assets to control voltage levels for an LV feeder through VAR control (solar PV inverter) if they had a network model.*

According to the Smart DR report by the DEE [45], the development of DR products has been hindered by market failure, in the form of "network externality". This is where the benefit an individual can derive from a product or service depends on the number of other users. For a household to benefit from having a flexible load product, there needs to be a sufficient number of other households with a similar product. This then enables Demand Response Service Providers (DRSPs) to achieve economies of scale, making it feasible for them to offer DR schemes to all consumers.

Again from the DR in the NEM report by Energy Synapse [65], one major barrier to implementing residential DR solutions by retailers and aggregators was a lack of consistency in technology standards, making aggregation difficult. In their Smart DR report [45], the DEE support this by pointing out that competing technologies and a lack of standardisation also undermine the economies of scale, increasing costs and risks for appliance manufacturers and deterring potential DR service providers. The DEE are referring to DR here, but it is equally applicable for direct load control (for controlled load shifting) and direct solar soaking through solar power diversion. Referring to the DER Visibility and Monitoring Best Practice guide (see below), if their target outcomes (around standardisation of DER data) targets were achieved, and there was a consistency of data provided by DER, then this would make integration of data from various brands of DER devices easier. This will make the job of the vendors (SwitchDin, ZepBen) easier, allowing them to develop reliable (again, only one standard API) customer DER software services solutions more efficiently which can be integrated with a suite of different technologies and brands. SwitchDin have had to develop numerous software interfaces to integrate with different brands and technologies.

DER Visibility and Monitoring Best Practice guide (DVM guide)

The DER Visibility and Monitoring Best Practice guide[26] has been developed by DER industry stakeholders to specify the data required to enable the transition of the electricity network to a high penetration DER grid. Its objectives are twofold:

- Establish a common static and dynamic (near) real time data set collected for new DER installed behind the meter on the low voltage electricity network, and to
- Increase confidence in the quality and performance of DER through the provision of this real time system performance data to DER owners and authorised industry entities.

The target outcomes of the DVM guide are given below.

DER Visibility and Monitoring Best Practice Guide: Target Outcomes

- Provide consistent data required to equitably and cost effectively increase network hosting capacity for DER.
- Enable regulatory bodies, DNSPs, academics and other parties to procure and combine data from multiple sources to meet their network modelling and visibility needs - subject to appropriate commercial arrangements.
- Enable consumers and industry participants to have consistent information sources to ensure and evaluate optimal operation and system quality.

If their target outcomes (around standardisation of DER data) were achieved, and there was a consistency of data provided by DER, then technology vendors could build functionality that was brand agnostic, drastically reducing costs, development time, and software complexity.

6.7 Future work

Ideas for future work are embodied by the following set of research questions derived from the key findings identified in each section.

Identify the best combinations of network and non-network options to provide network support and optimise utilisation of hosting capacity

What further analysis/comparisons between DERITs not covered in this review are required?

Research objectives:

- What advantages does orchestrated DER have over un-orchestrated? Orchestrated DER does have the potential advantage of being dispatchable (active DER) but will this matter if un-orchestrated substantially smooths out the LV network? Reducing

[26] https://www.dermonitoring.guide/

load peaks/troughs/rate of change, and therefore forecast error and requirements around dispatch, load following and FCAS?

- What are the “baseline” hosting capacity and power quality gains which can be made through simple tap changes of LV and MV transformers?
- When calculating curtailment- how is curtailment distributed across customers? What is the direct impact (in terms of lost revenue through curtailment and access to network capacity) of Volt-Watt/Var on individual customers?
- What is the potential of flexible loads, as part of a DERIT, to provide network support?
- What are the dependencies between cost-reflective network pricing and non-network solutions across different use-cases?
- Conduct investigations to further understand the relative merits of structured ‘bulk’ procurement of network support services, e.g. via capacity payments or incentives to activate particular autonomous modes or settings in DER, vs active dispatch of DER on an event basis

What is the potential impact of a fleet of orchestrated DER (VPPs) on LV network power quality?

Research objectives:

- To what degree of confidence are we able quantify/predict VPP operational behaviour? What (further) studies/trials need to be undertaken to gain sufficient confidence?
- [46] Can VPPs reliably deliver the contingency FCAS that they bid, and are enabled, for?
- To what extent do VPPs respond to energy market price signals? If this behaviour is extrapolated to reflect the potential for very large VPPs in future, what impact could VPPs have on energy market dynamics?
- There is the potential for some conflict between the objective of the VPP (maximising revenue for its participants) and maintaining LV network power quality. Will VPPs need to be regulated to ensure LV power quality is not jeopardised? If so, to what extent? Or would market signals ensure this?
- A VPP (as defined by AEMO) has 3 operating modes: Maximise self-consumption, enable response to contingency FCAS events, and optimise revenue (using market signals). What are the impacts on the LV network power quality for each mode?
- Should a VPP be required to meet performance metrics before deployment? If so, what should these performance metrics be? Forecasting accuracy, reliability, prove DER responds as expected?

- [46] What are appropriate ongoing operational arrangements for DER to participate in the FCAS and energy markets?
- The ability of VPPs to maintain (not jeopardise) LV power quality is dependent on the geographical distribution of the participants – a VPP with participants dispersed thinly across a large region will be less able to manage voltage across that region. If households within the same geographical region have a variety of DER technologies installed – how are they to be orchestrated effectively to provide network support? Will DER owners be forced to join their "local" VPP? Does this undermine the retail model?

Outline how the DNSP process for evaluating DER-based options for providing distribution network support can be standardised

When DNSPs are preparing a business case for a specific type of expenditure (relieve congestion, defer augmentation, increase DER hosting capacity), how should this process be standardised to ensure that customer DER integration solutions are given due consideration?

Research objectives:

- What (new) metrics (and their weighting) should be used to measure the performance of network and non-network solutions (and combination of) for a specific type of expenditure?
- What metric(s) can be used to measure how well a solution, or combination of, meet customer needs/values?
- Should the process (along with the metrics) be standardised? With broad industry consultation? If so – what should the standard methods be? Should the AER provide assumptions for business case evaluations?
- How should equity and access to hosting capacity be considered (as a metric) when evaluating Volt-Watt/Var (or any DERIT) and dynamic operating envelopes (DOEs)?
- As part of the DER value stream, cost-benefit analysis for DERITs: how much confidence does the industry have in its methods for calculating the value of deferred augmentation which comes from customer based DER integration? Do they need to be reviewed? Have they evolved (do they need to evolve) sufficiently to consider customer based DER integration?
- Is prohibiting DNSPs from claiming revenue expenditure for behind-the-meter (BTM) investments impeding investment in LV visibility? If so, what regulatory progress has made to remove this barrier?
- What regulatory changes are required to remove barriers preventing a standardised process for assessing DERITs?

improve DER device standards and compliance

What new device level standards are required to ensure that DER can be safely and reliably integrated and its operation benefits both the customer and the network?

Research objectives:

- Should network-friendly battery connection standards be introduced for batteries? Should standards around "smart battery" operation be mandated? Ensuring that battery charging/discharging operation smooths out household load profiles
- Should it be mandatory for regular checks of DER compliance to occur? If so, at what frequency? How difficult is this for manufacturers to implement?
- Has a comparison between API/internet and DRM in terms of interoperability been undertaken? Does DRM have a role in enabling flexible load or will APIs make it redundant? What impact will an increase in DRM resolution (25% down to 10% increments say) have on its effectiveness?

What are the potential negative network and customer impacts of Volt-Watt/VAR?

Research objectives:

- Are DNSPs concerned with the significant increase in imported Vars? What are the effects on power factor? Will a conflict arise between managing MV and LV voltage?
- What is the direct impact (in terms of lost revenue through curtailment and access to network capacity) of passive power quality control methods such as Volt-Var/Watt and dynamic export limits on customers? Based on these findings, should the AS4777 standard around Volt-Var/Watt be re-assessed? What are the alternatives?

What is the response of large numbers of DER (aggregated) to grid disturbances?

Research objectives:

- The response of aggregated DER to grid disturbances is critical but knowing precisely how aggregated DER is going to respond during a contingency is unlikely. The process of knowing would be an enormous undertaking. Can it be estimated using LV and MV data sets?
- For area's where the response of the aggregated DER to grid disturbances can't be reliably estimated – what are the alternatives? Should a response be orchestrated for these areas? At least then the response, while maybe not agreeable to customers, is known. What should this response be?
- What is the potential grid impact if %x percentage of PV inverters are non-compliant (to grid disturbances)?

Is there a process for DNSPs to reliably, quickly, and cheaply determining DER compliance?

Research objectives:

- What data (MV and LV) is required to estimate DER contingency response with reasonable accuracy?

- Can the proportion(s) of potential responses to grid disturbances (voltage/frequency/phase-angle excursion) by PV inverters be estimated? Through state estimation?
- Can an estimation of x% compliant PV inverters be gained through representative sampling/survey?

Provision data sharing between networks, DERs, and third parties

How can the secure and reliable flow of customer DER data to all industry stakeholders be enabled to maximise its benefit to network and customers?

Research objectives:

- Are smart meters able to provide data in the format required? How difficult will it be to re-configure smart meters in the NEM? What capability do smart meters have – what use case requirements can they meet now and with re-configuration? Is the current review of the Metering contestability framework addressing this issue of smart meter data access?
- How is customer DER data going to be used? What stage is the industry at on the issue of customer DER data access/ownership/rights/protection etc.
- Regulatory frameworks are not currently in place to give AEMO and DNSPs (as well as third-party solution providers, research institutions, aggregators, VPP operators, etc.) access to the customer DER data they need. How is this issue being addressed by the industry?
- Do DNSPs have the systems/platforms in place to efficiently process and share large volumes of DER data. What are the costs, complexity, and resourcing requirements associated with building these types of "data platforms"? This may not necessarily be the case for DNSPs in WA and VIC now, but this could change as DER penetration, integration and associated functionality levels increase

How reliably (and what volume/resolution) are DER devices (smart meter or third party) able to provide DER data?

Research objectives:

- What is the expected communication (3G/4G/5G) uptime/bandwidth required for DER devices to meet required use cases (DOE, VPP participation)?
- Does the 3G/4G/5G network have the capacity to meet uptime/bandwidth requirements?
- Should analysis of bandwidth required be mandatory as part of an evaluation of a VPP or orchestrated DER DERIT?
- Should fail-safe functions in response to lost communications be mandated/standardised? If so, what should they be?
- What are the standards around comms loss? Do these need to be reviewed?

Improve customer engagement through education and the development of new products and services.

How much do customers need to understand about DER and LV network operation before they can make informed decisions on an initial investment? Make informed decisions on new products/tariffs? Provide meaningful input to the decision makers who are trying to represent their best interests?

Research objectives:

- What content/tools exist which assist customers make sensible investment decisions, on both their initial DER investment decision and products/tariffs? If they do exist, are they adequate? Should a review be undertaken of existing tools?
- What services/tools/source of information exist which help customers understand the value smart control of their flexible loads offers? What would be the impact on uptake of customer DER products if they were offered?
- What do customers need to understand about access to network hosting capacity? And how it differs according to location?
- What do customers perceive as the best/most equitable ways of allocating existing network capacity for DER?
- What progress has been made on a DER code of practice? One which protects consumers and ensure they're informed about different network services, DER products, and tariffs?
- Customers may not understand how flexible loads, batteries etc. work in combination with solar PV systems. Will this lack of understanding impede DER up take? How much do customers need to understand about DER and LV network operation before:
    - They can make informed decisions on an initial investment?
    - They can make informed decisions on new products/tariffs?
    - Provide meaningful input to the decision makers who are trying to represent their best interests?

What are the best methods to effectively communicate network operation, hosting capacity, network support etc, to customers?

Research objectives:

- SAPN and Horizon Power relied on, and successfully communicated with their customers through installers. Can this success be "packaged" and replicated in other jurisdictions?

What potential do flexible loads have, as part of a DERIT, to provide network support?

Research objectives:

- What is the current capacity (in terms of percentage of households and total kW/kWh) of controllable flexible loads? How does this break down according to flexible load type?
- How does the current capacity of flexible load break down according to each potential use case? Solar soaking, DR, load shifting, and VPP participation.
- What technologies are currently available to enable control of flexible load? Under current pricing schemes, is it cost-effective for households to purchase these technologies? What tariffs/pricing schemes are required to incentivise households to purchase these technologies?
- How can flexible loads contribute to the effectiveness of a VPP?
- How can findings/experiences from past A/C Dr trials be used to increase uptake of AS4755 compliant A/C units and participation in DR schemes?
- Could batteries and/or flexible load be used for load following of their own PV systems (other others) to offset their variability?

What is required to enable open access to DNSP network information?

Research objectives:

- What are the barriers preventing DNSPs from sharing their network information with 3rd parties? What assistance do they need?

What is required to make progress on the target outcomes of the DVM guide?

It is recommended that to progress the objectives of the DVM guide that a project be undertaken to pilot the provision and use of a standardised set of solar PV and battery (DER) timeseries data and data management processes. The project will require industry partner participation, and will collaborate with industry partners to:

- Field test the DVM guide and to test the capability of technology providers to provide quality DER data
- Assist the API task force with their objective to develop a standard API for DER communications through trials of use cases, and provision of feedback
- Provide DER data sets for analysis to demonstrate the value of the data and also determine how “fit for purpose” such data sets are for particular applications (FCAS, VPPs etc.)
- Inform (both technical and social) a NEM wide DER data collection and management process.

6.8 Conclusions

This section took the question "How can customer DER be mainstreamed to provide network support and increase hosting capacity?" and framed the structure of the review by attempting to answer it.

Stemming from a pathway laid out in the Networks Renewed ARENA project to mainstream DER-based network support services, as well as drawing on findings from industry reports and IRG feedback, five related, but distinct enabling objectives to mainstream DER network services were identified:

1. identify the best combinations of network and non-network options to provide network support and optimise utilisation of hosting capacity
2. outline how the process for evaluating DER-based options for providing distribution network support can be standardised
3. improve DER device standards and compliance
4. provision data sharing between networks, DERs, and third parties
5. improve customer engagement through education and the development of new products and services.

Analysis of industry reports examining the various network and non-network options through which to provide network support revealed that there is no universal "best" solution, it varied according to PV penetration level and feeder type. It was also discovered that insufficient consideration has been given to non-network solutions which utilised flexible loads, either in conjunction with batteries or in isolation, to provide demand response. The potential benefits VPPs delivered to network and customers were also identified, as well as the potential risks to system security.

Findings from the reports on network and non-network options for providing network support, along with IRG feedback, revealed that a standardised process for evaluating DER-based options for providing distribution network support was needed, and recommendations to achieve this included that:

- the method be precise, meaning accurate models and historic load and generation profiles.
- its development be a collaborative effort, involving all industry stakeholders.
- it should take guidance from the AER, which should prepare a practice guide for DNSPs, and provide a list of input assumptions.
- the cost-benefit analysis be reliable, consistent, and comprehensive, ideally considering all DER value streams. It will also need to strike a balance between customer and network needs, as the two can sometimes be in conflict; and
- it is ensured that the customer is given due consideration, especially when allocating hosting capacity, which needs to be equitable.

Recommended changes to standards to ensure they are suitable to accommodate the mainstreaming of DER include new inverter standards (voltage ride-through for example) around response to grid-disturbances, that smart battery controllers be mandated, and regular compliance checks of DER. It is also recommended that Volt-Watt/Var be reviewed (to ascertain how fairly it distributes curtailment and the impact of Var absorption on the MV network) and DRM, to determine whether it will remains valid with the introduction of IEEE2030.5 and/or OpenADR communication standards.

Non-compliance was found to be a concern, with many major inverter brands shown to demonstrate non-compliance to simulated grid disturbances. The overall extent of non-compliance of installed PV inverters, not just due to firmware but also incorrect inverter settings, is unknown, this therefore means that the response of fleets of PV inverters to contingency events is also unknown, putting system security at risk.

To provision data sharing between networks, DERs, and third parties, it will be necessary to build robust DER data platforms that can support large volumes of DER data effectively, which are predominantly automated, and have the computing capacity to manage a large number of load flow simulations required to determine hosting capacity and calculate dynamic operating envelopes. DER operations will also require reliable and fast communications infrastructure (e.g. 3G/4G/5G). The quality of data coming from smart meters was also raised as a concern by IRG members, as it needs to meet user needs in terms of format and volume. Also, access to smart meter is currently restricted, and this barrier will need to be resolved as well to meet user needs.

Finally, to improve customer engagement through education and the development of new products and services, it was found that customer understanding is key, and that customers need some understanding of network operation, and a clear understanding of the benefits that can come from providing network services. Installers are a good way to facilitate communication of this information to customers. Cost-reflective tariffs are seen as a way to incentivise customers to change their consumption behaviour and smooth out residential load profiles, but customer acceptance of cost-reflective tariffs is generally poor but improves dramatically when some kind of incentive is included, like a free “automation device”. To improve uptake of customer DER products, which currently have a high upfront cost and a slow payback period, a better return will need to be assured through participation in network services. These services are currently lacking but could be improved through enabling 3rd party development (by giving them access to DNSP network information) and standardisation of technology standards to reduce costs, development time, and software complexity.

7 Barrier Identification and Analysis

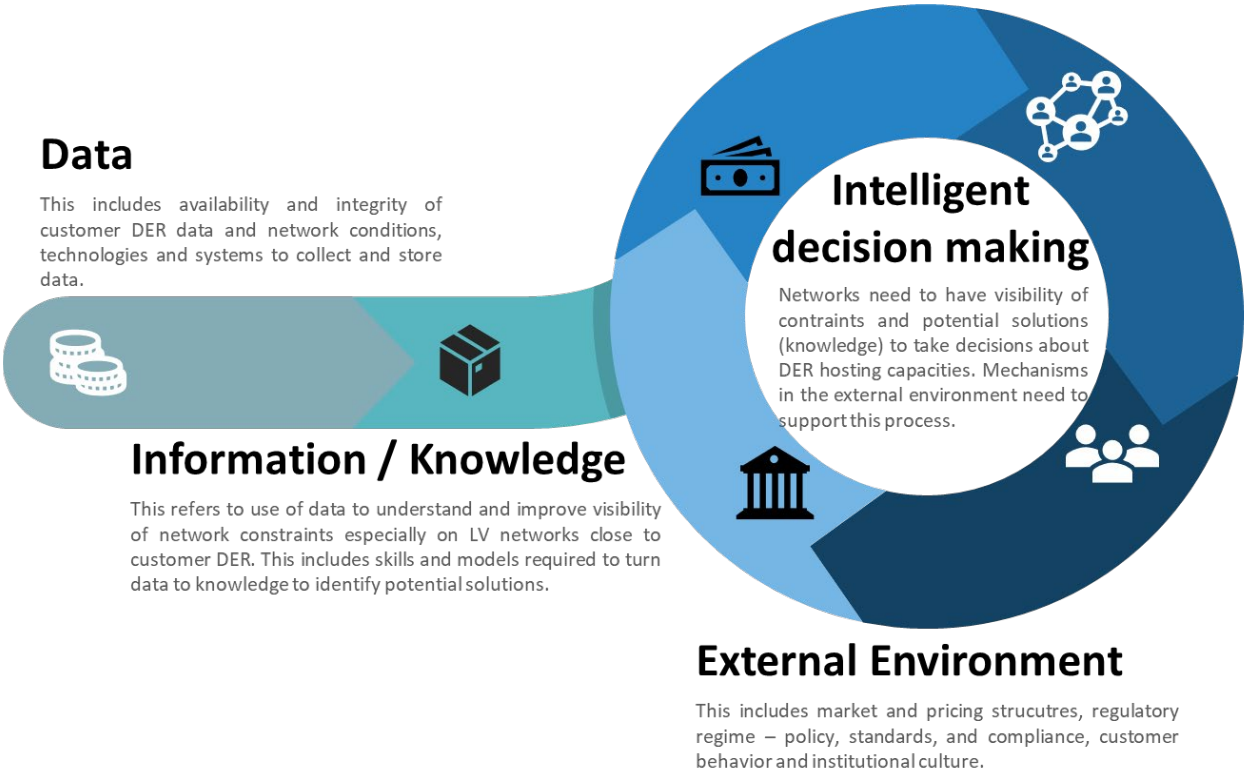
7.1 Context

This section examines the barriers and challenges faced by networks and other energy market participants as a key step in unlocking the potential of and mainstreaming DER. It is based on a detailed capability review, interviews with key industry stakeholders and a February 2021 workshop with Industry Reference Group (IRG) members.

7.2 Categorising Barriers

The key impact pathway to enable rooftop PV and other DER to reach their full potential is enhancing network hosting capacity and mainstreaming customer DER network support. This section examines the barriers that could impede this process.

Figure 7-1 Pathway from Data to Intelligent Design Making for Networks



The figure above uses the wisdom hierarchy to visualise the links between this translation from 'data' to 'decision-making' for networks, recognising the role of external environment factors in terms of market structures and behaviour, regulatory regime, and institutional culture.

The barriers identified through the review and consultation processes are categorised as either technical or institutional. They are then further disaggregated into an additional subset of barriers. The barrier taxonomy is a modified version of the classification used by Dunstan et al (2011).

The table below summarises the barrier classification.

Table 7-1 Barrier Classification

Technical Barriers		Institutional Barriers			
Data	**Information & Knowledge**	**Regulatory**	**Network Cultural**	**Customer Behaviour**	**Market**
Integrity of data	Analytical skills (gap)	Data access and ownership	DER & Minimum and maximum demand	Equitable access of consumer DER to network resources	Pricing structures and signalling
Data storage and processin g platforms	Fit for purpose network models	DER system standards, settings & compliance	Acceptance of non-network solutions	Consumer engagement in decision making & communicatio n	Network business case and value calculation
Data security	Sophisticated network planning methodologie s	Common definitions and calculation framework s for HC, Doyen	Standardisatio n across networks – (approaches)	Consumer privacy and protections	Customer incentives
			Co-ordination and engagement		Data procuremen t costs

7.3 Technical Barriers: Lack of visibility of LV networks and customer DER

Limited visibility and inability to manage DER limit hosting capacity and constrain the export capacity that can be safely released to DER. directly or indirectly

7.3.1 D1: Data integrity and availability

The lack of availability of data is a widely recognised challenge. With inadequate data, network interventions like tap changing, etc. are based on conservative estimates and can adversely impact customer DER export. Improved data availability would enable these interventions to be more targeted and effective with minimal impact on customers.

In most jurisdictions, there is not voltage data for all connections (only Victorian DNSPs and Horizon Power in WA have such data). Other LV network data collection tools (e.g. transformer monitors) are limited and vary significantly between jurisdictions. Lack of sensor data is another challenge. The sporadic deployment of smart meters obliges DNSPs to rely on cellular communications, instead of mesh communication networks, which can sometimes be unreliable. Moreover, network models –

demonstrating how customers connect to one another and the broader system – are sporadic, of questionable accuracy, and supplied in various formats, all of which are difficult to interrogate for DER-related use cases. Often, there is not a "single source of truth" for network connectivity within a given network.

There are technical challenges with the low capability of remote reading of smart meters. There is uncertainty around what data (network configuration / building / billing) and how much data is needed (real time vs delayed / 5 sec, 30 sec, 30 mins, etc.) and for what purpose / what problem will it solve and what measurements will best support outcomes. The other aspect is articulating who needs the data – researchers, networks, customers or those acting on their behalf, regulators, etc.

There are license and regulatory challenges around smart meter rollout and subsequent institutional challenges on accessing this data and ensuring security. (Commercial challenges are discussed in the section on customer incentives). Further, there are big differences in the quality of completeness of data across networks. This makes it hard to estimate the size of the network constraint and thus the size of contingency/reserve required.

7.3.2 D2: Data storage and processing platforms

While AMI provides a new level of visibility to distribution system loads, it comes at a cost. Large volumes of AMI data must be effectively recorded, communicated, stored and processed for applications in distribution planning and operations. The volume of AMI data is directly proportional to the time granularity at which the data is recorded and stored. This data is big and dirty and requires robust platforms and computing power to store and process it.

There is no standard way of developing data platforms. Cloud-based solutions may be one answer but have unique cyber and physical security challenges. New capabilities may also be required for central data coordinators. Is there adequate infrastructure (local processing, bandwidth) to pull this data at variable collection rates? Industry use cases can offer insights, but the more work is required to test and refine assumptions.

7.3.3 D3: Data security and interoperability

Cybersecurity of DER is a critical market gap at present.

Given DER (PV) is the biggest generator on the NEM, as more systems are automated and more data is generated, what systems are in place to protect data and privacy of customers and ensure system integrity? Effective cybersecurity protection requires a focus on securing communications and limiting multiple connection pathways. But this is an ecosystem problem that can't just be solved by encryption. Can we design data sharing models with robust security in mind rather than leaving it as a problem that must be fixed with band-aids later?

Also, inconsistency in the format of data provided by different third parties and delays in data collection and processing can make it difficult to implement use cases that require real-time information.

7.3.4 I1: Analytical skills

Smart meter data is underutilised. There is a lot of pressure on accessing data, but there seems to be a lack of analytical skill and capability to utilise the data. There is a view that at some point, there are diminishing returns on data, given current limitations on understanding what data can do and analytical skill sets.

There are also skills gap within the broader industry, often in the form of the lack of digital literacy within networks, management, regulators and policymakers.

Further there are no standard data models across the industry. Another challenge is that lack of algorithms for optimising distribution level markets. Mapping platforms for enhanced visibility also require new or more robust capabilities and tools for spatial data management and analysis.

A lack of analytical skills and digital literacy leads to a systemic undervaluing of data -- if you don't understand the data, you don't understand why it is or can be valuable.

7.3.5 I2: Fit for purpose network models

Current LV network models are poor. MV and LV network model simplifications arising from limited access to data and network information can lead to grossly inaccurate hosting capacity estimates. There is rarely information on which phase customers connect to, which makes robust power flow modelling a challenge. Furthermore, the basic geometry of the LV network -- the distance between customers and transformers, the impedance of lines, etc. – is often based on assumptions and takes significant time to clean.

For hosting capacity assessments, a detailed model including the topology and location of the customers on the circuit can be important. These may not be known for networks. Good networks models can enable much better analysis, especially as networks become more dynamic, but there is a significant gap from the current state of network models to ones that are fit-for-purpose. We are getting more intelligent at fitting data gaps and running models better and more quickly. Spatial data (network location) can help but it needs to be better integrated into operations, many networks have an incomplete understanding of the topology and lack voltage and power data.

Transparency & sharing of (existing and future improved) network models would enable a broader range of analysis - e.g. combination with solar potential assessment to assess impacts of DER penetration scenarios

7.3.6 I3: Sophisticated network planning methodologies

Central to DER visibility is the ability to accurately predict – in operational and planning timeframes – the behaviour of customer devices. Lack of visibility of retail tariffs/aggregator arrangements means that networks may be blind in estimating behaviour or active demand like batteries and EVs. Solar forecasting techniques are applied to large-scale solar farms but are only now starting to be used for distributed PV.

There is an important interface between forecasting and scheduling to develop appropriate incentives. Accurate understanding of when electric vehicles and other devices will be used is crucial for better utilisation of existing network assets.

We need to develop more sophisticated network planning methodologies, as with more granular data and diversity of supply- and demand-side solutions, decision making complexity balloons. Given the high level of uncertainty on data, robustness of methodologies is very important. Firmness is important as is the need to create opportunities to test the demand side to provide solutions to overcome this barrier.

7.4 Institutional Barrier: what slows it down

7.4.1 R1: Data Access & Ownership

Getting access to the right data is critical. Outside of Victoria (with the exception of Horizon Power WA), smart meter penetration is low (though growing), and networks have to pay for access to smart meter data. Whereas access to smart meter data is structured and regulated, access to network and DER data is neither. The DER being deployed today can provide valuable data but networks and AEMO don't have access. What can incentivise good data provision - awards, costs, data trades?

There are concerns around who owns what data and who can it be shared with – who is an authorised user? Currently in many use cases, consent is often implied and de-identified data analysis is frequent. Stakeholders and customer advocates believe that customers need to have some say on who can access their data and for what purpose (e.g. research, network management, commercial exploitation). There are challenges around data privacy and where effective protections lie. (also see section on Customer: privacy and protections)

Since data applications are not well articulated, there are various opinions on how much data is required. This begs the question, who needs this data and why?

7.4.2 R2: DER system standards, settings & compliance

Inverters can be a big part of making better use of existing network infrastructure. However, there are concerns around communication standards and DER settings unable to correctly respond to the right signals. Reports suggest that installers often install inverters with the wrong settings or factory (manufacturer) settings and have limited market accountability on compliance. There is also some anecdotal evidence that suggests customers may be unaware their system is not working, or on the other hand, gaming the system or inadvertently changing settings disadvantaging other customers and/or the network.

There are communication standards in place that mandate use of protocols in new connections but there are gaps in implementation for certification. There is a lack of knowledge on how they compare to international standards and whether they are fit for purpose. It is important to bring manufacturers into discussions of what inverters can do and the different levels of engagement required to support networks and facilitate export. Many see a need to incorporate cost-benefit analysis into the standard-setting process and recognise that the existing AS4777 committee may not be the appropriate group to conduct such analysis. There is an expectation that the revisions to the standard (AS 4777.2) will improve some of these concerns but currently compliance and enforcement is not effective.

Installers' compliance with network requirements for inverter standards is a major issue. There is no single point of responsibility or accountability for ongoing compliance at the moment and the role of different key bodies needs to be reviewed. Non-compliance negatively impacts the level of active DER, which has flow on impacts for market liquidity and system security. There are also implications for how this is managed in terms of cyber-security. Compliance and enforcement need to be undertaken together but there is a gap in understanding clear responsibilities and consequences for this. Getting compliance right requires rigorous training and inspection processes.

How can a regulatory framework around national standards help improve the situation? Similarly, what role can technology play in improving compliance levels e.g. remote testing by energy management products, manufacturer access to settings? What investments in installer and DER system retailer education are required to gain the level of reliability and assurance of inverter operations required for utilities?

7.4.3 R3: Common definitions and calculation frameworks

A common definition of hosting capacity and an agreed upon approach for calculating it appears to be an important industry gap. Limited visibility of network constraints and the lack of a clear robust methodology for setting the hosting capacity promote a conservative, network-centric approach. Although hosting capacity is complicated, basic metrics and agreed understanding of the challenges and opportunities for its application would be helpful.

The quality of the network model affects the quality of the hosting capacity estimation. It is essential to know the hosting capacity to calculate operating envelopes and then effectively communicate this to the customer and DER installers and aggregators. Open and transparent calculation frameworks are very important in developing customer acceptance and trust.

There is a diversity of approaches used by different networks to understand hosting capacity, constraints, etc. While it is important to allow flexibility for each network to work out what's best for them, there does need to be some consistency in the approach to these calculations. This requires rationalisation and standardisation across the industry.

Dynamic connection agreements and dynamic export limits are seen as an elegant solution to overcoming challenges from increased distributed PV penetration. Important challenges remain such as, how are they best calculated? What are the steps in the evolution of refining these limits away from gross and conservative estimates? What data is required to accurately calculate them? What are the best and most equitable ways to share the limits of the network among customers? How do dynamic exports impact customers and how can that impact on generation and savings be calculated?

7.4.4 N1: DER & Minimum and maximum demand

EVs and the shift to renewables have created a challenge as well as an opportunity for the electricity infrastructure, one that it was not built for. Managing solar loads is already a challenge; EVs could exacerbate the challenge and might be here sooner than we expect. Alternately, the flexibility and large loads of electric vehicles could be an elegant and cost-effective solution for reducing costs of renewable integration. More control and visibility of EV charging infrastructure is seen as a large maximum demand concern. Greater visibility will be important to deal with orchestration challenges, though the DER register does not currently include EVs.

In this context, increasingly, networks and system operators are struggling with minimum demand. This is a problem of serviceability of energy. From a network perspective, they need to be prepared for a lack of load. On the other hand, if the network loses generation, what will service the load? The other concern is interconnectors and the interstate impact of low demand (frequency).

There is reasonable visibility of the MV network but poor visibility of the LV network. Sensors and meters need to be able to capture data that directly identifies minimum demand constraints on the network in real time. Further, there is a need to understand if available data is an estimate or forecast. Besides visibility, it is also important to consider the impact of operating envelopes on minimum demand.

7.4.5 N2: Acceptance of non-network solutions

There is uncertainty around the level of comfort, both from the network and customer side, on the use of “non-network” solutions for providing network services, such as voltage regulation. There is limited understanding on the realistic potential of customer demand flexibility. It is important to quantify what role DERs are already playing in providing non-network solutions for the network service of voltage management, both in terms of curtailment during high voltages but also in reducing peak network load to help hold voltage up during network peaks. There needs to be clarity on what systems are paid for (value add services) and which are mandated (do no harm services).

Research needs to address the economic benefits and costs of using non-network solutions to provide network services as well as the non-monetary barriers that need to be resolved to enable the greater use of customer demand flexibility and other DER to provide network services. A mapping tool for shared network support needs would support market development as well as reduce transaction costs around procuring and retaining customers.

For aggregators, VPP developers, and battery providers there is a lack of clarity on what the network needs are. Solutions can be developed based on network needs (either as a standardised service or bespoke solutions), which is a key reason for more data transparency for third parties (with customer control over who accesses their identifiable data). Aside from VPPs, there is a need to obtain a better understanding of how batteries may provide non network support through reducing network peaks, reducing peak PV exports, and possibly voltage regulation. Research needs to focus on projecting likely impacts of the future high uptake of batteries operating in load-following mode.

7.4.6 N3: Standardised approaches across networks

The fragmented nature of the network industry has led to different networks using unique approaches to calculate hosting capacity and dynamic operating envelopes and applying different aspects of the AS4777 inverter standards. There is no consensus, and often very little discussion, around how to establish common approaches so that technology vendors do not have to create distinct interfaces and technology for each network. The working group for standardising using 2030.5 is one of too few examples of how the industry could better collaborate on common approaches.

Knowledge sharing forums where networks compare, and debate methodologies is another industry gap sorely felt by various stakeholders. Discussion also touched upon the creation of a national standards harmonisation body that would look at standards, customer connection agreements, customer consultation, etc.

7.4.7 N4: Co-ordination and engagement

Lack of transparency of and access to network LV issues and constraint data beyond network businesses themselves limits the ability of other parties to develop or coordinate solutions. It also limits the social license for networks to invest in solutions in the absence of clear and transparent rationale and business case outcomes. While the RIT-D process is intended to compare network and non-network solutions, non-network participants feel it fails to do so. There is limited incentive to innovate to increase the utilisation of the network assets. The network asset owners are understandably reluctant to make data available to external parties. This tension is difficult to resolve.

LV data visibility and associated challenges are seen as technical network problems, and other stakeholders (DER asset owners/aggregators) are often not involved in solution development. The lack of consultation is a critical challenge. It retards the development of industry consensus about operational decisions that affect customers.

7.4.8 C1: Equitable access of consumer DER to network resources

The customer expectation is to be able to connect their DER systems to the grid through a simple process and have the same access to network resources (grid) as their neighbours. However, there is unresolved tension about who can access new grid connection capacity for DER or EVs. Many new customers will have their PV exports curtailed because the network has reached its hosting capacity already because of everyone who has already connected solar. Often legacy DER systems are too old to be curtailed either due to their contracts or the settings on the system. It is important that networks are able to address this inequity and find ways for people to continue to connect to the grid. Dynamic operating envelopes may be a solution that needs to be explored further.

Equity has private and public aspects which could be better articulated. PV exports provides a private benefit (payment), and perhaps both public benefits (reduced emissions and downward pressure on wholesale prices) as well as costs (network expenditure). There are also equity implications associated with, for example, ducted air-conditioning which provides a private benefit but, if only used during peaks, no real public benefits and significant network costs. Proper accounting for externalities is a key aspect of equity.

The other aspect of this inequity is linked to industry-wide standards on the basis of sophisticated devices which may cut certain customers out of the discussion. Consumer facing stakeholders feel people need to have the option to buy cheaper systems if they want. Some solutions provided via standards may be unfair because they can operate on DER differently depending on their location. For example, the Volt-VAR/Volt-Watt mechanisms in Standard AS/NZS4777 for grid-connected inverters will curtail output of PV more frequently in locations with more frequent over/under voltages. However, there needs to be a shared understanding on how much curtailment is reasonable or acceptable. Expectations on minimum standards versus paid services need to be established and communicated.

7.4.9 C2: Consumer engagement in decision making & communication

Many solar owners have some understanding that solar generates environmental and societal goods, but the broader understanding of the network and community benefits of dynamic export limits (or load control, etc.) is harder to articulate, but necessary. Often customers don’t understand concepts of hosting capacity and network constraints and export limits. However, they need to know what is happening with their systems to plan their investments better. There is already a tangible sharing of value between the network and customers, but the specific values need to be transparent and clearly communicated, particularly as the exchange changes in the years to come.

Customer trust and confidence in many of the market players is currently low, often tied to data transparency. A key challenge is to enhance and increase this trust and transparency. Consumers are not traditionally consulted while developing connection agreements. Including the voice of the customer in these discussions is another challenge. Understanding the level of engagement customers want, what makes customers happy, and their expectations is critical to designing a system in which customer devices are integral to safe, reliable, and affordable network operation.

There is a lack of maturity in the conversation with customers, especially on aspects of controllability and curtailment. Installers often have no incentive to educate customers on controllability as it increases the length of the sale cycle and often reduces the likelihood of sale. The predominate market practice is to sell the largest system possible with no conversation around energy management. This raises questions around the appropriate channels for communicating the tradeoffs between curtailment and hosting capacity. Does this require national standard / principles? How can business practice be adapted to change this while still remining competitive?

7.4.10 C3: Consumer privacy and protections

Customer device data can be enormously useful in solving network challenges. Customers are keen to understand how data collected from their DER systems will be used and shared. While a lot of the analysis can be done in protected environments as networks and retailers already have access to meter and billing data, there are challenges in understanding how customer data will be shared with third parties and the protections in place to preserve their confidentiality.

There are national level reforms (DAT Bill) setting new policy in what “public good” uses consumer data can be put to. It will be interesting to see how this applies in the energy context i.e. data should be able to be accessed for research if privacy can be protected and it is clearly in the customer interest (e.g. lower network costs, higher DER benefits, etc). This depends on accepted standards around de-identification and ways to use the data safely.

The Privacy act becomes important here as does the retention of IP by the utility or research organisation around the whole data set. Under the Privacy Act, data sovereignty might apply if the customer data has been collected under the customer (electrical) connection agreement. A bespoke agreement for DER data or data collected from behind the meter may be required to facilitate data analysis by a third party other than the utility and that third party may be required to adhere to the privacy act under certain conditions. But there are gaps in coverage of Privacy act for data collected by some devices relating to size/turnover of business. What other regulatory frameworks are required for informed consent and privacy for customers?

As noted above, transparency in customer consultation and communication is paramount. There is work to be done through consumer groups on when and what data customers would be comfortable sharing (and with whom and for what purpose).

7.4.11 M1: Pricing structures and signalling

There’s little incentive for networks to engage with cost-reflective pricing until they have the access and pricing rule change. Tariff reform needs to include locational as well as temporal pricing if it is serious - the low apparent willingness to address present zonal network tariffs may reflect a lack of seriousness in tariff reform, given the amount of money involved in supplying remote and regional consumers.

Dynamic export limits can be seen as proxy tariffs with limited upside for individual customers. Some fear that pricing reforms may bypass the need for a two-sided market and dynamic operating envelopes.

Cost reflective pricing will become increasingly important as customers move to systems that can autonomously respond to dynamic tariffs. Determining network tariffs and customer-facing incentives that promote reliable and affordable solutions and delight customers is a central challenge with limited existing research.

How can we simultaneously maintain simplicity and certainty for consumers on prices, whilst incentivising technologies which can take advantage of real-time cost-reflective pricing? Do regulations need to allow for multiple entities to have a retail relationship with a consumer to facilitate this?

7.4.12 M2: Network business case and value calculation

There is a lack of clarity on how hosting capacity impacts the network's return on investment, given the different ownership models of DNSPs. Without an obvious business case, policy will not be able to do anything to help bring about change. Business cases and rationales for network control strategies and planning decisions generally need to be transparent and defensible, and more clearly linked to customer benefits. Better clarity on how networks describe and quantify capacity would help support ROI and other investment decisions.

Moreover, there is a lack of understanding of the true value of increased network visibility. Improving visibility can improve use cases in planning, operations, and maintenance, but in many cases, the value of data is only discovered after it has been collected and analysed. How do networks make more effective business cases to improve the visibility of the network?

7.4.13 M3: Customer incentives

There is a belief that demand management is not prosecuted to the desired level. Without this, there needs to be better understanding on the interest and influence of the current structures and stakeholders to recognise where there is pushback. Increasing demand-side management and customer engagement is too often reduced to a marketing problem, without understanding the technical and social constraints. The lack of end user engagement in LV solutions is likely to require engagement via data, either directly or via third party representatives (e.g. retailers or aggregators).

There are a lot of rules and frameworks that are suited to what is now an antiquated vision of the electricity market. Policy is also trying to play catch up to different solutions being experimented with in different jurisdictions. While the post-2025 market reform process includes a focus on two-sided markets, the current lack of consistency and certainty dissuades investors and market participants from committing to a path to more effectively engaging customers.

7.4.14 M4: Data procurement costs

Provisioning data has a clear cost (especially storing and maintaining big data). Cost of procuring smart meter data can prevent implementation of use cases at-scale. Another area of extra expense is upgrading the communication infrastructure (hardware and software) to facilitate faster / real time data capture. But the value of data is not very well articulated. Providing data is not rewarded and standard data exchange agreements don't exist. More clarity is needed on what data is needed and why, to build a better economic case.

The business case for retailers is pretty marginal, as the value of the data for networks is not well articulated. Secondary data streams are emerging and have started to compete with smart meter data unless the value is evaluated and unlocked. The commercial relationships needed to get data from metering companies are not very good. There is competitive tension between DNSPs, retailers and other service providers concerning data, which is complicated by the fact that interconnected data is often exponentially more valuable than siloed data. Can DER ease this tension as more data will be potentially visible to the DNSP – how will concerns of customer privacy and value of data be addressed in this case?

7-1

8 Research questions

This section focuses on a list of research questions that emerged from the review of industry capability and in consideration of the barriers identified in the previous section. The purpose of these research questions was to further sharpen and define the project team and industry stakeholders' view of the most salient research to conduct. The research questions were thus an essential steppingstone toward developing the research roadmap, which is highlighted in Section 9.

These research questions were "workshopped" at a Project Steering Committee meeting on 23 April 2021; the summary list below ranks the research questions in order of importance as voted by this group. The extended text below the summary list more fully express and define the research questions.

8.1 Summary list

Table 8-1 Summary List of Research Questions

RQ1	What are the most efficient combinations of network modelling and network and customer monitored data to support optimal integration of DER in the operation, planning and market services in low-carbon, reliable and secure electricity systems?
RQ2	What are the potential network vulnerabilities to the synchronised, autonomous response of large groups of distributed inverter-connected resources to network and market signals and weather disturbances?
RQ3	What are the most appropriate combinations of network and non-network forecasting and control strategies to optimise DER hosting capacity?
RQ4	What do customers perceive as the best/most equitable ways of allocating network capacity for DER?
RQ5	How do we engage customers to enlist their devices and modify their behavior to provide a variety of grid services, including optimizing hosting capacity?
RQ6	What data and technology standardisation are required for optimal integration of DER in the operation and planning of the electricity system?
RQ7	How might we streamline, automate and standardise network processes for collating, cleaning, and sharing LV data?
RQ8	What are the most effective approaches to monitor, meter, and audit demand-side transactions in the post 2025 market?
RQ9	What is the value to network operators and customers of applying different DER at different locations in the network?
RQ10	What are appropriate methodologies for determining device level standards that balance customer and network needs, and how do we best ensure compliance with standards?
RQ11	What are the current and future cybersecurity risks from the increasing reliance on data sharing and DER to enable low-voltage management and how do we best manage them?
RQ12	What is the optimal proportion of flexible, controllable DER relative to large-scale, firm generation, and how does that proportion change as large generation changes

8.2 Research questions and sample research objectives

RQ1	What are the most efficient combinations of network modelling and network and customer monitored data to support optimal integration of DER in the operation, planning and market services in low-carbon, reliable and secure electricity systems?

Sample research objectives:

O1. Evaluate the comparative advantages and limitations of network modelling approaches and their data requirements according to accuracy to represent the network over a range of timescales and use cases: real-time operation, planning, distribution system state estimation, network data estimation and cleaning (phasing, connectivity, impedances), fault detection and remediation studies, network simulation and optimisation for DER dispatch, cybersecurity studies, reliability, scalability and integration into ADMS.

O2. Quantify the comparative value of various data sources (smart meter infrastructure, DER monitoring systems, phasor measurement units) according to cost and capabilities, locational network information, reliability and scalability of communications, integration into SCADA and ADMS.

O3. Quantify uncertainty bounds in the estimation of hosting capacity for a range of combinations of modelling approaches and monitored data. Evaluate potential risks ensuing for hosting capacity end-use applications, such as the calculation of dynamic operating envelopes, potential for DER services and planning, other strategies to maximise hosting capacity utilisation.

O4. Quantify data and modelling error bounds to deliver best investment value according to application use case and the volume, coverage and quality of monitored data required.

RQ2	What are the potential network vulnerabilities to the synchronised, autonomous response of large groups of distributed inverter-connected resources to network, market signals and weather disturbances?

Sample research objectives:

O1. Identify data requirements to assess DER contingency response scenarios for system security risk identification and management. Examples include assessment of impacts of flicker and disruptions in quality of service of large DER connected to the distribution network ramping rapidly on weak parts of the network.

O2. Investigate impact of rate of change of frequency (RoCoF) on distributed PV generation, utility-scale generation, switched reserve providers, and protection relays used in various network functions.

O3. Evaluate adequacy of Emergency Frequency Control Schemes (EFCS), including Under Frequency Load Shedding (UFLS), under decreasing levels of system inertia.

O4. Identify robust communication and control strategies to mitigate impacts of disruptive synchronised response of large groups of autonomous DER to disturbances.

RQ3	What are the most appropriate combinations of network and non-network forecasting and control strategies to optimise DER hosting capacity?

Sample research objectives:

O1. Evaluate costs and benefits of a range of mixed network and non-network – DER management – solutions to LV network issues.

O2. Quantify the value of end-to-end modelling of whole-of-the-network constraints and capacity, encompassing high, medium and low voltage, and extending beyond voltage considerations to current (thermal) and other asset limits (such as transformer tap ranges, reactive power flows, phase unbalance, harmonics).

O3. Assess modelling approaches to forecast future substation tap limitations.

RQ4	What do customers perceive as the best/most equitable ways of allocating network capacity for DER?

Sample research objectives:

O1. Design and conduct customer surveys to explore customer perceptions and preferences on options for managing DER hosting capacity.

O2. identify the key factors that explain whether or not a consumer engages in two choices from a segmentation framework. For example, choosing a better energy deal and choosing alternative energy sources, such as solar.

RQ5	How do we engage customers to enlist their devices and modify their behavior to provide a variety of grid services, including optimizing hosting capacity?

Sample research objectives:

O1. Examine options in the design and communication of tariffs to enable customer participation and acceptance.

O2. Quantify the level of current untapped, available capacity of flexible demand and approaches for unlocking it to maximise value from DER to customers and the system.

RQ6	What data and technology standardisation are required for optimal integration of DER in the operation and planning of the electricity system?

Sample research objectives:

O1. Examine the level of network visibility required to sufficiently monitor, evaluate, and audit the participation of DER in markets, and what are the most effective approaches to achieve it.

RQ7	How might we streamline, automate and standardise network processes for collating, cleaning, and sharing LV data?

Sample research objectives:

O1. Identify most effective strategies to facilitate a diversity of solutions and solution providers for LV issues.

O2. Evaluate data access and mapping pathway alternatives across end-use applications according to requirements for granularity and consistency for LV data release, requirements for cross-jurisdictional coordination.

O3. Assess data interoperability maturity of DER communications and control technologies to support VPP network services.

RQ8	What are the most effective approaches to monitor and audit demand-side transactions in the post 2025 market?

RQ9	What is the value to network operators and customers of applying different DER at different locations in the network?

Sample research objectives:

O1. Map and forecast areas of the network that offer the best value opportunities for customer and networks from additional adoption of DER.

O2. Map and forecast areas of the network that offer best value opportunities for community/grid-scale storage.

O3. Analyse conditions and high impact use cases for which grid-scale storage located at substations can offer best value of investment, for example to mitigate risks for major outages through controlled islanding of sections of the network.

O4. Assess opportunity costs and benefits (including equity considerations) of locationally optimising DER connection and operation.

RQ10	What are appropriate methodologies for determining device level standards that balance customer and network needs, and how do we best ensure compliance with standards?

RQ11	What are the current and future cybersecurity risks from the increasing reliance on data sharing and DER to enable low-voltage management and how do we best manage them?

Sample research objectives:

O1. Survey cyber-based contingency studies to identify operation critical cyber assets in substations, DER communications, and tools for impact analysis and asset security protection and planning.

O2. Identify vulnerabilities arising from vendor web interfaces to smart devices and approaches to manage potential cybersecurity weaknesses that can trigger large unwanted aggregate DER responses.

RQ12	What is the optimal proportion of flexible, controllable DER relative to large-scale, firm generation, and how does that proportion change as large generation changes

Sample research objectives:

O1. What are effective methodologies for comparing similar – but not identical – technologies at the customer-scale and large-scale? In other words, how should you discount – if at all – the output of a consumer solar installation or battery compared to a utility-scale solar field or large-scale battery?

02. What degree of “firmness” or essential system services are required in different system architectures and what options are best for providing those services?

9 Research Roadmap and Impact Planning

This section focuses on sharing three interrelated outcomes from this project: a research roadmap, an impact framework, and a set of key performance indicators and metrics to measure progress in this theme during the course of RACE for 2030. The section begins with a description of six research priorities. These research priorities help frame the research roadmap, which identifies a number of milestones over the coming ten years for each research priority. The research roadmap itself is a high-level, long-term tracking tool that does not include specific research activities. To address the reality that certain potential priority research activities have been identified by stakeholders, we have included a section outlining recommendations for potential near-term research actions. The second half of the section focuses on impact planning, first by describing our theory of impact and an impact framework. The section concludes by identifying key performance indicators and metrics

9.1 Research priorities

Real barriers of limited visibility, inadequate market integration, customer engagement and policy support need to be addressed. Six research priorities for targeted interventions have been identified through an extensive process involving literature review and industry consultations. Interviews with industry stakeholders like network service providers, retailers, regulators, technology companies, and energy user peak bodies drew out barriers and related knowledge gaps present today. The research questions articulate these gaps and highlight the opportunities present in the sector today. These have helped shaped the priorities for this research roadmap.

PRIORITIES	BARRIERS	RESEARCH QUESTIONS
DATA ACQUISITION	**Data Barriers** • Integrity & Availability • Processing & Storage • Security	RQ11 What are the current and future cybersecurity risks from the increasing reliance on data sharing and DER to enable low-voltage management and how do we best manage them? RQ7 How might we streamline, automate and standardise network processes for collating, cleaning, and sharing LV data?
DATA PROCESSING & ACCESS	**Information Barriers** • Analytical skills • Network Models • Planning methodologies	RQ1 What are the most efficient combinations of network modelling and network and customer monitored data to support optimal integration of DER in the operation, planning and market services in low-carbon, reliable and secure electricity systems? RQ3 What are the most appropriate combinations of network and non-network forecasting and control strategies to optimise DER hosting capacity?
DECISION SUPPORT TOOLS	**Network Barriers** • DER & Minimum demand • Acceptance of NNS • Standardisation • Co-ordination	RQ2 What are the potential network vulnerabilities to the synchronised, autonomous response of large groups of distributed inverter-connected resources to network and market signals and weather disturbances? RQ12 What is the optimal proportion of flexible, controllable DER relative to large-scale, firm generation, and how does that proportion change as large generation changes
POLICY SUPPORT	**Regulatory Barriers** • Data Access • Standards & compliance • Common definitions / framework	RQ6 What data and technology standardisation are required for optimal integration of DER in the operation and planning of the electricity system? RQ10 What are appropriate methodologies for determining device level standards that balance customer and network needs, and how do we best ensure compliance with standards?
CUSTOMER ENGAGEMENT	**Customer Behaviour** • Equitable access to network • Consumer engagement • Privacy & protections	RQ4 What do customers perceive as the best/ most equitable ways of allocating network capacity for DER? RQ5 How do we engage customers to enlist their devices and modify their behavior to provide a variety of grid services, including optimizing hosting capacity?
MARKET INTEGRATION	**Market Barriers** • Pricing structures & signalling • Business case and value stack • Customer incentives • Data Procurement	RQ8 What are the most effective approaches to monitor and audit demand-side transactions in the post 2025 market? RQ9 What is the value to network operators and customers of applying different DER at different locations in the network?

Figure 9-1 Research priorities

The six research priorities that have been identified are:

Data acquisition: Different use cases require different levels and types of data. This research priority focuses on the need to collect data, including the development of "models as meters" to help lower the cost and streamline data acquisition.

Data processing & access: Big data is also dirty data, and this priority targets developing appropriate tools for collating and cleaning data, including effectively combining disparate data sources into effective, easily manipulated datasets. This priority also focuses on processes and techniques for providing effective access to data for a variety of stakeholders.

Decision support tools: Improved network and DER visibility enables better planning and operation of the grid, resulting in better outcomes for both customers and the network. This priority articulates the tools and methodologies needed to assist in this decision making.

Policy support: This priority seeks to develop uniform standards, guidelines, and regulations that will meaningfully contribute to reducing the barriers to mainstreaming DER.

Customer engagement: Customers are the keystone of the RACE for 2030 CRC. This research priority explores strategies for improving customer awareness and engagement, specifically related to network access and allocation of network resources. It seeks to ensure equitable access to network resources for all customers.

Market integration: This research priority aims to facilitate the integration of DER into the energy marketplace. It calls for development of business cases for as well as enabling market integration of network and DER data and reducing barriers to DER transacting for value with new and established industry players.

9.2 Research roadmap and milestones

The overarching aim of Theme N2 is to help customers connect and operate DER in ways that make financial and common sense to them by improving network and DER visibility. This research roadmap takes a phased approach to achieve a series of intermediate milestones to help the six research priorities deliver on this aim.

These milestones were determined through two processes. First, the research team identified what needs to be achieved to show progress against a research priority and towards answering one or several of the research questions outlined previously. Second, the research team has used the following criteria to guide selection:

- **Appropriate:** RACE partners should be well placed to help answer the key research question. Many of the research questions have active work programs in play by the ESB, AER, AEMC, ARENA, DEIP or others. These forums are in some cases adequately addressing important aspects of the research questions and research priorities. Therefore, milestones should only include areas where research by RACE and its partners – alongside and integrated with these processes – can more fully resolve the questions and priorities at hand.
- **N2 Theme-Specific:** To limit overlap with other RACE themes, areas with a distinct focus (such as electric vehicles, tariffs, or building trust) will not be included as explicit activities. However, research outcomes should be interpreted broadly enough that proposed research can meet multiple goals.
- **Time-criticality and path dependence:** Activities in the first years of the program should target time-critical issues that need to be resolved and foundational research that enables more confident and rapid progress for later technology or market functioning.

- **Long-term gaps:** As RACE has a 10-year view, this means it can target longer-term research needs or use cases that the industry is not yet grappling with but are foreseeably on the radar.
- **Impact:** Activities and outputs that directly contribute to the desired outcomes and impacts identified in the impact framework.

The Research Roadmap table below highlights the milestones for each research priority across three timeframes: short-term (1-3 years), medium term (5 years), long-term (10 years). Each milestone is also linked back to the research question(s) it will address.

Table 9-1 Research Roadmap

Research Priorities	Milestones 2023	2025	2030
Data Acquisition	• Definition of “right data” for use cases (RQ1) • Protocols for interoperability & information exchange (RQ7)	• Low-cost technology to provide right data mainstreamed (RQ7)	• Data release framework operationalised (who, what, when) (RQ1,RQ7, RQ11)
Data Processing & Access	• Standardised definition of Hosting Capacity – inputs & outputs (RQ3, RQ12)	• Common digital infrastructure for LV data access use cases (RQ7) • HC calculation framework and tools facilitate transparency (RQ3, RQ12)	All stakeholder types have ready access to granular data required to execute role in DER (RQ7, RQ3)
	• DER processing platforms / LV network model development (RQ1, RQ3)		• LV network models have 3rd party access for solution development (RQ7, RQ3)
	• Integration of spatial data for network operations (RQ1)		
Decision Support Tools	• Capacity allocation use cases & value proposition for customers articulated and communicated (RQ2, RQ3) • Standardised assessment methodologies for non-network options to provide network support that address customer equity and other considerations (RQ1, RQ2, RQ3)	• Tools for connecting medium term use cases (RQ1, RQ2, RQ3) • Methods and tools for rapid risk-based decision making in spatial LV network planning (RQ1, RQ2, RQ3)	
Market Integration	• Data value proposition for different use cases (RQ9, RQ1)	• Business models / marketplace integration for data services (RQ9, RQ1)	• LV data feeds unified transaction platforms and settlement procedures for LV solutions (RQ8, RQ1)
	• Appropriate pricing structure and signalling mechanisms for different use cases (RQ9)	• DER Customers can equitably participate in wholesale and network markets (RQ8, RQ4, RQ5)	• Solutions to LV network issues are tailored to time and location (RQ2, RQ8)
	• Business case for flexible DER products / Better return on investment for customers (RQ5, RQ9)		• Established market for DER services (RQ5, RQ8,RQ9)
Customer Engagement	• Customer education / awareness programs (RQ5)	• Strategies to enable equitable customer access to network resources (RQ4)	
Policy Support	• DER device standards / settings (RQ10) • Technology Standards (RQ6)	• Safe integration of DER to electricity system to manage non-compliance (RQ6, RQ10)	• Compliance ecosystem for DER devices (RQ10)

9.2.1 Recommendations

The research roadmap above identifies broad milestones that the research program should meet to enable reliable, affordable, clean energy by 2030. Given the rapid transition in the industry, identifying a detailed, prescriptive research program that spans the next ten years is inadvisable and prone to large errors. Nevertheless, some critical actions can be identified now that are important to achieving the program's broad aims. These were developed through industry consultations that focussed on prioritising research questions and workshopping project ideas industry was interested in resourcing.

A primary focus of Theme N2 is improved visibility of LV networks which will enable network companies to better plan their resources, allow more DER integration at the customer-level, and improve network utilisation. There are strong interdependencies in the first three research priorities identified. Better planning and decision-making require better tools and methodologies to assess hosting capacity and network constraints, which in turn require appropriate network models and the 'right data' for different use cases. The critical actions identified below align with this narrative:

4. Understanding the data landscape
    a. Exploring effective ways of showcasing and sharing information
    b. Developing rules for governing data
5. Developing tools and models for efficient and equitable network planning
6. Exploring integrated approaches to using DER to provide network services
    a. Identifying value of DER services for networks and customers

Prioritising investment in projects that address these three high-level opportunities is recommended but there are notable limitations to this list. Despite the research highlighting the significance of issues relating to the market, customer behaviour and policy support, these were absent from the stakeholders' list of prioritised research projects. These research topics should not be ignored but may be better prioritised within other RACE themes. Given the interdependencies and overlap of opportunities regarding market structure, policy, and customers being explored by other RACE themes, a key role for RACE will be integrating lessons across the four different programs.

9.3 Impact Planning

The impact framework is an essential component of RACE for 2030 as it enables each of its four program themes to strategically plan their research. It also provides the opportunity for those proposing projects under the themes to consider their pathway to impact early in the design phase and enable them to then demonstrate their impact over time.

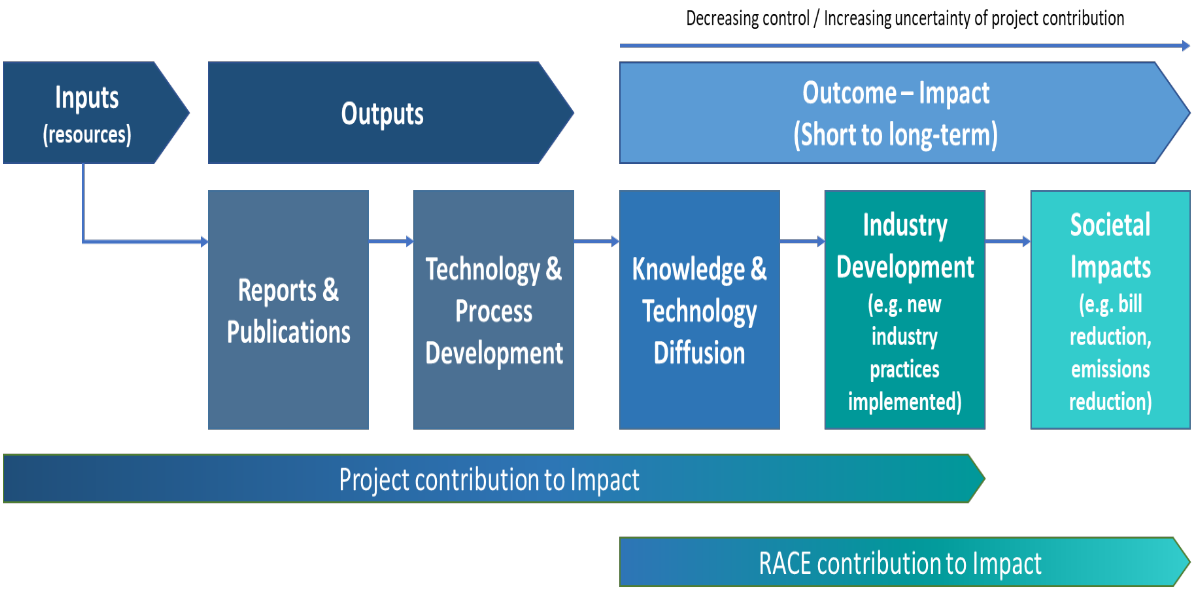
This impact framework is designed to align with the overarching objectives of RACE for 2030 and Theme N2, whilst retaining sufficient flexibility to accommodate the diversity of projects that are likely to emerge. The structure of the framework is based on the CSIRO Impact Framework and the UK Research Impact Framework (UK REF).

9.3.1 Path of Impact and Impact Framework

The path of impact for Theme N2 follows a familiar chain, from inputs (time, funds, people, etc.) and activities to outputs, outcomes, and impact. For projects funded by RACE for 2030, resources (e.g. grant funds and time) are used as inputs to support various project activities (e.g. software development, demonstration projects, and desktop studies). The effectiveness of these activities depends on knowledge and technology diffusion – the reach of the knowledge sharing activities or the uptake of the newly developed product. This diffusion will seed new ideas among stakeholders and enable industry development, such as implementing new practices or reducing barriers to mainstreaming DER. These new practices, in turn, can lead to wider societal impacts, such as reduced greenhouse gas emissions.

As shown in Figure 9-2, the control over the outcomes and ability to attribute them to project activities generally decreases along this chain. Projects funded under Theme N2 can contribute to the identified outcomes. The role of RACE for 2030 will be ensuring that the outputs and outcomes integrate with other relevant industry processes in order to deliver their full impact.

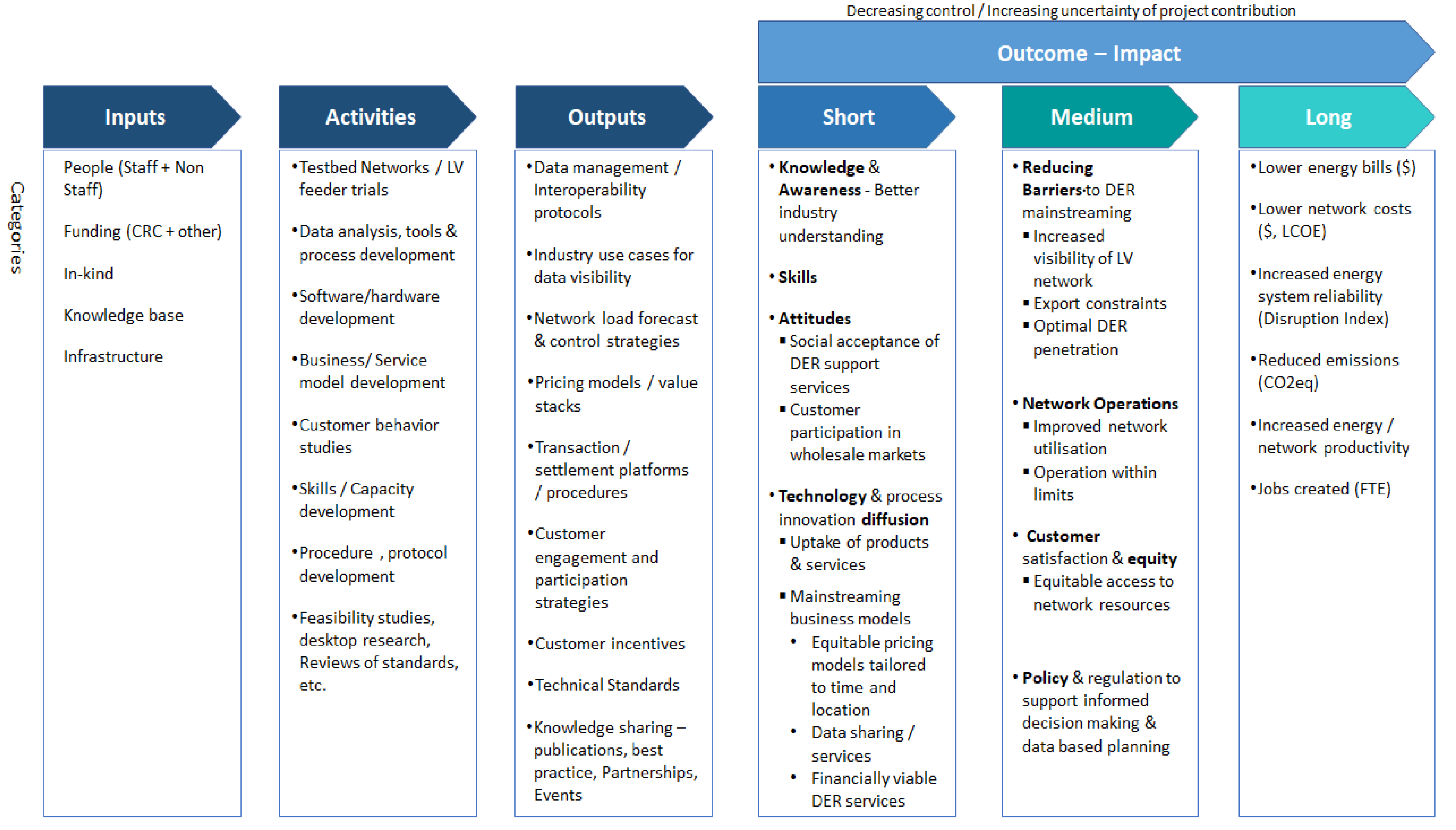
Figure 9-2: High-level impact framework for N2



The impact framework is a tool for the research theme to strategically plan how it seeks its desired impact and articulates the various impact pathways projects may take. The framework is also a tool for projects to help identify and plan for impact over and beyond their lifecycle. While the representation of the impact logic is linear for ease of communication, it is important to note the feedback loop, from the desired impact to planned activities, while designing the research program.

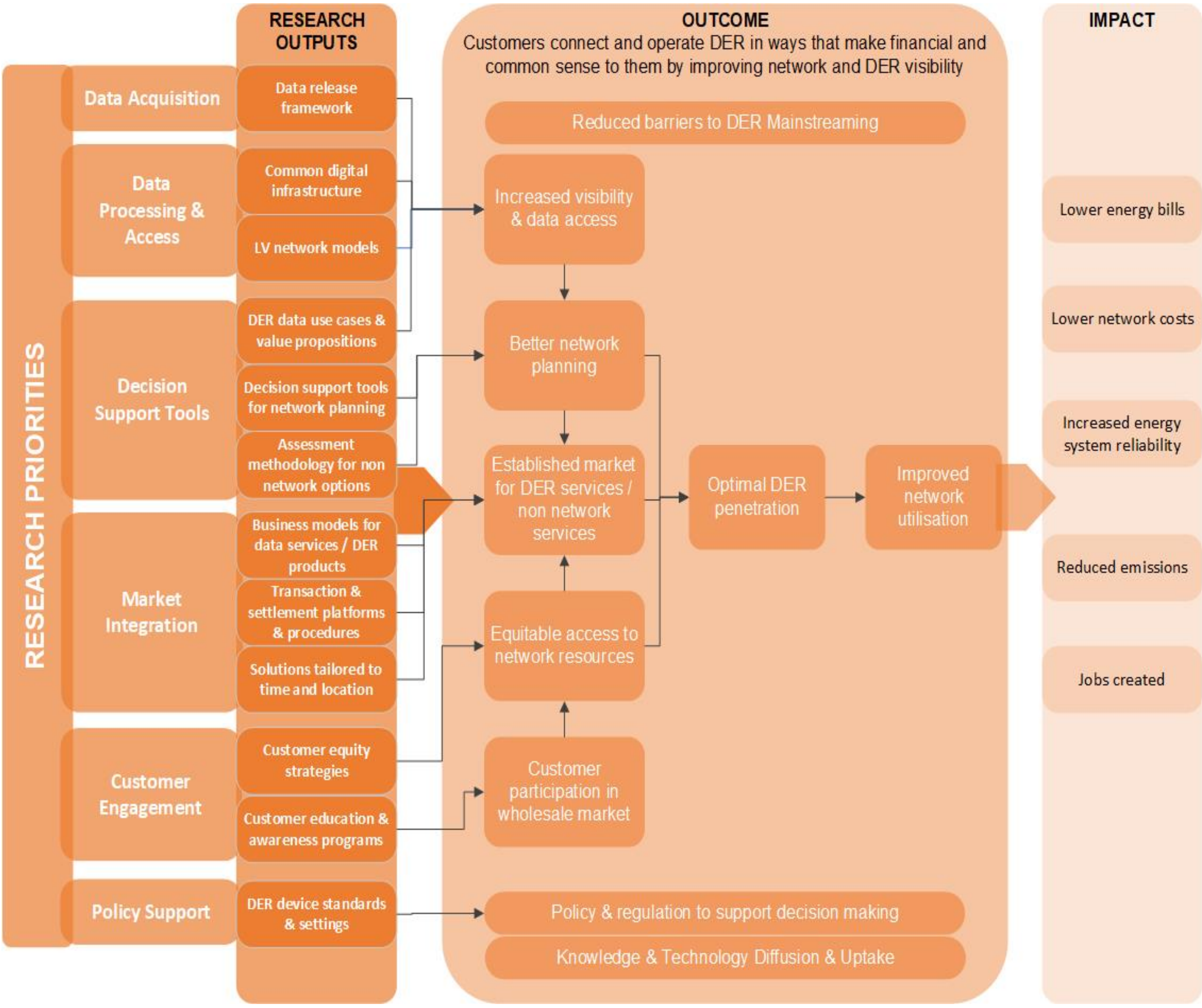
Figure 9-3 provides additional detail on the impact framework and applies it specifically to this research theme. The logic is the same but each link in the chain is broken up further into categories. The figure also identifies indicators that can be evaluated at each stage of the chain. These categories and indicators are explained in the next section.

Figure 9-3 Summary of the full impact framework for N2



The framework recognises that there can be multiple pathways to impact and allows flexibility for projects to choose their own pathway(s).

Figure 9-4 Multiple Impact Pathways for N2



9.4 Impact Categories and Key Performance Indicators

This Opportunity Assessment provides a baseline for the state of knowledge in the sector. The activities and outputs listed in Figure 9-3 are derived from the research priorities, questions, and opportunities identified above. The list is broad but should not be considered exhaustive. An individual project may consist of multiple activities and outputs described here or propose new ones.

This section focuses on identifying key performance indicators (KPIs) and metrics for three categories of outcomes: knowledge and technology diffusion; industry development; and societal impact. Each outcome type is subdivided into a number of outcome sub-categories, and there is at least one KIP and often several associated with each sub-category. Similarly, each KPI has at least one metric, though often several.

9.4.1 Knowledge and Technology Diffusion

Table 9-2 Categories and indicators for knowledge and technology diffusion outcomes

Category	Indicators	Metrics
Knowledge, Awareness & Skills	Better understanding through knowledge diffusion.	Self-reported change by industry stakeholders.
	Specialised skill development.	# of people trained. # of skill sets identified.
Attitudes	Social acceptance of DER support services. Customer participation in wholesale markets	# of networks buying non-network support services. Change in connection agreements. MW of non-network support traded
Technology & process innovation diffusion	Increased uptake of products & services.	Product /services sales #. # of Retailers / aggregators offering services.
	Increased uptake of tools & methodologies for better network planning in existing businesses.	# of businesses adopting tools.
	Mainstreamed business models: • Equitable pricing models tailored to time and location • Data sharing / services • Financially viable DER services	# of businesses adopting models.

9.4.2 Industry Development

Table 9-3 Categories and indicators for Industry development outcomes

Category	Indicators	Metrics
Reducing Barriers to DER Mainstreaming	Increased visibility of LV network.	• Use cases • % visibility on network
	Alleviate export constraints.	• Export limits (static vs dynamic) • Average solar installation size
	Optimal DER penetration / Increased Hosting Capacity.	• Grid decentralization ratio • % DER on LV feeders,
Network Operations	Improved network utilisation.	• % Utilisation • Annual load variation curve
	Network operates within limits of all applicable quality standards.	• Annual average breach hours / day

		• Occurrences of overvoltage and undervoltage events. • Power quality metrics (e.g. voltage sags, swells and fluctuation, phase unbalance, transients and harmonics)
Policy & Regulation to support informed decision making & data-based planning	Influenced decision making / decision-makers. Informed changes in industry policy, market rules, legislation, regulations or guidelines.	• Evidence of policy change – reports, guidelines, etc. • Citations in key industry decision-making forums
Customer Satisfaction & Equity	Equitable access to network resources.	• Network connection agreements • Customer complaint rates • Solar spillage

9.4.3 Societal Impacts

Table 9-4 Impact indicators and metrics

Category	Indicators	Metric
Economic	Lower household energy bills	$ (bill reduction)
	Lower network costs	Network LCOE
Economic / Environmental	Increased energy system reliability	Change in Disruption Index
Environmental	Reduced emissions	CO_2 equivalent
Economic / Social	New jobs created	FTE

10 Economic Potential Analysis

The objective of this section is to provide a preliminary analysis of the value of the potential impacts of research into optimising distribution system distributed energy resources (DER) hosting capacity. This is a broad and complex question. There are many types of DER and they can potentially impact many parts of the electricity system.

We have deliberately sought to keep the scope narrow. The analysis leverages existing models and datasets to identify the costs and benefits across different scenarios. A definitive cost-benefit analysis is not possible and outside the scope of this report; we seek rather to provide an indicative range, compare that range with other estimates and understand which drivers and uncertainties are most impactful.

10.1 Background

DER is being deployed by customers somewhat regardless of hosting capacity constraints. Some distribution network connection requirements may have shaped the size of systems being deployed. For rooftop solar PV, 5kW per phase export limit is a typical connection requirement, but in some remote distribution areas connection has been disallowed.

Rooftop solar PV is the most widespread and affordable DER technology and its capacity continues to grow strongly. Batteries are growing more slowly. Electric vehicles are lagging but are expected to grow strongly in the longer run. It is becoming increasingly likely that global vehicle manufacturing will eventually switch over to this technology with several international car manufacturers openly discussing a future where they will no longer design internal combustion vehicles. As a country depending on vehicle imports, Australia will be carried along with that change.

Given the existing and continued large scale deployment of rooftop solar, this type of DER should be a key focus of the analysis. The greatest impacts to changes in hosting capacity will be to rooftop solar and the wholesale electricity market where increased availability of rooftop solar generation would either reduce the amount of large-scale solar PV investment required or reduce the running costs of existing generation [69].

We have also assessed vehicle to grid batteries as the next highest value opportunity for value to be gained from improved hosting capacity. Our assessment acknowledges that the Australian road fleet may eventually be dominated by electric vehicles (see for example, AEMO Step change scenario which results in near 100% electric vehicle adoption by 2050). This scale of electric vehicles, if significant numbers are available for vehicle to grid services, could potentially offset (or exceed) the generation sector's requirement for large-scale storage capacity.

There are also many other worthy cases to examine benefits of increased hosting capacity, both in terms of DER technologies – such as air conditioners, pool and spa pumps and heaters, water heating, small-scale batteries – and beyond the generation sector, by examining distribution and transmission sector benefits. Some of these other benefits feature in existing studies [34], [69]. However, the generation benefits of increasing hosting capacity for rooftop solar and electric vehicle battery exports to the grid (the two benefit cases examined in this study) are expected to be the largest sources of value and represent a manageable scope for a targeted update such as this.

Broadly speaking, the methodology of the study is to determine the DER energy or capacity that is being limited by existing or expected hosting capacity constraints and what value they would have for the electricity system if they were no longer constrained.

The rooftop solar analysis is the most involved because the phenomenon of current and future curtailed rooftop solar generation is obscured by poor visibility in the low voltage distribution sector. Consequently, arriving at a reasonable range of assumptions (in lieu of hard observations) will take up most of this section. The electric vehicle analysis is relatively short because its impact is more direct (avoided investment) requiring less approximations.

No new estimates of the costs of increasing hosting capacity are presented in this report. However, we have included some data and insights from existing studies. We also use existing studies to check the plausibility of the updated benefits estimates.

10.2 Analysis of rooftop solar PV and hosting capacity

The current lack of network visibility means we do not have a readily observable metric for defining the current limits to rooftop solar generation due to hosting capacity. We can reasonably expect that curtailment due to high voltage (generation outages due to inverter responses) are likely to increase as more rooftop solar PV is deployed.

We acknowledge that some metering data is available, particularly in Victoria. However, this data is private and therefore not included in this study. Our alternative approach is to model the circumstances that are associated with rooftop solar PV curtailment. There are broadly five key curtailment categories:

1. Economic curtailment – reduction in production due to economic reasons, such as a low or negative price for electricity, this is likely to occur where there is system wide oversupply or near oversupply to the limit of ramp down or minimum-run constraints of other generators.
2. System strength curtailment – these are localised conditions whereby there is insufficient infrastructure to deliver renewable electricity to where it can be used.
3. Directed curtailment – where a market operator directs the production of specific generators to be curtailed to maintain system security.
4. Connection curtailment – where the renewable energy producer is either prevented from connection or generation size is reduced prior to connection to the electricity grid.
5. Other curtailment – such as self-scheduled reduction, distribution network outages and other network events.

The key driver of system strength curtailment is the coincidence of high rooftop solar, during a low demand period in a weakly connected area of the distribution network. This study does not have the resources to overlay a map of the distribution network interconnectedness. However, we can project rooftop solar PV generation and the level of operational demand in most zone substations in Australia.

We do this by drawing on several data sources. For the current operational demand of each zone substation we have used data published by each distribution network service provider. We have sourced projections of DER deployment (specifically, rooftop solar, batteries and electric vehicles) and operation from [70]. Note that, the deployment of batteries and electric vehicles may ameliorate the impacts of rooftop solar on load and voltage, and so it is important that these are included in future operational demand projections.

Our analysis was developed to focus on system strength curtailment. It is highlighting times when it is likely that inverters will disconnect from the electricity system due to overvoltage on the network. This occurs at times of localised oversupply in the distribution sector. We further expanded the analysis to consider the wider level of demand in the system, including times where the level of state-wide demand is low. This would correlate with times of both economic and directed curtailment.

10.2.1 Estimation of rooftop solar PV curtailment

There is a large degree of uncertainty around the level of solar PV curtailment. To make an initial exploration of the potential range of curtailment a range of scenarios were explored. Our analysis uses the projected incidence of half-hourly reverse power flow at a zone substation level to identify curtailment of solar PV systems due to inverter disconnects due to overvoltage.

Firstly, we examined different AEMO projection scenarios, the Central scenario and the High DER scenario[27]. These scenarios have differing amounts of projected solar PV uptake. These scenarios also have different projections of underlying demand and other DER adoption, such as electric vehicles and batteries.

Secondly, curtailment of solar PV is assumed to be triggered by negative flows at a substation level combined with a range of state demand constraints. Periods of both localised negative demand and low state demand are more likely to result in high voltage events and inverter disconnects.

Thirdly, different curtailment levels of solar PV were considered. The mechanism of inverter disconnects during periods of high voltage is difficult to simplify as there are a range of inverter controls. Our analysis therefore summarised a range of curtailment from full curtailment of all PV systems on a substation to only a proportion of systems, to partial curtailment based on the size of negative demand.

10.2.2 Detailed methodology summary

Historical half-hourly load data from 1746 zone substations is combined with historical PV estimations for each zone substation. This generates the historical demand at each zone substation. This underlying demand is projected forwarded in five yearly intervals from 2025 to 2050 under two different AEMO growth rate scenarios, Central and High DER. The demand model then includes half-hourly electric vehicle loads, customer side battery operation profiles and solar PV generation profiles to produce a finalised after-DER load at each zone substation. This finalised load is then analysed to observe any half hour period where negative load or equivalently, negative power flows at the zone substation level occur.

If there is a negative power flow while solar PV production is present two different estimations of solar PV curtailment are made. Firstly, full curtailment (FC) assumes that this negative flow causes an overvoltage event whereby all PV system inverters are disconnected. Secondly, partial curtailment (PC) assumes that the amount of power curtailed is limited to the negative power flow and so it is assumed that some PV systems on the zone substation will continue exporting to the grid whilst others are disconnected.

Additionally, an overlay of state demand is placed over the results to further examine the variation in curtailment, as it would be expected that as the overall state demand lowers, it will be more difficult for localised oversupply to be absorbed elsewhere resulting in either system strength or economic curtailment. Two different demand overlays are analysed. Firstly, a median demand constraint is applied, whereby curtailment is assumed to only occur under conditions whereby the state demand is less than the median demand for that year. Secondly, a minimum demand constraint is applied, whereby, curtailment is assumed to only occur under conditions whereby the state demand is in the bottom third of state demand observed for that year.

10.2.3 Solar PV curtailment results

The level of projected PV curtailment is shown in Figure 10-1 for Central and High DER AEMO scenarios. There is a wide variation of projected curtailment depending upon the curtailment method and level of demand constraint. The final value at 2050 varies from as low as 2.2GWh to 13GWh. Figure 10-2 shows that the level of curtailment can be a significant source of lost electricity, for example up to 9% of NEM operational demand by 2050.

[27] Information on these scenarios is available in various documents associated with 2020 AEMO planning projects such as the Electricity Statement of Opportunities and Integrated System Plan

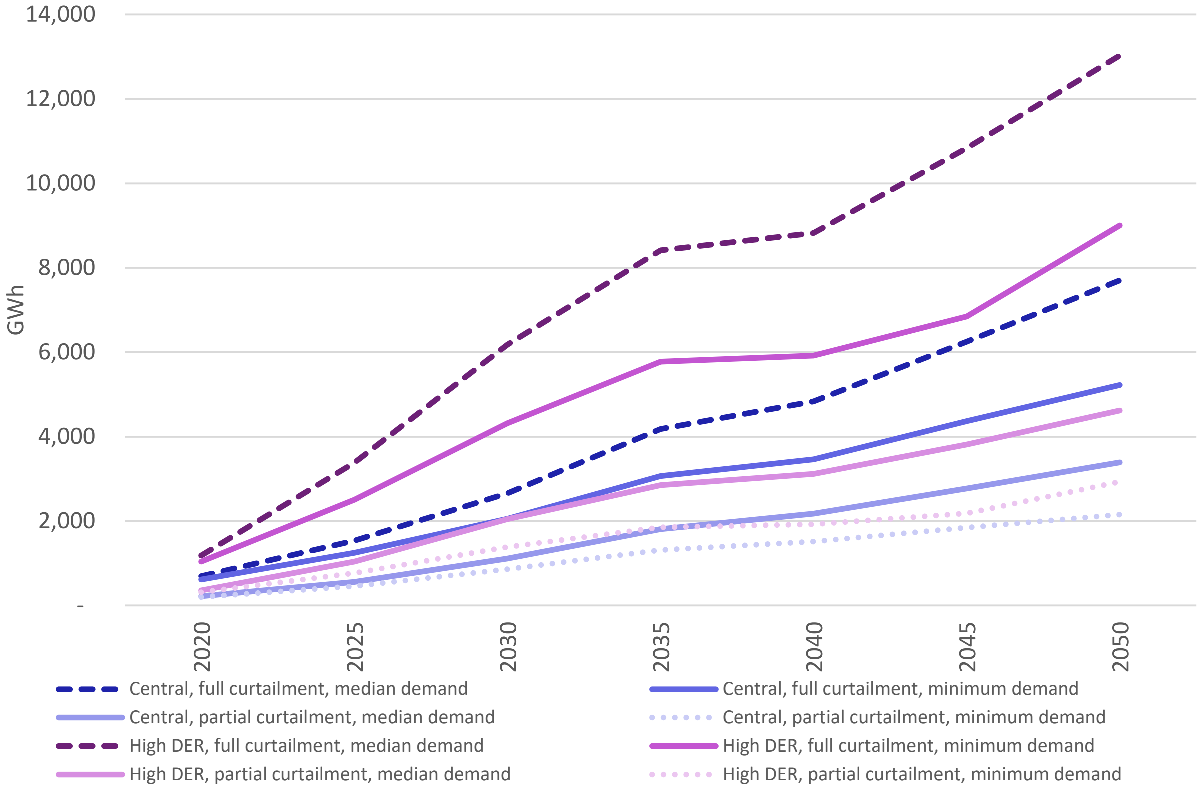


Figure 10-1 Projected curtailment of rooftop solar PV generation under different AEMO scenarios and curtailment methods for the NEM

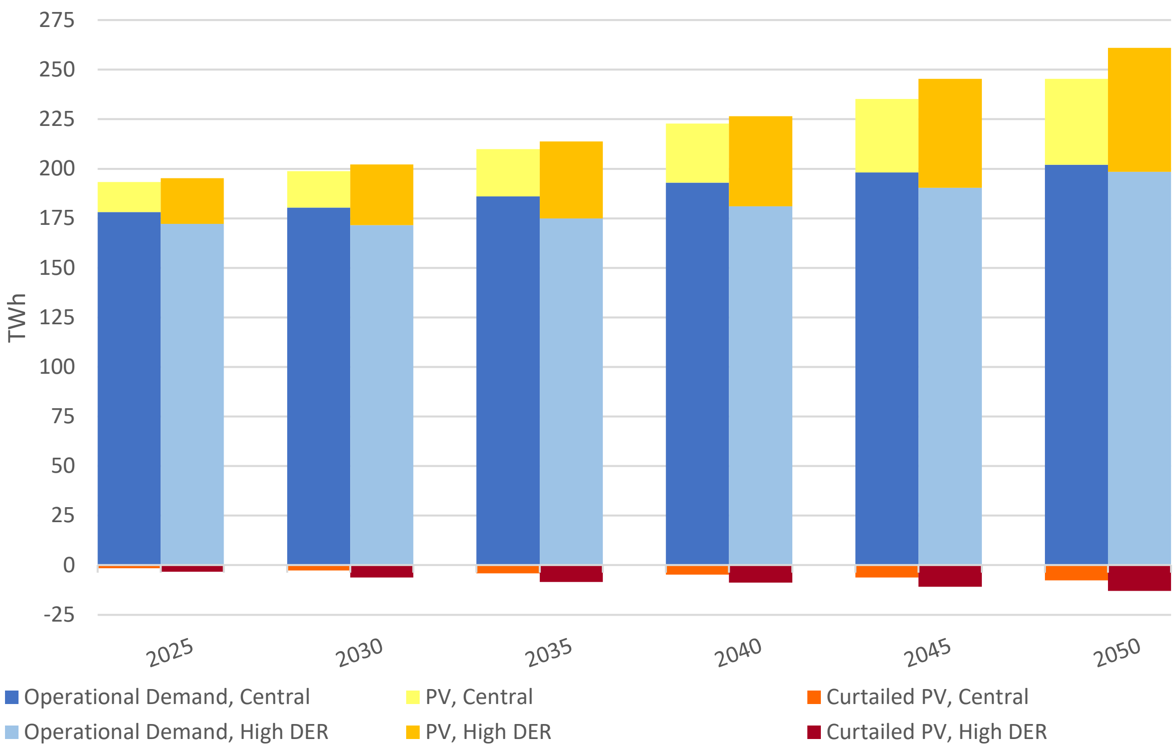


Figure 10-2 Projected total demand in the NEM broken down into operational demand and solar PV generation. The curtailed PV amount is shown for full curtailment and median demand.

Figure 10-3, Figure 10-4, Figure 10-5 and Figure 10-6 show the variability of PV curtailment as a percentage of PV production under the range of methods. For the NEM there is a variation in curtailment from 21% of production (in the High DER, FC, median demand constraint scenario) down to 5% (in the Central, PC, minimum demand constraint scenario). The figures illustrate the variations in each of the states. South Australia and Queensland are historically the highest solar PV uptake states and continue to be so. Queensland has stronger connection growth owing to population and economic growth and so can level with or overtake South Australia over time.

The quantum of PV generated under the Central scenario is lower, but a similar percentage of PV generation is curtailed to the High DER scenario. The High DER scenario has a greater penetration of electric vehicles and batteries which would facilitate a higher penetration of PV without greater curtailment. This illustrates that the coordination of DER is an important factor in augmenting the system to allow greater penetration of solar PV.

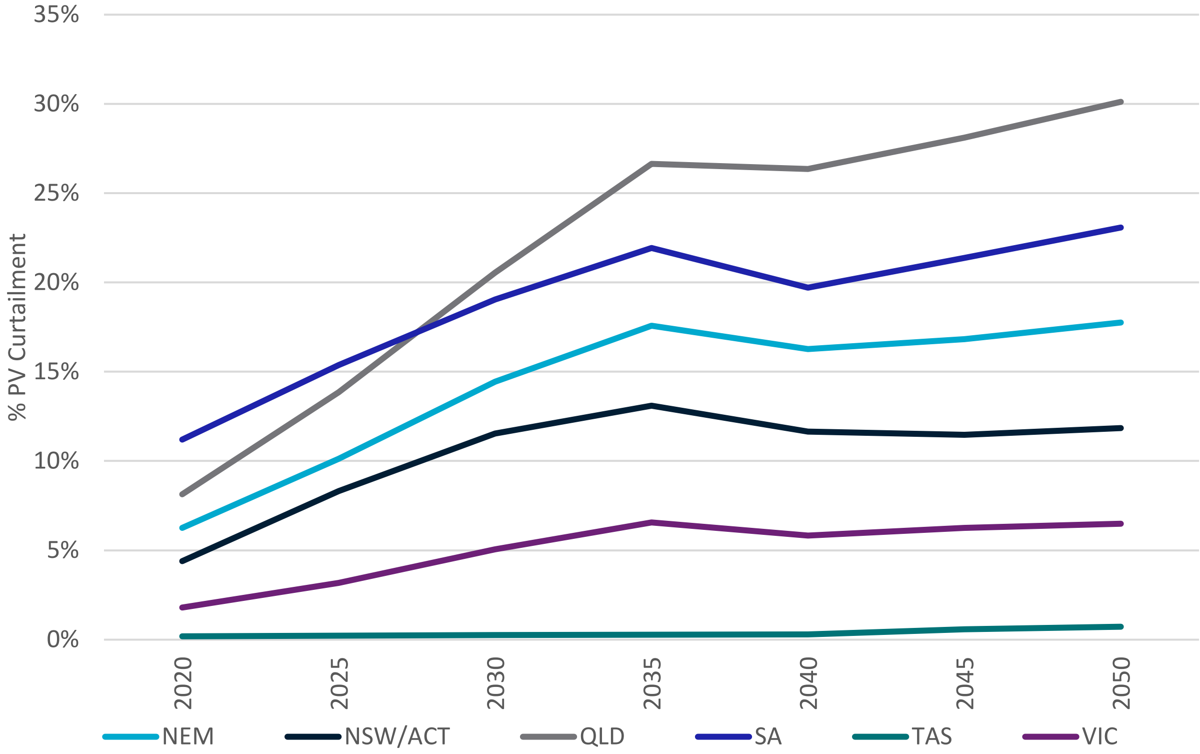


Figure 10-3 Projected percentage of curtailment of rooftop solar PV generation by state under the AEMO Central scenario under full curtailment and median demand

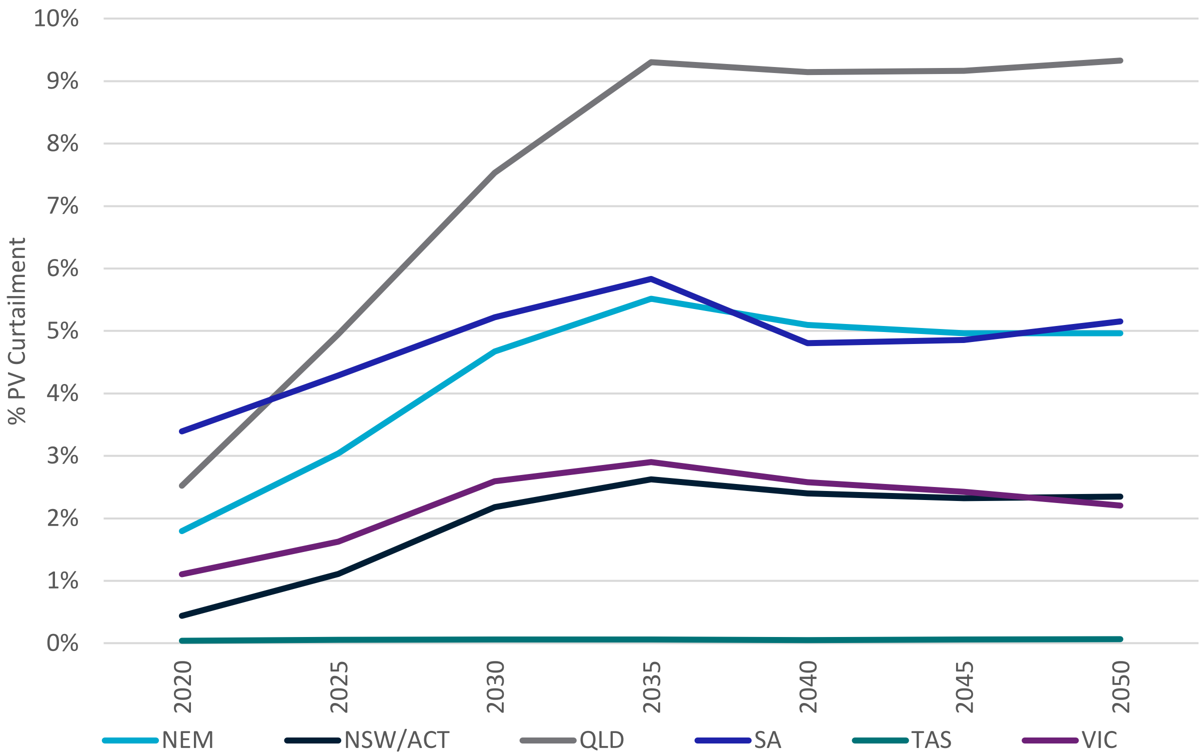


Figure 10-4 Projected percentage of curtailment of rooftop solar PV generation by state under the AEMO Central scenario under partial curtailment and minimum demand

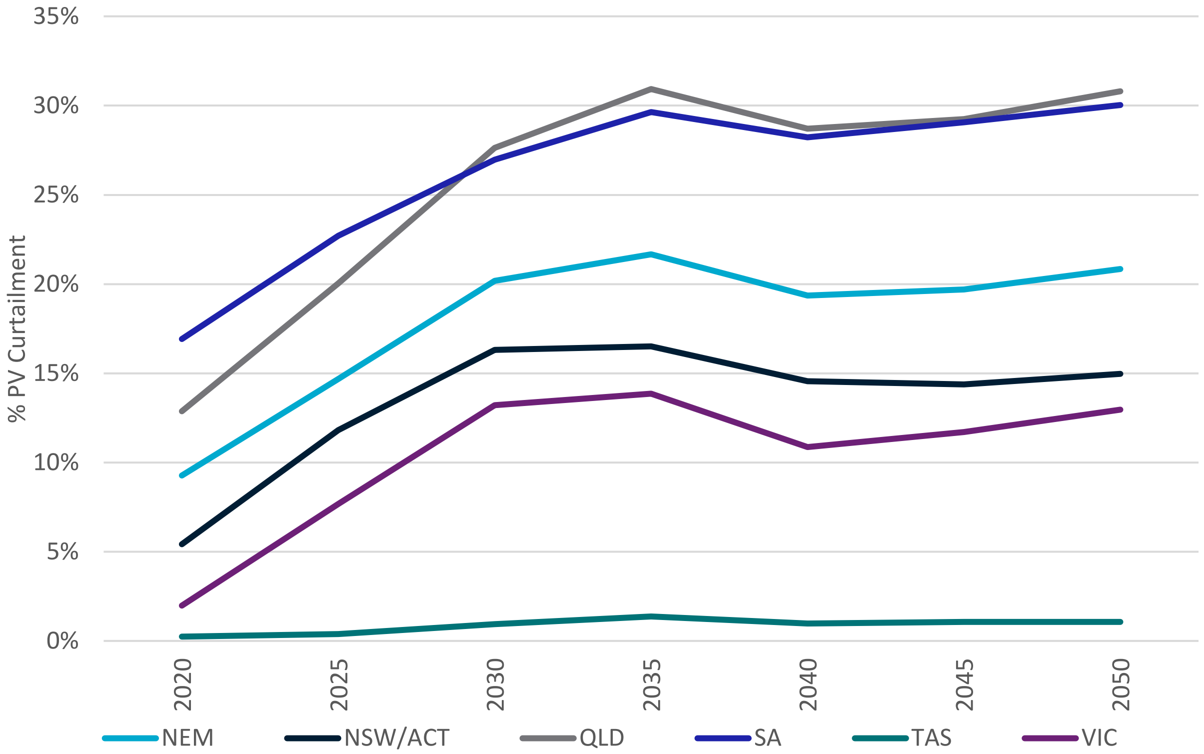


Figure 10-5 Projected percentage of curtailment of rooftop solar PV generation by state under the AEMO High DER scenario under full curtailment and median demand

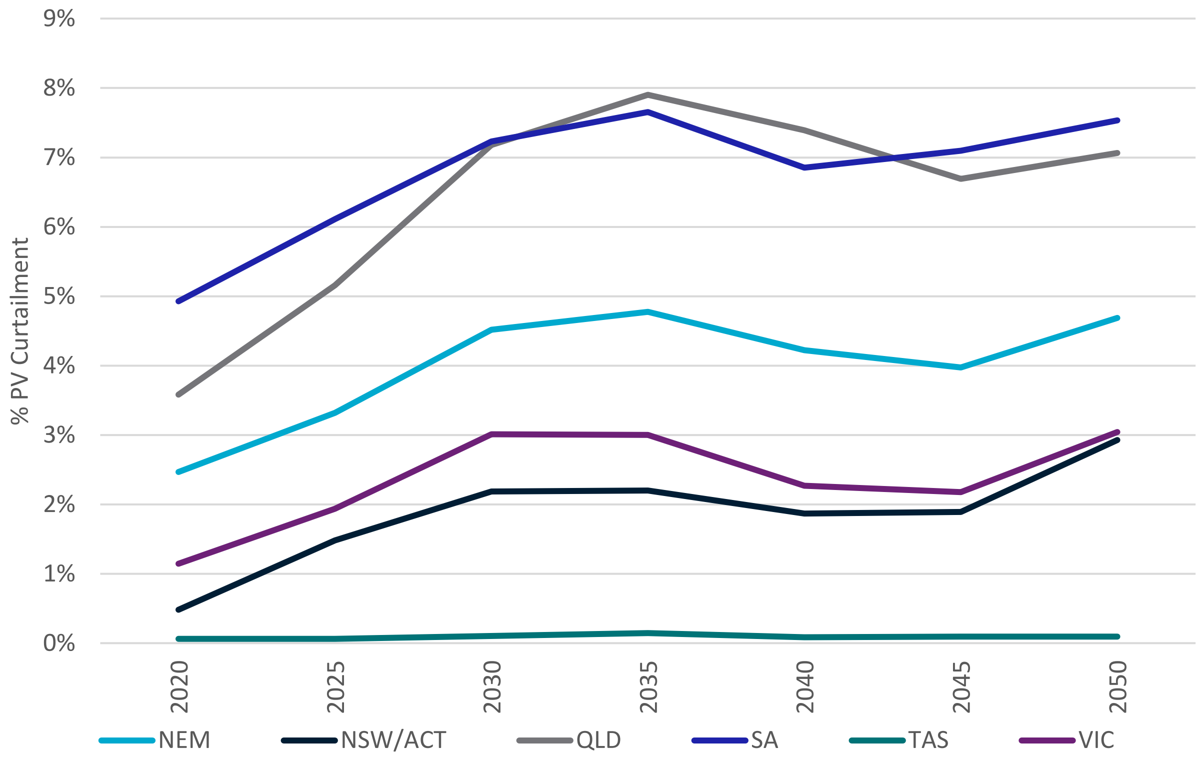


Figure 10-6 Projected percentage of curtailment of rooftop solar PV generation by state under the AEMO High DER scenario under partial curtailment and minimum demand

10.2.4 Benefits of avoided rooftop solar PV curtailment

The method for calculating the benefits of avoided rooftop solar PV curtailment for the generation sector follows the method outlined in [69]. In choosing a method, the study emphasises the need to identify whether the benefit flows from avoided investment or from avoided short run marginal costs. To offset investment costs, the profile of the curtailed rooftop soar would have to be near enough to the profile of large-scale solar for development of large-scale solar to be crowded out of the market (with the ratio of capacity factors being one possible measure to determine closeness). The average daily load profile for curtailment typically fails this test because:

- Even in high rooftop solar PV share zones, for most days of the year demand is not low (during daylight hours) and so curtailed generation is far more intermittent than large scale solar
- Rooftop solar does not include tracking and so its profile is narrower

We therefore turn our focus on using the avoided short run marginal costs method. Under this method, half hourly generation prices at the time of the curtailment event are used to estimate value. This ensures that the method recognises that generation prices are also low during periods of low demand and high rooftop solar output. We have sourced historical half hourly electricity prices in the National Electricity Market (NEM) and as a result we confine our conclusions to the NEM. To take account of changes in future day time half hourly prices, we have reduced all future prices. The rate of reduction has been aligned with reductions in large scale solar generation costs. Under this approach, by 2050, daytime prices are assumed to be around 55% lower than current prices which already include periods of negative pricing in most regions.

We adjust for avoided transmission losses by assuming an average transmission loss by region based on data in the AEMO Input and Assumptions Workbook (July 2020). All future values are discounted at the rate of 5.99% which is taken from the same source.

The results of the projected range for the value of curtailed rooftop solar PV generation under the AEMO Central and High DER scenarios are shown in Figure 7. The value represents the discounted sum of avoided generation sector short run marginal costs between 2025 and 2050 (on the basis that the outcomes of hosting capacity research begins to be felt in the market from 2025 and provides ongoing benefits).

For each scenario the lowest values were associated with the assumption that outage conditions only resulted in a partial curtailment within the half hour. The range of ways for defining low demand conditions only had a more limited impact on the range of values estimated. The second greatest source of differences in value of curtailment is the DER uptake scenarios. The discounted value of curtailment in the Central scenario is 36 to 52% lower than the High DER scenario. Recent strong growth in rooftop solar PV deployment has made the High DER scenario more likely in the short term. However, we cannot define the probability of each scenario in the long run.

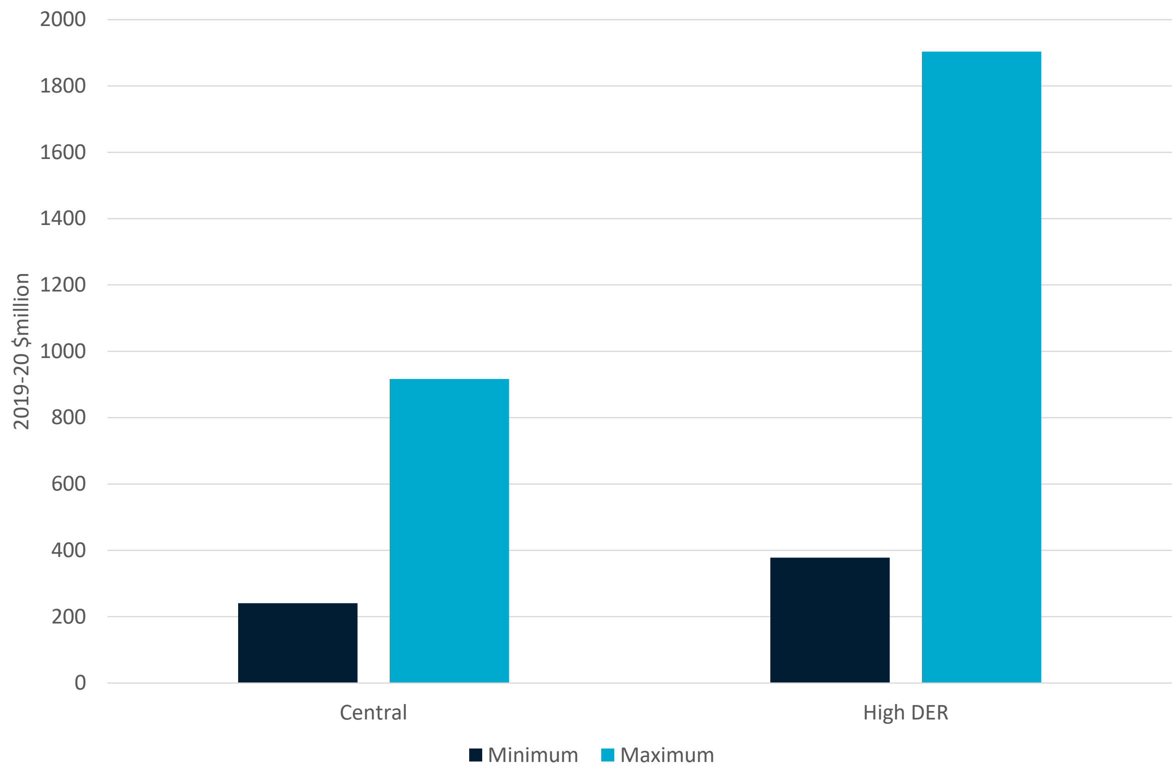


Figure 10-7 Projected range for the value of curtailed rooftop solar PV generation in the NEM under the AEMO Central and High DER scenarios

10.3 Analysis of vehicle to grid and hosting capacity

The avoided total costs method will be applied to determine the degree to which large-scale battery costs are avoided by allowing the full power capacity of V2G participating electric vehicles to be available to perform similar services to large-scale batteries. The key data and assumptions are as follows:

- Participating vehicles have 50% availability (i.e. they are connected to the grid 50% of the time on average across the V2G fleet for the times when battery capacity is needed)
- Based on our examination of typical vehicle ranges and charger capacities and assuming a depth of discharge no lower than 50% then V2G battery duration is around 8 hours
- Avoided large-scale battery capital costs are those published in the GenCost 2020-21 consultation report for 8 hours batteries [71]
- Electric vehicle adoption is taken from the Step Change scenario [70] with an assumption that 30% of vehicles participate by 2050 starting from 1% in 2030.

- Without further expansion of hosting capacity, EVs can only contribute 5kW of their power rating on discharge. Increased hosting capacity allows for an additional 2kW of V2G battery capacity to be available to the NEM
- A discount rate of 5.99% consistent with the AEMO Input and Assumptions Workbook (July 2020)

Based on these assumptions the increased storage capacity available from increasing hosting capacity available to V2G participants is 6.8GW by 2050. Summing up the discounted values to 2050, we find the benefit of increased hosting capacity through avoided large-scale battery costs is $2.3 billion. While this seems a large number, we would generally expect to spend between $500 and $1000 billion on new electricity generation and storage infrastructure between 2020 and 2050. Based on AEMO's published 2020 ISP modelling of the Step Change scenario, the system will require 23.3 GW of storage by 2042. Using [71] data, the cost of installing this storage capacity is estimated to be around $26 billion (undiscounted).

The major risk to realising the V2G benefits is that, given the slow start to electric vehicle uptake in Australia and accelerating deployment of renewables, substantial quantities of large-scale battery storage may be constructed before V2G may begin to compete as an alternative source of storage. Roll out of bidirectional capable chargers may also be delayed as well as the vehicles. Should this be the case we also considered a case where only half the vehicles were available in which case the benefit is reduced to $1.2 billion.

10.4 Sum of benefits

The benefits considered in the analysis presented here only considered two DER technologies and their impact on the generation sector. Combining the benefits estimated for rooftop solar PV and V2G batteries, this puts the benefits to the successful realisation of increased hosting capacity in the range of $1.4 to $4.2 billion by 2050 (NPV basis) for the generation sector in the National Electricity Market. Scaled up to a full, Australian-sized electricity system, the benefits could be $1.7 to $5.1 billion.

Some studies also confine themselves to the generation sector while others have considered both generation and network benefits.

Graham et al. (2019) [1] provided this summary of estimated benefits from three studies with and without network benefits

"the estimates for benefits are fairly wide ranging depending on the type of grid architecture chosen in the UK ENA Open Networks ranging from under $1 billion to over $5 billion by 2030. The two Australian studies are reasonably well aligned at just under $2 billion dollars by 2030 for ENTR or 2035 for SAPN. SAPN benefits are higher due to the extra five years despite the more limited DER integration. These data have been normalised to an Australia-sized electricity generation system.

By 2050, benefits are projected to increase to between $2 billion and $30 billion in NPV terms in the UK ENA Open Networks project when normalised to an Australia-sized electricity generation system…… The estimated benefits from the ENTR are just over $10 billion on an NPV basis"

An additional report that followed [1] was delivered by Baringa Partners [34] for the Australian Energy Market Operator and Energy Networks Australia. It found benefits to 2039 in the range of $2.5 to $6.5 billion with most benefits in the latter part of the period they studied. These are on a NEM basis and so could be scaled up by around 20% for an Australian level estimate to 2039.

10.5 Literature on costs of increasing hosting capacity

The cost of increasing hosting capacity can encompass many activities from expanding distribution infrastructure to managing existing resources in a way which increases the scope of existing infrastructure to accommodate DER operation. Management itself can be achieved through various levels of intervention from standards and incentives through to direct control.

There is a reticence to look to expanding distribution infrastructure. This reflects that Australia has experienced a period where distribution costs increased significantly through the 2010s and are the second largest component after wholesale costs (AEMC, 2020 [72]). Distribution costs are expected to moderate but appetite for augmentation expenditure remains low, particularly as costs to support DER integration raises issues of cost-sharing fairness for non-DER owners (although other work such as Mountain et al. (2018) [73] has pointed to DER contributing to moderating wholesale costs for all customers).

In this context, costing studies have tended to focus on better management of the system and of DER to realise system benefits. At the simplest level, distribution network service providers (DNSPs) could provide more dynamic signalling of hosting capacity constraints. This would not stop the limitations on DER operation associated with constrained periods but would mean DNSPs do not have to set static connection or export limits which unnecessarily limit operation during periods when the system is not constrained.

At the highest level, DER operation could be coordinated in real time with large scale generation and storage assets. Under such a scheme, the most cost competitive assets would be dispatched as part of a joint optimisation of the system. This requires a much more robust investment in both physical and institutional infrastructure. To understand what this range of costs might look like Graham et al. (2019) [1] reviewed studies by SAPN (2019) [2] and Baringa Partners (2019) [3]. It also included AEMO's organisational running costs as a ballpark estimate of the cost of running an additional Australian electricity market institution. The SAPN study represents an example of the simpler approach of dynamically signalling network constraints. The costs in that study only relate to South Australia but were scaled up to national levels for comparison purposes. The Baringa Partners study was commissioned by the UK Open Energy Networks project and has been adjusted for currency differences and UK electricity system scale. The discounted cost estimates are shown in Figure 10-8 for 2030 or 2035 and in Figure 10-9 for 2050.

The higher costs for SAPN, compared to the low range of UK ENA Open Networks, is because it includes five more years of cost data which is not insignificant. If we could trim those years, the SAPN costs would align more closely with the lower end of the UK ENA Open Networks estimates. The 2030 estimate based on current AEMO costs fit neatly within the centre of the range of UK ENA Open Networks estimates and are higher than SAPN costs (consistent with the additional costs of full integration).

The 2050 costs only include the UK ENA Open Networks project and the estimate based on current AEMO costs. These estimates are reasonably aligned with the AEMO based cost estimate sitting in between the low and high range provided by UK ENA Open Networks.

Graham et al. [1] concluded that, based solely on these available data, a reasonable estimate of the cost of DER integration for an Australia-sized electricity generation system might be $600 million to 2030 and $1 billion to 2050 on an NPV basis.

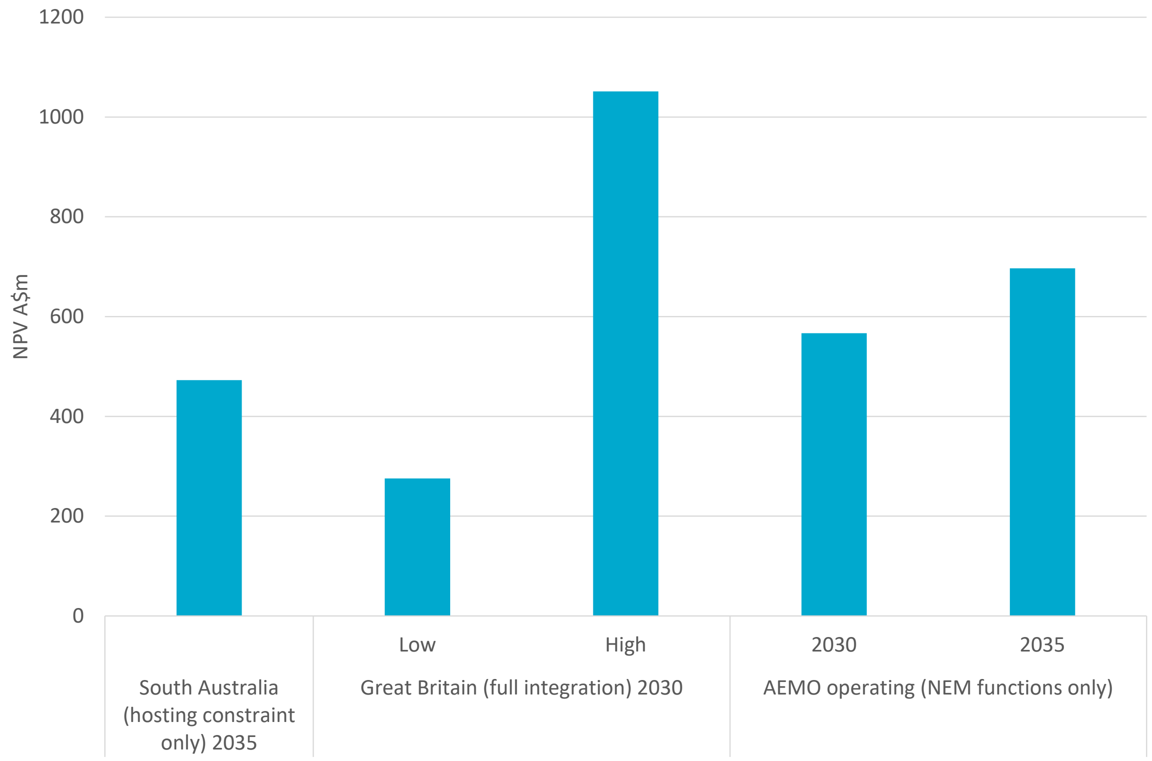


Figure 10-8 Estimates of the cost of DER integration (partial or full) to 2030 or 2035 normalised to an Australian-sized electricity generation system

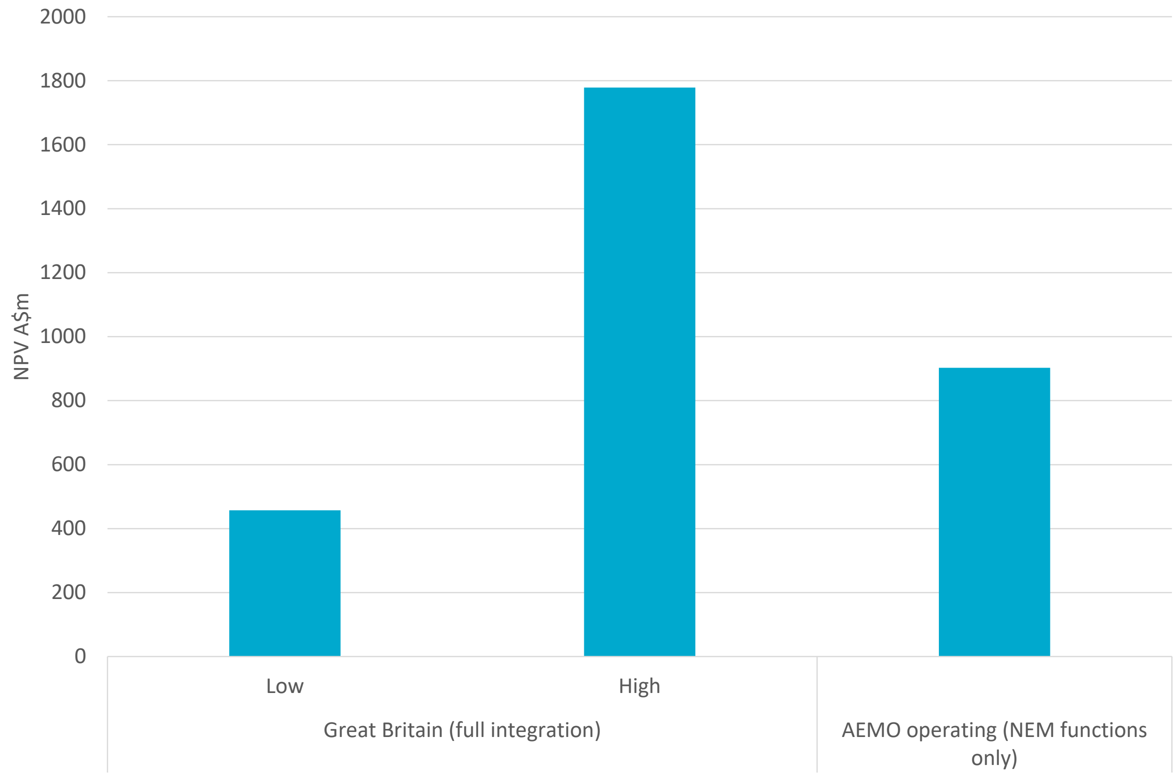


Figure 10-9 Estimates of the cost of DER integration to 2050 normalised to an Australian-sized electricity generation system

A Baringa Partners study [34] which was carried out after [1] was published finding higher costs of $2.5 to $3.5 billion to 2039 for high level DER integration systems (i.e. high level of management and control of DER technologies). These NEM cost estimates could equate to $3 to $4.2 billion when scaled up to include non-NEM regions.

An interesting finding of the Baringa study [34] was that the uncertainty in the monitoring costs and in the amount of DER was more important than the type of model chosen for implementing the high level management and control of DER technologies (several designs were costed).

10.6 Net benefits of increased hosting capacity

On a limited technology and electricity system basis, the analysis here finds benefits from increased hosting capacity of $1.7 to $5.1 billion by 2050 (NPV basis). Pre-2020 studies point to benefits as high as $30 billion for very high levels of DER integration. A Baringa Partners study of the whole electricity system [34] found benefits of $3.0 to $7.8 billion to 2039.

Graham et al. [1] indicated the costs of achieving increased hosting capacity to 2050 to be around $1.0 billion as a mid-point but costs for high level of integration as estimated by Baringa Partners [34] was $3 to $4.2 billion to 2039. This suggests potential benefits of $0.7 to $4.1 billion from the updated data in this report and 2019 cost data. Net benefits under the Baringa Partners study [34] was $0 to $3.6 billion. This is reasonably comparable when considered against the different time frame. The Baringa Partners study already notes that most benefits were towards the end of its projection period. Had it calculated benefits through to 2050 it would likely have exceeded those calculated in this study.

Table 10-1 Summary of estimated cost and benefits of increasing hosting capacity summary

Study	Costs	Benefits	Comments
Current study	-	$1.7b to $5.1b	Two DER technologies, generation sector only to 2050
Graham et al. 2019 [1]	$1.0b	$2.0b to $30.0b	All technologies, all sectors to 2050. From basic to high level of DER management
Baringa Partners 2020 [34]	$3.0b to $4.2b	$3.0b to $7.8b	All technologies, all sectors to 2039. High level of DER management

10.7 Limits to analysis and practical barriers

This analysis was designed to be a targeted update of key opportunities for benefits for increased hosting capacity. The narrowness of the scope has meant there is more work to do in terms of a definitive answer on this topic. However, even were the scope broader there are range of uncertainties and practical limits to overcome. We highlight the following issue for consideration in future studies

- It is difficult to understand how big the current problem of rooftop solar PV outages is due to lack of low voltage network visibility and confidentiality of customer data. (There is a circular problem in that a lack of network visibility frustrates a good approximation of benefits from greater DER integration, which itself relies upon greater network visibility. In other words, a lack of network visibility leads to opaque benefits for optimising DER integration, which leads to continued low funding to increase network visibility required to accurately assess benefits and identify the value of DER integration.)
- There is significant uncertainty about how electric vehicles will be integrated into the electricity system – where will they need to charge when away from the home, what will be the availability of bidirectional chargers.

- There is limited information on how well other distributed energy devices will participate in the electricity system. Specifically, it is difficult to identify the extent to which appliance manufacturers and installers are making their air conditioners, hot water systems, spa and pool pumps ready for seamless participation in wider electricity system goals.
- The prevalence of half hourly data may be insufficient resolution to understand whether inverter disconnects may over or understate the amount of curtailment.

Some suggested priorities for future work are:

- Coverage of more technologies than rooftop solar PV and V2G batteries
- Updated estimates for network sector benefits (this study only provided new insights for generation sector benefits, relying on older studies for network benefits)
- Further exploration of the driving factors of overvoltage on system strength curtailment to better understand the range of results
- Gathering of data on the prevalence of current settings and future intentions around connection curtailment and regulatory constraints
- Understanding the range of inverter disconnection events to better quantify the level of curtailment, full or partial and length of time.
- Considering additional impacts of high voltage events beyond solar production outages such as energy losses and shorter lifespan of consumer equipment.

Appendices

A.1 Projects and Trials Reviewed

In recent years, several projects have been developed to investigate different use cases relevant to network visibility and DER integration, and this section provides a review of such projects. These projects are examples of network operation and network planning use cases. In these projects data is used to enable better management of generation and demand and support the further integration of intermittent renewables and DER, either through the identification and dynamic response to power quality issues or the coordination of DER to relieve local network constraints. Each project is an example of application of data and analytics to improve network visibility and facilitate DER integration. These projects are investigated to answer three essential questions:

- What data is required as the input?
- What are the employed technologies to collect the required data?
- What are the key findings and limitation in each project?
- More details about these projects can be found in Appendix 0.

Project: Distributed Energy Resources Hosting Capacity Study

This project aims to establish a replicable methodology to assess the hosting capacity of LV networks. The objective is to assess the techno-economic performance of potential measures to increase the hosting capacity in future.

Input data/employed technologies:

The hosting capacity is calculated using geospatial and topological Geographic Information System (GIS) data, including customer and asset locations, conductor types and asset connection graphs. Customer AMI data is used for historical customer load profiles and historical voltage levels. Moreover, PV capacity, solar irradiance, and air temperature are used as other required data for the hosting capacity calculation.

Key findings:

This project is focusing only on LV networks and does not capture the interaction with upstream HV networks. Therefore, potential technical issues on upstream HV networks and also on LV networks might be missed, thus potentially leading to over or underestimations of Hosting Capacity.

- Network Topologies were built manually using geospatial and geographic information.

- Phase unbalance has not been precisely incorporated since the customer's phase allocation is not correctly known.
- Capturing the variability between CPPAL's LV networks and representing the operation of certain network assets are other anticipated challenges of establishing hosting capacity.

Project: Advanced Planning of PV-Rich Distribution Networks Study

This project aims to develop analytical techniques to rapidly assess residential solar PV hosting capacity of electricity distribution networks by leveraging existing network and customer data. Additionally, the project aims to provide recommendations to increase hosting capacity using non-traditional solutions that exploit the capabilities of PV inverters, voltage regulation devices, and battery energy storage systems.

Input data/employed technologies:

Smart meter demand data (provided from smart meters, hybrid; produced based on provided data) plays an important role in the developed methodologies in this project. Moreover, solar PV irradiance, penetration/forecast, panel and inverter size are considered in designing the dynamic capacity constraints. HV network models - (three-phase modelling, integrating HV (e.g., 22 kV) and LV (400 V)) are employed to realistically capture the corresponding interactions. The LV networks are modelled based on Australian electrical distribution substation standards and design manuals. LV networks are modelled based on the number of customers (i.e., either provided or estimated) per distribution transformer and LV design principles.

Key findings:

- Smart Meter data are not yet available for each of the selected feeders, hence demand profiles used in a previous project "AusNet Mini Grid Clusters" were considered in this project to demonstrate the behaviour of the feeders.
- For HV feeders the input data included topologies, impedances, phase connections, tap ranges, elements connected (i.e., SWER transformers, capacitors, voltage regulators) and number of customers for several distribution transformers.
- Rural networks with long high impedance lines present a challenge for increasing hosting capacity.

Project: Advanced VPP grid integration project

The aim of this project is to explore the potential of dynamic capacity constraints to increase VPP DER export limits. The dynamic capacity constraints are proposed to increase the capacity of the network to host VPP DER and to release value to VPP DER aggregators and DER owners.

Input data/employed technologies:

The VPP uses DER registration data including location, capabilities and control affiliations of the DER, as well as DER monitoring data including site real power (5-minute average, minimum and maximum), battery terminal voltage (5-minute average, minimum and maximum), and battery state of charge (instantaneous). The Project has implemented an interface (API) to exchange real-time and locational data on distribution network constraints ('operating envelopes') between SA Power Networks and the Tesla South Australian VPP, enabling the VPP to optimise its output to make use of available network capacity.

Key findings:

- A constraint engine that estimates the latent network capacity that can be made available to each VPP site at any given time. The constraint engine is based on a prototypical network modelling approach, where detailed modelling of a small subset of representative network sections are used to estimate the hosting capacity of the entire network.
- Due to privacy concerns, a mixture of synthetic load profiles based on customers real data is employed.
- SAPN constraint engine is able to provide an average daily capacity curve per month of the year, without incorporating real-time weather data and real-time voltage and load data to produce daily forecasts of network capacity.

Project: Increasing Visibility of Distribution Networks

The main objective of this project is to demonstrate the technical feasibility of Distribution System State Estimation (DSSE) using existing data. A semi-automated PV connection assessment tool is developed to support Distribution Network Service Providers (DNSPs) to use the full network visibility the DSSE provides to assess operational conditions more accurately in their network and identify further PV export capabilities where possible.

Input data/employed technologies:

This project employs aggregated customer measurements, including half hourly average active and reactive power. Also, five-minute voltage measurements from smart meter customers located closest to the distribution transformers are used in the DSSE. Real-time observation on two Energex 11 kV feeders, network model and customer static data are the other information used to design the PV connection assessment tool.

Key findings:

- The state estimation method is developed for MV networks. Data privacy can become an issue when expanding the use of state estimation into Low Voltage

networks, where data of individual customers might be required, or in sparsely populated areas where distribution transformers might supply single customers.
- The PV assessment tool is not able to set the power factor.

Project: evolve DER project

This project is focused on increasing the network hosting capacity of DER to maximise their participation in energy, ancillary and network service markets, while ensuring the secure technical limits of the electricity networks are not breached. This will be achieved through the calculation and publication of operating envelopes for all DER connected to the distribution network. Operating envelopes can address multiple use cases including challenges currently being faced in both electricity distribution networks and at the whole of system level.

Input data/employed technologies:

The network hosting capacity calculation requires detailed information about the electricity network assets, historical and real time measurement data for power and voltage in different parts of the network, historical and forecast weather data, energy data from individual consumers, and data exported from GIS. DNSPs will supply data about their electrical networks from their GIS and ADMS and via their own telemetry via SCADA and AMI systems. Aggregators will be responsible for sourcing and supplying DER data. The supply of this data will be via the evolve API (based on the IEEE 2030.5 protocol).

Key findings:

- The evolve framework ingests the relevant network and DER data and then makes this available for analysis in a standards-based form.
- Uses some form of state estimation to approximate the initial operating state of the network
- In modelling the nodal power injections and branch power flows, it is assumed that they are constant real and reactive power over the time interval (typically 5 or 30 minutes).
- Network visibility is a key requirement for the implementation of dynamic operating envelopes.
- Complementary approaches to increase network visibility:
    - Enhanced network monitoring
    - Using alternate or additional data sources
    - Implementing state estimation techniques

Project: UNSW Addressing Barriers to Efficient Renewable Integration

This project's objective is to identify and address the roadblocks to having high degrees of renewable energy deployment related to system integration. The response of a range of photovoltaics (PV) and storage inverters will be tested to disturbances of different kinds on the network. Results from this will provide detailed information that can be used to develop a "composite PV-load model".

Input data/employed technologies:

To test the response of PV inverters a suitable root mean square-type DER model is needed, i.e., DER_A. Also, inverter type should be compliant with standards**.** High-speed disturbance recorders on key distribution network feeders (PMU, PQM). The generic composite load proposed by Western Electricity Coordinating Council (WECC) has been used. A computational tool to estimate and tune the composite PV-load model parameters has been devised.

Key findings:

- *"Our attempts at understanding inverter behaviours based on grid incidents using combinations of high-frequency data, Solar Analytics data, and bench testing is improving but needs more time, 'deeper' inverter testing, and better visibility of the network (more measurement nodes and higher sample rates)."*
- This project is related to "National Low-Voltage Feeder Taxonomy Study: this project aims to create detailed models of the low voltage distribution networks. This is useful for the project "UNSW Addressing Barriers to Efficient Renewable Integration" as it investigates effects of transmission disturbances on the distribution grids, requiring accurate models of low voltage grids."
- A future work of the project is to find a solution to tune the 'dynamic' parameters, i.e., time constants, based on the outcomes of the inverter test benchmarking.

Project: AGL Virtual Power Plant

The AGL Virtual Power Plant (VPP) is a world-leading prototype of a VPP created by installing and connecting behind the meter (BTM) solar battery storage systems across 1000 residential premises in Adelaide, to be managed by a cloud-based control system.

Input data/employed technologies:

The VPP has 100% smart meter penetration. Each hardware vendor system has its own proprietary API communication system – this reflects the maturity of the VPP industry currently. AGL are utilising Enbala (VPP software provider) to deliver consistent control capability across the whole of the mixed vendor fleet.

Key findings:

- Whilst the need for DNSP site export limits is understood, this trial raises a further question regarding battery inverter capacity limits.

- Demonstrates the value that grid-connected batteries can create for a range of stakeholders when managed as part of a coordinated program.
- Local network voltage is a key factor in the performance of the overall fleet.

Project: SA Power Networks Closed Loop Voltage Control Trial

The project is establishing voltage control techniques at SA Power Networks' zone substations to boost network hosting capacity and provide demand response services. A key goal is to determine whether closed-loop substation voltage control, which has been demonstrated successfully in Victoria, can be achieved in other states without access to ubiquitous smart meter data. Demonstrating how network visibility can be enhanced by combining data from a variety of distributed data sources with data science, providing significant opportunities to optimise DER integration and customer experience.

Input data/employed technologies:

This project utilises sparse smart meter data, retailer smart meters, smart streetlights, grid-side monitors, and customer inverters. Moreover, third-party devices (e.g., the Solar Analytics home energy monitor) and weather data along with the use of data science methods are used to produce a rolling forecast of customer voltages. Smart meter voltages in real-time are estimated by modelling the relationship between SCADA and weather in the historic data. The network topology is extracted from PSS/Sincal. A standard API is employed to receive monitoring data from a variety of devices.

Key findings:

- The method relies on a high level of visibility of customer voltages in the area, which can vary significantly and dynamically due to the intervening network topology, distribution of customer loads and DER and weather.
- Victorian DNSPs have successfully demonstrated this method using AMI smart meters to monitor customer voltage. Outside of Victoria, the Power of Choice smart meter roll out means that smart meter penetration remains low and the meter data available to networks is sparsely distributed and of variable quality, availability and cost.
- The key innovation in this project is to determine whether closed loop voltage control can be achieved without access to ubiquitous smart meter data, by combining a variety of different data sources including retailer smart meters, smart streetlights, grid-side monitors, customer inverters, third-party devices (e.g. the Solar Analytics home energy monitor) and weather data along with the use of data science to produce a rolling forecast of customer voltages.

Project: Decentralised Energy Exchange (dex)

Decentralised Energy Exchange (dex) is a digital platform that enables electricity grids to support more renewables, handling the growing increase in rooftop solar, electric vehicles and DER. It provides DNSPs with the capability to manage the impacts of DER on their networks.

Input data/employed technologies:

Measured real-time information about the DER and its present operation, including DER output or consumption of active and reactive power (kW, V, A), grid measurements (voltage, frequency) and DER status (state of charge) are visible in deX visibility. Also, non-measurable information, which is not updated frequently including NMI, DER specifications (e.g., electrical characteristics, technical characteristics and settings) are visible in deX. deX visibility provides (DNSPs) and system operators with visibility of the location, performance and technical characteristics of DER (including historical, present and future operational behaviour) as well as contractual parameters. Information such as dispatch events, site load and solar PV generation data can be viewed and reported on via this visibility tool. deX mediation allows system operators to intervene in market dispatch and prevent DER operation from causing the power system to exceed its technical limits. Customer (DER owner) permissions and API communications pathway are employed for telemetry from deX integrated device to vendor cloud to deX and from deX to other systems (such as networks).

Key findings:

- Increases network hosting capacity in two ways: Firstly, by enabling smoother DER integration (one integration can then enable communication with multiple networks), providing a pathway for improved DER visibility for networks. Secondly, by deploying the concept of 'Dynamic Connection Agreements' to target a key issue for networks and customers: customer consent for DER management and network changes to export limitations, enabling higher export in exchange for customer consent to support the grid at specified times.

Project: Simply Energy VPPX

The Simply Energy VPP project will employ a centrally managed network of energy storage systems installed behind the meter that can be collectively controlled to deliver benefits to households and the local community. The project will develop the GreenSync decentralised energy exchange or "deX" platform to a commercial scale. The innovative deX platform will provide an energy marketplace that changes the way electricity is produced, used, stored and traded.

Input data/employed technologies:

The types of data identified as important include

- Standing data – Technical: non-measurable information which is not updated frequently (typically with contract or DER changes). Examples include NMI, DER specifications (e.g., electrical characteristics, technical characteristics and settings). Currently visible in deX visibility.

- Standing data – Contractual: all contractual information where relevant to power system operations/planning (excluding commercially sensitive or person identifiable information). Examples include contract ID, connection agreement, contractual limits on DER capability.
- Measured real-time data: measured real-time information about the DER and its present operation. Examples include DER output or consumption of active and reactive power (kW, V, A), grid measurements (voltage, frequency) and DER status (state of charge). Currently visible in deX visibility.
- Forecast data: forecast behaviour of the DER, which could be due to decisions the DER is making itself (e.g., site optimisation) or from decisions of aggregators which have contractual control over some aspect of the DER. Examples include forecast output (voltage, current) and available capacity.
- deX Visibility interfaces with deX marketplace to obtain standing data for DERs in the Simply Energy VPPx within the SAPN network. This user interface allows the network operator to monitor DER activity along with other important information pertaining to the location of the DER on the network. Information such as dispatch events, site load and solar PV generation data can be viewed and reported on via this visibility tool.

Key findings:

- The main factor in influencing consumer uptake of residential home battery systems and participation in VPP programs is price. Or more specifically, the level of subsidy available to reduce the price of a battery storage system over its lifetime.
- Applying different levels of VPP benefit payments, based on the size of the energy storage system's inverter and reflecting the benefit of the battery type to a VPPs trading activities, is an effective way to drive uptake in preferred technology and tailor the composition of the VPP fleet.

Project: Demonstration of Three Dynamic Grid-Side Technologies

This project demonstrates how increasing the visibility of LV networks can help manage grid power and voltage fluctuations. A demonstration, at two LV network sites, of the potential of three dynamic grid-side technologies (phase switching devices, dynamic power compensation, grid battery with Virtual Synchronous Generator capability) for increasing network DER hosting capacity and improving LV network power quality. It provides an assessment of the technical performance and cost-effectiveness of these technologies in increasing DER hosting capacity and improving network power quality for the demonstration network sites.

Input data/employed technologies:

Locally measured data is utilised for decision making on dynamic phase switching, integrating with the SCADA system. Inputs for the network analysis include physical parameters of poles and wires to calculate impedances, unbalanced load flow, wireless communication between PSD controllers, historic demand profile of customers, and PV generation data. The customer phase switching can be planned day-ahead based on the load/generation forecast.

Key findings:

- The Battery element of this project differs from other grid-side battery and community battery projects because it has a specific focus on increasing DER hosting capacity. The energy in the battery is not traded in the retail market.
- It is concluded that a more balanced network via optimal control of PSDs can increase hosting capacity.

Project: Consumer Energy Systems Providing Cost-Effective Grid Support (CONSORT)

The project objective is the orchestration of household batteries to obey and even alleviate distribution voltage and congestion constraints, making use of Reposit Power home energy management systems. It demonstrates how battery coordination can increase hosting capacity by taking network constraints into account.

Input data/employed technologies:

A full three phase model of the network is needed to solve a multi period optimal power flow problem. The Reposit Fleet software and API are used to monitor residential systems. The load prediction service takes as input recent SCADA data for the total cable import and diesel, recent participant data, and weather forecasts.

Key findings:

- The batteries and orchestration algorithm were able to deliver a 33% reduction in diesel and completely avoid all diesel generation on one network peak.
- In some cases, customer phasing was unknown and needed to be randomly assigned.
- Scaling to larger numbers of participants and networks, and understanding the overall integration with other parts of the power system including the wholesale market are introduced as two paths for future developments of the project.

Project: Dynamic Limits DER Feasibility Study

The project explored implementing dynamic operating envelopes for DER to better manage voltage and thermal constraints on electricity networks.

Input data/employed technologies:

The implementation of the Distributed Dynamic Limits (DDL) Control Scheme Control Scheme involves:

- The use of **network sensors** to measure the point of constraint. The network sensors are intelligent edge-controllers operating on an Industrial Internet of Things (IIoT) platform, which will measure the actual operating status of a network constraint location. The sensors may measure thermal constraints (current) on up-stream network assets, or voltage constraints (either upstream or end of line), or both.
- The DDL Control Scheme requires the use of an **Open Network Data Platform-ONDP**, which serves two functions. The first is to collect and store network sensor data and securely send this to authorised data subscribers. The second function is to enable DNSPs/DSOs to manage and administer the DER Controllers and Network Sensors and review the data they Generate.
- The third key component of the DDL Control Scheme is the use of a pre-assigned Dynamic Limit profile DLP.
- The final key component of the DDL Control Scheme is the use of intelligent edge controllers operating in an IIoT framework, which serve as local DER Controllers.
- The DDL Control Scheme uses network sensors at the point of constraint to measure and report the current operating state of the network at those critical locations, rather than applying network models and constraint engines to estimate the operating state.
- The DDL Control Scheme is less well suited to complex or dense metropolitan networks with automated switching, multiple network layout scenarios, and constraint locations that can move. However, these dense networks often have a high revenue base that can justify the costs to establish (and maintain as accurate) the relevant network models, alongside the physical sensors and telemetry needed to report the current network configuration.

Key findings:

- The key innovation from the project is the finding that, for rural and regional networks, the management of dynamic DER limits is best achieved when implemented at the lowest level of the control hierarchy.
- By decentralising the management of local network constraints, the control scheme is able to ensure that this control agenda is enforced, thus enabling orchestration agendas to occur without breaching the allowable network conditions.
- For rural, regional, and remote networks, the ability of the DDL Control Scheme to operate effectively without the need for network models is a major advantage.

- The use of network sensors located at network constraint locations (together with relevant DLPs) effectively side-steps the requirement of developing and maintaining network models prior to the scheme’s implementation for simple, radial networks (as discussed previously). Further, the network sensors are actively contributing to increasing the visibility of electricity networks. This improves what the Newport Review defines as Observability and what the OpEN Initiative outlines as a “least regret” capability.

Project: Indra Monash Smart City

This project objective is to demonstrate how smart and renewable technologies can be integrated at the Monash University Clayton embedded network to maintain power quality and test market driven responses and business models. The Monash Microgrid provides a realistic and useful platform for research into technological, business and customer behavioural features of the deployment of distributed resources and their coordination through microgrid operations. The microgrid system is intended to be a fully functioning local electricity network and trading market with dynamic optimization of resources interacting with an external energy market.

Input data/employed technologies:

The centralised components of the platform include AGM software modules (i.e., InGRID.MonitoringPortal, InGRID.OTS, InGRID.iPA, InGRID.DMS) that enable centralised data storage, as well as monitoring and control activities. InGRID.NODE#1 provides the logical infrastructure for AGM to connect with all relevant microgrid elements and collects data from meters, inverters and BAS. InGRID.iSPEED container provides real time communication services using the DDS (Data Distribution Service) standards. InGRID.OTS is a centralised component of the AGM system that will simulate the steady-state real-time behaviour of the Microgrid.iPowerAnalytics (iPA) is a centralised component of the AGM system that delivers the automatic, real-time execution of grid analytics, either scheduled or event-triggered.

Key findings:

- Transactive energy approaches enable the distributed control for DER coordination considering preferences of DER and network constraints.
- A challenge is how to model flexibility of flexible DER, particularly buildings with several flexible loads.
- DER can be coordinated to provide services for either local network management or responding to external requests.

Project: NOJA Power Intelligent Switchgear

This project aims to reduce the complexity and cost of connecting renewables to the grid and increase the hosting capacity of distribution networks by developing, demonstrating and industrialising an economical intelligent switchgear. This device can capture high-resolution real-time network data and can provide protection, control, and monitoring solutions to facilitate the connection of renewables to the grid. The Intelligent Switchgear and trial deployments will generate significantly more granular power system data than is currently available and will help improve the visibility and modelling of the power system.

Input data/employed technologies:

PMUs at the renewable connection points are the main source of the providing required data.

Key findings:

- This project is one of the first large scale MV deployment of synchrophasors in the world.
- The project contributes to reduction in the cost of connection and increasing the value delivered by renewable energy in Australia.
- It develops new protection, control and monitoring firmware to address renewable energy challenges and reduces barriers to renewable energy uptake.

Project: National low-voltage feeder taxonomy study

The project aims to produce the first national low voltage network taxonomy that outlines the real-world characteristics of the distribution system. It will provide improved data required to identify nationally representative consequences on the low-voltage power system of DER integration possibilities, supporting assessment of DER integration relevant design options.

Input data/employed technologies:

Data and information on the state of the low-voltage network are collected to develop a standard representation of low-voltage network characteristics for Australia, and a distributed energy resources model.

Project: Networks Renewed

This project investigates pathways to increase the amount of renewable energy in Australia by paving the way for small-scale solar photovoltaic (PV) and battery storage installations to improve the quality and reliability of electricity in Australia's distribution networks. Two demonstrations focussing on voltage management, recruited 90 customers in three locations across NSW and VIC under new commercial models for network-related businesses.

Input data/employed technologies:

It uses external data including weather, and NEM data, and network data including SCADA, and AMI DER data. Other required data includes customer preferences, customer load, generation, and voltage data, which are made available through the aggregation platforms.

Key findings:

- Proving realistic alternatives to network-side voltage solutions
- Integrating DER-based voltage support services into network operating practices
- Determining network value of DER-sourced voltage support.
- Obtaining good results for participating customers

Project: Horizon Power Carnarvon DER Trials

The project aims to conduct DER trails to resolve the technical, operational and transitional barriers to a high penetration DER future. The trials are conducted to explore economically efficient options for microgrid operation. The Carnarvon DER trials aim to experientially understand how to manage DER in a microgrid environment, how DER orchestration can be used to remediate power quality issues and how a system operator can effectively exchange DER value with customers.

Input data/employed technologies:

SCADA system monitors feeder parameters (voltage, current, reactive power, real power and frequency) for all medium -voltage feeders. AMI devices collect billing information (energy consumption) in addition to other network parameters, but the AMI meters are not time-synchronised with one another, and the sample rate varies between 5 and 15 minutes. To overcome the limitations of using AMI devices for project-specific data acquisition, Wattwatchers (WWs) are installed as the monitoring infrastructure on a sample of distributed PV systems capturing more than half of the aggregated output of all PV systems in Carnarvon. Data from WWs is used to extract the required parameters for calculating hosting capacity. These parameters are the output fluctuation factor, diversity factor and fluctuation factor. Solar Analytics solar smart monitors (rebadged Wattwatchers) are used to separately meter customer solar PV system production and network load every five seconds. The Horizon Power monitoring system monitors and provides environmental data.

Key findings:

- Data collection from customers required a bespoke contract which each participant was required to sign as they were on boarded into the trials.

- The most impactful knowledge gap is customer understanding of energy storage options.

Project: Enhanced Load Modelling

This project aims to find what new information is required and how that information should be used to improve load modeling, while being aware that there is a trade-off between modeling accuracy and the effort to acquire/process those data. The project focuses on practical and efficient methods to leverage data from AMI and other measurement sensors for improved distribution system load modeling.

Input data/employed technologies:

Four methods of modelling loads and PV systems were proposed with only requiring monthly customer net energy measurements and annual feeder head SCADA net current measurements. These methods were analysed on the modified EPRI Ckt5 distribution feeder with high PV penetration. Five cases of load modelling approaches with different level of visibility of load and PV generation are considered. Depending on the model, the required data includes:

- Customer measurement for load allocation (Net metering/approximated native load)
- Feeder head measurement for load allocation (Net phase current at feeder head/ approximated native current at feeder head)
- Reactive power load modelling (AMI data/computed from measurements)
- PV system modelling (AMI data/ PV systems following a time-series profile**)**

Key findings:

Four different analysed time granularities (60-min, 15-min, 5-min, and 1-min) showed variation in the quasi-static time-series load flow-simulated minimum voltages up to 2.0% for secondary circuit buses and 0.5% for primary circuit buses. Depending on the distribution time-series analysis of interest, distribution engineers may want to increase/decrease the granularity of the input data. Modelling loads with net-metering data while also modelling PV systems leads to double counting the feeder PV generation and thus, considerably over-estimating PV impacts. Modelling loads with net-metering data without modelling PV systems can reasonably well represent the current (historical) feeder conditions. However, this approach under-estimates PV impacts particularly at the low-voltage secondary circuits.

No.	Project	Objective	Involved stakeholders?	Input data			Data-driven	Requires model?	Requires smart meter?	MV network data?	Notes
				Data source / technology	**Data ownership**	**Data access**					
1	Distributed Energy Resources Hosting Capacity Study	1. Establish a replicable methodology to assess the hosting capacity of LV networks 2. Assess the techno-economic performance of potential measures to increase hosting capacity in the future.	**Lead Organisation** Powercor Australia Ltd **Project Partners** ENEA Australia	1. Using geospatial and topological Geographic Information System (GIS) data, including customer and asset locations, conductor types and asset connection graphs 2. Using customer AMI data for historical customer load profiles and historical voltage levels 3. PV capacity, solar irradiance, air temperature	CPPAL (DNSP)	DNSP		✓	✓		
2	Advanced Planning of PV-Rich Distribution Networks Study	1. To develop analytical techniques to rapidly assess residential solar PV hosting capacity of electricity distribution networks by leveraging existing network and customer Data. 2. Additionally, planning recommendations to increase the hosting capacity using Non-traditional solutions that exploit the capabilities of PV inverters, voltage regulation devices, and battery energy storage systems.	**Lead Organisation** University of Melbourne **Project Partners** Ausnet	1. Smart meter demand data (provided from smart meters, hybrid; produced based on provided data) 2. Solar PV Irradiance, penetration/forecast, Panel and inverter size 3. HV Network model *- (three-phase modelling, integrating HV (e.g., 22 kV) and LV (400 V)) to realistically capture the corresponding interactions.*	Ausnet (DNSP)	DNSP		✓	✓		1. PSS Sincal Model for each selected HV Feeder. These models correspond to the databases (.mdb format) used by the software PSS Sincal and contain all the details for each feeder (i.e., conductor details, connections, capacitors, regulators, transformers etc.) 2. Distribution Substations Information. These files (.xlsx format) correspond to the details of the distribution substations (i.e., Substation ID, Substation Name, Substation Number, Transformer Size and Connected Phases, number of customers, number of customers with solar PV) connected in each HV feeder. Given that this information is not included in the PSS Sincal models it will help realistically model the LV networks. 3. AMS – Electricity Distribution Network: Subtransmission Line and Station Data for Planning Purposes (Number AMS 20-24). 4. AMS – Distribution Network Planning

											Standards and Guidelines (Number AMS 20-16). 5. Specification for Pole Mounted Distribution Transformers (ENA DOC 007-2016). Given that LV network models are not readily available from AusNet Services, LV networks are modelled based on the number of customers (i.e., either provided or estimated) per distribution transformer and LV design principles, as specified by the industry
3	Advanced VPP grid integration project	1. To explore the potential of dynamic capacity constraints to increase VPP DER export limits 2. To increase the capacity of the network to host VPP DER 3. To release value to VPP DER aggregators.	**Lead Organisation** SA Power Networks **Project Partners** Tesla, CSIRO	1. DER registration: location, capabilities and control affiliations of the DER 2. DER monitoring: Site real power (5-minute average, minimum and maximum), Battery terminal voltage (5-minute average, minimum and maximum), Battery State of charge (instantaneous)	VPP Owner (SAPN)	**?**		✓	✓		The Project has implemented an interface (API) to exchange real-time and locational data on distribution network constraints ('operating envelopes') between SA Power Networks and the Tesla South Australian VPP, enabling the VPP to optimise its output to make use of available network capacity. SAPN receives telemetry from all Tesla VPP batteries via the API
4	Increasing Visibility of Distribution Networks	1. To demonstrate the technical feasibility of Distribution System State Estimation (DSSE) using existing data 2. Developing a semi-automated PV connection assessment tool to support Distribution Network Service Providers (DNSPs) to use the full network visibility the DSSE provides to assess operational conditions more accurately in their network and identify further PV export capabilities where possible.	**Lead Organisation** University of Queensland **Project Partners** Queensland University of Technology, Australian Power Institute, Energy Networks Australia, TasNetworks United Energy, Energex Part of the Energy Queensland Group, Aurecon, Redback Technologies, Springfield City Group	1. Aggregated Customer Measurements: - Half hourly average P and Q - Five-minute voltage measurements from smart meter customers, located closest to the distribution transformers 2. Network model 3. Customer static data 4. Real-time observation on two Energex 11 kV feeders	DNSP (most Australian DNSPs are likely to have sufficient existing data to use DSSE)	**DNSP**	?	✓		✓	Using transformer monitor data to set broad PV export limits
5	evolve DER project	1. Increase the network hosting capacity of distributed energy	**Lead Organisation** Zeppelin Bend Pty Ltd **Project Partners**	1. Detailed information about the electricity network assets	**?**	**?**		✓	?		- Aggregators will be responsible for sourcing and supplying DER data. The

		resources (DER) by maximising their participation in energy, ancillary and network service markets, while ensuring the secure technical limits of the electricity networks are not breached.	The ANU, Energy Queensland, Ergon Energy, Energex, Essential Energy, Endeavour Energy, Ausgrid, Reposit Power, Evergen, Redback Technologies, SwitchDin, NSW Government	2. Historical and real time measurement data for power and voltage in different parts of the network 3. Historical and forecast weather data 4. Energy data from individual consumers 5. Data exported from GIS							supply of this data will be via the evolve API (based on the IEEE 2030.5 protocol). - DNSPs will supply data about their electrical networks from their GIS and ADMS and via their own telemetry via SCADA and AMI systems.
6	UNSW Addressing Barriers to Efficient Renewable Integration	1. To identify and address the roadblocks to having high degrees of renewable energy deployment related to system integration. 2. The response of a range of photovoltaics (PV) and storage inverters will be tested to disturbances of different kinds on the network. Results from this will provide detailed information that can be used to develop a "composite PV-load model".	**Lead Organisation** UNSW **Project Partners** AEMO, ElectraNet, TasNetworks	1. a suitable RMS type DER model is selected, i.e., DER_A 2. high-speed disturbance recorders on key distribution network feeders (PMU, PQM) 3. Inverter type (compliance with standards)	**?**	**?**					
7	AGL Virtual Power Plant	1. The AGL Virtual Power Plant (VPP) is a world-leading prototype of a VPP created by installing and connecting behind the meter (BTM) solar battery storage systems across 1000 residential premises in Adelaide, to be managed by a cloud-based control system	**Lead Organisation** AGL Energy Limited **Project Partners** None	1. 100% smart meter penetration	**?**	**?**		?	✓		- Each hardware vendor system has its own proprietary API communication system – this reflects the maturity of the VPP industry currently. - AGL are utilising Enbala (VPP software provider) to deliver consistent control capability across the whole of the mixed vendor fleet.

8	SA Power Networks Closed Loop Voltage Control Trial	1. The project is establishing voltage control techniques at SA Power Networks' zone substations to boost network hosting capacity and provide demand response services. A key goal is to determine whether closed-loop substation voltage control, which has been demonstrated successfully in Victoria, can be achieved in other states without access to ubiquitous smart meter data. 2. Demonstrating how network visibility can be enhanced by combining data from a variety of distributed data sources with data science, providing significant opportunities to optimise DER integration and customer experience.	**Lead Organisation** SA Power Networks **Project Partners** FutureGrid (high performance data platform), CSIRO (data science, research and knowledge sharing), SA Government (funding partner)	1. Sparse smart meter data retailer smart meters, smart streetlights, grid-side monitors, customer inverters, 2. third-party devices (e.g. the Solar Analytics home energy monitor) and weather data along with the use of data science to produce a rolling forecast of customer voltages. 2. SCADA Voltage and power measurements (real time) 3. Network topology **(**Extracting network model from PSS/Sincal**)** 4. Temperature and solar irradiance	DNSP (smart meter data purchase d from providers)	DNSP. Project partners for R&D (data extracts)	✓	✓	✓	✓	- Data science used to forecast customer voltage histograms from sparse and imperfect historical data - Weather and MV SCADA data used with (imperfect) MV network connectivity model to estimate network state and provide OLTC substation setpoint recommendations. - Use of standard API to receive monitoring data from a variety of devices - Smart meter voltages in real-time are estimated by modelling the relationship between voltage, SCADA, and weather in the historic data.
9	Decentralised Energy Exchange (dex)	1. A digital platform that enables electricity grids to support more renewables, handling the growing increase in rooftop solar, electric vehicles and DERs 2. Provides DNSPs with the capability to manage the impacts of DER on their networks.	**Lead Organisation** GreenSync **Project Partners** United Energy Distribution Pty Limited, The Australian National University, Mojo Power, ACT Environment and Planning Directorate, DELWP (Victoria), ActewAGL Distributio n	1. Measured real-time information about the DER and its present operation, including DER output or consumption of active and reactive power (kW, V, A), grid measurements (voltage, frequency) and DER status (state of charge) are visible in deX visibility. 2. Also, non-measurable information which is not updated frequently including NMI, DER specifications (e.g. electrical characteristics, technical characteristics and settings) are visible in deX visibility.	**?**	**?**		✓	✓		- deX visibility provides (DNSPs) and system operators with visibility of the location, performance and technical characteristics of DER (including historical, present and future operational behaviour) as well as contractual parameters. Information such as dispatch events, site load and solar PV generation data can be viewed and reported on via this visibility tool. - deX mediation allows system operators to intervene in market dispatch and prevent DER operation from causing the power system to exceed its technical limits.

10	Simply Energy VPPX	1. The Simply Energy Virtual Power Plant (VPP) project will employ a centrally managed network of energy storage systems installed behind the meter that can be collectively controlled to deliver benefits to households and the local community. 2. The project will develop the GreenSync decentralised energy exchange or "deX" platform to a commercial scale. The innovative deX platform will provide an energy marketplace that changes the way electricity is produced, used, stored and traded.	**Lead Organisation** Simply Energy **Project Partners** GreenSync, SAPN, AEMO, Tesla, Flextronics	The types of data identified as important include • Standing data – Technical: non-measurable information which is not updated frequently (typically with contract or DER changes). Examples include NMI, DER specifications (e.g. electrical characteristics, technical characteristics and settings). Currently visible in deX visibility. • Standing data – Contractual: all contractual information where relevant to power system operations/planning (excluding commercially sensitive or person identifiable information). Examples include contract ID, connection agreement, contractual limits on DER capability. • Measured real-time data: measured real-time information about the DER and its present operation. Examples include DER output or consumption of active and reactive power (kW, V, A), grid measurements (voltage, frequency) and DER status (state of charge). Currently visible in deX visibility. • Forecast data: forecast behaviour of the DER, which could be due to decisions the DER is making itself (e.g. site optimisation) or from decisions of aggregators which have contractual control over some aspect of the DER. Examples include forecast output (voltage, current) and available capacity	?	?		✓	✓		

11	Demonstration of Three Dynamic Grid-Side Technologies	1. Demonstrates how increasing the visibility of LV networks can help manage grid power and voltage fluctuations. 2. A demonstration, at two LV network sites, of the potential of three dynamic grid-side technologies (phase switching devices, dynamic power compensation, grid battery with Virtual Synchronous Generator capability) for increasing network DER hosting capacity and improving LV network power quality. 3. An assessment of the technical performance and cost-effectiveness of these technologies in increasing DER hosting capacity and improving network power quality for the demonstration network sites.	**Lead Organisation** Jemena **Project Partners** AusNet Services, University of NSW, State Grid International Development Co.	1. Locally measured data (??) is utilised for decision making on dynamic phase switching 2. Integration with SCADA system 3. Inputs for the network analysis: - Physical parameters of poles and wires to calculate impedances - Unbalanced load flow - wireless communication between PSD controllers - historic demand profile of customers -PV generation	**?**	**?**		✓			- The costumer phase switching can be planed day-ahead based on the load/generation forecast - They measure voltage and current unbalance (at transformer or customer??) - Through associated modelling and simulation, provide analysis and conclusions regarding the expected technical potential and cost-effectiveness of the technologies to increase DER hosting capacity of distribution networks more broadly, both for each individual technology and when two or more of the technologies are used together.
12	Consumer Energy Systems Providing Cost-Effective Grid Support (CONSORT)	1. Orchestration of household batteries to obey and even alleviate distribution voltage and congestion constraints, making use of Reposit Power home energy management systems.	**Lead Organisation** The Australian National University **Project Partners** TasNetworks, Reposit Power, The University of Sydney, University of Tasmania.	1. A full three phase model of the network 2. Use of Reposit Fleet software and API to monitor residential systems. -3. The load prediction service takes as input recent SCADA data for the total cable import and diesel, recent participant data, and weather forecasts.	**?**	**?**		✓			- The network aware coordination does not require detailed information about each participant and their DER. It needs just where they connect to the network and their expected power consumption at their network connection point. - Every 5 minutes the NAC is run to find the cheapest plan covering approximately 24 hours. - Solves a multi period optimal power flow problem.

13	Dynamic Limits DER Feasibility Study *	1. The project explored implementing dynamic operating envelopes for distributed energy resources (DER) to better manage voltage and thermal constraints on electricity networks.	**Lead Organisation** Dynamic Limits Pty Ltd **Project Partners** UniSA, SAGE Automation, Opto22	The implementation of the Distributed Dynamic Limits (DDL) Control Scheme Control Scheme involves: - The use of **network sensors** to measure the point of constraint. The network sensors are intelligent edge-controllers operating on an Industrial Internet of Things (IIoT) platform, which will measure the actual operating status of a network constraint location. The sensors may measure thermal constraints (current) on up-stream network assets, or voltage constraints (either upstream or end of line), or both. - The DDL Control Scheme requires the use of an **Open Network Data Platform-ONDP**, which serves two functions. The first is to collect and store network sensor data and securely send this to authorised data subscribers. The second function is to enable DNSPs/DSOs to manage and administer the DER Controllers and Network Sensors and review the data they Generate. -The third key component of the DDL Control Scheme is the use of a pre-assigned **Dynamic Limit profile DLP**. -The final key component of the DDL Control Scheme is the use of intelligent edge controllers operating in an IIoT framework, which serve as local DER Controllers.	**?**	**?**		✓			

14	Indra Monash Smart City	1. Demonstrates how smart and renewable technologies can be integrated at the Monash University Clayton embedded network to maintain power quality and test market driven responses and business models.	**Lead Organisation** Indra Australia Pty Limited	1. InGRID.NODE#1 provides the logical infrastructure for AGM to connect with all relevant microgrid elements. Collects data from meters, inverters and BAS 2. InGRID.iSPEED Container provides real time communication services using the DDS (Data Distribution Service) standards. 3. InGRID.OTS a centralised component of the AGM system that will simulate the steady-state real-time behaviour of the Microgrid. 4. iPowerAnalytics (iPA) is a centralized component of the AGM system that delivers the automatic, real-time execution of grid analytics, either scheduled or event-triggered.	**Monash University, Indra, DNSP**	**DNSP, Monash University, Indra**	✓	✓	✓		
15	NOJA Power Intelligent Switchgear	1. The Intelligent Switchgear and trial deployments will generate significantly more granular power system data than is currently available and will help improve the visibility and modelling of the power system.	**Lead Organisation** Noja Power **Project Partners** AEMO, AusNet Services Ltd, Energy Queensland Ltd, Deakin University, University of Queensland	PMU data at the renewable connection points	**Noja, DNPSs, Universities**	**?**	?	?	?	?	
16	National low-voltage feeder taxonomy study	1. The project aims to produce the first national low voltage network taxonomy that outlines the real-world characteristics of the distribution system. 2. It will provide improved data required to identify nationally representative consequences on the low-voltage power system of DER integration possibilities, supporting assessment of DER integration relevant design options	**Lead Organisation** CSIRO **Project Partners** Energy Networks Australia, Ausgrid, AusNet Electricity Services, Western Power, Endeavour Energy, Energy Queensland, Essential Energy, Horizon Power, SA Power Networks, TasNetwork		?	?	?	?	?	?	

17	Network Renewed	1. The demonstrations proved that both solar and batteries can support network voltage, using the real and reactive power capabilities of their inverters, providing realistic alternatives to network-side voltage solutions.	**Lead Organisation** University of Technology Sydney **Project Partners** Reposit Power, Essential Energy, AusNet Services, Australian PV Institute, United Energy	1. External Data: weather, NEM 2. Network data: SCADA, AMI DER data 3. Customer preferences Customer load, generation, and voltage data made available through the aggregation platforms	?	?		✓			
18	Horizon Power Carnarvon DER Trials	1. The project aims to conduct DER trails to resolve the technical, operational and transitional barriers to a high penetration DER future. 2. To experientially understand how to manage DER in a microgrid environment, how DER orchestration can be used to remediate power quality issues and how a system operator can effectively exchange DER value with customers.	**Lead Organisation** Horizon Power **Project Partners** Murdoch University	1. SCADA (voltage, current, reactive power, real power and frequency) 2. AMI data 3. Wattwatchers 4. The Horizon Power monitoring system monitors and provides environmental data.	DNSP	DNSP	✓		✓		

19	<u>Enhanced Load Modelling</u>	This project aims to find what new information is required and how that information should be used to improve load modeling, while being aware that there is a trade-off between modeling accuracy and the effort to acquire/process those data. The project focuses on practical and efficient methods to leverage data from AMI and other measurement sensors for improved distribution system load modeling.		1. Monthly customer net energy measurements 2. Annual feeder head SCADA net current measurements. Five cases of load modelling approaches with different level of visibility of load and PV generation are considered. Depending on the model, the required data includes: - Customer measurement for load allocation (Net metering/approximated native load) - Feeder head measurement for load allocation (Net phase current at feeder head/ approximated native current at feeder head) - Reactive power load modelling (AMI data/computed from measurements) - PV system modelling (AMI data/ PV systems following a time-series profile)					✓		- Four different analysed time granularities (60-min, 15-min, 5-min, and 1-min) showed variation in the quasi-static time-series load flow-simulated minimum voltages up to 2.0% for secondary circuit buses and 0.5% for primary circuit buses - Depending on the distribution time-series analysis of interest, distribution engineers may want to increase/decrease the granularity of the input data. - Modelling loads with net-metering data while also modelling PV systems leads to double counting the feeder PV generation and thus, considerably over-estimating PV impacts. - Modelling loads with net-metering data without modelling PV systems can reasonably well represent the current (historical) feeder conditions. However, this approach under-estimates PV impacts particularly at the low-voltage secondary circuits

A.2 Hosting capacity analysis (technical details)

Table A2-1: Feeder Metrics Mapped to Impact Factors [13]

Impact Factors			Feeder Metrics								
			Over-voltage	Under-voltage	Regulator Voltage Deviation	Voltage Deviation	Thermal Ratings	Reverse Power Flow	Protection Coordination	Unintentiona l Islanding	Operational Flexibility
EPRI Recommended Impact Factors	Grid Factors	Configuration	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Source Impedance	✓	✓	✓	✓	X	X	✓	X	✓
		Voltage Regulation	✓	✓	✓	X	X	X	X	X	✓
		Connected Load	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Connected DER	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Control-Autonomous	✓	✓	✓	✓	✓	✓	X	✓	✓
		Control-Managed	✓	✓	✓	✓	✓	✓	X	✓	✓
		Time	✓	✓	✓	✓	✓	✓	X	✓	✓
	DER Factors	Location–Site Specific	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Location-Distributed	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Technology-Output	✓	✓	✓	✓	X	X	X	X	✓
		Technology-Timing	✓	✓	✓	✓	✓	✓	X	✓	✓
		Technology-Interface	✓	✓	✓	✓	X	X	✓	✓	✓
		Portfolio	✓	✓	✓	✓	✓	✓	✓	✓	✓

Table A2-2. Relative Effect of Hosting Capacity Impact Factors [12]

Impact		Hosting capacity impact factor
DER	High	Location
	High	Type/Technology
	High	Communication and Control
	High	Aggregation
	Medium	Efficiency
	Low	Vendor
	Low	Plant layout
	Medium	Local weather patterns (renewables)
	Medium	Panel orientation (PV)
Distribution	High	Voltage control scheme
	High	Configuration
	High	Load
	High	Phasing
	Medium	Protection system design
	Medium	Granularity of MV models # of nodes
	High	Grounding practices
Ot he	High	Time

	Medium	Service transformers
	Medium	Service drops
	Low	Planning software
	Medium	Transmission constraints
	Medium	Transmission grid configuration/dispatch

Table A2-3. Evaluation Criteria Comparison [12]

Category	Criteria	Stochastic	Iterative	Streamlined	Hybrid
Voltage	Primary over-voltage	Y	Y	Y	Y
	Primary under-voltage	Y	Y	Y	Y
	Primary voltage deviation	Y	Y	Y	Y
	Regulator voltage deviation	Y	N	N	Y
	Secondary over-voltage	Y	N	N	N
Thermal	Charging DER (Demand)	N	Y	Y	Y
	Discharging DER (Generation)	Y	Y	Y	Y
Protection	Additional element fault current	Y	Y	Y	Y
	Sympathetic breaker relay tripping	Y	N	N	Y
	Breaker relay reduction of reach	Y	Y	Y	Y
	Reverse power flow	Y	Y	Y	Y
	Unintentional islanding	Y	Y	Y	Y

Table A2-4. DER Technology and Scenario Comparison [12]

Category	Criteria	Stochastic	Iterative	Streamlined	Hybrid
DER technologies	Solar	Y	Y	Y	Y
	Storage	N	Y	Y	Y
	Wind	N	Y	Y	Y
	Fuel cell	N	Y	Y	Y
	Synchronous	N	Y	Y	Y
	DER portfolios	N	Y	Y	N
DER scenarios	Three-phase, single site	N	Y	Y	Y
	Three-phase, distributed	Y	N	N	Y
	Single-phase, single site	N	N	N	N
	Single-phase, distributed	Y	N	N	Y

A.3 LV Mapping precedents reviewed

Name/ Jurisdiction	Link	Use Cases
Xcel Energy (Minneapolis, USA)	https://www.xcelenergy.com/working_with_us/how_to_interconnect/hosting_capacity_map	Hosting capacity for solar PV connections & interconnections
New York Utilities (USA)	https://jointutilitiesofny.org/utility-specific-pages/hosting-capacity/	Hosting capacity for solar PV connections & interconnections
California utilities (USA)	PG&E here. SCE Distributed Energy Resources Interconnection Map here. SDG&E by registering at this link.	Hosting capacity for solar PV connections & interconnections
Western Power (Aus)	https://www.westernpower.com.au/industry/calculators-tools/network-capacity-mapping-tool/	New load connections (TBC)

A.4 Terminology

Term	**Definition**
Dynamic Operating Envelope (DOE) *(DEIP Dynamic Operating Envelope Working Group)*	Operating envelopes represent the technical limits within which customers can import and export electricity. Dynamic operating envelopes vary import and export limits over time and location based on the available capacity of the local network or power system.
Export limits *(AER definition)*	Export limits represent the maximum amount of power that the individual consumer is allowed to export into the grid. This is typically measured in kW or kVA. The export limit is usually agreed when the consumer is seeking to connect a DER asset. Customers without an agreed export limit are assumed to have a default export limit of zero (0kW).
Hosting capacity	The real and reactive power contributions from DER that can be imported or exported into the electricity grid without breaching the physical or operational limits within a segment of an electricity distribution network
LV network visibility	The knowledge that a DNSP has of its network. Full network visibility is built upon three key capabilities: 1. Complete knowledge of the network topology and the electrical characteristics of the network. 2. Complete network monitoring. 3. Accurate forecasting capabilities for both individual and aggregate demand and generation sources
DER	Distributed Energy Resources (DER) are smaller-scale devices that can either use, generate or store electricity, and form a part of the local distribution system, serving homes and businesses. DER can include renewable generation such as rooftop solar photovoltaic (PV) systems, energy storage, electric vehicles (EVs), and technology to manage demand at a premises.
PV Penetration Level (%)	Sum of the rated output (kW) of all PV systems connected to a transformer as a percentage of the rated capacity of that transformer (kVA).
Mapping (pertaining to this scope)	The availability and presentation of LV data (obtained via the means outlined in N2a) to supply applications or "use cases" that require participation, knowledge or buy-in of stakeholders *outside* the network business. Primarily this will take the form of maps, given the inherently granular spatial nature of LV data, however other forms of data access, such as live API data streams – some of which will have a spatial component – will be considered.
(LV Data) Use Case	A description of the application of LV data by a specific set of user/s, in order to produce a specific result (or goal).
Virtual power plant (VPP)	AEMO definition: A VPP broadly refers to an aggregation of resources (such as decentralised generation, storage and controllable loads) coordinated to deliver services for power system operation and electricity markets. In Australia, grid connected VPPs are focused on coordinating rooftop photovoltaic (PV) systems, battery storage, and controllable load devices, such as air-conditioners or pool pumps, through the market. This is heavily integrated with AEMO's uplift of distributed energy resources (DER) performance standards development.

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