RACE for 2030 Fast Track Project

CANVAS: Curtailment and Network Voltage Analysis Study Draft Project Report

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Collaboration on Energy and Environmental Markets

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About CEEM

The UNSW Collaboration on Energy and Environmental Markets (CEEM) undertakes interdisciplinary research in the design, analysis and performance monitoring of energy and environmental markets and their associated policy frameworks. CEEM brings together UNSW researchers from the Faculty of Engineering, the Australian School of Business, the Faculty of Arts and Social Sciences, , the Faculty of Built Environment and the Faculty of Law, working alongside a number of Australian and International partners.

CEEM's research focuses on the challenges and opportunities of clean energy transition within market oriented electricity industries. Key aspects of this transition are the integration of large-scale renewable technologies and distributed energy technologies – generation, storage and 'smart' loads – into the electricity industry. Facilitating this integration requires appropriate spot, ancillary and forward wholesale electricity markets, retail markets, monopoly network regulation and broader energy and climate policies.

Distributed Energy Resources (DERs) are a vitally important set of technologies, and equally important stakeholders, for achieving low carbon energy transition, and CEEM has been exploring the opportunities and challenges they raise for the future electricity industry for over a decade. More details of this work can be found at the Centre website. We welcome comments, suggestions and corrections on this submission, and all our work in this area. Please feel free to contact Dr Baran Yildiz (CANVAS project lead) baran.yildiz@unsw.edu.au, Dr Anna Bruce (CEEM DER research program leader) a.bruce@unsw.edu.au, or Associate Professor Iain MacGill (Joint Director of the Collaboration) i.macgill@unsw.edu.au.

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Executive summary

Australia has world leading uptake of distributed energy resources (DER), including distributed Photovoltaic (D-PV) and battery energy storage systems (BESS). Recent reports estimate one in four households own DER and installation rates are anticipated to grow in the years ahead. DER can provide various economic and environmental benefits to energy users, network companies and other industry stakeholders. However, integrating increasing levels of DER into electricity networks present a range of social, technical, and regulatory challenges.

Voltage management in low voltage networks is one of the most imminent challenges posed by the integration of increasing levels of DER. Traditionally, in a network with uni-directional energy flow, distribution network service providers (DNSPs) set the LV voltages at the higher end of their allowed range to maintain reasonable voltages during periods of peak demand and hence voltage drop. However, as energy flows bi-directionally through the LV network with increasing levels of DER installations, DER exports can increase the local voltage range. To help DNSPs in managing network voltage effectively, it is increasingly required that inverter based DER implement one or more of the following power quality response modes (PQRM):

1. Tripping (anti-islanding and limits for sustained operation) on excessive voltages
2. Volt-VAr (V-VAr)
3. Volt-Watt (V-Watt)

The PQRMs effectively curtail power output which may limit opportunities and revenue that DER owners obtain from their investments. On the other hand, these modes can help with the management of voltage and therefore, support the integration of higher levels of DER.

The Curtailment and Network Voltage Analysis Scoping Study (CANVAS) is a RACE for 2030 scoping study conducted by the Collaboration on Energy and Environmental Markets at UNSW, with industry partners AGL, SA Power Networks (SAPN) and Solar Analytics. As a five-month scoping study, CANVAS's main motivation is to develop preliminary socio-technical insights to inform industry stakeholders and policy makers about the current state of DER curtailment due to PQRM requirements. CANVAS consists of two research streams, social science and technical, with both delivering evidence-based results that have important implications for Australia's fast growing and ever-changing energy landscape, where previous evidence-based results and studies have been limited.

The social science component involved focus groups and interviews which included 20 South Australian residential energy users, most of whom own a D-PV system. The discussions revealed that most of the participants have no prior knowledge or experience of DER curtailment. When the concept of curtailment was made clear to them, most found the concept of curtailment 'off-putting' and questioned whether D-PV owners should be made to bear any losses given the perceived benefits of D-PV helping the environment and energy sector. There was a broad appreciation of the potential for inequities in the distribution of the impacts of curtailment. Participants reflected on potential differences across geographies (urban vs rural households), the sizes of D-PV systems, periods of ownership (impact of feed-in tariffs on payback periods), energy retailers, types of D-PV owners (residential vs commercial), and even considered those who do not own solar systems. Participants also expressed concerns about potential misconceptions regarding curtailment and had a clear expectation for total transparency from installers, retailers and DNSPs regarding the issue. This was expressed in terms of the need for consumer education campaigns, clear clauses in contracts, notifications about curtailment events, and household-scale modelling of the likely impacts of curtailment on electricity bills. Participants also appreciated the benefits of having BESS which may potentially reduce curtailment loss. However, they also found the required investment to deploy BESS unaffordable and expressed the need for financial support to encourage adoption in the short-term.

The technical data analysis studied two datasets including 996 BESS sites from AGL's Virtual Power Plant (VPP) trial in metropolitan Adelaide and 500 D-PV sites from Solar Analytics' customer database in metropolitan Adelaide. The study focused on the first two PQRM modes: tripping (anti-islanding and limits for sustained operation) and Volt-VAr curtailment and did not analyse Volt-Watt mode. Volt-Watt mode is expected to cause more significant curtailment than the first two modes; therefore, the results presented in this report are likely to underestimate the extent of curtailment. Another important point is that the study captured a snapshot of the state of curtailment by using data from 2020 and as the integration of DER continues to grow, experienced curtailment will likely be higher in the future. It was found that tripping (anti-islanding and limits for sustained operation) and V-VAr curtailment was not significant for the majority of energy users. On average, the D-PV systems experienced around 13 kWh of curtailed generation per year (less than 1% of their total generation). BESS systems (excluding D-PV systems) experienced 5 kWh of curtailed generation per year (again less than 1% of total generation) by the first two studied PQRM modes. Although average curtailment per site was small, preliminary analysis estimated that the upscaled curtailed generation is in the order of 22 GWh/year with emissions impact of 16.5 mega-tonnes of CO_2-e across Australia.

For some energy users, curtailment was much more significant. This was evidenced in some users losing up to 20% of their total generation and thus highlights the issue of fairness in relation to curtailment. The discrepancy between the different levels of curtailment experienced amongst the energy users may be due to the location of the site within the low-voltage network, local D-PV penetration level, type of the network (rural vs. urban) or specifics of D-PV and BESS systems such as size, inverter settings and installation dates. These factors require further investigation in a future study, particularly inverter settings as it appears the most impacted sites may have had lower anti-islanding set points than specified in the standard, AS4777.2-2015. Besides investigating curtailment from the energy user's perspective, further analysis was carried out to assess potential curtailment losses from the VPP aggregator's perspective. As the average curtailed generation was low, the modelled VPP aggregator did not incur a high revenue loss. However, the analysis for the aggregator only considered BESS and did not include losses due to D-PV curtailment; therefore, the results presented here may underestimate the curtailment loss for the aggregator. Preliminary analysis estimated that aggregators with around 996 sites could incur total average losses of \$270 to \$1740/year and maximum losses of up to \$10k to \$35k/year under different scenario analyses.

The V-VAr analysis found that the majority of BESS and D-PV did not appear to operate according to the recommended V-VAr curves outlined by the current standards. Most BESS had legacy settings in place due to prior installation dates and therefore, were not mandated to show any V-VAr responses. However, some that have more recent settings appeared to show inconsistent V-VAr response which requires further investigation. Most of the D-PV inverters did not show any V-VAr response and operated at unity power factor (PF). Others showed different VAr and PF behaviour such that some increased PF with increasing real power and some others decreased PF with increasing levels of real power. As some D-PV systems absorbed significant VArs, V-VAr curtailment was found to be more significant for D-PV systems than BESS according to this preliminary analysis. Tripping (anti-islanding and limits for sustained operation) curtailment was a more significant issue for BESS compared to V-VAr based curtailment in our initial analysis. On the other hand, D-PV systems showed almost equal amounts of curtailed energy between tripping (anti-islanding and limits for sustained operation) and V-VAr.

The study also carried out a scenario analysis to assess the degree of potential V-VAr curtailment if all the analysed BESS and D-PV operated according to different V-VAr curves such as AS/NZS 4777-2015, TS-129, AS/NZS 4777-2020 and Energy Networks Australia (ENA) recommendations. Amongst the analysed scenarios, the ENA V-VAr curve resulted in the highest average curtailed energy followed by TS-129 and AS/NZS 4777-2020, both of which showed similar levels of curtailment. For BESS owners, average V-VAr curtailment increased with the analysed scenarios compared to the current case. For D-PV systems that operated at unity power factor, V-VAr curtailment was negligible. On the other hand, for some D-PV systems V-VAr curtailment was reduced if all D-PV responded according to one of the reference V-VAr curves instead of changing power factor as a function of real power. However, it is important to note that overall curtailment remained negligible for the majority of sites under all considered scenarios.

Due to the time constraints of the scoping study, V-Watt curtailment could not be investigated. This is an important limitation of the study as V-Watt response is anticipated to result in higher levels of DER curtailment than the other modes. Although the overall quantity of curtailment due to tripping (anti-islanding and limits for sustained operation) and V-VAr modes were small across most sites, growing levels of DER penetration will likely increase curtailment in the future. In addition, key questions remain regarding why certain sites are experiencing significant curtailment, and how rapidly this subset of heavily impacted sites might increase over time as DER penetrations increase. Some of the results of this study, especially the V-VAr behaviour of BESS and its associated curtailment, could benefit from further research and discussions with BESS original equipment manufacturers. Moreover, the applied methods for tripping (anti-islanding and limits for sustained operation) and V-VAr can be further improved, and metrics developed that could usefully be adopted by DNSPs to report on curtailment through regulatory processes. Alongside the analysis of real operational data, curtailment can also be investigated through network modelling, where the relationship between site location on a low-voltage network and curtailment can be further investigated. Ideally, measured data would be used to validate such modelling. A further contribution could involve developing an open-source curtailment tool that can be used to estimate DER curtailment for energy users; however, we note that this would require knowledge of voltages at energy user sites and further research and validation of the curtailment algorithms used in this study.

We aim to incorporate stakeholder feedback on this report and address these additional research objectives through a future RACE for 2030 standard track project. The CANVAS team is interested in discussing possible collaborations on a future project in this critically important area of DER integration and invite interested participants to contact the corresponding author.

1 Introduction

1.1 Project objectives and scope

Project CANVAS aims to develop socio-technical insights into energy user experiences of voltage related distributed energy resource (DER) curtailment. The project includes operational data analysis and user research in collaboration with AGL, Solar Analytics and SA Power Networks (SAPN).

Australia's world-leading uptake of DER can offer substantial value to energy users and industry stakeholders. However social, technical, regulatory and market integration challenges remain. Voltage management in the distribution network is the first, acute issue to emerge under high penetration DER. DNSPs are required to maintain voltage within an allowable range and historically, LV voltages have been 'set high' at the upper end of this allowed range to maintain reasonable voltages during periods of peak-demand, and hence voltage drop along the lines. However, the voltage range seen in Australian distribution networks is increasing with DER uptake.

Proponents of technical standards amendments have required DER inverters to assist DNSP management of voltage through automated power quality response modes (PQRM) including Volt-VAr (V-VAr) and Volt-Watt (V-Watt) response modes. In addition, inverters 'trip' (cease to operate) due to anti-islanding requirements and limits for sustained operation, and may also be required to abide by export limitations. Such modes are now a requirement for Australian systems although the specifics vary according to the Distribution Network Service Provider (DNSP).

Despite the growing fleet of DER, there are limited real-world studies showing the impact of PQRM on energy users. Therefore, there is a need for evidence-based studies analysing real-operational data to understand and quantify DER curtailment. The technical analysis presented in this report focuses on BESS and D-PV curtailment due to tripping (anti-islanding and limits for sustained operation) and V-Var operation. The scope of the CANVAS project is summarised in Table I alongside different modes of curtailment.

Table I Types of DER curtailment and scope of the CANVAS project

	AGL VPP dataset	Solar Analytics dataset
	BESS	D-PV
'Tripping' (anti-islanding and limits for sustained operation)	✓ Preliminary	✓
Volt-Var		
• **Observed curtailment**	✓	✓
• **Scenario analysis**	✓ Preliminary	✓ Preliminary
Volt-Watt	Future work	Future work
Export limits	Future work	Future work

All three PQRM effectively reduce power output, limiting opportunities for DER participation. Early work has shown that energy users are unevenly impacted, with some energy users experience generation losses of up to 46-95% per site on certain days in extreme cases, but most sites do not experience significant curtailment [1]. Importantly, value loss is largely 'invisible' to users, and difficult to predict before investing in DER.

However, PQRM could potentially support higher DER penetrations, and will likely play an important role in this respect. Addressing voltage management through network solutions can involve significant costs, and this cost burden is shared across all energy users, not just those with DER. In an evolving energy landscape, it is important to get the balance 'right' between managing voltage through network solutions, PQRM and more sophisticated market structures.

1.2 Project partners

AGL: AGL is an integrated essential service (electricity, gas, and telecommunications) provider and multi-product retailer operating across WA, VIC, SA, NSW, and QLD. Since September 2016, AGL has been operating a Virtual Power Plant (VPP) as part of an ARENA project [2] which consists of 1,000 residential storage systems installed at homes across metropolitan Adelaide, South Australia with a total of 5 MW dispatch capacity. For the CANVAS project, AGL has provided a year's worth of high-resolution anonymised data from BESS participating in their VPP trial.

Solar Analytics: Solar Analytics Pty. Ltd. is an Australian company specialised in automated monitoring and energy management services for solar households and businesses [3]. For the CANVAS project, Solar Analytics provided 10 months' worth of data from 500 D-PV sites in Metropolitan Adelaide.

SA Power Networks (SAPN): SAPN is the electricity distributor in the state of South Australia, delivering electricity from high voltage transmission network connection points operated by ElectraNet. SAPN was in the industry reference group of CANVAS project and has provided feedback from a DNSP's point of view.

1.3 Structure of this report

This project report firstly introduces some background information regarding DER curtailment, its impacts on various stakeholders, Australia's DER status and integration challenges as well as prior social and technical studies in the DER curtailment subject. In Section 3, studied datasets are introduced from AGL VPP trial and Solar Analytics customer database. In Section 4, methods for the social and technical analysis are introduced. The findings of each stream are presented in the following two Sections 5 and 6, including discussions around the important implications of DER curtailment for different stakeholders. Section 7 presents relevant socio-technical insights born out of the conducted analysis and synthesises the findings of the social and technical streams. Section 8 provides concluding remarks and identifies future research directions.

2 Background

Energy users are driving the shift to a more decentralised power system, largely through their investment in DER. The success of DER – and particularly D-PV – in many parts of the world is resulting in a number of challenges and opportunities for the electricity sector. DER differ significantly from traditional generators in that they are owned by individual energy users. As a result, it is critical that the integration of DER considers social challenges and opportunities alongside the technical.

This section introduces DER curtailment due to over-voltage conditions (2.1) and outlines why curtailment is of interest (2.2). It then provides a brief overview of the Australian context including its world leading deployment of D-PV (2.3). Prior research into the social (2.4) and technical (2.5) aspects of curtailment are then considered, and key gaps that we aim to address through this project are identified (2.6).

2.1 What is DER over-voltage curtailment?

Over-voltage in the local distribution network is widely cited as the first technical impact of DER to emerge in the power system [4–8], particularly during the middle of the day when low load combines with high solar generation conditions.

Over-voltage can result in inverter connected DER curtailment. In the case of DER without a storage component (such as D-PV) this results in the loss of generation, however for DER with storage (such as BESS) it effectively defers the ability to charge or discharge until a later time period.

Despite growing interest amongst energy users and electricity industry stakeholders, curtailment of DER does not yet have a well-accepted definition within the Australian industry. The following definitions are adopted here for the purpose of this scoping study, including the Australian Energy Market Commission (AEMC)'s proposed definition of 'customer export curtailment'. However, further consideration is required to refine these definitions, including through consultation with key industry stakeholders.

Table II Proposed definitions of DER curtailment

DER curtailment:	Means any limits placed on DER operation. DER curtailment may therefore impact export, import or behind the meter operation of DER.
Customer export curtailment:	"Means reducing, tripping or otherwise limiting customer export." [9]
Over-voltage DER curtailment: *(focus of this study)*	Means any limits placed on DER operation as a result of local over-voltage conditions after DER installation.

Table III summarises the scope of each definition. It lists potential energy user impacts and includes 'can reduce imports' and 'can reduce behind the meter consumption' for completeness. However, it is important to note that these impacts of DER curtailment are not currently formalised in the way that export limits are via connection agreements. Currently, the impact of DER curtailment on an energy user's ability to self-consume generation, or import occur when voltage response modes operate. For example, the ability of an energy user to self-consume may be reduced due to DER disconnection caused by anti-islanding limits or limits for sustained operation being breached, or a BESS may be prevented from importing due to the operation of V-VAr mode.

Table III The scope of the proposed DER curtailment definitions

	Types of curtailment		Potential energy user impacts		
	Voltage response modes (V-W, V-Var, limits for sustained op, anti-islanding)	Export limits	Can reduce behind the meter consumption	Can reduce exports	Can reduce imports
DER curtailment	✓	✓	✓	✓	✓
Customer export curtailment	✓ Relating to export only	✓	X	✓	X
Over-voltage DER curtailment *(focus of this study)*	✓ Only V-Var, limits for sustained op and anti-islanding are considered in this study	X	✓	✓	✓

Voltage response modes are typically specified via inverter connection standards and DNSP connection requirements. In Australia, this includes over-voltage anti-islanding set-points, limits for sustained operation and volt-var and volt-watt modes (Figure 1). These modes are intended to 1) ensure network operation safety and 2) ensure the network voltage remains within allowable limits.

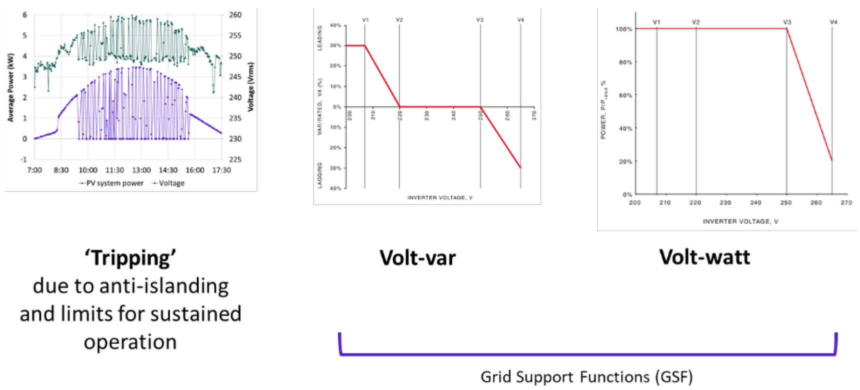


Figure 1 Potential causes of DER over-voltage curtailment

This study focuses on over-voltage DER curtailment. As shown in Table III, this includes the impact of voltage response modes that are specified in inverter connection standards and DNSP connection requirements and excludes the impact of export limits. Arguably, export limits could be put in place due to known or projected over-voltage conditions. In fact, SAPN has indicated that they intend to introduce dynamic export limits that could reduce when necessary to prevent local over-voltage conditions. Therefore, this could be considered within scope of 'over-voltage DER curtailment'. This is an important area for future work, however for the purpose of this scoping study, export limits are excluded.

2.2 Why is DER curtailment of interest?

As decentralisation progresses the role and responsibilities of DER owners and other electricity industry stakeholders are evolving. DER curtailment may have significant impacts for how DER are able to participate in the power system, with resulting financial implications. DER curtailment is therefore of considerable interest for energy users (2.2.1), DNSPs (2.2.2) and the integration of DER more broadly (2.2.3).

2.2.1 Impacts on energy users

DER curtailment will reduce the extent to which energy users are able to utilise their DER by, for example, reducing the volume of D-PV generation exported to the grid, or even the volume of D-PV generation that is self-consumed behind the meter, as shown in Figure 2 from [1].

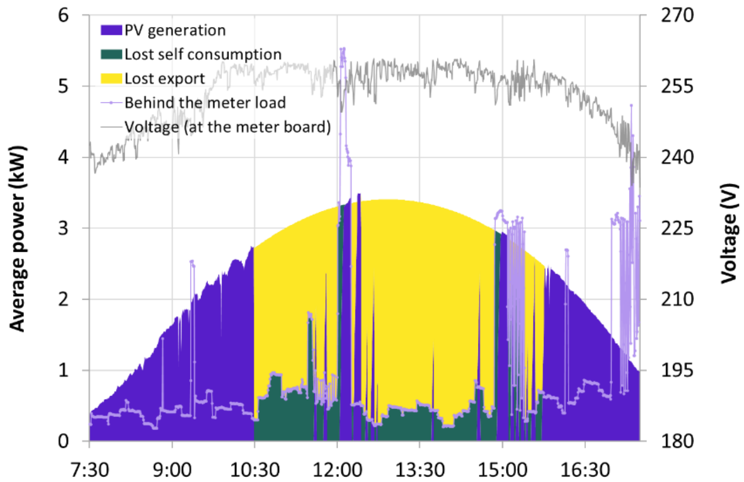


Figure 2 Example of curtailment resulting in lost self-consumption of DPV [1]

DER curtailment therefore has financial impacts on energy users with DER, although prior work in [10] found that these costs remain small for the majority of cases with an average of $3 to $12 per year in impact based on 'worst case' conditions. It is important to note that this study used 2018 data with lower DER penetrations and only considered curtailment due to 'tripping' and therefore may underestimate current curtailment, however it is also critical to note that this previous study provided an upper limit on curtailment at the time, given that it only analysed clear sky days and was therefore likely to be a 'worst case scenario' under 2018 conditions [1]. Since 2018, other factors such as changing market conditions and the increasing prevalence of PQRM modes such as V-Var and V-W will have affected both the level and financial impact of curtailment.

2.2.2 Impacts on the distribution network

DNSPs have historically focused on managing under-voltage conditions, which can occur during periods of peak consumption. However, as D-PV deployment continues and over-voltage becomes more common, the range of voltage conditions occurring on the network is widening. This poses new challenges for DNSP voltage management and the evolution of voltage management strategies [11,12].

In addition, DNSPs have reported increased numbers of energy user inquiries related to D-PV curtailment, and addressing these inquiries requires resources. Other DER such as BESS can cause further complications, with coincident exports and imports from many systems located within the same feeder having the potential to significantly impact local voltage conditions.

The current DER access and pricing rule change process underway at the AEMC [13] is considering a number of measures, including changes to the rules that would allow DNSPs to specifically consider managing DER curtailment when planning network investments.

2.2.3 Implications for DER integration and market design

There are ongoing efforts to develop mechanisms for DER participation in the power system, with the goal of capturing the benefits DER offer. DER curtailment will likely hinder the ability for DER to participate and reduce the efficacy of these mechanisms or increase uncertainty associated with DER participation.

For example, local voltage conditions may prevent a VPP from exporting to the grid (or in some cases, importing). The degree to which it should be the responsibility of the VPP operator to be able to forecast curtailment, or the responsibility of the DNSP to enable exports, is an area of ongoing discussion in Australia.

In addition, the extent to which services provided by DER should be procured, versus mandated via connection standards, is an ongoing area of discussion. In the case of voltage management, DER export causes local voltages to increase and therefore it may not be appropriate to pay DER to reduce voltages or compensate DER for curtailed export, however DER self-consumption (resulting in a net reduction in load) also effectively increases local voltage and may result in curtailment via PQRM. Reducing energy-consumption behind the meter is intuitively something that energy users should be able to do, for instance through energy efficiency measures or DER self-consumption. The fact that distribution network voltages are generally maintained towards the upper end of the allowed range is important context to this discussion, as this leaves minimal opportunity for DER to export and participate in the broader power system. Further, DER may also provide voltage management services at times when the over-voltage conditions are not caused by DER and therefore are aiding DNSPs to meet voltage requirements. Determining an appropriate mix of 'on-market and off-market' services is an area of consideration under the Energy Security Board's Post-2025 review [14].

2.3 Australian context

2.3.1 World leading DER deployment

Australia offers a valuable case study for understanding DER integration given the world leading deployment of D-PV and growing fleet of BESS [15].

As shown in Figure 3 there is now more than 10GW of D-PV deployed in the Australian National Electricity Market (NEM) with almost one in three dwellings having installed D-PV across the country (around 28%). The sunny regions of Queensland and South Australia have experienced the highest uptake as shown, and therefore offer important opportunities to understand the impacts of the very high penetration of DER.

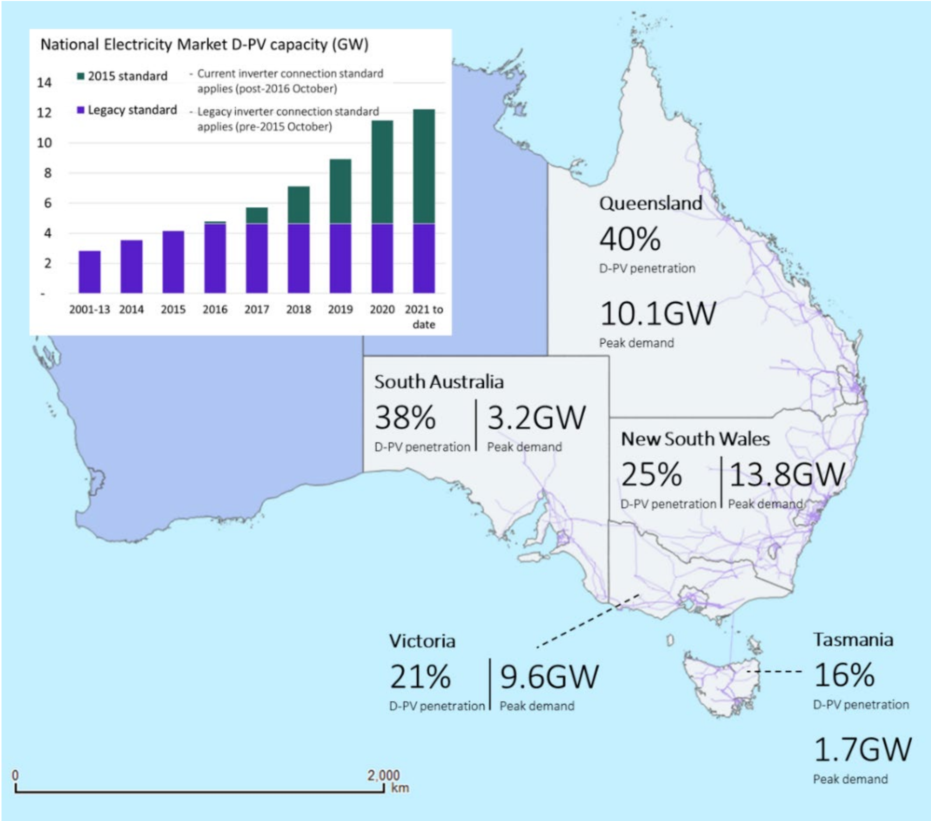


Figure 3 Uptake of D-PV across the Australian NEM
Data on PV penetration from APVI [16] **and peak load from AER** [17]

Importantly, the inverter connection standard AS4777.2 has undergone a number of updates and as result there is a substantial fleet of 'legacy' DER installed in the Australian NEM, as shown in Figure 4.

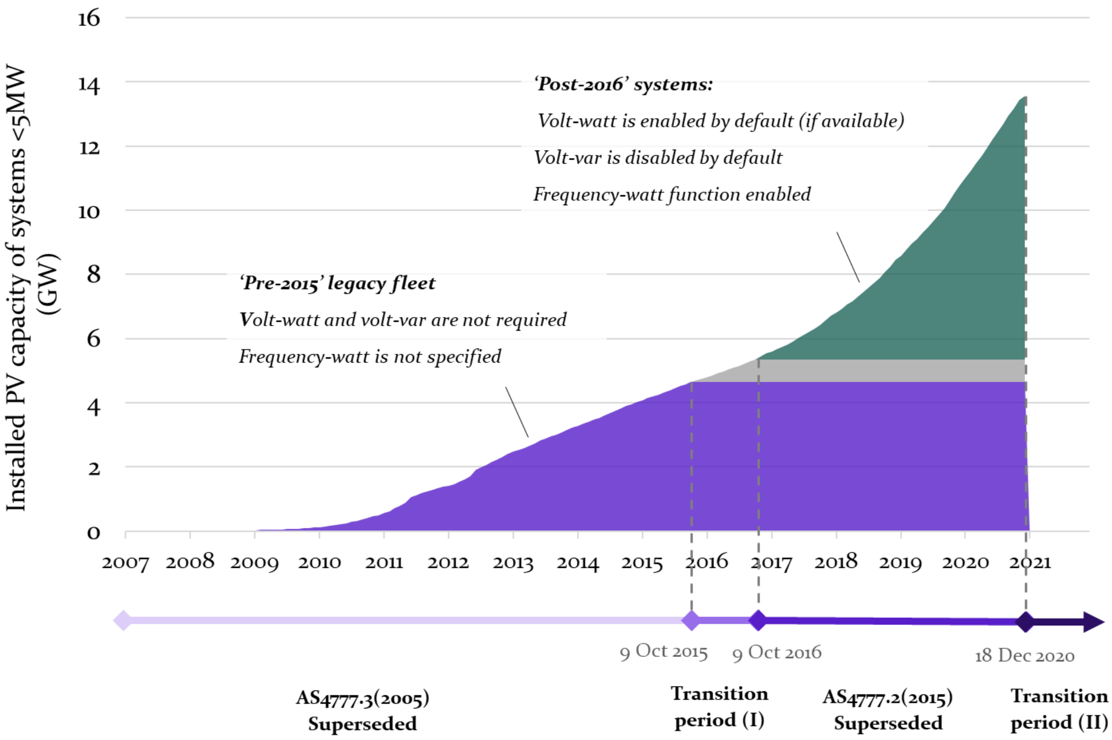


Figure 4 D-PV deployment and the evolution of inverter connection standard AS/NZS 4777.2

2.3.2 Increasing distribution network voltage range

As noted in Section 2.2.2, there is an increasing spread in the range of network voltage conditions occurring over the year. Distribution network voltages have typically been maintained near the upper end of the allowed range in order to manage peak demand conditions, and due to the shift from a historical nominal voltage of 240V to 230V.

High distribution network voltages are significant because they reduce the available 'head room' for D-PV and other DER exports, as shown in Figure 5.

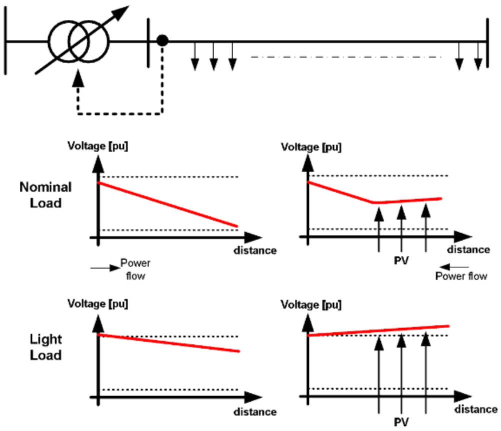


Figure 5 – Impact of D-PV on local network voltage [12]

There has been considerable interest in whether tapping down distribution transformers offers a simple means of integrating more D-PV. Whilst this may offer initial opportunities, there are also clear limitations due to the ongoing need to manage low voltage conditions during peak demand periods, as well as the physical limitations of distribution transformers such that they may not have lower tap set points available; moreover, most older transformers operate at a fixed tap setting which would require a complete replacement in order to be able achieve lower the tap settings.

As the deployment of DER continues, DNSPs are considering a range of network and non-network voltage management approaches, including the use of flexible export limits.

2.3.3 Ongoing DER integration efforts

As outlined in the sections above, there are a number of areas of ongoing debate regarding the roles and responsibilities of DER in the Australian NEM. These include questions regarding what services DER should be required to provide, and what services should be procured, how DNSPs should be regulated to best support DER integration and what opportunities or rights energy users should have to access and export to the grid.

This study is relevant to the following key rule changes, trials, and policy development processes:

- AEMC Access and Pricing Rule change [13]
- ESB Review of DER connection standards governance
- AEMC Technical Standards Governance rule change
- ESB Post-2025 Market Design [14]
- AEMO's VPP trial [18]
- AER DER Integration Guideline
- Flexible export limits trials [20]
- The review of AS/NZS 4777.2-2015 (completed in 2020, with the standard coming into effect from 18 December 2021)
- AER study into the Value of DER [21]

Whilst this report improves the evidence base available for decision making, further work is required through a 'deep dive' project and potentially periodic curtailment reporting, either by DNSPs if regulated to do so, or by independent organisations such as research institutes.

2.4 Prior work on social aspects of curtailment

There is a paucity of research on the social dimensions of curtailment at present. The emerging research on the issue of curtailment tends to centre on the extent of utility scale PV curtailment occurring across a range of countries with fast-growing adoption, and the implications of various technological approaches to it [22]. There is a broad view that curtailment is a necessary part of energy futures that feature increasing levels of PV adoption at various scales, with Koerner et al. [21] stating that there is a need to for the "stigma" which frames curtailment "as a loss" to be re-examined considering changing grid and technological contexts. However, this recasting of curtailment as an issue to be managed, and not avoided, is complicated by issues of equity that are recognised in recent literature on the curtailment of D-PVs [1,23,24].

Stringer et al. [1] focus on the Australian energy landscape to illustrate how there tend to be two "competing narratives" concerning responsibility when it comes to the high voltage conditions that necessitate curtailment. One perspective is that over-voltage in the network is caused by the surge in D-PV adoption and should thus be the focus of efforts to address the problem e.g., through the curtailment of exports. The competing narrative is that voltage conditions in the network are set inappropriately high e.g., to accommodate air conditioning loads, and thus network service providers (DNSPs) should be responsible for addressing the issue of over-voltage. Thus, Stringer et al. [1] highlight how the acceptability of curtailment as a means to manage high voltage conditions is contested.

Concerns regarding the equity of curtailment extend to how it is distributed across populations. Stringer et al. [1] demonstrate this through data from South Australia, stating that while curtailment was not deemed significant in broad terms, a small number of sites experienced significant losses of 46% - 95% of generation, particularly during spring. In a similar vein, Liu et al. [23] argue that while active curtailment can be an effective way to address technical issues in "PV-rich residential distribution networks", applying it in a fair manner can be "quite challenging". This study drew upon a 22kV feeder in Australia with "realistically modelled LV networks (4500+ households)" and used household metrics such as D-PV generation (total output measured at the PV inverter), energy exported to the grid, and the impact on electricity bills to assess the fairness of four proposed curtailment schemes, including comparisons to fairness outcomes through a Volt-Watt scheme. The study concluded that the "quantification of the cost of fairness may help to justify alternative avenues of addressing fairness" while acknowledging that the multi-faceted nature of the problem means that the ultimate fair solution may not exist.

Focusing on South Australia, Kuiper and Blume [25] offers a critical assessment of the curtailment of D-PV exports as a regulatory response from technical, economic, and social perspectives in their briefing note. While this assessment relates to a case for curtailment to mitigate system stability risks in SA at times of low minimum demand, which differs from this study's focus on the issue of high voltage in distribution networks, it highlights several broader issues of fairness from the perspective of rooftop solar owners. The authors emphasise the critical role that consumers are playing in the NEM by providing cost-effective supply through their private investments in over $4 billion in generation assets (including batteries and electric vehicles) at the end of 2020. Illustrative of the different perspectives on curtailment in [1], Kuiper and Blume [25] argue that the Australian Energy Market Operator (AEMO) "is prescribing the technical requirements and the solution to a problem of its definition". They [25] express concerns about the precedent that mandatory measures such as curtailment might set with respect to the "control of private, consumer-owned resources", particularly when factoring in the growing adoption of electric vehicles. The lack of independent economic modelling of the costs of curtailment to households, and procedural inadequacies in terms of consultation and transparency are also cited as key areas of concern in terms of the long-term impacts on consumers. As such, the authors argue that regulators have not sought a "social license" to make changes to privately-owned electricity assets [25]. It is argued that this might involve considering issues such as consumer compensation, exemptions for those unduly affected, and an openness to more cost-effective voluntary measures.

Social research that examines household perspectives about curtailment is scarce. In late 2018, SAPN engaged an independent market research firm to conduct an online survey (1,004 respondents) to gauge community attitudes towards network investments to enable greater uptake of DER in SA [27]. The research indicates that 76% felt positively about SAPN investing in infrastructure upgrades to facilitate greater uptake of D-PV across the state, with just 4% expressing negative views about this. More specifically, the research also sought to gauge community sentiment towards three approaches to facilitating greater DER uptake in SA: static export limits (no change), capacity investment (comprehensive network upgrades) and dynamic export limits. This research offered explanations of these three options, including the overall cost and predicted bill impacts across a range of customer segments, including non-DV households [27]. The research identified dynamic export limits as being the most preferred option (54%), with 48% also considering it in the long-term interests of consumers. Interestingly, there was also moderate support for comprehensive investments in grid capacity to accommodate D-PV (33%), and 40% believed that it was in the long-term interests of customers, despite it being the most expensive option.

Overall, our review of the limited prior work on the social aspects of curtailment indicate that it is an area that requires further investigation. In particular, the emerging literature suggests that there are several issues of fairness that relate to curtailment in an Australian setting. As such, an energy justice framework, which considers issues of equitable distribution, recognition (representation), and process (decision making) in energy systems, may be a useful normative and evaluative lens through which to examine the implications of curtailment [28].

2.5 Prior data-driven technical analyses of DER voltage control and curtailment

Increasing uptake of DER and associated integration challenges has led to increased research attention in recent years. We firstly summarise previous research done in Australia, then move on to reviewing global research efforts.

Several Australian studies have focused on the effectiveness of different D-PV power quality modes for managing LV network voltages. Carter et. al. [29] ran network modelling simulations for varying levels of D-PV VAr absorption and line drop compensation of transformers and observed their impact on the LV network voltages. The aim was to observe D-PV's voltage control capabilities to facilitate higher DER penetration for the South-West Interconnected Network in Western Australia. Mallamo et. al. [30] conducted lab tests and field trials in collaboration with SAPN in South Australia to measure the impact of different V-VAr controls on local voltage conditions. Tests showed that the effectiveness of V-VAr control highly depends on the circuit's X/R ratio. Condon & McPhail [31] carried out detailed investigation into inverter reactive power functionality through a desktop study, network modelling, laboratory tests and field trials in Townsville within the Ergon Energy network. Various inverter VAr modes such as constant power factor, VAr as a function of real power and V-VAr were modelled for different network classes and distribution transformers. The study found V-VAr mode to be the most effective reactive power function for regulating local voltages. Collins & Ward [32] tested different implementations of V-VAr and V-Watt functions of D-PV inverters at sites located in Newcastle, New South Wales (NSW). The authors found that D-PV inverters were able to successfully regulate distribution network voltages and reduce associated network losses. Networks Renewed [11], an ARENA project led by the Institute for

Sustainable Futures at the University of Technology Sydney (UTS) organised small pilot-scale and market scale demonstrations including 90 energy users. The demonstrations tested the local voltage control capabilities of D-PV and BESS inverters using V-VAr function. The field results showed that both D-PV and BESS inverters can successfully reduce local voltages through adequate levels of VAr absorption (on average, 1.5% and 2.5% voltage drop were observed for the sample D-PV and BESS systems, respectively).

More recently, research attention has been directed to the issue of fairness regarding DER curtailment. Lusis et. al. [33] tried to address the fairness issue around coordinated D-PV inverter dispatch in LV regions with high D-PV density. Through the studied network modelling, the study found an optimal operation point for V-VAr and V-Watt modes. With the help of coordinated D-PV control with the optimal settings, total experienced curtailment was reduced, and curtailment was distributed more fairly among D-PV owners. Liu et. al. [23] studied different D-PV curtailment schemes in terms of fairness amongst a large number of energy users. The study proposed different optimal power flow-based schemes to determine optimal D-PV power quality function and curtailment settings. The authors modelled a 22kV feeder with a LV network including 4,500 households and used household centric metrics that quantify PV self-consumption, energy export and financial benefits and assessed the fairness of curtailment among the households, including the ones in more remote locations. Stringer et. al. [1] studied D-PV system tripping (anti-islanding and limits for sustained operation) curtailment due to high voltage conditions and assessed its impacts on energy users. The study analysed 1,300 households in South Australia with real operational data for 24 clear-sky days. The results indicated that the overall curtailment was low, however some energy users experienced significant curtailment up to 46-95% curtailment per day during spring. The uneven distribution of curtailment across the energy users raised concerns regarding fairness of curtailment. The authors emphasised the importance of using real operational data when informing regulatory processes to improve fairness of curtailment. The method developed for estimating D-PV tripping (anti-islanding and limits for sustained operation) curtailment in [1] is also used in this study (Section 4.2.2.1). Miller et. al. also conducted a data driven analysis to assess curtailment in [34]; however, the study was limited by small sample size. Gebbran et. al. [24] proposed an optimal power flow method which incorporated D-PV V-VAr control to achieve fair DER coordination and curtailment. Authors demonstrated the effectiveness of the proposed method on 50 different test cases using LV network of different sizes and topologies with different D-PV penetration levels. Heslop et. al. [35] studied a combined power set point and voltage set point control method to manage the low voltage network voltages. The presented modelling case study showed the effectiveness of the method in terms of accuracy, efficiency, and energy user equity.

Apart from Australia, DER voltage control and curtailment research has been especially prominent in Hawaii, USA, where the uptake of DER has been significant. Work undertaken by the Hawaiian Electric Companies and the National Renewable Energy Laboratory (NREL) [36] modelled and simulated V-VAr and V-Watt functions and assessed their effectiveness in terms of voltage management and impact on D-PV curtailment. The study made further algorithm improvements from a past study by the same authors [37] which found that although D-PV curtailment was small overall, some energy users lost significant amount of generation. In the latter study, authors found that for 99% of the energy users, curtailment due to V-VAr or V-Watt was negligible (less than 2% of generation for the week with highest voltage conditions) and much less on an annualised basis (around 0.23% of generation). The study also found that in very high D-PV penetration cases, V-VAr is highly effective in reducing the voltages during the D-PV generation window which made V-Watt activation redundant. The study further indicated that, D-PV generation was higher when V-Watt settings were active, as D-PV generation loss due tripping (anti-islanding and limits for sustained operation) curtailment would be greater when V-Watt was inactive. The V-VAr related findings of [36] is consistent with our findings in this study.

In a later study conducted in Hawaii by Emmanuel et. al. [38], the authors developed a method which estimated D-PV curtailment due to V-Watt control. The method only used voltage data without the need for additional sensors and monitoring to capture D-PV inverter or weather data. The study compared the proposed method against actual field measurements using irradiance and D-PV inverter data as well as a previous simulation driven study. The authors concluded that the method gave reasonable accuracy in estimating D-PV curtailment due to V-Watt, especially considering its minimal data requirement. A later study by Howlader et. al. studied different D-PV grid support functions such as Frequency-watt, V-Watt and a fixed curtailment setting on a feeder serving a residential neighbourhood on the island of Maui, Hawaii [39]. The authors found that frequency-watt and V-Watt modes were effective in controlling the frequency and voltage of the local LV network, respectively.

Perhaps one of the earliest studies regarding D-PV curtailment was carried out in Japan. Ueda et. al. collected and used high-resolution D-PV generation data from 533 households alongside with irradiance and temperature to estimate D-PV curtailment [40]. The study found that only a few households experienced significant D-PV curtailment due to high grid voltages and on average curtailment was small. Authors attributed the uneven distribution of curtailment to the differences of line impedance, D-PV inverter settings as well as the imbalance of the loads along the distribution network. Procopiou et. al. investigated V-VAr's capability in managing local high voltages in a UK case study [41]. In contrast to previous studies, the authors concluded that V-VAr's capability of regulating voltage was rather limited because D-PV inverters prioritised real power output which limited their capability to absorb VArs during high voltage events. Based on the analysed real-operational data our study, we found conflicting evidence with [41] such that some D-PV inverters were capable of absorbing VArs in higher quantities than real power output during high voltage instances. Furthermore, the studied BESS in our study showed that they are capable of absorbing VAr at their rated VA capacity. Shaughnessy et. al. compared utility scale PV curtailment across Germany, China, Chile and four states of USA [22]. The study found that the analysed utility scale curtailment events were mainly driven by the mismatch of supply and demand. Authors emphasised that in this context a shift is required in the perception of curtailment, as it may also help in achieving optimal grid management rather than being solely associated with 'loss'. However, curtailment of consumer DER raises a range of different issues around equity of distribution of impacts, transparency, and knowledge of curtailment risk both prior to and after investment in DER.

2.6 Key gaps that CANVAS aims to address

The literature review presented here has shown that there have been a limited number of studies that have analysed DER curtailment using real operational data. Furthermore, even though some studies had real operational data, the data was either limited by the number of sites or duration of the dataset. Moreover, there seems to be a missing link between analysis of the social and technical aspects of DER curtailment as most studies tend to focus more on the technical side of DER curtailment without considering its social dimensions. And finally, most of the existing studies have focused on D-PV curtailment, as the availability of real operational data from BESS has been very limited to date. Considering these points, the unique contributions of CANVAS can be listed as follows:

- Tripping (anti-islanding and limits for sustained operation) and V-VAr curtailment analysis carried out on high-resolution data from 996 BESS (12-months) and 500 D-PV (10-months) sites in metropolitan Adelaide.
- V-VAr curtailment analysis based on real operational data in Australia (to the authors' knowledge, this is the first Australian study analysing V-VAr curtailment using real operational data).
- Comparison of curtailment between D-PV sites against BESS sites (to the authors' knowledge, this is the first Australian study comparing curtailment between D-PV and BESS using real operational data).
- Integration of social science and technical data analysis components to provide key socio-technical insights regarding DER curtailment in Australia (to the authors' knowledge, this is the first Australian study to bring together social and technical insights on DER curtailment).

3 Datasets

3.1 Overview of datasets

Each of the data sets used in this study is unique and presents opportunities and challenges for the analysis. It is important to understand the datasets well to draw accurate conclusions. The details of these datasets are outlined below.

3.1.1 AGL VPP dataset - Tesla sites

There are 796 sites in the AGL data set with Tesla BESS, all of which are AC coupled systems and have detailed BESS inverter measurements monitored at the BESS inverter terminals (see Figure 6). These sites do not include any measurements from D-PV inverters; nevertheless, solar generation is measured with an external measurement device on the AC side of the D-PV inverter alongside with site's net consumption. Tesla sites have high resolution measurements in consistent intervals and most of the sites have missing data less than 10%. According to the information obtained from Tesla, power and voltage data measurements are instantaneous (i.e., single snapshot) and there were no averaging, min and max applied during the measurement interval.

3.1.2 AGL VPP dataset - Solar Edge sites

There are 198 sites with Solar Edge BESS all of which are AC coupled systems and have detailed BESS inverter measurements monitored at the BESS inverter terminals (see Figure 6). These sites do not include any measurements directly from D-PV inverters; though, solar generation is measured with an external measurement device on the AC side of the solar inverter.

According to the information obtained from Solar Edge, all power and voltage data measurements are instantaneous (i.e., single snapshot) and there were no averaging, min and max applied during the measurement interval.

Figure 6 presents a simple diagram for AGL VPP site components and the location of monitoring.

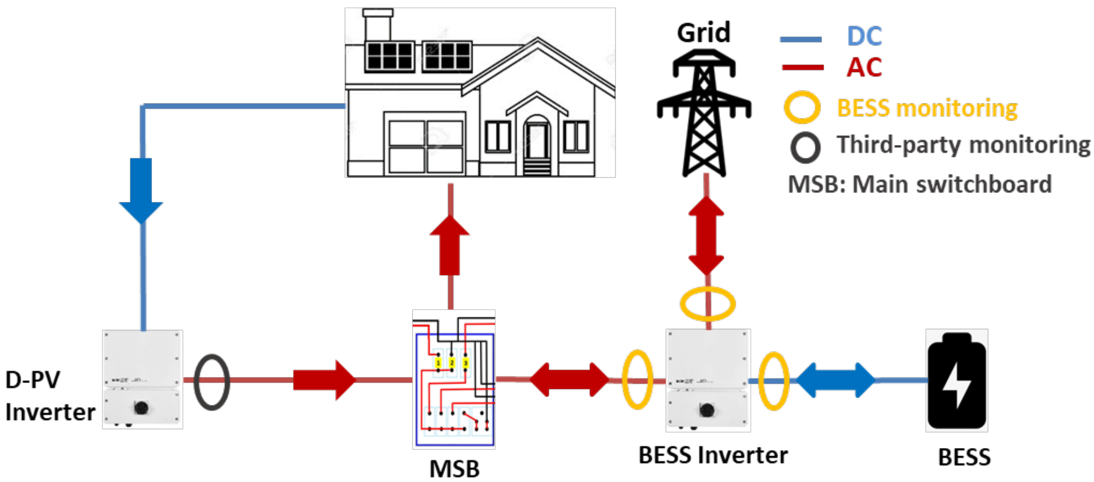


Figure 6 A simple diagram for AGL site components and monitoring

3.1.3 Solar Analytics dataset

The Solar Analytics data set includes 500 sites which have D-PV systems without a BESS. All of the sites have detailed D-PV inverter measurements measured at the main switch board (MSB) as well as meta-data such as D-PV system's DC rated generation capacity, D-PV inverter's AC capacity and installation date. The sites have generally consistent measurement intervals; however, missing data is significant for around 10% of the sites.

Figure 7 presents a simple diagram for the Solar Analytics site components and the location of monitoring.

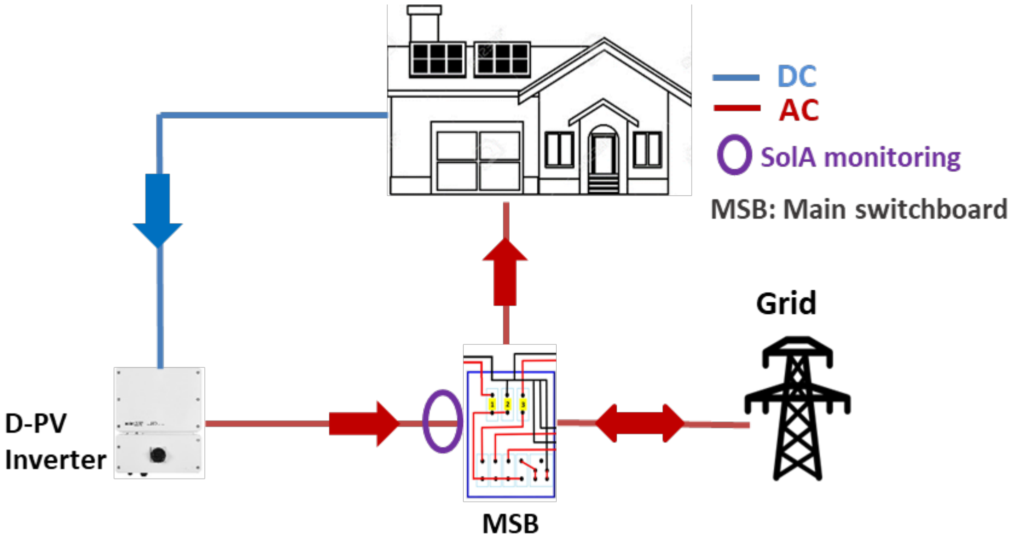


Figure 7 A simple diagram for Solar Analytics site components and monitoring

3.1.4 Bureau of Meteorology (BOM) weather data

Complementary global horizontal irradiance (GHI) data was obtained from the Bureau of Meteorology automated weather station located at Adelaide airport. The irradiance measurements cover the entire D-PV dataset period from July 2019 to July 2020.

A summary of the analysed datasets and their key parameters are given in Table IV below.

Table IV Summary of the analysed datasets

Data set source	Number of sites	Key parameters	Time increments	Site location	Time period	Notes
AGL VPP (Tesla sites)	796	**Battery inverter measurements:** power, reactive power, voltage, frequency, energy, and state of charge **External monitoring:** site net power, D-PV power	1sec., 5 sec., 300 sec. based on the signal	Adelaide, South Australia Postcodes available	1-Feb-20 to 31-Jan-21	Do not report any measurements from D-PV inverters.
AGL VPP (Solar Edge sites)	198	**Battery inverter measurements:** power, reactive power, voltage, current, power factor, frequency, energy, and state of charge **External monitoring:** D-PV power, site net power	60 sec.	Adelaide, South Australia Postcodes available	1-Feb-20 to 31-Jan-21	
Solar Analytics	500	**PV inverter:** power, reactive power, voltage, AC inverter capacity, DC capacity	60 sec.	Adelaide, South Australia Postcodes available	1-Jul-19 to 30-Apr-20	10 months of data available and sites do not own BESS data.
Bureau of meteorology (BOM)		Minutely global horizontal irradiance data	60 sec.	Adelaide airport, South Australia	1 July 2019 to 31 July 2020	

4 Methods

4.1 Social analysis

A total of 20 respondents participated in the research through focus groups and interviews. All participants are based in South Australia, and most have rooftop D-PV systems. The focus group participants were recruited through a market research agency, allowing a targeted mix of demographic factors, locations in South Australia, and D-PV system ownership. Two interviews were additionally conducted with individuals who are engaged professionally or through advocacy in supporting household DER adoption. The composition of the focus groups and interviews are shown below.

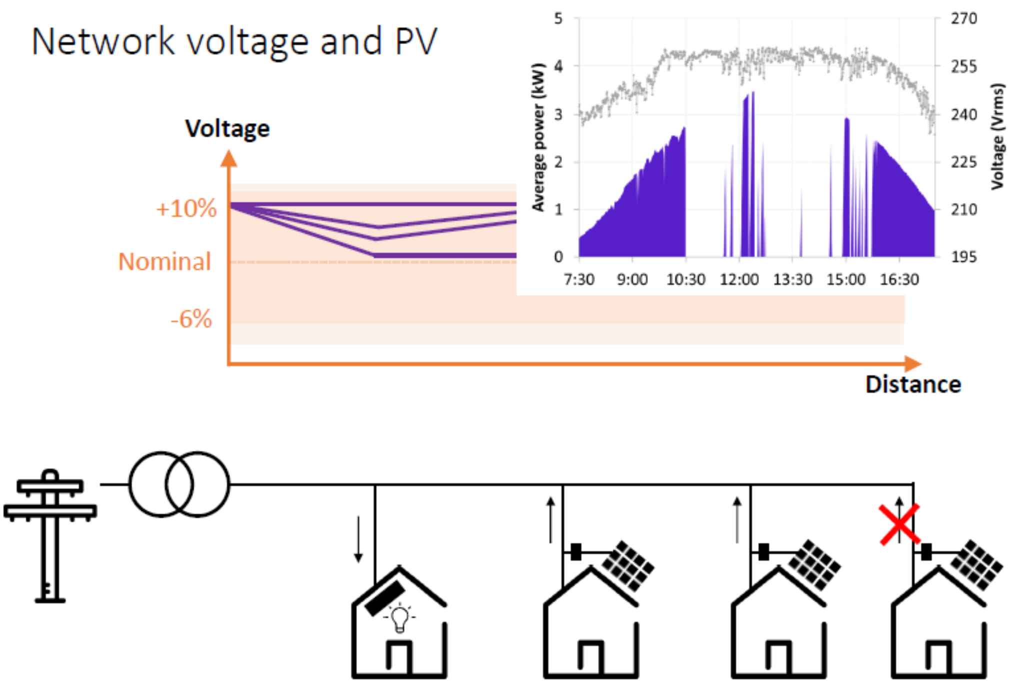
	Number of participants	Participant characteristics
Focus group 1	4	Residents of houses with D-PV systems. Mix of gender, income bracket, tenure and urban/regional location.
Focus group 2	4	Residents of houses with D-PV systems. Mix of gender, income bracket, tenure and urban/regional location.
Focus group 3	5	Residents of houses; 2 with D-PV systems and 3 without. Mix of gender, income bracket, tenure and urban/regional location.

	Number of participants	Participant characteristics
Focus group 4	4	2 residents of apartments and 3 residents of houses; all without D-PB systems. Mix of gender, income bracket, tenure, and urban/regional location.
Interview 1	2	Participants have D-PV systems and are engaged professionally in providing advice on renewable energy solutions to households and businesses.
Interview 2	1	Participant has a D-PV system and is engaged in advocacy on issues related to D-PV systems.

The focus groups were scripted and included an introduction to curtailment as well as information about alternative perspectives and proposed solutions to elicit responses from the participants. The interviews were semi-structured, with less formal prompts and a flexible question sequence, and took some understanding of curtailment and the issues surrounding it as given.

The focus groups began with introductions and questions about the participants' D-PV system (its size, when it was installed) and battery ownership (whether they own one or would be interested to purchase one, and why or why not). We asked all participants why they had purchased a D-PV system and whether they are satisfied with it. Those participants in Focus Groups 3 and 4 who do not have D-PV systems were asked whether they would be interested to purchase one, why or why not, and which barriers they might have encountered.

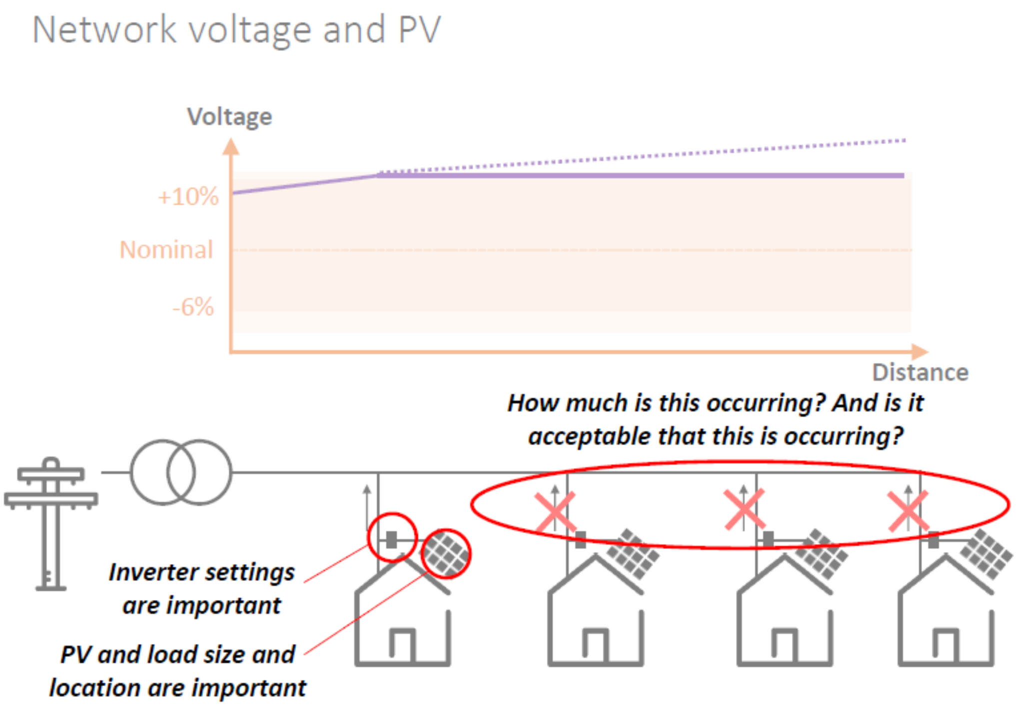
The participants were then asked about their prior awareness of the issue of curtailment, before they were given a basic introduction to the issue through the slides and description below.



Slide 1

"Curtailment happens when voltage in the network is getting high, and D-PV inverters cut off the flow of electricity into the grid. Electricity networks in Australia are required to keep voltage at a nominal level of 230V, +10%/-6%. Voltage tends to be run fairly high these days, so at the upper end of the permitted range, as you can see here [in Slide 1]. Down the bottom here – in this very stylised, simplified diagram – we've got a distribution transformer providing power to a local feeder, which is serving this row of

houses. In the first house there may be an aircon unit and lights, and perhaps some other appliances, using electricity. This will cause the voltage on the feeder to drop. But then the second house has a solar system on the roof, and by exporting electricity into the line, it's going to push voltage back up a bit. If the other houses have solar systems too, the voltage may increase further, until it's pushed above the permitted voltage range. In this diagram [in the top right corner of Slide 1] we can see that solar system being curtailed at 10:30 in the morning, trying to start again in the sunniest hours of the day, but continuing to experience curtailment."



Slide 2

"In a context in which voltage is being run high, and more and more D-PV systems are being installed, curtailment may become more common. An important factor is inverter settings: the standards for inverters are changing, which is changing how inverters respond to voltage conditions in the grid, and typically means that newer systems are being curtailed more of the time. We also know the size of the solar system, the amount of power the house is using, and the location of house in the network are also important factors, e.g., bigger systems may experience more curtailment because they are increasing voltage on the local feeder. We are working on a research project with some engineers who are trying to understand how much this is occurring. And, as social scientists, we are interested in whether it is acceptable that this is occurring."

Following this introduction, participants were invited to share their initial impressions and answer a range of questions, including why they think that curtailment is occurring in South Australia, what they think it might mean for themselves or others with D-PV systems, what they think solar systems owners need to know about the issue, and whether it might make them think differently about the decision to install a D-PV system.

We asked them to comment on the broader benefits of D-PV adoption in Australia, how they see the impacts of curtailment weighing against those benefits, and what they think that the potentially uneven distribution of curtailment could mean for the further uptake of D-PV across the state and country. Finally, we asked the participants to consider alternative perspectives on how the issue of curtailment should be managed, including through the following prompts:

"Network operators would argue that curtailment has to happen to maintain a safe grid in a context in which many Australians – and particularly South Australians – have chosen to install solar on their roofs. What do you make of this perspective? Are you confident that the network is being managed in the best interests of households?"

"SAPN currently limits South Australian households to exporting a fixed maximum of 5kW. They are currently trialling a flexible export limit that would enable potentially higher export limits depending on conditions in the network. This is facilitated by the use of internet-enabled inverters which can monitor the network and raise or lower export limits based on congestion in the grid. For example, it can potentially raise the export limit up to 10kW when network congestion is low. How do you feel about this initiative? Would it be something you'd be interested in?"

Participants were invited to freely raise questions and ideas in response to our basic introduction to the issue of curtailment and subsequent prompts. While some of these responses revealed a difficulty in understanding the issue and a lack of knowledge about electricity networks on the part of many of the participants, they offered a crucial insight into how this issue is likely to be approached by many South Australians, as well as often very telling and incisive assessments of the stakes.

Following the completion of the focus groups and interviews, the recordings were transcribed. The transcripts were then coded using Computer-Assisted Qualitative Data Analysis Software *NVivo* to organise participants' comments according to key themes and ideas, which formed the basis for the analysis presented in Section 5.

4.2 Data-driven technical analysis

Technical analysis has focused on the two types of DER curtailment in this scoping study:

- Tripping (anti-islanding and limits for sustained operation)
- V-VAr

The analysis is undertaken to assess two central questions:

- How much curtailment is <u>currently</u> occurring in the field?
- How much curtailment <u>may occur in the future</u>?

To respond to the first question, operational data from BESS (provided by AGL) and D-PV (provided by Solar Analytics) is analysed to quantify existing curtailment due to tripping and V-VAr operation.

To respond to the second question, scenario analysis is undertaken by leveraging both the BESS and D-PV data. In this analysis, real operational voltage measurements are used, and ideal inverter responses are modelled based on different inverter performance standards. A limitation of this scenario analysis is that it assumes voltage is not impacted by the modelled BESS and D-PV inverter response. Another limitation of this analysis is that the analysed operational voltage, BESS, and D-PV data may not be representative of a future scenario as both DER and DNSP's management strategies are changing very quickly.

Before presenting the methods applied for the technical analysis, we present the data analysis platform which has had a pivotal role in dealing with the pertinent big data analysis challenges.

4.2.1 Data analysis platform

AGL's VPP dataset is hosted in Microsoft Azure and access and analysis of the dataset was found to be most convenient using this platform. For this purpose, the required data sharing, storage, and analysis platforms were established within Microsoft Azure.

The AGL VPP dataset is in the order of 7 TBs and required high performance virtual machines for the data analysis. The CANVAS team won an Artificial Intelligence for Earth (AI for Earth) Grant facilitated by

Microsoft [42]. The grant credits have been used for the storage and computational expenses of the CANVAS technical stream.

A schematic for the data access and analysis platform is presented in Figure 8 below. The shared dataset was migrated to a local New South Wales (NSW) Microsoft data centre via Azure Data Share and stored in a newly created Azure Storage account. The stored data was then transferred to Azure's data analysis platform, Azure Data Explorer (ADX). The data exploration and preliminary analysis was done in the ADX platform through using its native query language, Kusto Query Language (KQL). More detailed curtailment analysis was carried out in Jupyter Lab/Python through the ADX - Jupyter Lab plug-in. The results were visualized by Python's visualization package Matplotlib and Microsoft Power BI.

The dataset provided by Solar Analytics consisted of 'csv' files, and as a result data could be directly analysed within Jupyter Lab/Python.

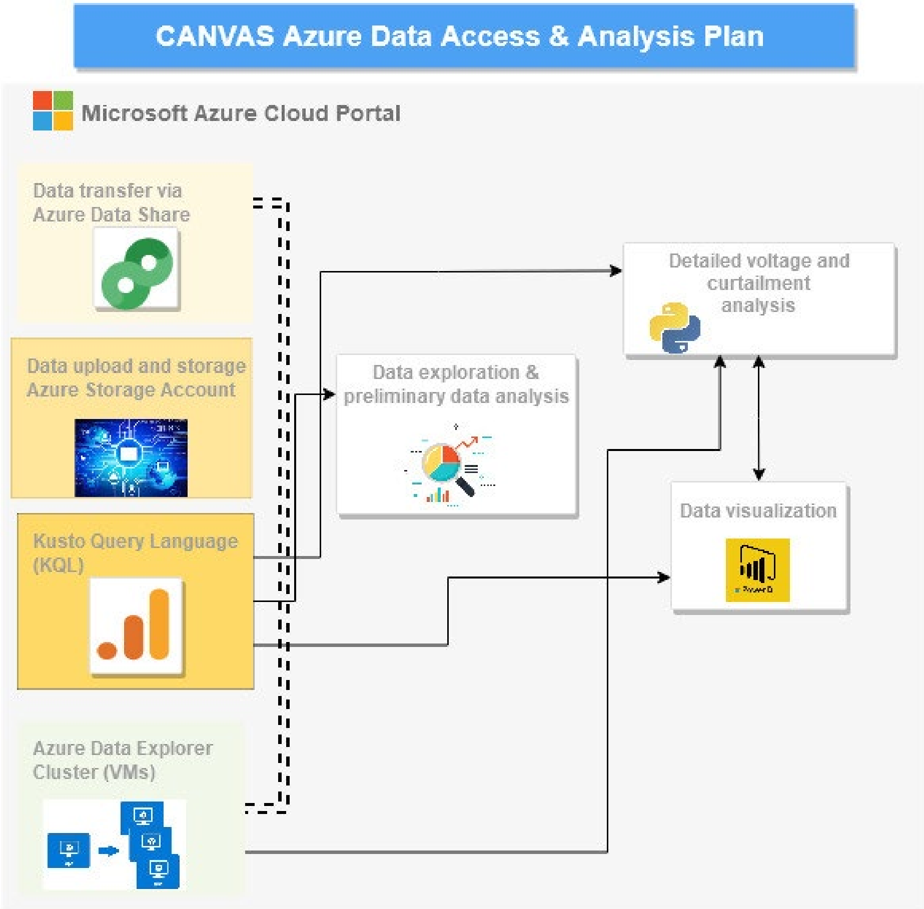


Figure 8 A schematic for data access and analysis structure for AGL's VPP dataset

4.2.2 Tripping (anti-islanding and limits for sustained operation) curtailment

DER inverters can trip under two different conditions as specified in AS/NZS 4777.2 (year depends on inverters installation date):

- **Anti-islanding:** When the voltages are outside the lower and upper bounds of the anti-islanding settings for a short period
- **Limits for sustained operation:** When voltages are sustained above an upper bound for 10 minutes

The studied datasets capture a snapshot of the voltage every interval (e.g. a snapshot at the end of each 60s period in the case of the Solar Analytics dataset) and therefore the dataset does not offer a complete picture of voltage conditions experienced by the inverter. Further, a 10min average calculated using the available datasets may differ to the 10min average calculated by the inverter. As a result, the datasets don't give the complete picture of the voltage conditions to be able to separate anti-islanding tripping from sustained voltage tripping. In this study, all tripping curtailment is analysed together – this is an important limitation and should be considered in future work.

4.2.2.1 D-PV tripping (anti-islanding and limits for sustained operation) curtailment

The D-PV 'tripping' analysis applied the methods developed in [1] to identify the start and end points for periods in which D-PV generation reduced to near zero. The linear method is applied to non clear-sky days, whilst the polyfit-iteration method is applied to clear-sky days in most cases, as described in [1].

These methods output an estimate of the D-PV energy curtailed at each site for each day in the 10 month dataset, as well as the estimated profiles for all sites over the period. The results are then analysed to assess the following:

- **Significance of curtailment:** how much energy is being lost due to D-PV 'tripping'?
- **Distribution of impacts:** are some sites more impacted than others?
- **Seasonality of curtailment:** when is 'tripping' curtailment occurring most throughout the year?

The five most impacted sites are presented as case studies.

4.2.2.2 BESS tripping (anti-islanding and limits for sustained operation) curtailment

It was more challenging to define the tripping (anti-islanding and limits for sustained operation) curtailment for BESS compared to D-PV systems. This is because BESS has storage capability and for the instances where BESS could not discharge due to tripping, the unused stored energy will be available for later use. Similarly, for the instances where BESS could not charge due to tripping, the excess-D-PV generation can be exported (assuming there is no export-limitation which is out of the scope of this study). Therefore, identifying and quantifying 'loss' due to BESS tripping is not straightforward. Nevertheless, the analysis focused on the instances where BESS's operational capabilities were limited by the identified tripping instances and assessed curtailment under two categories:

1. ***BESS tripping curtailment when BESS could be discharging.***
2. ***BESS tripping curtailment while BESS could be charging.***

Further details for the BESS tripping (anti-islanding and limits for sustained operation) curtailment calculation are given in the Appendix.

4.2.3 Volt-VAr curtailment

Volt-VAr (V-VAr) curtailment analysis is carried in three steps. Firstly, BESS and D-PV system VAr characteristics are investigated using real operational data. In the next step V-VAr curtailment is investigated using real operational data and in the final step, future V-VAr curtailment scenarios are modelled under different V-VAr curves referenced from different regulations and standards.

4.2.3.1 V-VAr characteristics

Before quantifying V-VAr curtailment, preliminary analysis was done to reveal the operational VAr characteristics of BESS and D-PV inverters. Analysis focused on the following points:

- How often do BESS and D-PV inverters inject and absorb VArs?
- What are the statistics of the injected and absorbed VArs?
- Are there any specific months or hours of the day where VArs were observed more significantly than others?
- Do the D-PV and BESS inverters follow the V-VAr curves specified by the standards?

4.2.3.2 V-VAr curtailment for D-PV inverters (Solar Analytics dataset)

During the D-PV generation window, injection, or absorption of VAr may limit the maximum real D-PV output as per the limited VA rating of the D-PV inverter. Considering this point V-VAr curtailment is calculated considering the following points:

- Identify instances where D-PV is operating at its rated VA capacity while injecting or absorbing VAr (potential curtailment events)
- Estimate un-curtailed D-PV generation using D-PV characteristics and BOM irradiance data
- Calculate D-PV curtailment during potential curtailment events as the difference between estimated and real D-PV generation.

Further details for the D-PV V-VAr curtailment calculations is given in the Appendix.

4.2.3.3 V-VAr curtailment for BESS inverters (AGL data-set)

Different from D-PV V-VAr curtailment analysis which focused on the solar generation window, BESS V-VAr curtailment analysis covered the entire daily period since BESS output could be curtailed at any point during the day.

V-VAr curtailment analysis for BESS had similar challenges for identifying a definite 'loss' to those for estimating BESS tripping curtailment losses. This is because BESS has storage capability and for the instances where BESS could not discharge at its maximum rated capacity due to V-VAr curtailment, the unused stored energy will be available for later use. Similarly, for the instances where BESS could not charge at its maximum rated capacity due to V-VAr curtailment, the excess-D-PV generation can be exported (assuming there is no export-limitation which is out of the scope of this study). Nevertheless, the analysis focused on the instances where BESS's operational capabilities were limited by V-VAr and assessed curtailment from two different perspectives:

- ***Energy user perspective***
  Curtailment instances which limit energy user self-consumption capacity during BESS discharge.
- ***Aggregator (VPP operator) perspective***
  Curtailment instances which limit BESS capacity during both charge and discharge.

Details for each V-VAr curtailment calculation is provided in the Appendix.

4.2.3.4 V-VAr scenario analysis

The V-VAr scenario analysis is carried for both D-PV and BESS inverters, from both an energy user's perspective and aggregator's perspective. In the V-VAr scenario analysis, D-PV and BESS inverters are assumed to follow the V-VAr curves specified by different standards and regulations:

- TS129 (South Australian Power Networks- SAPN) [43]
- AS/NZS 4777.2-2015 [44]
- Energy Networks Australia (ENA) recommendations [45]
- AS/NZS 4777.2-2020 [46]

The V-VAr curves for each specific standard is demonstrated in Figure 9 below.

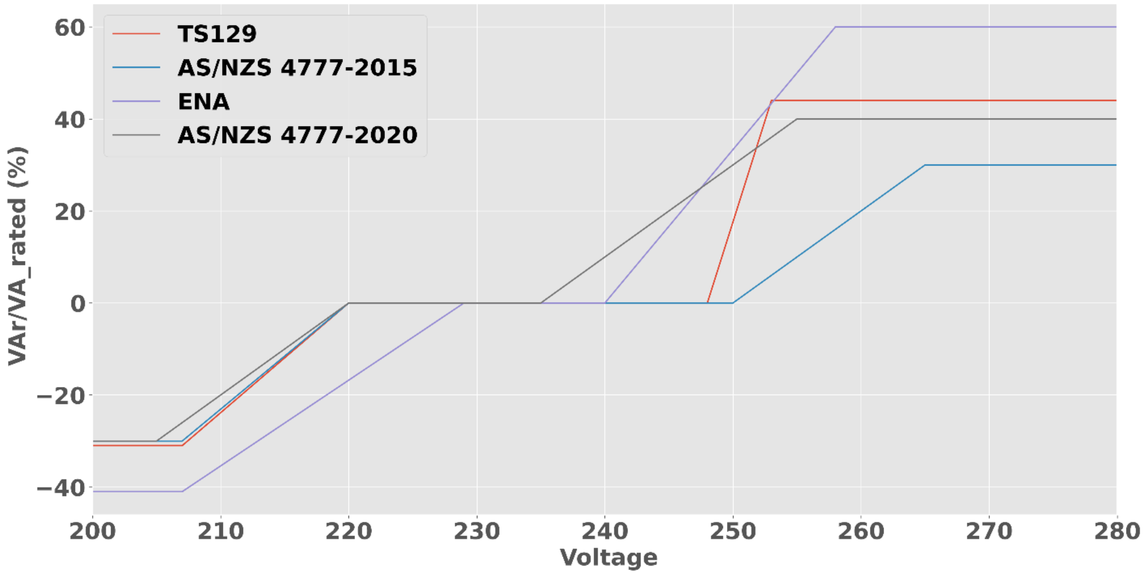


Figure 9 Studied reference V-VAr curves

Key voltage and VAr thresholds of the respective V-VAr curves are noted in Table V below.

Table V V-VAr curve key parameters

V-VAr standards	VAr_injection/ VA_rated (%)	V1	V2	V3	V4	VAr_absorbtion/ VA_rated (%)
SAPN TS-129	31	207	220	248	253	44
AS/NZS 4777-2015	30	207	220	250	265	30
ENA recommendation -2019	41	207	220	240	258	60
AS/NZS 4777 - 2020 (Australia B - small systems)	30	205	220	235	255	40

In the scenario analysis, rather than using the measured VAr values, new values were calculated for each D-PV and BESS (which will be referred as '*ideal VArs*'), using real operational voltage data and each of the respective V-VAr curve parameters presented above. The V-VAr curtailment estimation procedures described in Section 4.2.3.1 and 4.2.3.2 are repeated after this calculation step. Further details for the scenario analysis are provided in the Appendix.

4.3 Development of socio-technical insights

Through a thorough evaluation of the results obtained from the technical and social streams, key socio-technical insights are presented in Section 7. The socio-technical insights particularly focus on the understanding of curtailment, meeting energy user expectations as well as regulatory and policy developments to manage curtailment and support higher integration of DER.

Key findings from both streams are summarized in Table XIV which addresses three important questions regarding DER curtailment:

- What is the state of curtailment?
- What are the impacts of curtailment?
- How could curtailment be managed?

Further reflections are also presented by comparing the alignment of the findings from the social and technical streams to identify future research opportunities and policy processes.

5 Social analysis findings

5.1 D-PV adoption and satisfaction

5.1.1 Motivations for D-PV adoption

There was a mix of economic and environmental reasons for the adoption of D-PV systems by research participants.

Participants were keen to reduce "extremely expensive" electricity bills, particularly in relation to costs associated with heating and cooling. Some participants considered the primary economic benefit of D-PV adoption for households at present to be the possibility to maximise self-consumption and reduce imports, rather than to maximise exports: *"As it stands, the main benefit for solar right now for most households does not come from the feed-in tariffs. It comes from a reduction in their power bills, which comes from being able to use their own generation."* Some participants saw the broader economic and infrastructural benefits of D-PV adoption in terms of lowering demand for power from the grid: *"I think that it should be helping lower prices because there should be less demand on the grid [for] power."*

There were often environmental motivations running in parallel to economic considerations: *"I just see myself as actually trying to become more self-sufficient myself, and also helping the environment as well."* Broadly speaking, D-PV adoption was seen as part of transition towards renewable energy and sustainability, at both a household and societal level. Participants cited the broader environmental benefits of reducing the extent of fossil fuels used in the nation's energy mix: *"The environment benefits the most because we can cut out all those fossil fuels."*

There appeared to be a temporal dimension to participants' motivating for purchasing D-PV systems, with early adopters suggesting that their motivations were *"primarily ecological"* as the upfront cost of being an early adopter was high – although, as reflected in their comments about satisfaction, they typically also enjoy higher feed-in tariffs than later adopters do.

The main reasons participants did not have D-PV systems related to being in rental properties or being unsure of how long they would be staying at their current places of residence. Some of these respondents said that they *"found it too hard"*, had concerns around the quality of panels, or found that it *"did not seem cost-effective"* (without a battery) relative to their current lifestyle. Some participants with D-PV systems also reflected on how renters and lower socio-economic groups are currently excluded from some of the benefits associated with them and that efforts should be made to better include them. *"I guess, we should be aware that its benefits are to owners, such as you and me, but not renters or people living in tower blocks."*

5.1.2 Interest in BESS

While few participants owned a BESS, most D-PV owners were positive about the idea of owning one, with some making clear links between BESS ownership and the potential impacts of curtailment. The main constraint to adoption was primarily in relation to cost, with one participant stated that *"paying three times the amount for a battery than what it costs for the solar just isn't justifiable at this point in time."* Some commented that they were advised or thought it best to wait a few years for prices to fall. Some participants also expressed hesitancy because *"batteries are still not at that advanced stage, that lasts a long time".*

5.1.3 Satisfaction with D-PV

Participants expressed satisfaction with their systems in terms of performance: *"Our return in investment was very fast and we're getting a lot more out of it than I had anticipated".* A primary factor in their assessment of satisfaction was the impact of their D-PV system on their electricity bills, as reflected in comments such as *"we had a couple of hundred dollars knocked off it pretty much and that was thanks to the solar"*. One user (with a BESS) also cited reliability as a key factor in determining their level of satisfaction as their town had recently experienced power outages.

There were temporal aspects of satisfaction centered on the changing feed-in tariff over the years. Several participants mentioned family members who had purchased systems earlier (at higher upfront cost) and thus enjoy significantly higher feed-in tariffs: *"My parents got solar many years ago and I think they get, I don't know, some – I think their feed-in tariff is 50 or 60 cents or something. And so, they haven't had a bill in years and usually they get credit. Whereas, I think, now is it six or eight cents or something?"* Yet despite the significant reduction in feed-in tariffs, there was a sense that even recent adopters were satisfied with the value (in terms of costs weighed against benefits) that their systems were offering.

An interesting dimension of this is how the date of adoption and feed-in tariff might shape perspectives on the relative significance of curtailment: *"I think the amount you see on your quarterly bill or whatever that you're not getting compared to your neighbour that might've signed on five years ago or something is probably more of an issue than what curtailment is gonna do*." These differences in the period of ownership and feed-in tariffs may account for different perspectives on the part of users about whether they are getting as much economic value from their systems as they originally envisaged. Thus, these differences may have a bearing on perceptions of the fairness of curtailment.

5.1.4 Monitoring D-PV

Most participants with D-PV systems tended to monitor their systems via an inverter or retailer's mobile app on a daily or weekly basis.

5.1.5 Role and responsibilities as a prosumer

Most participants did not indicate that they perceived a notable shift in their role and responsibilities when becoming prosumers: *"I certainly would still consider myself a consumer, especially considering we had a loan for the product."* Most of the responses centered on how becoming a prosumer had made them more conscious of their energy consumption and shaped household practices, e.g., using more appliances during peak generation periods. Some participants remarked on how they felt good about being able to contribute to the wider community but did not necessarily associate this with a change in responsibility: *"It wasn't a change in the responsibility, it was more like I just brought this kit which makes me feel a bit greener.*"

5.2 Knowledge and experiences of curtailment

5.2.1. Prior knowledge of curtailment

A clear finding was that most participants had no prior knowledge of curtailment. This was reflected in comments such as *"I'm not sure that people know about curtailment. Until this session, I wasn't really aware of it. So, I'm not sure that it's a public issue yet.* The few that did claimed that they had experienced it themselves and/or had heard of it through active engagement with community organisations that support the transition to renewable energy in SA.

5.2.2. Prior experiences of curtailment

Only two participants stated that they had experienced any curtailment of their electricity exports. One of these participants described that it was *"Last summer, maybe it was twice where they just shut off our exports to the grid, I think, for six or seven hours a couple of times. It's as far as I know".* In this case, the participant was alerted to this occurrence via media reports and subsequently confirmed that it had happened by reviewing their D-PV inverter app.

There was a sense among participants that they might not even recognise any occurrence of curtailment, and one asked, *"So would you even know if it was happening with your own solar system?"* Indeed, most participants had little understanding of how it might be apparent to them. As a participant remarked, *"if there's not really a clear way of seeing if there's curtailment happening, then I can see that might be a problem with people thinking that their system is not functioning properly".* Participants' concerns about a lack of visibility of curtailment events related to expectations of transparency that are discussed in Section 5.4.

5.3 Perceived impacts of curtailment

5.3.2 Potential disruption of the energy transition

Participants shared broad concerns about the impact of curtailment on the ongoing adoption of D-PV in SA. Participants expressed that curtailment could be "off-putting" to households that are considering purchasing D-PV systems, echoing the 'stigma' that is associated with curtailment [22]. The potential for curtailment was seen to add another layer of technical and economic complexity: *"For me, the whole issue of curtailment just means that it's another budgetary item that's a little bit up in the air. You don't know how much money you're going to get back."* This reflects the concerns about impacts on the economic viability of purchasing a D-PV system mentioned above, with curtailment making it more difficult for prospective purchasers to develop a full view of the costs and benefits [25].

There was a broad view that D-PV adoption is to be lauded and encouraged, and that the curtailment of exports could form the basis of negative perceptions or misconceptions of D-PV. Some participants pointed out that such negative perceptions might persist even if curtailment has relatively minor impacts for D-PV owners in practice and underlined the importance of transparency about the real impacts of curtailment in order to prevent misconceptions. There was also a concern raised some participants that the issue of curtailment might be deliberately used by vested interests to deter D-PV adoption: "*I guess that's my first thought […] people who aren't on the solar bandwagon and how they will spread it to other people."*

5.3.3 Distribution of the impacts of curtailment

Most participants told us that they think that the impacts of curtailment should be *"fair"*, but there were contrasting views on what constitutes fair or equitable distribution of impacts in this context. There was a suggestion that the curtailment of D-PV exports should be *evenly* distributed across populations, as opposed to affecting *"certain people that are having it all the time."* However, there was a broader recognition that factors such as location and system size mean that households may contribute to and experience curtailment differently. As such, there was general acceptance that there would be unevenness in the distribution of the impacts of curtailment.

- **Spatial distribution**

Participants tended to be of the view that new housing developments in densely populated areas were more likely to be curtailed as they had a higher rate of D-PV installed. In contrast, rural households were typically perceived as having a lower risk of being curtailed due to smaller populations and fewer D-PV owners on a given line: *"We live rurally. I'm thinking on the lines in the city, it's probably gonna happen more because in a street of 20 houses, you might have 10 houses with it. Whereas in my street of 20 houses, I think we're the only ones who have it".* Interestingly, these perceptions contrast with findings that suggest that remote rural locations on a radial feeder might experience greater levels of curtailment than urban areas [23].

- **System size**

Several participants felt that larger D-PV systems contribute more towards the over-voltage conditions in the network that necessitate curtailment than do smaller systems. Thus, there was a broad sense that owners of larger systems *should* bear more of the burden of curtailment. There were also a wide range of comments concerning residential owners being sold excessively large systems, often based on attractive rebates and the promise of maximising exports to the grid. This was framed as an issue of equity, with some participants suggesting that there should be upper limits on the size of D-PV systems, in order to reduce the likelihood of curtailment and allow a greater number of households to adopt more moderately sized D-PV systems:

> *"Is it likely that the state government might reduce the amount of kilowatts or panels or whatever you have on a household now? So instead of those massive systems that are on some of the houses, they might make everyone have just a small system rather than basically being a solar panel hulk, so to speak."*

- **Duration of ownership and feed-in tariffs**

Some responses offered by participants suggested that their perceptions of the impact of curtailment could be shaped by the duration of ownership, and the feed-in tariff associated with their D-PV system. For instance, some users with older systems had significantly higher feed-in tariff rates and suggested that they were less likely to be discouraged by the curtailment of exports as they felt they had already got substantial value from their systems:

> *"In terms of the bigger picture, how much of my total bill, how much difference it's gonna make between what I could have earned and what I actually do earn after curtailment, and just with people with small systems like me, that makes no difference, but I think it was overly generous for us in the first place. So, I'm never gonna complain about anything because we got a lot more back than we ever bargained for our $16,000, ten years ago."*

In contrast, those who had purchased systems more recently with lower feed-in tariffs could view curtailment less favorably as they were typically still recovering the initial outlay on their system and thus more conscious of factors that might impact their payback period. This was also reflected in several comparisons made by recent adopters in terms of their feed-in tariffs relative to those in their social networks who adopted several years ago. These dynamics may be worthy of further investigation, given Australia's substantial fleet of legacy D-PV systems [1].

- **Residential vs commercial**

Several participants expressed concerns around whether the impacts of curtailment would be fairly distributed between utility-scale commercial generators (including solar farms) and residential D-PV owners: *"Are the actual retail consumers gonna be adversely affected compared to people that own solar farms?"* There was a perception among these participants that such commercial generators may be contributing to high voltage conditions to a larger extent than households. While this reflects a misconception about the potential for utility scale PV generation to directly impact household voltage conditions, these sentiments also reveal a principle widely articulated among participants: that those contributing more towards high voltage conditions should bear a greater proportion of the impacts of curtailment.

Participants who worked in the renewable energy sector also commented that it might be more feasible for network operators to focus attention on convincing commercial operations to shift their energy consumption and strategically increase demand, when necessary, compared to convincing millions of residential owners in South Australia that curtailment is acceptable: "*It's probably a lot easier to talk to those five businesses and support them with some tech than it is to try and talk to half a million solar users."*

- **Differences across retailers**

Participants also raised questions about whether the impacts of curtailment might be distributed unevenly across the customers of different energy retailers: "*My husband is listening in on the side and he said if next-doors are on Lumo and we're on AGL, who gets shutdown, everybody or just certain companies*..." Similarly, there were concerns around how the varied feed-in tariffs offered by different energy retailers would yield different outcomes when the potential for curtailment is considered: *"I think the complicating factor is you can be with one retailer, getting a really [good] feed-in terms, let's say, 15 cents per kilowatt hour, or you could be with another retailer who's only paying six cents per kilowatt hour, and if you get curtailment on the six-cent plan, then there's no benefit to you whatsoever."* This was another instance in which there was uncertainty around how unevenness in the distribution of the impacts of curtailment across households would manifest.

- **D-PV owners vs non-D-PV owners**

Many participants reflected on the fairness of curtailment in the context of non-D-PV owners disproportionately bearing the burden of network costs. These responses arose while discussing the broader implications of curtailment, the management of grid infrastructure, and ACOSS's rationale for endorsing two-way pricing of solar exports. For example, at one point a participant commented, *"For everybody else who doesn't have solar and is not planning to, I can see why that would feel a bit unfair that you're paying for something that doesn't really benefit you at all."* Some solar owners commented that they would not want to be part of an *"elitist solar panel owner club"* that pushes back against measures that might make the energy system more just. Indeed, some commented directly on their position of relative privilege as D-PV owners: *"The people who are 'Woe is me. I'm gonna install solar panels on my roof and gonna lose some of that solar output' are not going hungry either, let's be honest".* However, some participants also suggested that the power produced through the D-PV boom could be better harnessed by networks to address the needs of lower socio-economic groups e.g., heating and cooling during periods of low demand.

5.3.4 Relative significance of curtailment

Most participants did not have a clear grasp of what to expect and thus could not form a more definitive view of what curtailment might mean for them as current or potential D-PV owners. Participants' perceptions of the significance of the impacts of curtailment were mediated by the perceived frequency and magnitude of curtailment events. For example, one user who claimed to have experienced curtailment said that "*it's had very minimal impact at the moment, but I guess as more people get solar, perhaps it's gonna get worse...".*

In the absence of more information about the extent of curtailment, the general view was that it would be acceptable if it occurred on only a few occasions per year:

> *"If it was only one or twice in the 12 months, we'd all go, "Well, we have to take our turn, fair enough," but if it was every other week through summer, then that would really make you question whether it's, A, doing what you wanted it to do, or B, whether it was even worth buying because – it's like having a car with a flat wheel, isn't it?"*

Some participants perceived curtailment to be a relatively insignificant issue given that the main economic benefits of having a D-PV system are derived from self-consumption rather than exports. This tied into discussions around the differences in feed-in tariffs over time and between retailers: *"Because simply put the solar feed-in tariffs are not at a high enough rate to make, it makes more sense to use the energy that you generate rather than to sell it to other people, and I think that's what people have to be encouraged to do."* This indicates that some respondents had not grasped the potential for curtailment to impact self-consumption as well.

There was also a temporal dimension to participants' views on the significance of curtailment. Several participants identified BESS as integral to curbing the impact of curtailment as it enables households to prioritise self-consumption over the export of the solar electricity they generate. While households generally viewed current BESS prices as unaffordable, there was an expectation that BESS prices would be reduced in the coming years. Echoing some of the arguments laid out in [25], some participants tended to see curtailment as a relatively short-term problem that will be remedied by increased BESS uptake by households, as well as larger grid-scale storage solutions. This was apparent in comments such as *"this curtailment problem might be only a three-year issue if enough batteries are coming".*

Finally, we noted that a few participants also saw curtailment as a less significant issue when placed against the long-term social and environmental benefits associated with the role of D-PV in the transition to renewable energy: "I *think just from an environmental standpoint, I think you're doing more good in having it even though you may lose out financially possibly more frequently than you'd like, at least you're doing something good for the wider community and longevity-wise."*

5.4 Measures to address curtailment

5.4.1 Expectations of management of the grid

The general sentiment among participants was that SA's grid infrastructure is inadequate in its capacity to cope with the demands of D-PV adoption across the state. This was framed as a failure to anticipate the limitations of the network and undertake upgrades to accommodate the D-PV boom, particularly as incentives had been provided to drive adoption. One participant commented that "*all this infrastructure needs to be and should be put in place beforehand"* and another that *"They've had a very long time to deal with this and they've done nothing, so I'm not sympathetic. Curtailment shouldn't be acceptable at all".* Some participants attributed this to slow-footed responses on the part of state and federal governments to a rapidly changing energy landscape, as reflected in comments such as *"I think it's the government's a bit surprised about how it's happening, and don't know how to deal with it."*

Most participants intimated that they did not feel the grid was being managed in the best interests of households. Broadly, their comments in this respect pertained to the state of grid infrastructure and to energy prices, and implicated both SA Power Networks (SAPN) as well as energy retailers. However, it was not clear whether participants could distinguish between the roles and responsibilities of SAPN and those of energy retailers. We observed that while participants were familiar with a range of energy retailers, only a few were aware of SAPN and its role in SA's energy system. There was some distrust in the management of SA's grid infrastructure, with a few participants claiming that facets of SA's grid infrastructure were *"over-engineered"* and that the costs of *"unnecessary infrastructure"* were being passed to the consumer while the requisite upgrades to accommodate D-PV adoption were proceeding at a slow pace e.g., grid-scale battery storage. Many of the participants' expressions of distrust about the management of the grid referred to the effects of its privatization and the profit imperative that motivates the company within the sector. Distrust of retailers in particular was widely expressed as a perception that they are profiting from the low-cost power produced by households with D-PV systems: *"they're buying a product at ten cents and selling it at anything upwards to 35 to 40 cents, that's a nice margin. I'm not very sympathetic".*

Some participants questioned the distribution of the burden of accommodating the conditions of over-voltage that is seeing some households' exports curtailed, and considered that households are unfairly carrying this burden for having made a private investment that the network in fact benefits from: *"it's not our fault that we've actually spent an investment amount of money to actually be involved with this all of a sudden".* This reflects one of the two "competing narratives" that [1] outline in relation to managing high voltage conditions, with some D-PV owners clearly suggesting that the balance of responsibility ought to lie with network service providers. It also aligns with arguments made by [25] about the need for an equitable distribution of responsibilities and burdens considering the pivotal role that D-PV owners play in the energy system.

Some participants viewed D-PV curtailment as an unfair response to over-voltage because they considered alternative options to be available: *"I know the reasoning why they're doing it, but at the same time, I'm just like trying to say there are better ways of utilising that energy that is not utilised*". Others offered examples such as rapidly switching loads to manage voltage and ramping up the adoption of batteries: "*But if we have more regular demand and steady demand on the grid, from things like desalinating water or industrial processes it has helped to absorb some of the energy and drop the voltage and ease curtailment*". Participants' views on possible measures to prevent curtailment are discussed in Section 5.4.3.

5.4.2. Expectations of transparency

A common theme apparent in participants' responses was a concern about a lack of information and projections of the potential impacts of curtailment, particularly on the economic viability of their D-PV systems, including impacts on the payback period. One participant expressed the uncertainty in the following way:

> *"...there's no particular system for who's going to experience the curtailment and who's not. We've identified that it's not necessarily fair or equitable. So, it's like you're just taking a gamble from going into it. You're just gonna hope that you are not affected in a huge way. So, I think it's hard to make a balanced, informed judgement when it seems a bit unpredictable."*

Many participants also voiced strong sentiments about the need for transparency about the timing and extent of curtailment. These seemed to be grounded in a conviction that curtailment is visible and predictable to retailers and/or network operators. One participant commented that they would expect to be able to "*get an SMS and that can predict how long it's going to be. There's got to be some way and they've got so much information about this".*

Importantly, the participants unanimously believed that South Australians ought to be informed about curtailment before choosing to purchase a D-PV system: *"You would, I think, logically want to have some sort of estimate built into this process, which shows what the cost of the curtailment might be, and how often they might occur and how it might affect your particular household...."* One participant said "*We never got told about curtailment at all when we got ours. I think it would be quite beneficial that people can have a full knowledge before they consent to getting solar."* There was often an underlying assumption that actors in the sector such as installers would have access to granular information on the likelihood for curtailment in a particular area and estimates of what the resultant economic loss might be, as evident in comments such as *"a good installer, good solar company will be up to speed on this and should be able to give you an unbiased opinion as to how much you can possibly lose through curtailment.*" Others thought that information about curtailment should be provided by retailers in addition: *"I think it should definitely be highlighted by the providers as well, as one of the main points in a contract"*.

Respondents' expectation that they be able to access household-specific cost-benefit analysis to gauge whether curtailment would be acceptable to them is consistent with suggestions by [25]. These expectations can be viewed as an issue of procedural justice (Jenkins et al, 2019) as they refer to the extent to which consumers are able to access information and make well-informed decisions about the adoption and use of a D-PV system. This procedural justice lens is particularly relevant given the evidence that there is unevenness in the distribution of curtailment [1,23]. Access to information about how they would be impacted by curtailment seemed to be a vital means of maintaining trust and confidence in the management of voltage: "*Be transparent, yeah. Because I think if people believe something is fair […] you can sell us [on how] the benefits outweigh the impact to us".*

5.4.3 Proposed measures to address the impacts of curtailment

- **Consumer education**

Curtailment was seen as an added layer of complexity and uncertainty to the already challenging enterprise of researching, purchasing, and optimising the usage of a D-PV system. Participants tended to be of the view that consumer education campaigns were an important means through which both D-PV and non-D-PV owners could be better informed about curtailment and how it might affect households, especially as the energy landscape is subject to rapid technological and policy change.

As mentioned previously, most participants were not aware of curtailment or proposed policy changes prior to this research. This was reflected in comments such as "*I don't know that this curtailment issue [has] necessarily percolated to everybody's awareness yet".* It was also reflected in some of the initial responses to the concept of curtailment, with some conflating the curtailment of D-PV exports with a power cut. This was conveyed in responses such as "*It occurred to me that the curtailment is gonna be a bit like load shedding."*

Participants said that *"it is hard to know who should sell the message"* but that it should come from a trustworthy source, with one participant mentioning *"an independent body."* These sentiments around trust were couched in concerns regarding the business interests of actors such as installers and retailers, as their experiences of these actors was that they were sales-oriented and as such tended to focus on the positives of solar adoption, low upfront costs or competitive feed-in tariffs, but not on downsides like curtailment.

The emphasis on consumer education also encompassed information on how households could optimise their energy consumption considering potential curtailment. This was seen by some participants as a practical means through which households could better adapt their current energy practices to mitigate the impacts of curtailment. Responses such as *"there should probably be an education campaign on how people can maximise the efficiency of their solar systems."* reflected this sentiment. These participants also added that they felt that, as discussed previously, the true benefits of D-PV ownership lie in maximising self-consumption instead of exports to the grid.

- **BESS**

BESS were widely recognised as a necessary part of the broader transition to renewable energy. Several participants mentioned the *"Tesla battery"* in South Australia and tended to be of the broad view that it had had a very positive impact in terms of stabilising SA's grid. Thus, participants tended to be very supportive of efforts to add grid-scale storage solutions to the network and framed it as an important part of modernising the grid to accommodate the growing role of D-PV generation in South Australia. However, while most participants did recognise that home-scale energy storage (including EVs) could help mitigate the impacts of curtailment, at both the level of the household and the network, BESS were considered by most participants to be unaffordable at present, as discussed in Section 5.1.2. One participant expressed concerns that the growing issue of curtailment might lead to a surge in demand for BESS and keep prices high.

Some participants also made broader remarks about the need for legislation and incentives to drive the adoption of household batteries. For example, one solution that was offered was that new housing developments should be required to incorporate D-PV with BESS as a standard installation.

- **Network upgrades**

Overall, participants responded positively to the suggestion that network upgrades could be undertaken that could minimise, if not eliminate, the need for curtailment. They responded negatively, however, to the possibility that electricity prices could be raised to finance such upgrades. The pattern of responses indicated that participants felt that energy prices were already high and that they should be sufficient to invest in the necessary infrastructure: *"I think we already pay enough in SA. If you didn't have solar, you'd pay a ridiculous amount for electricity".* In other words, while participants were in favour of network upgrades to support the further penetration of D-PV, they did not feel that it was fair for households to bear the cost of these upgrades.

However, it is worth nothing that this study did not provide participants with specific scenarios and projections of potential bill impacts of network upgrades. As such, the sentiments expressed by participants may hinge on their own assumptions regarding the potential bill impacts of network upgrades. Related to this, an independent study commissioned by SAPN found that the vast majority (76%) of 1,004 residential customers felt positively about network upgrades when presented with information on the overall cost and predicted bill impacts of three social infrastructure investment scenarios [27]. In contrast to the negative response to the prospect of electricity price increases to fund network upgrades among our participants, that study found considerable support for a comprehensive upgrade of network capacity to enable more DER in the long-term despite it being the most expensive option for customers (although potentially more modest than they would have otherwise assumed) [27]. This aligns with our findings on the need for greater visibility of the bill impacts of curtailment, and the solutions to mitigate it. The results of SAPN's study suggest that energy users may be more amenable to shouldering network costs associated with high DER penetration if presented with clear information on proposed options and their bill impacts.

- **Flexible export limits and two-way pricing**

Most participants were unfamiliar with flexible export limits and two-way pricing as possible interventions to alleviate the issue of curtailment. When briefly introduced to these proposed solutions, participants tended to express a more favourable view of flexible export limits than two-way pricing. After being introduced to the concept of flexible export limits, a participant responded:

> *"It does mean you could recover what you lost on one day of curtailment by benefiting from an increased ability to export on a day where energy was less abundant for some reason. So, it does sound [like] it might be attractive, but really to take advantage of it, you need to have a system that could produce in excess of five kilowatts at any instant otherwise you wouldn't gain anything from it."*

Our introduction to the AEMC's proposal for two-way pricing presented participants with a broad overview of the concept and included perspectives for and against it. It should be noted that participants were generally unaware of media reports about it, such as those that framed it as a "solar tax". The responses from participants were varied, with some agreeing with the principle of two-way pricing, while others felt that it might be unfair to D-PV owners.

One participant who had a more favourable view said they think that *"the principle of the measure is a good one",* but would need to know more about *"how it would work in practice."* Connected to previous points about the perceived visibility and predictability of curtailment, some participants expected more tailored information to form a clearer view of the merits of such a proposal, with one participant stating that they "would like to see how the numbers work out over a 12-month period".

Some respondents were particularly sensitive to the concept of being charged for exporting power to the grid. This was seen as a punitive measure when owning D-PV systems and contributing power to the grid should be lauded and encouraged. In this vein, one participant said *"They're gonna charge us for producing too much when they don't need it. No, that's a flat-out no for me".*

Participants also grappled with the implications of such a proposal for non-D-PV owners, particularly those in socio-economic groups who spend more of their income on electricity in proportional terms. Several participants grappled with these issues of equity and expressed the need for fairer solutions. There was a general view that D-PV owners are in a position of relative privilege compared to these groups, and that they *"did not want to be part of that group"* that is uncaring for those who could not afford D-PV or faced other structural barriers to adoption.

However, some participants also pushed back against narratives that pit D-PV and non-D-PV owners against each other, suggesting that issues of accessibility and energy poverty are symptomatic of broader failures in governance: *"If [the] government is really concerned about non-solar households, if in fact the operators were concerned about non-solar households, they might invest in a few community-based systems... but none of that is happening."*

- **Compensation for curtailment**

Some participants were of the view that compensation for curtailment might be a more equitable approach. An example of such a response was *"'Yeah, you can turn my power off. Can you give me something for that?' it's a two-way gain"*. Another participant elaborated on this in terms of both the fairness of compensation, and a means through which to overcome potential D-PV owner resistance to proposals that might be framed as a "loss" or a "solar tax." This speaks directly to arguments outlined in [25] about customer compensation for losses as an important means through a "social license" for curtailment could be obtained and maintained. One participant commented:

> *"I was talking to someone the other day who was all upset about solar and this external ability to control it and turn it on and off, but it's a pretty easy problem to resolve...it's not that hard to put a sum against it and go "Oh, gee, we're doing it five times a year and it's for two hours at a time and so the feed-in tariff you would have lost is this, $2 or something like that. So, we're gonna reimburse you $4." It means nothing to anyone, improves the stability of the grid, makes everyone feel good. I think it's kind of a no brainer. It's all in the messaging."*

- **Community-scale solar**

There were also a range of responses that mentioned community-based PV schemes to include a broader base of the population in the transition to renewable energy and, reduce the need for curtailment e.g., community-scale batteries. One participant described Australia's reliance on D-PV as an *"individualistic approach"* to energy generation: *"Australia is unique, one household, one system, one battery, the household wears the cost, wears the benefits mostly but community schemes are effectively missing."* Other respondents spoke of "community-size batteries", referred to community-based models of ownership that exist in other countries and cited the need for businesses and councils to facilitate solutions at this scale.

6 Data-driven technical analysis findings

This section presents the findings from data-driven technical analysis. Initially the voltage conditions are presented for the AGL and Solar Analytics sites located in the Adelaide metropolitan region. Next, the results of the tripping (anti-islanding and limits for sustained operation) and V-VAr curtailment analysis are presented.

6.1 Voltage conditions

Previous research has presented the voltage conditions across the low voltage networks in South Australia, as well as across other states in Australia [10]. This study particularly focuses on the sites within the metropolitan Adelaide region, with a smaller sample of sites; nevertheless, it is useful to observe and compare the voltage conditions in order to provide context to the over-voltage curtailment analysis that follows.

Figure 10 presents the distribution of voltages from the AGL data-set across the 12 month period via the use of Box-Whiskers plot*. The voltages are lower during winter and higher during spring consistent with previous analysis [10]. On the other hand highest voltages are observed during summer instead of spring months. The monthly 99th percentiles sit above the required 253 V threshold (shown with the red line) across the year except for the winter months. It is critical to note that this does not necessarily indicate non-compliance with the voltage standard, due to differences in voltage measurement point, measurement interval and population considerations of the dataset vs standards.

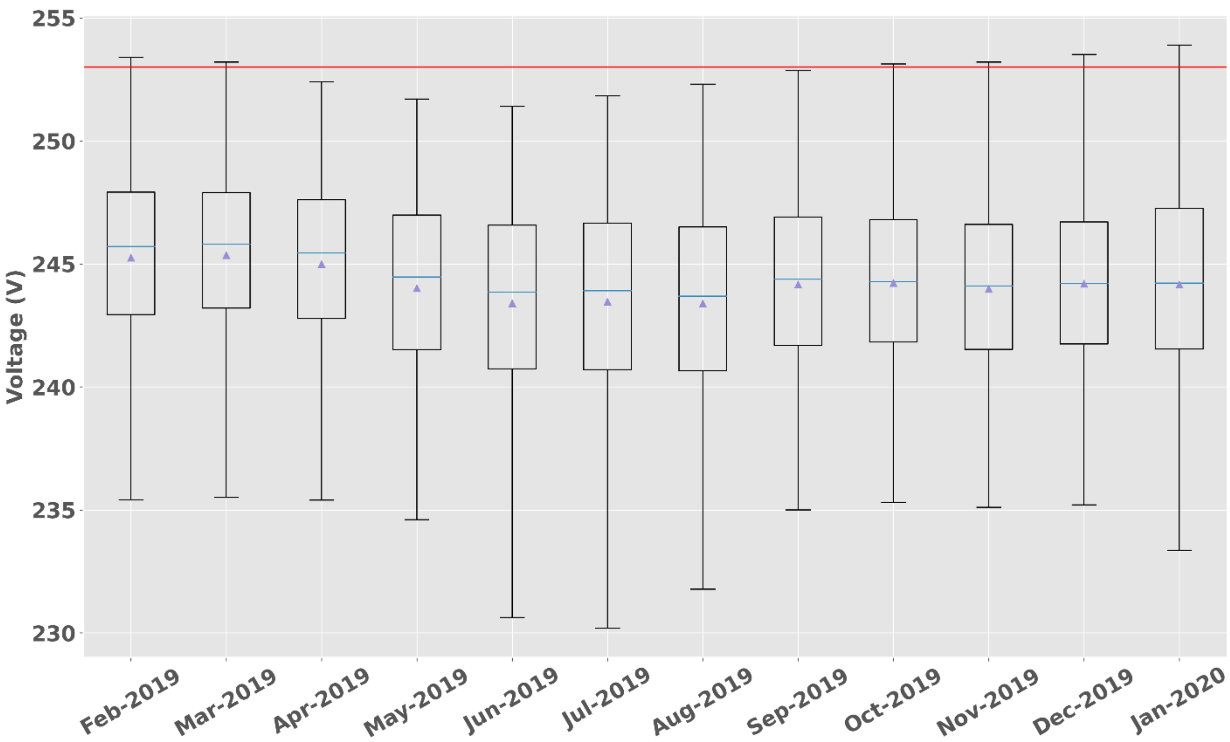


Figure 10 Distribution of voltages from AGL VPP sites over 12-month analysis period

Figure 11 presents the distribution of voltages from the entire yearly analysis period, grouped by 24-hourly periods for the AGL data-set. The results support the findings of our previous research [10], as the voltages are high both during the solar window period as well as late-night periods where the network load is lower. Nevertheless, this figure indicates that voltages are high during the middle of the day as expected, corresponding to lower load and higher D-PV generation.

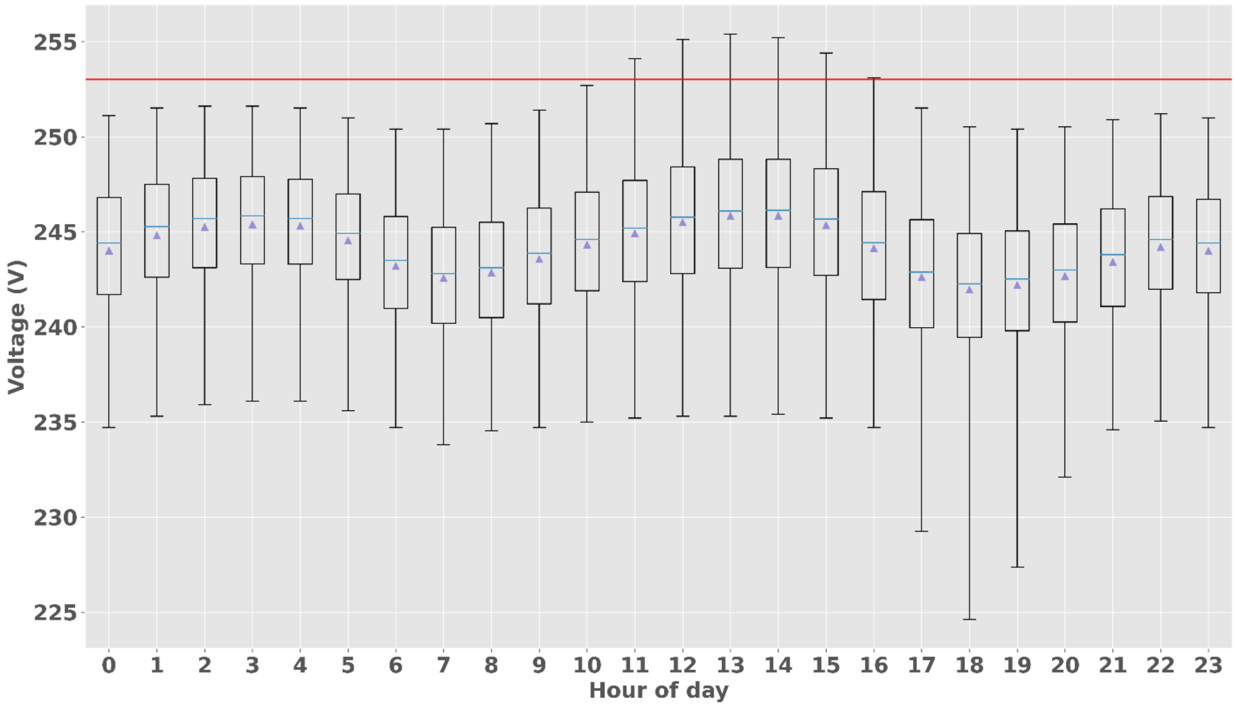


Figure 11 Distribution of voltages from AGL VPP sites over 24h

Figure 12 presents the monthly distribution of voltages from Solar Analytics sites across the 10-month analysis period. It is seen that the 99th percentiles of monthly voltages are consistently above the 253 V threshold and voltages are highest during spring, as expected from our previous research [10]. Contrary to the results obtained with AGL data and reported in previous research [10], December and January show the low voltage distributions like the winter months July and August. Solar Analytics dataset didn't include household load data which may have had an impact in this voltage behaviour and further research is required to understand the reason behind this phenomenon.

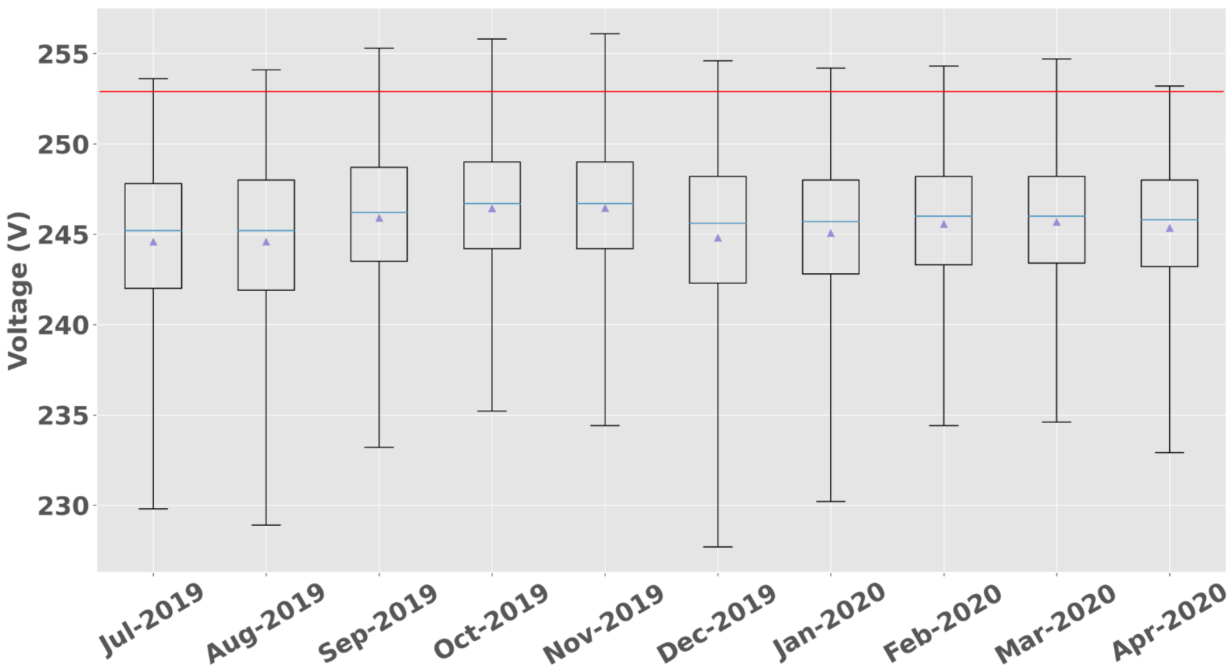


Figure 12 Distribution of voltages from Solar Analytics sites across 10-month period

Figure 13 presents the distribution of voltages from the 10 month study period grouped by 24-hourly periods for the Solar Analytics data-set. The results show higher voltage distribution compared to the

AGL data-set especially across the solar generation window. It should be noted that the voltage measurements are recorded at the main switch board (MSB) for the Solar Analytics dataset in contrast to the BESS inverter terminals from the AGL dataset; therefore, during the solar generation window, a voltage drop is expected from MSB to BESS which may contribute to this voltage difference. The results also support the findings of our previous research [10], as the voltages are also high during late-night periods where the network load is lower.

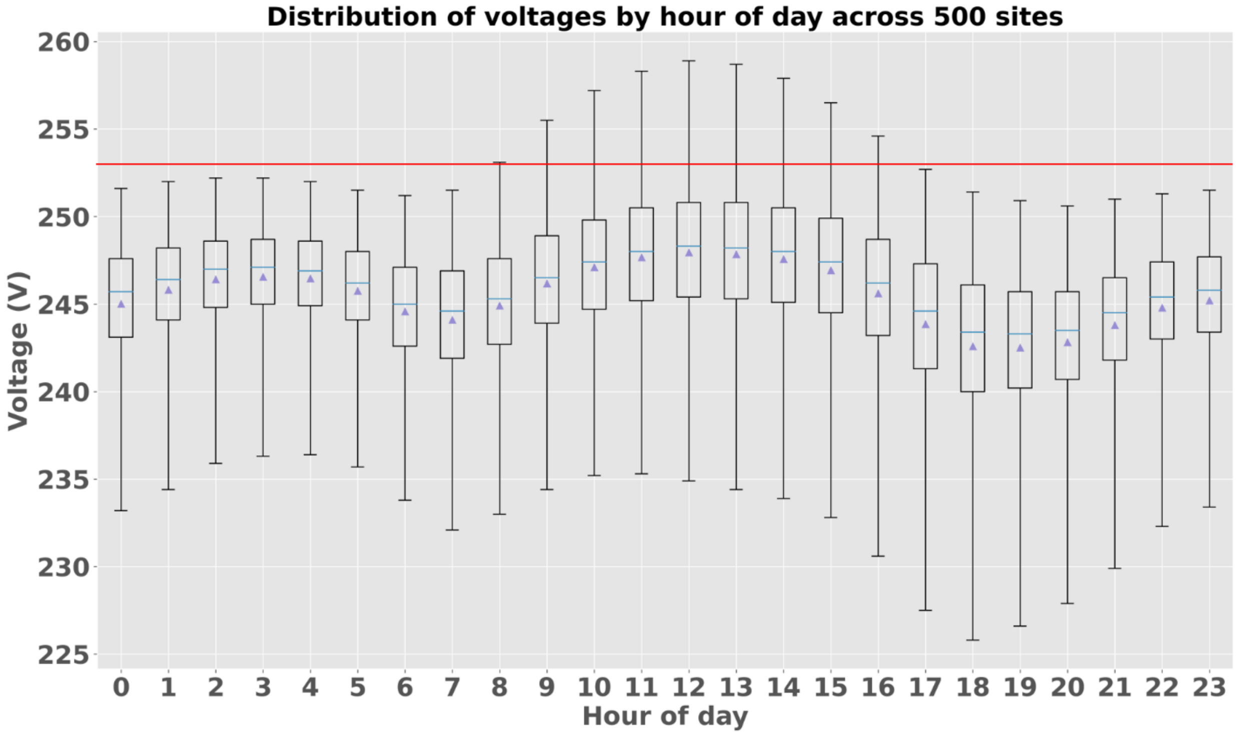


Figure 13 Distribution of voltages from Solar Analytics sites over 24h

6.2 'Tripping' (anti-islanding and limits for sustained operation)

6.2.1 D-PV 'tripping' (anti-islanding and limits for sustained operation)

6.2.1.1 Significance

Analysis of the Solar Analytics data indicates that overall, the proportion of generation lost due to tripping curtailment is very low, with an average of 0.35% generation being curtailed across all sites across all days. Surprisingly, when only clear sky days were considered average curtailment remained very low, with 0.37% generation being curtailed across all sites.

This is lower than previous analysis that found around 1.1% of generation on average was being curtailed due to 'tripping' on clear sky days [1]. The discrepancy in curtailment on clear sky days is possible due to differences in the sample, since large samples are required to capture 'edge cases' experiencing significant curtailment and previous work analysed over 1,300 sites whereas the work presented here analyses 500 sites. In addition, all of the sites in the dataset analysed here are located in greater Adelaide, whereas previous analysis considered sites across South Australia and so was more likely to capture curtailment occurring in rural regions. Further, discrepancies may also be due to differences in the characteristics of identified 'clear sky days', with only a small number of clear sky days identified in each year, and potentially highly varied load conditions across the clear sky days in this study, compared with previous work. This is a valuable area for further investigation.

Table VI Average 'tripping' (anti-islanding and limits for sustained operation) curtailment experienced at 500 D-PV sites

Average curtailment:	All days	Clear sky days only
All sites (including zero curtailment sites)	0.35%	0.37%
Impacted sites only	2.17%	5.61%

Although curtailment was low overall, a small proportion of sites are found to be significantly impacted, consistent with previous work. The most impacted D-PV site in the dataset experienced around 20% curtailment over the entire 10 month period, however all other sites experienced a maximum of 10% curtailment over the period and the majority experienced negligible curtailment as shown in Figure 14.

Further, the proportion of days on which *some* curtailment occurs is relatively high, with 20% of sites experiencing curtailment on at least 21% of days over the 10 month period. This suggests, that whilst curtailment due to anti-islanding and limits for sustained operation activation impacts a small proportion of overall generation, it does appear to occur very frequently.

Five of the 'most impacted' sites shown in Figure 14 are considered as case studies in section 6.2.1.3.

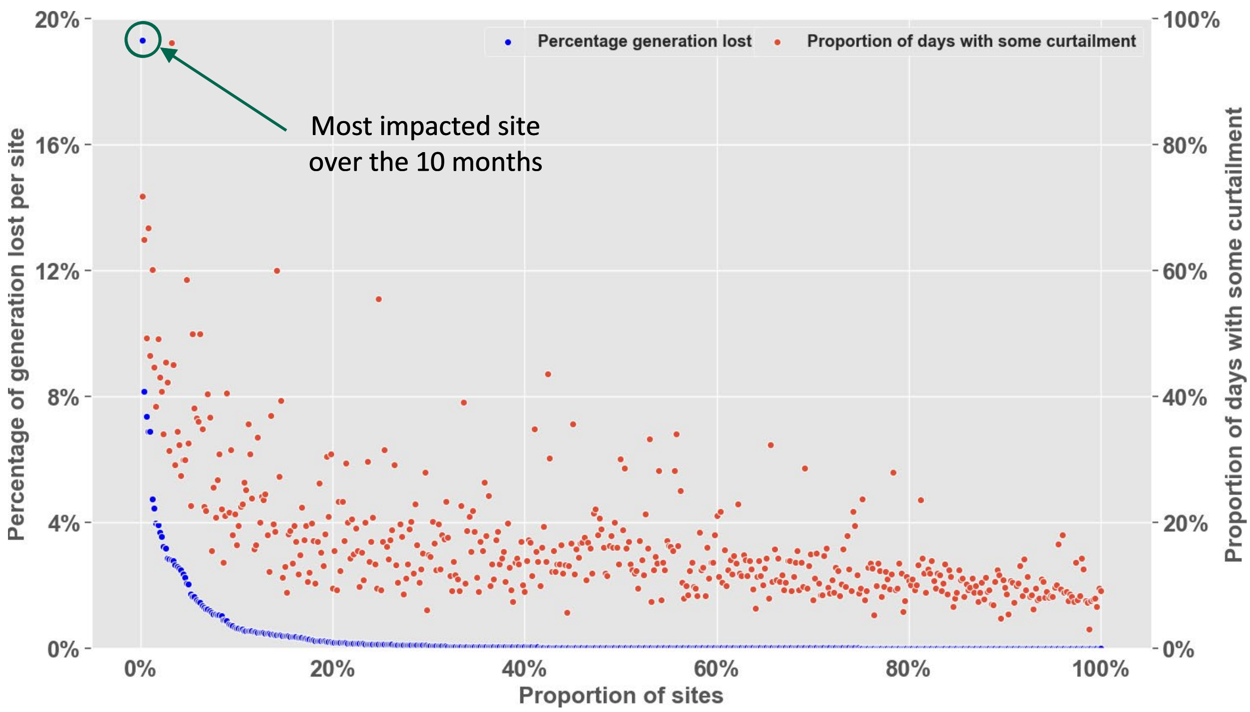


Figure 14 – Distribution of D-PV 'tripping' curtailment
Percentage of total generation being curtailed and proportion of days with curtailment occurring, 500 Solar Analytics sites from Greater Adelaide

6.2.1.2 Seasonality

Consistent with previous analysis, 'tripping' curtailment occurs more in spring and late winter compared with other months. Curtailment rates also appear to be significantly higher on 'clear sky days' compared with non-clear sky days, as expected given the likely higher rates of PV export on clear sky days (Figure 15).

Figure 15 indicates that some sites experience very high daily curtailment upon occasion, with a few outliers in the range of 60-80%. However, the majority experience minimal curtailment over the course of the year.

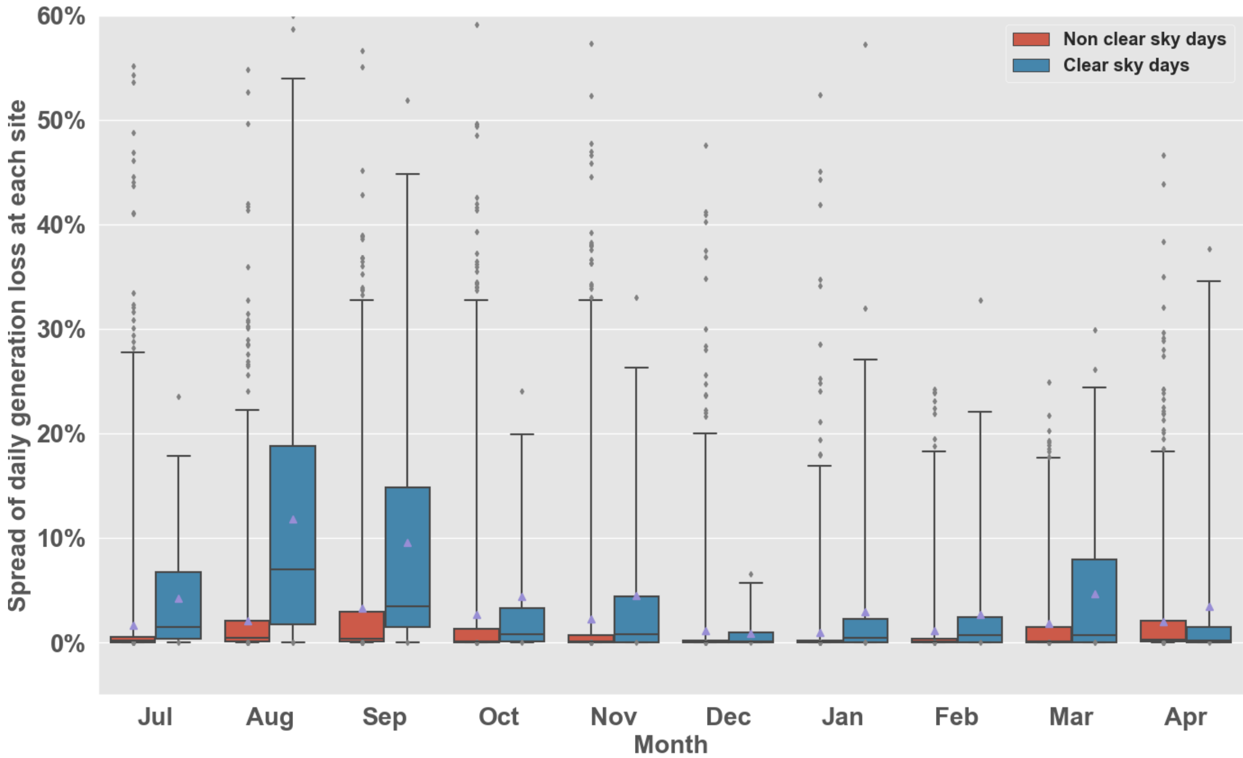


Figure 15 – Distribution of daily D-PV 'tripping' curtailment by month
Impacted sites only (excludes zero curtailment sites). Solar Analytics data from 500 sites July 2019 to April 2020

6.2.1.3 Case studies: most impacted D-PV sites

A key question that emerges from this analysis, is how curtailment may change over time, and particularly whether the number of 'edge cases' experiencing significant curtailment are growing. This is a complex question and an important area for future work. It is important to note that anti-islanding and limits for sustained operation set points have increased in the updated standard (AS4777.2-2020) compared with the previous standard (AS4777.2-2015). This change will likely reduce the degree of curtailment due to over-voltage 'tripping' into the future.

As an initial exploratory step, several of the most impacted sites are considered as 'case studies' to investigate whether there may be common characteristics resulting in higher levels of curtailment.

The five most impacted sites are considered. Each was in a different postcode as shown in Figure 16. Other sites in these same postcodes were not heavily curtailed, although based on the data available, it is not possible to assess whether any other sites in the Solar Analytics dataset were on the same feeder as these five most curtailed sites. All five systems have similar capacities (4-5kWac) and all installed after October 2016, meaning the inverters are expected to comply with AS/NZS 4777.2-2015. The majority of sites in the dataset are of a similar capacity and vintage – therefore it is unlikely that either factor is the cause of the higher levels of curtailment observed.

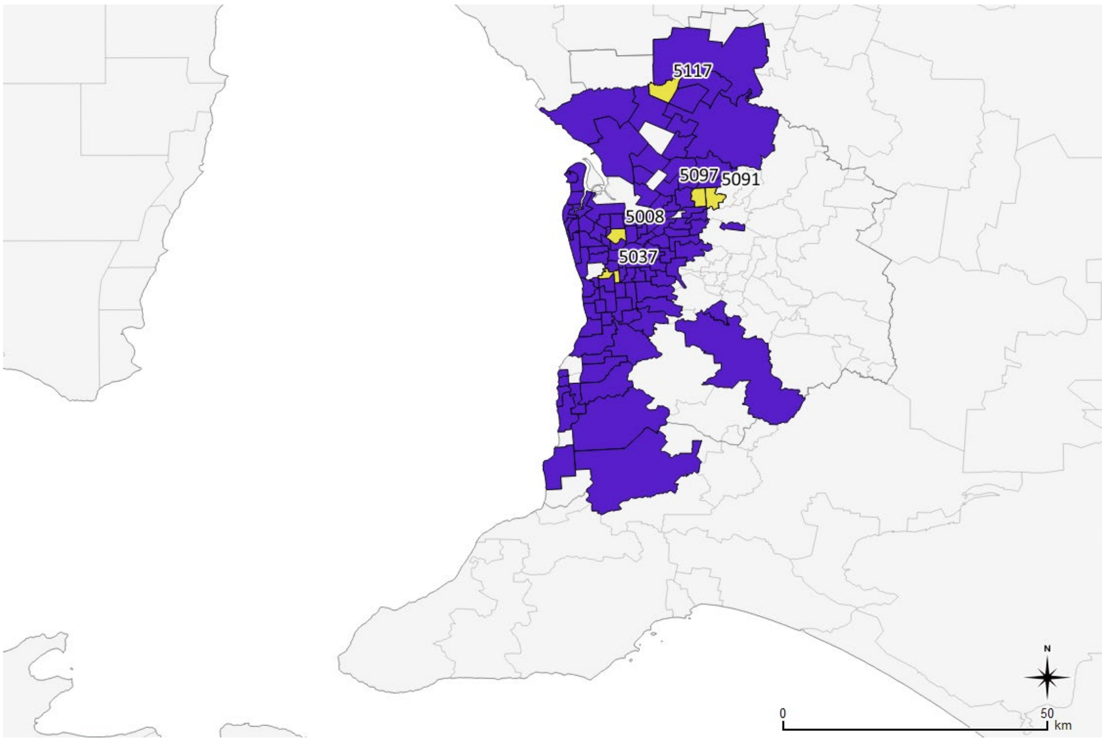


Figure 16 – Postcodes included in the Solar Analytics dataset (purple) including regions containing five most impacted sites (yellow)

Figure 17 shows the spread of 'pre-curtail voltages' compared with all other voltages during D-PV generation hours. It indicates that generally the pre-curtail voltage is higher than voltages the rest of the time. This supports the assumption underpinning the analysis that the 'tripping' behaviour observed is due to local over-voltage conditions. However, it is important to note that the vast majority of observed 'pre-curtail voltages' at these sites are lower than the default anti-islanding set points specified in AS4777.2-2015 (260V and 265V). The majority of observed 'pre-curtail voltages' at these sites are also lower than the default limits for sustained operation set point (255V). Possible explanations for this discrepancy include the following:

- The voltage measurements may not be capturing the conditions that caused tripping, given that the measures are a 'snapshot' during each 60s interval.
- The anti-islanding and limits for sustained operation set points may be set lower than the default values at these sites.

Further investigation of these specific sites is therefore warranted, as the actions required to reduce tripping could vary substantially if it is indeed the case that these most impacted sites had anti-islanding and limits for sustained operations set points that are lower than the default values. It is worth noting that under the revised standard, AS4777.2-2020, the default set points are increasing (to 265V, 275V in the case of anti-islanding and 258V in the case of limits for sustained operation).

It is important to note that the site experiencing the greatest level of curtailment ('site 1') exhibits a very wide spread of voltage conditions. Despite that the majority of voltages are between 240-250V, voltages below 220V are not uncommon, and outliers fall nearly to 180V at which point the inverter would also be expected to 'trip' on anti-islanding set points.

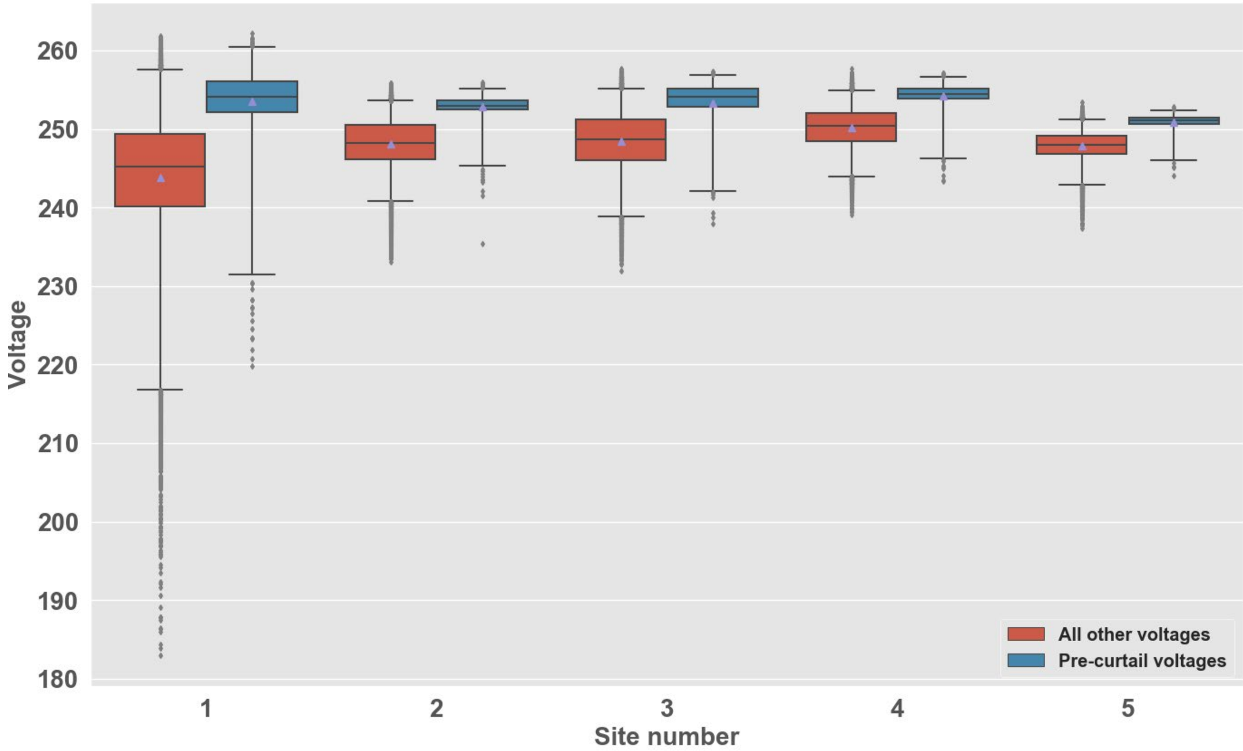


Figure 17 – Spread of pre-curtailment voltages compared with all other voltages (during D-PV generation hours) for the five most impacted sites

Examples of the dates on which these sites experienced the greatest level of curtailment are shown below. The two most impacted sites ('Site 1' and 'Site 2') are shown in Figure 18 and Figure 19 respectively. These daily profiles also indicate that Site 1 experiences a much wider voltage range than Site 2. It also appears that voltage at Site 2 is impacted by the reduction is D-PV generation when it trips, whereas the voltage at Site 1 appears to be more impacted by other activity on the local network.

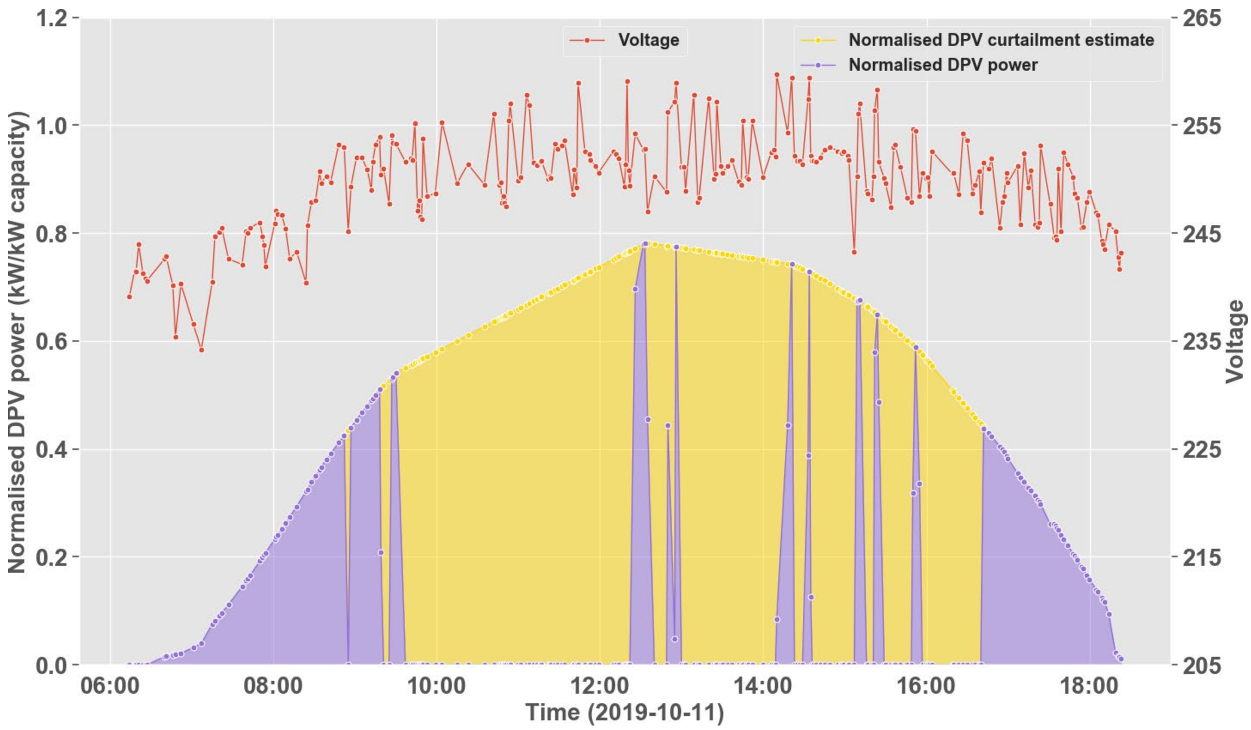


Figure 18 – Site 1 most curtailed day 11 October 2019
(non clear-sky, ~61% generation curtailed)

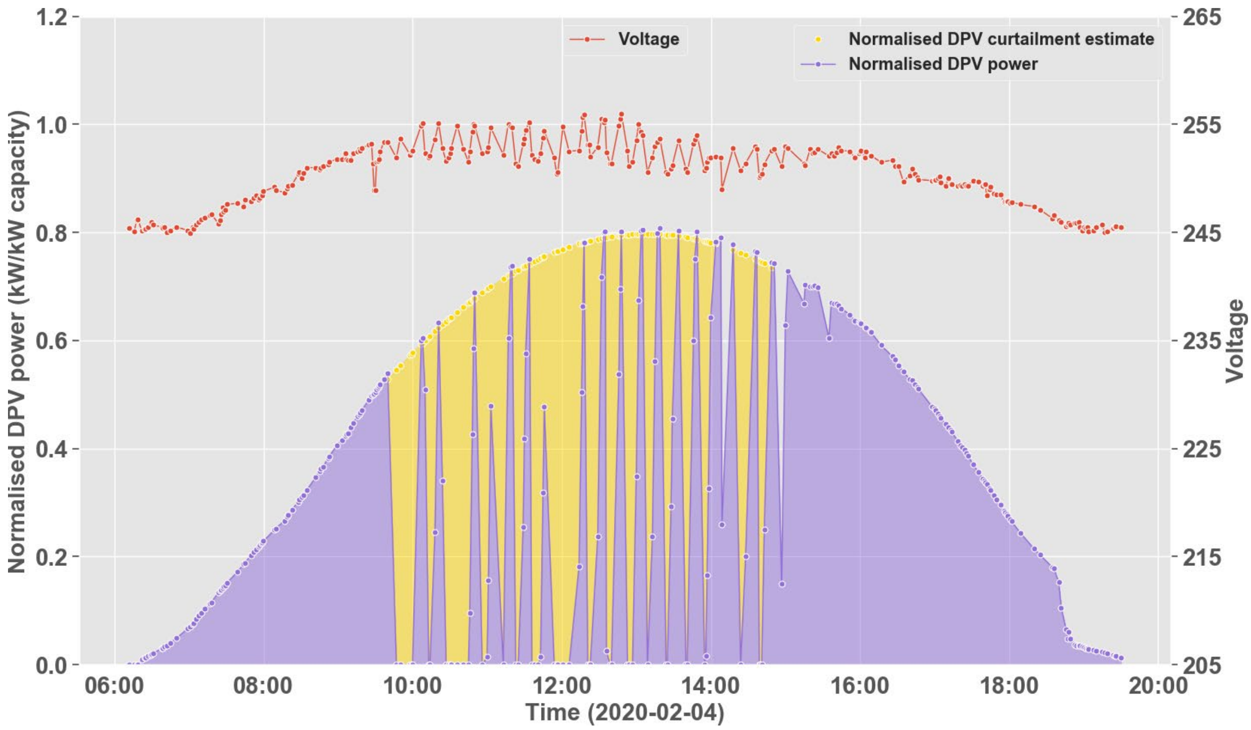


Figure 19 - Site 2 most curtailed day 4 February 2020 (clear-sky, ~33% generation curtailed)

6.2.2 BESS 'tripping' (anti-islanding and limits for sustained operation)

Before presenting tripping (anti-islanding and limits for sustained operation) curtailment results for AGL VPP sites with BESS, it is important to emphasize the assumptions and challenges associated with this particular analysis. Depending on the VPP's operational strategy, the VPP operator may decide to stop discharging batteries at any point in time and reserve the BESS's SOC. For example, a short term forecast of a high spot price event may trigger BESS to stop discharging immediately. Or similarly, a VPP operator may decide to stop charging batteries and start exporting all available excess D-PV generation due to an operational decision. Therefore, it is not straightforward to differentiate these VPP decision-based events from real tripping (anti-islanding and limits for sustained operation) events, since during both types of events BESS power reduces to zero and remains inactive for a period of time.

In addition, during the analysis, it was found that for some BESS, minimum SOC was non- zero; moreover, the minimum SOC value changed over time. We understand that for Tesla batteries, customers can configure the minimum state of charge for their batteries themselves using the Tesla app (to ensure a minimum level of backup power), which could explain some of the variation in behaviour observed. This created further difficulties in estimating available BESS SOC when assessing tripping (anti-islanding and limits for sustained operation) curtailment for discharge events. In some cases, the algorithm therefore would assume that charge was available for discharge, when in fact the battery had stopped charging due to reaching its minimum SoC. For these reasons, the results presented here are likely to be an over-estimation for the tripping (anti-islanding and limits for sustained operation) curtailment for BESS.

Figure 20 presents 100 AGL VPP sites with highest tripping (anti-islanding and limits for sustained operation) curtailment shown as a percentage of the total D-PV generation. The site with the highest curtailment loses around 1.75% of total generation and great majority (99%) of the VPP fleet loses less than 1% of total D-PV generation due to tripping (anti-islanding and limits for sustained operation) curtailment. Figure 20 also breaks down the curtailment into instances associated with BESS charging and discharging. It is seen that tripping (anti-islanding and limits for sustained operation) curtailment is mostly attributed to instances where BESS would otherwise be discharging to avoid importing energy.

On average the fleet loses 0.06% of total D-PV generation due to tripping (anti-islanding and limits for sustained operation) curtailment.

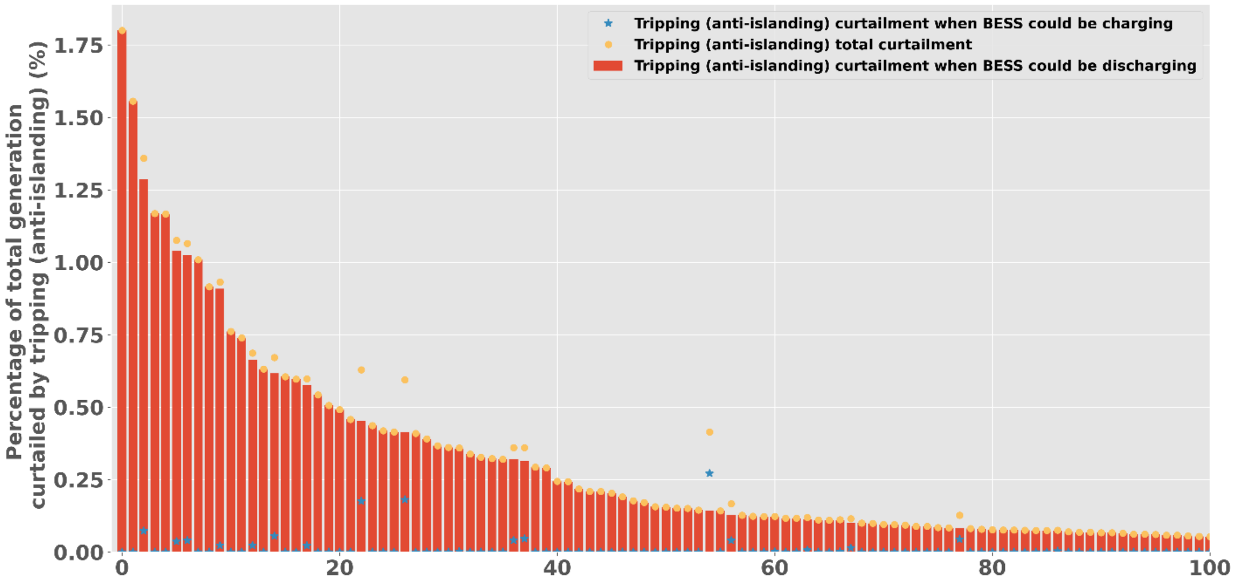


Figure 20 Percentage of total generation curtailed by tripping (anti-islanding and limits for sustained operation) for 100 AGL VPP sites with highest curtailment

6.3 Volt-VAr response mode

6.3.1 BESS V-VAr characteristics

Before presenting V-VAr curtailment results, it is important to understand the VAr operating characteristics of the BESS. To the author's knowledge, there has not been publicly available information on actual operational reactive power characteristics from a large number of BESS in Australia.

Figure 21 below shows the percentage of times each of the BESS is injecting or absorbing VAr (left y-axis) and the ratio of average VAr to rated VA of BESS (right y-axis). Absorbing VArs are denoted with negative values and injecting VArs are denoted with positive values on the right y-axis. The sites are ordered according to the percentage of VAr injection.

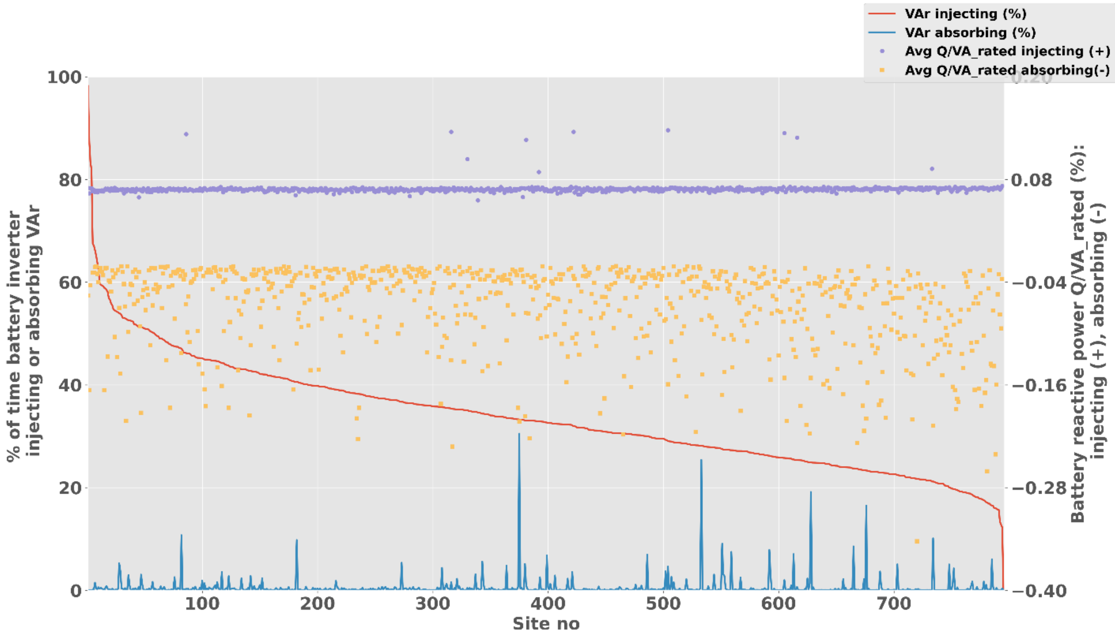


Figure 21 Percentage of time BESS is injecting or absorbing VArs (left y axis) and average rate of VAr injection or absorption (right-axis) ordered by the percentage of injecting VArs

An important observation from Figure 21 is that most sites have similar average VAr injection, around 8 % of rated VA; on the other hand, VAr absorption varies more significantly across sites with some sites have average VAr absorption rate up to 35% of rated VA. It is also seen that some BESS inject VArs almost all the time and a great majority of BESS inject VARs at least 20% of the time. However, BESS absorb VArs for a much less significant amount of time, and the majority of BESS absorb VArs less than 5% of the time.

Figure 22 shows an example weekly operation from a sample BESS. The BESS injects a constant quantity of VArs especially during the D-PV generation period. This phenomenon is observed for almost all sites where BESS injected a small quantity of constant VAr during the D-PV generation window.

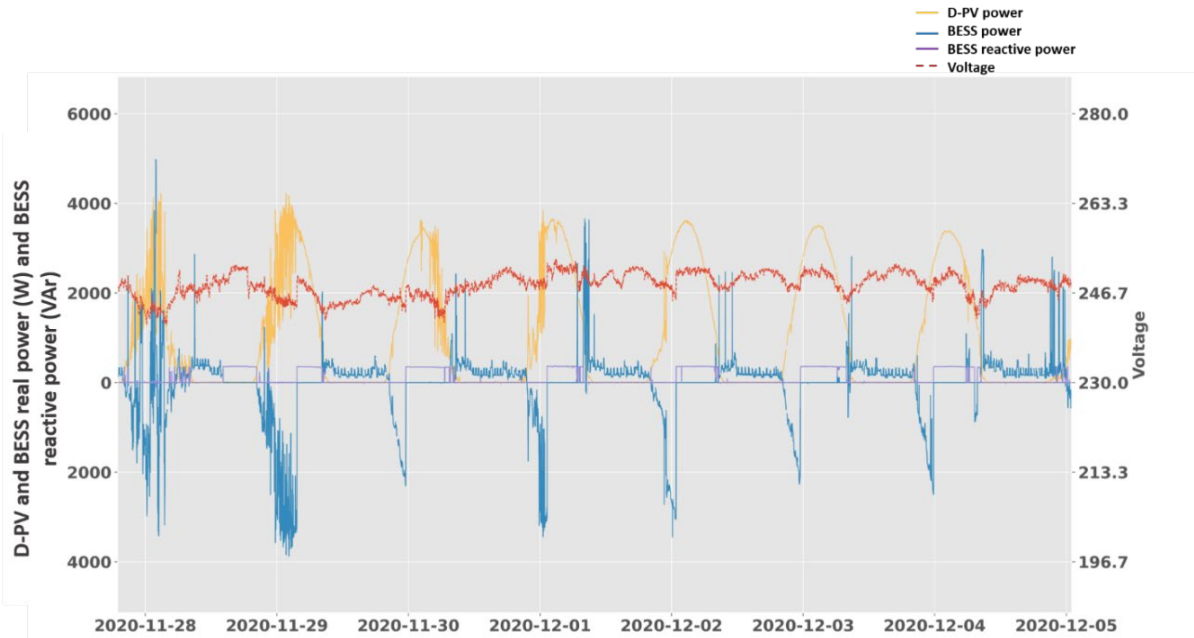


Figure 22 Example daily operations from a sample site showing daytime constant reactive power (VAr) injection

Figure 23 further analyses the temporal characteristics of BESS VAr injection across AGL VPP sites by plotting the box plot distribution of VAr injection across 24-hours. The distribution clearly shows VAr injection is especially prevalent during the D-PV generation window. In response to our enquiries, BESS original equipment manufacturers (OEM) stated that BESS are expected to inject small quantity of VArs during D-PV generation and charging periods; however, the exact reason for this type of behaviour was not specified.

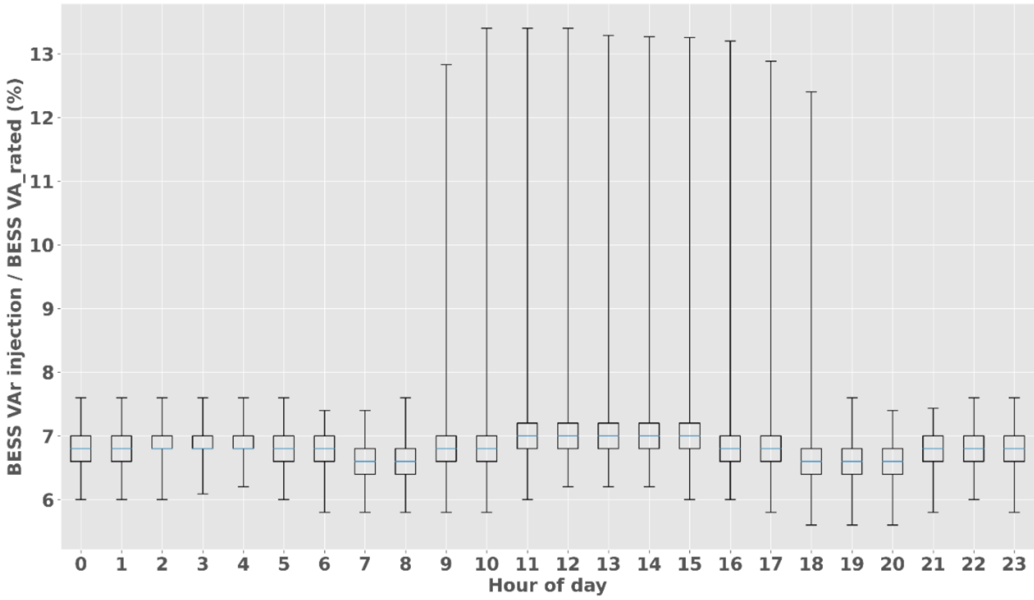


Figure 23 Distribution of BESS VAr injection across 24-hours from AGL VPP sites

Figure 24 shows the distribution of VAr absorption across 24-hours for the Tesla VPP sites. It can be seen that the rate of the rate of VAr absorption is higher than the rate of VAr injection shown in Figure 23. More importantly, rate of VAr absorption increases during D-PV generation period. This may suggest that higher voltages during the D-PV generation may trigger BESS to absorb higher VAr as per the V-VAr characteristics specified in standard. This point will be further investigated in the next section. Another interesting point is that at 3 am, BESS showed extremely high VAr absorption, with the 99th percentile reaching up to a 100% VAr/VA ratio. This phenomenon was further investigated and after consultation with AGL, it was found that this high VAr absorption distribution is due to occasional VPP operational tests that was carried late at night.

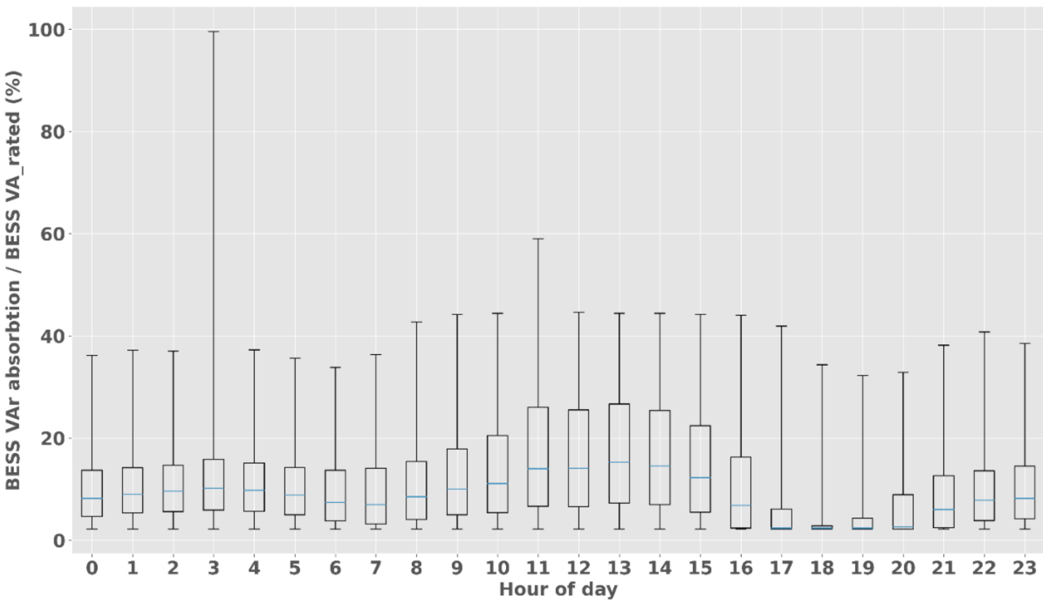


Figure 24 Distribution of BESS VAr absorption across 24-hours from AGL VPP sites

6.3.2 BESS and D-PV Volt-VAr curves

Both D-PV and BESS inverters are expected to inject or absorb VArs based on the experienced voltage conditions according to the rules defined in Australian Standards AS/NZS 4777 (i.e., Volt-VAr settings). The inverter's VAr behaviour will also depend on its installation date and the respective standard version that was in place at that time, since newer standards have different settings compared to legacy standards (see Figure 9).

The AGL VPP dataset does not include any information regarding the inverter settings or the version of the standard that applied at the time of installation. Therefore, it was found useful to investigate scatter plots of the VArs vs. voltage to identify which V-VAr curve each BESS inverter operates according to. Figure 25 shows VAr vs V scatter plots for 12 months from the BESS inverter which had the highest VAr response amongst 996 sites from the AGL VPP dataset. As per the site monitoring sign convention, absorbing VArs are denoted with negative values and injecting VAr are denoted with positive values. It is observed that this BESS mostly operates according to the TS-129 V-VAr curve characteristics (see Table V). It is also seen that there is VAr injection at the 0.08 VAr/VA_rated level across a wide range of voltages which is consistent with the previous finding where BESS injected constant quantity of VAr across the D-PV generation window. As voltages go lower than 220 V in winter months, there are higher levels of VAr injection as per the TS-129 V-VAr requirements.

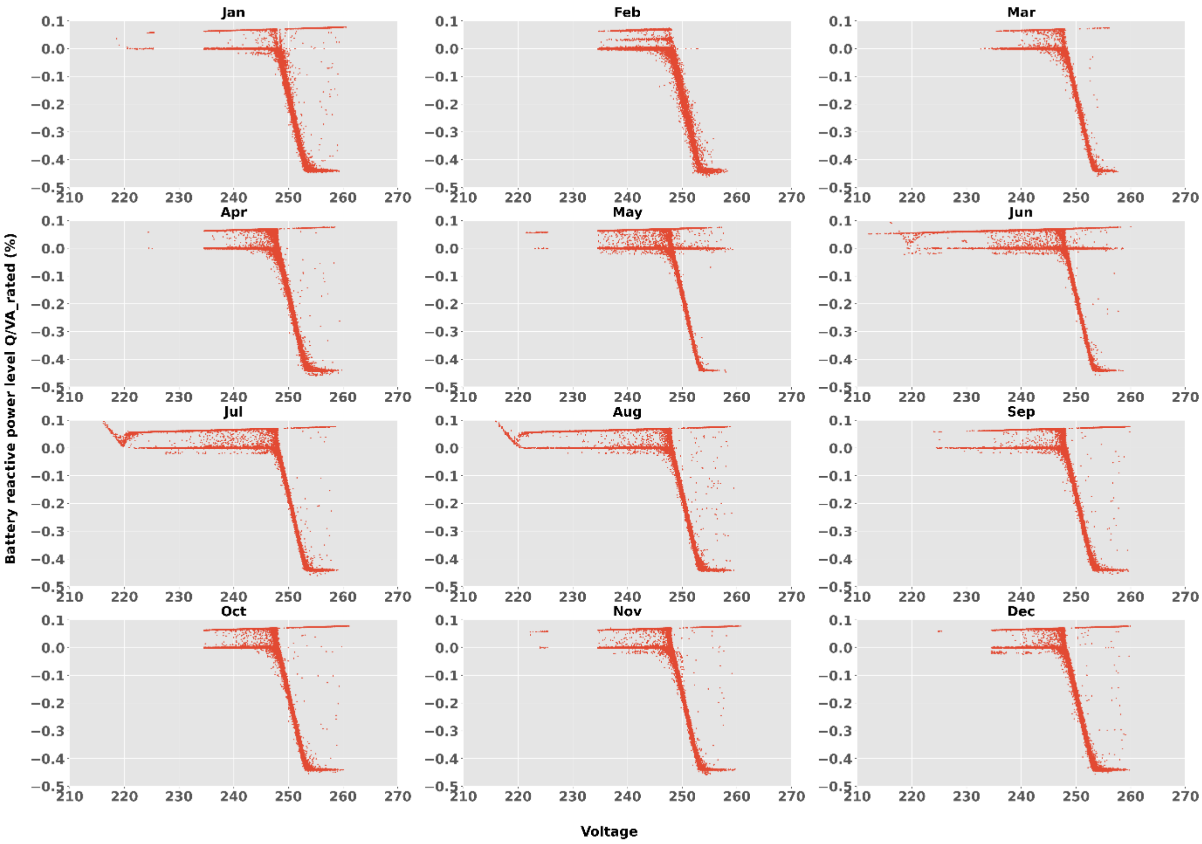


Figure 25 Q/VA_rated (%) vs. voltage scatter plot from the BESS inverter with highest VAr response across 12 months

In contrast to Figure 25, Figure 26 demonstrates a sample BESS which does not show any clear V-VAr response. The BESS inverter injects or absorbs random quantities of VAr across the experienced voltage conditions.

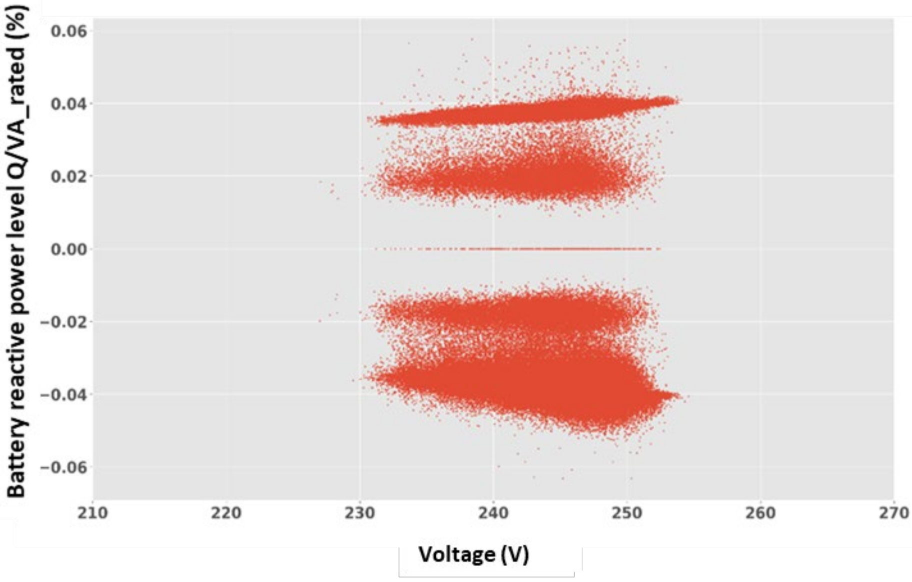


Figure 26 Q/VA_rated (%) vs. voltage scatter plot from a sample BESS inverter with no clear V-VAr response

In fact, the analysis showed that only a small number of BESS inverters showed a clear V-VAr response according to one of the reference V-VAr curves (see Figure 7) and the majority failed to inject or absorb VArs during under and over voltage events, instead showing negligible or zero VArs. After consultation with AGL, it was confirmed that most BESS were installed prior to July 2019 after which TS-129 took effect and therefore, even though BESS could be equipped with the previous AS/NZS 4777-2015 V-VAr settings, they were not mandated at that time to show any V-VAr response. This explains the reason why most BESS didn't show any V-VAr response. Table VII below summarizes the results of the V-VAr curve investigation for the AGL sites.

Table VII Percentage of BESS inverters that show V-VAr response according to one of the reference V-VAr curves or shows no V-VAr response

	SAPN TS-129	AS/NZS 4777-2015	ENA 2019 recommendations	AS/NZS 4777-2020	No V-VAr response
Percentage of BESS inverters that are compliant with reference V-VAr curves (%)	7	1	0.4	0	91.6

Similar investigation was carried out for D-PV inverters from the Solar Analytics dataset. It was found that only a small number of D-PV systems showed V-VAr response similar to any of the studied reference V-VAr curves. Figure 27 shows an example from the D-PV inverter which showed the clearest V-VAr response amongst the studied Solar Analytics fleet. It is seen that it starts absorbing VArs at 248 V and reaches peak VArs at 253 V as per TS-129 however peak VArs are at the 70% level, much higher than the reference threshold 44%.

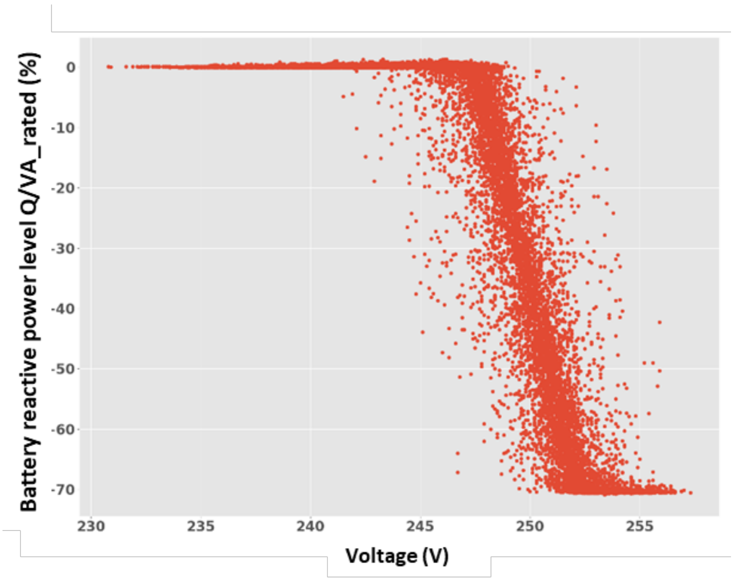


Figure 27 Q/VA_rated vs. voltage scatter plot from the D-PV inverter with most clear V-VAr response

Further analysis has shown that D-PV inverters exhibited different VAr and power factor (PF) characteristics. The majority of the D-PV inverters did not show V-VAr response and operated at unity power factor as shown in Figure 28. Figure 28 a) shows scatter plots for reactive power level Q/VA_rated (%) vs. real power level P/VA_rated (%) with blue dots (left y-axis) and PF vs. real power level P/VA_rated (%) with purple dots (right-y axis). Figure 28 b) shows the scatter plot for reactive power level Q/VA_rated (%) vs. voltage.

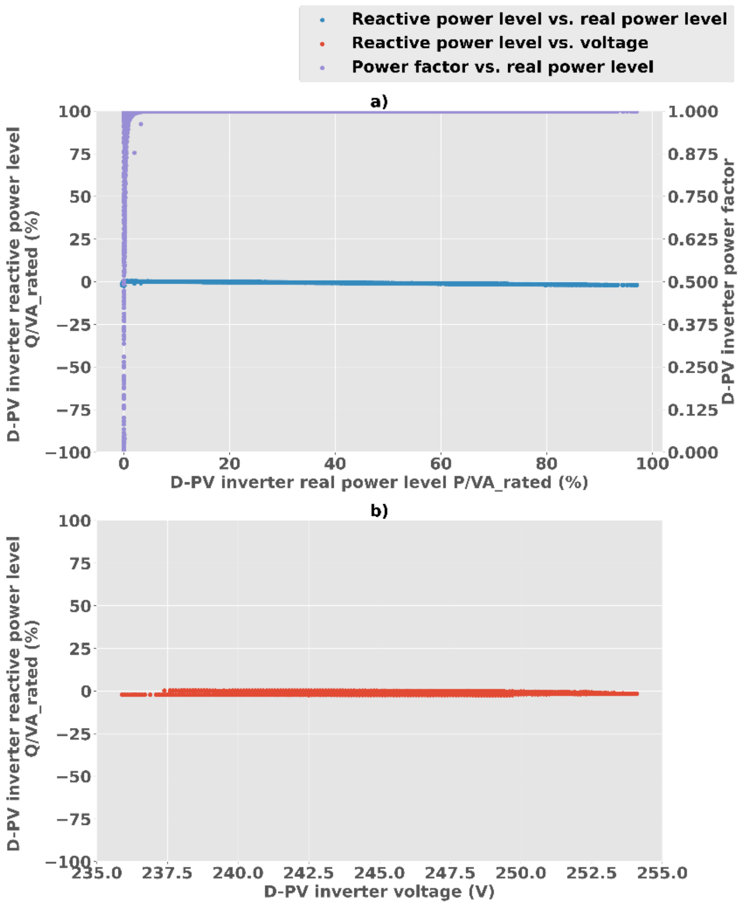


Figure 28 VAr and PF characteristics of a sample D-PV inverter which doesn't show any V-VAr response and operates at unity power factor

Figure 29 shows a sample D-PV inverter which doesn't show any V-VAr response, but its PF increases with increased real power. Figure 30 on the other hand shows a different sample of D-PV inverter whose PF decreases with increasing real power due to significant increase in VAr absorption. Daily example operations for this type of VAR and PF behaviour are also presented in Figure 39.

A final sample D-PV inverter is presented in Figure 31 which shows varying PF behaviour depending on the real power level: PF increases with real power at lower real power levels and decreases with real power at higher power factor level. D-PV inverter behaviour seen in Figure 28 and Figure 29 is expected given that these had AS/NZS.2.4777 settings in place; however, the behaviour observed in the latter two figures (Figure 30 and Figure 31) requires further investigation. Future project aims to conduct further lab tests and have conversations with inverter original equipment manufacturers to get to the bottom of this observed phenomenon.

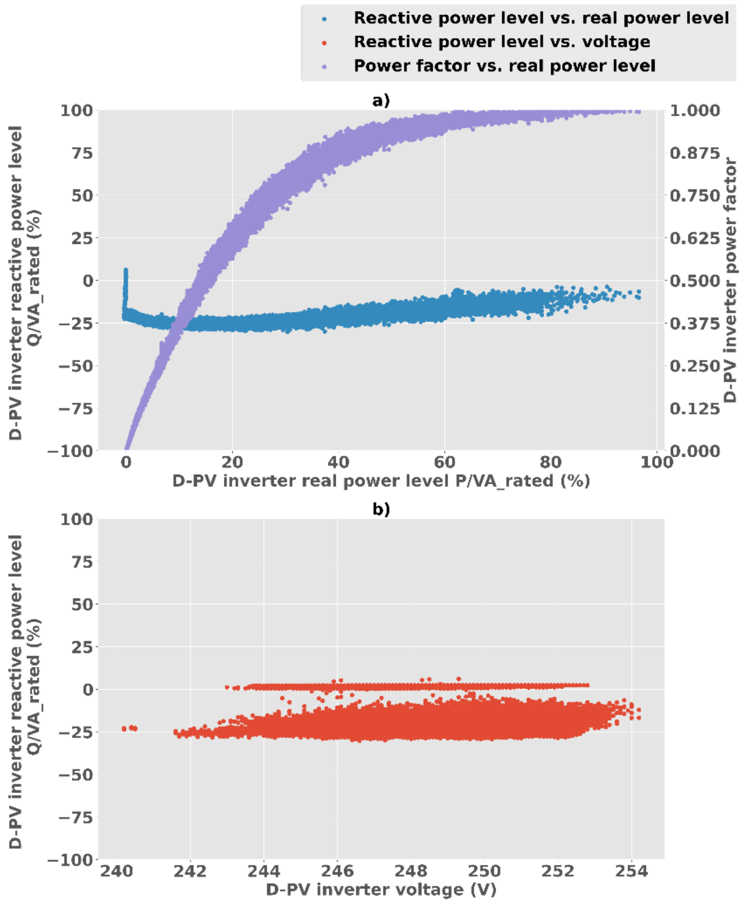


Figure 29 VAr and PF characteristics of a sample D-PV inverter which doesn't show any V-VAr response and increases PF with increasing real power.

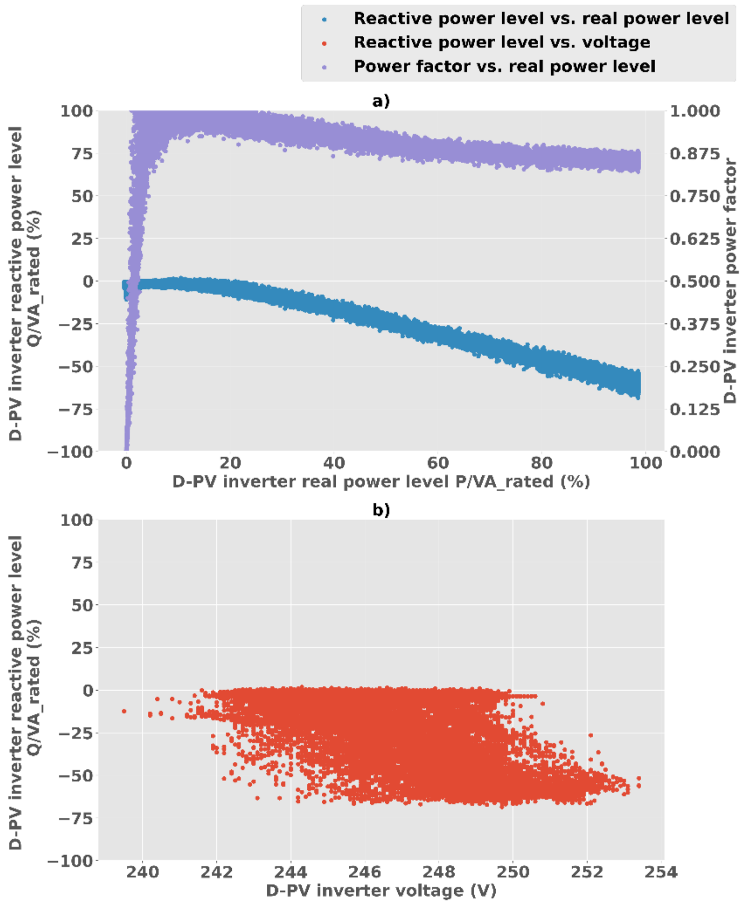


Figure 30 VAr and PF characteristics of a sample D-PV inverter which doesn't show any V-VAr response and decreases PF with increasing real power.

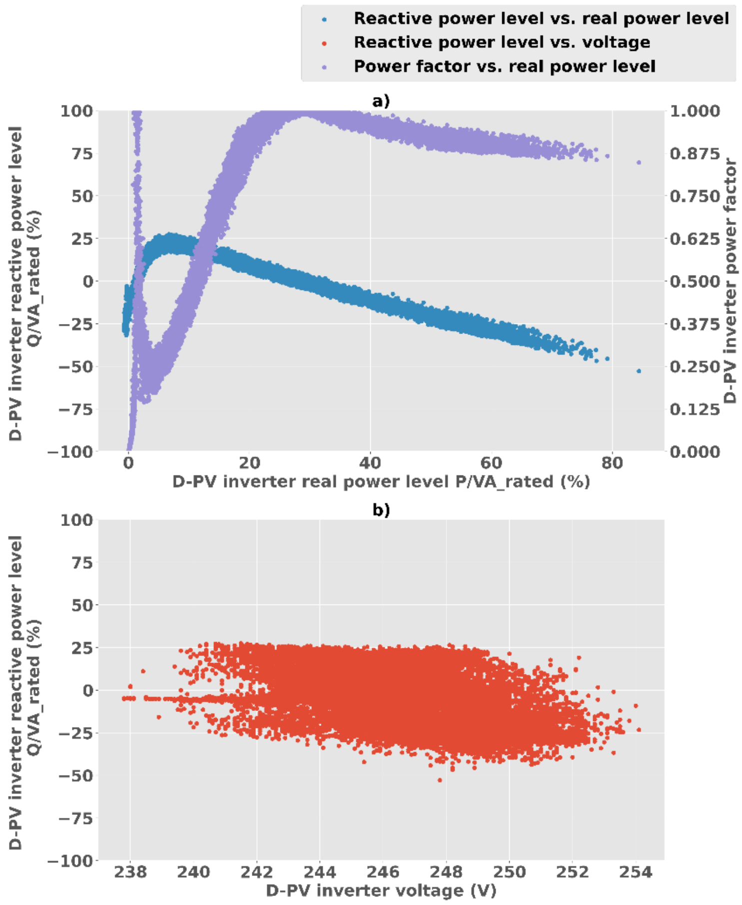


Figure 31 VAr and PF characteristics of a sample D-PV inverter which doesn't show any V-VAr response, and its PF behaviour changes across different real power levels

Table VIII summarizes the percentage of D-PV inverters according to their V-VAr response and PF characteristics seen in the studied Solar Analytics data set.

Table VIII Percentage of D-PV inverters with different V-VAr response and PF characteristics

	Reference V-VAr curves (Figure 27)	No V-VAr response, unity PF (Figure 28)	No V-VAr response, increasing PF with real power (Figure 29)	No V-VAr response, decreasing PF with real power (Figure 30)	Other (Figure 31)
Percentage of D-PV inverters (%)	0.5	80	15	2.5	2

6.3.3 Volt-var curtailment (real case)

This section presents the V-VAr curtailment results from the analysis of real operational data. The results are first presented for BESS from AGL VPP dataset followed by D-PV systems form Solar Analytics dataset.

6.3.3.1 BESS V-VAr Curtailment (AGL VPP dataset)

Before presenting the BESS V-VAr curtailment results, Figure 33 demonstrates an example case for curtailment from a sample site. Around 3:00 am (circled in red), the BESS absorbs high VArs and the real discharge power is curtailed as the BESS VA reaches its rated capacity of 5 kVA.

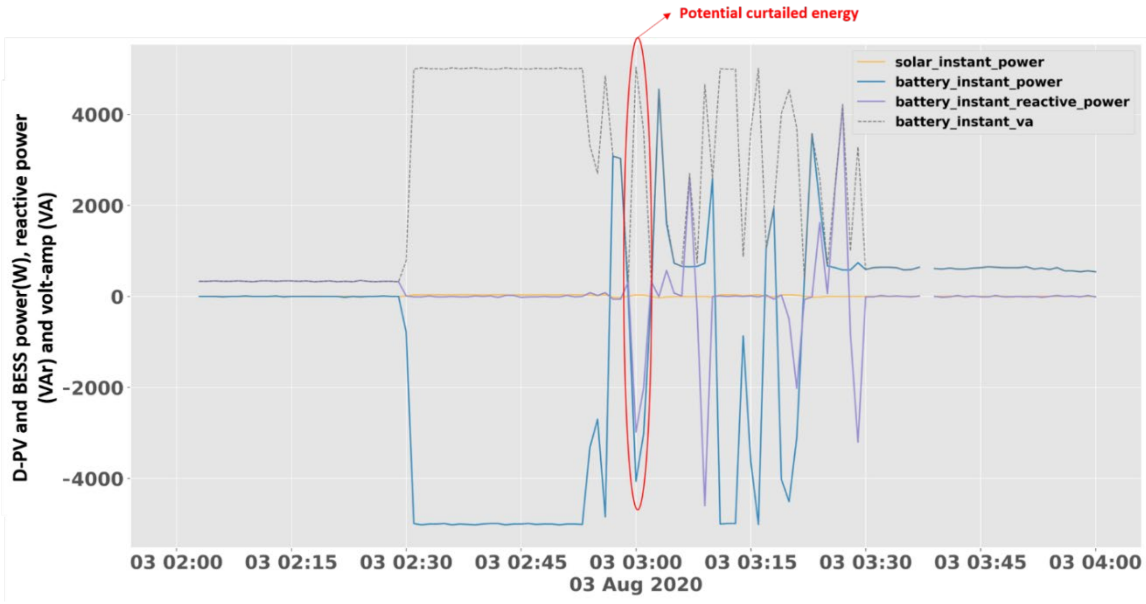


Figure 32 Example daily operation from a sample BESS where V-VAr curtailment instance can be observed

As described in Section 4.2.3.3, BESS V-VAr curtailment is analysed from the energy user and aggregator's perspective where the energy user analysis focuses on the potential reduction in BESS self-consumption rate when the site is net-importing and the BESS is discharging. Figure 34 shows the curtailed energy from BESS which is given as a percentage of the total D-PV generation. Only 78 sites are plotted as they are the only ones which showed some V-VAr response. The sites are plotted in a descending order and the curtailment is broken down into V-VAr curtailment during VAr injection and absorption. For the remaining sites V-VAr curtailment is zero.

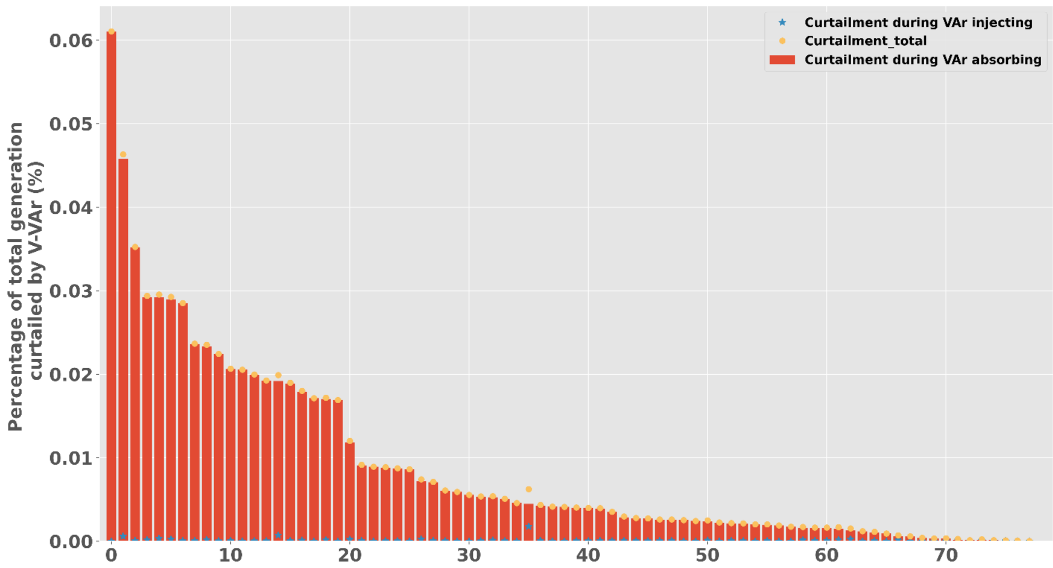


Figure 33 Percentage of total generation curtailed by V-VAr for 78 Tesla sites that shows V-VAr response (energy user's perspective)

It is seen that overall, V-VAr curtailment is negligible and the BESS that experiences highest V-VAr curtailment only lose 0.06 % of total generation which corresponds to 4 kWh/year. The main reason for this outcome is that for the majority of the time BESS VArs remain at a relatively small quantity (see Figure 23 and Figure 24) and higher BESS VArs coincide with D-PV generation periods where the site is in a net-export state and therefore, it's self-consumption is not directly impacted. As a result, the BESS's discharge capability is not significantly compromised due to V-VAr responses during the net-import instances. Another observation is that almost all of the V-VAr curtailment is attributed to instances where BESS is absorbing VArs. Figure 35 below presents the V-VAr curtailment from the aggregator's perspective (also labelled as potential curtailment instances – PCE) where this time instances of both

BESS charging and discharging were considered. It is seen that the V-VAr curtailment results didn't change when curtailment is assessed from the aggregator's point of view where the site with highest V-VAr curtailment lost 0.068 % of its total D-PV generation. This slight increase was due increase in V-VAr curtailment during VAr injection which was associated with the BESS charging instances (especially during the D-PV generation window).

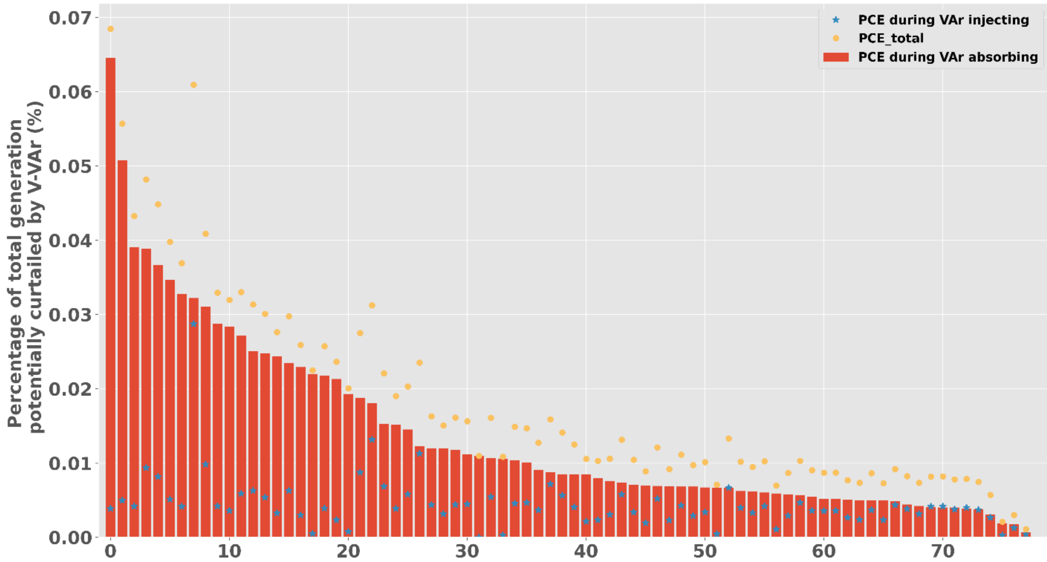


Figure 34 Percentage of total generation curtailed by V-VAr for 78 Tesla sites that shows V-VAr response (aggregators perspective)

Figure 36 shows AGL VPP site postcodes in purple, where the postcodes for the five BESS with most significant V-VAr curtailment is shaded with yellow. Note that two of five of the most impacted BESS were located in the same postcode; however, it is not possible to assess whether any of the other BESS sites were on the same feeders as these five most curtailed sites. It is difficult to infer any causal relationship attributed to spatial characteristics of these sites with the available data. Note that as all BESS had similar size, the differences in V-VAr curtailment outcomes are due to combination of BESS inverter settings, local voltage conditions as well household consumption patterns (i.e., net-load vs export conditions).

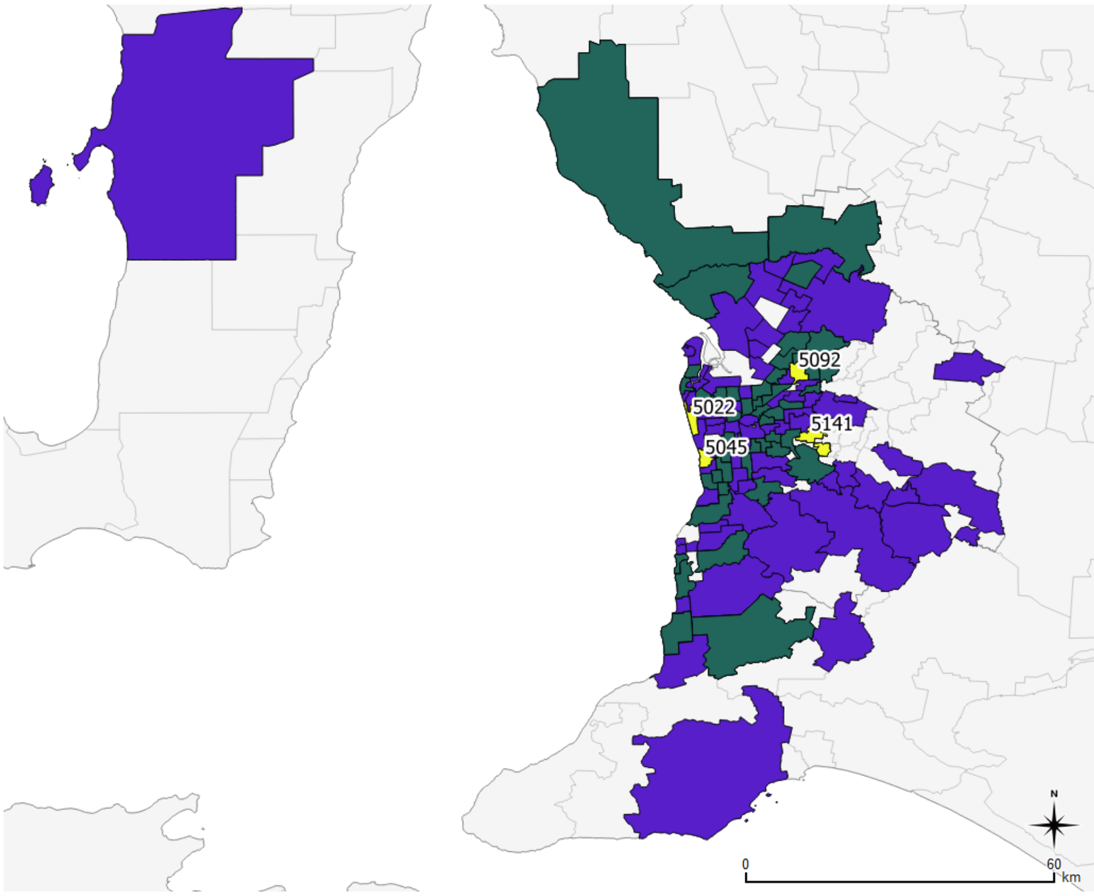


Figure 35 Postcodes included in the AGL VPP dataset (purple) including regions containing sites performing V-VAr response (green) and postcodes of the five most impacted sites (yellow)

6.3.3.2 D-PV Curtailment (Solar Analytics dataset)

Before presenting the D-PV curtailment results, Figure 37 presents an example case of curtailment from the site which showed the highest V-VAr curtailment. D-PV real and reactive power are plotted against voltage, global horizontal irradiance (GHI), D-PV DC rated power and AC apparent power rated. As the site absorbs higher quantities of VArs during the D-PV generation window, the D-PV inverter reaches its rated apparent power capacity and as a result D-PV real power cannot reach its maximum. It is seen that the site loses a significant amount of generation during the analysed week as demonstrated by the green shaded area.

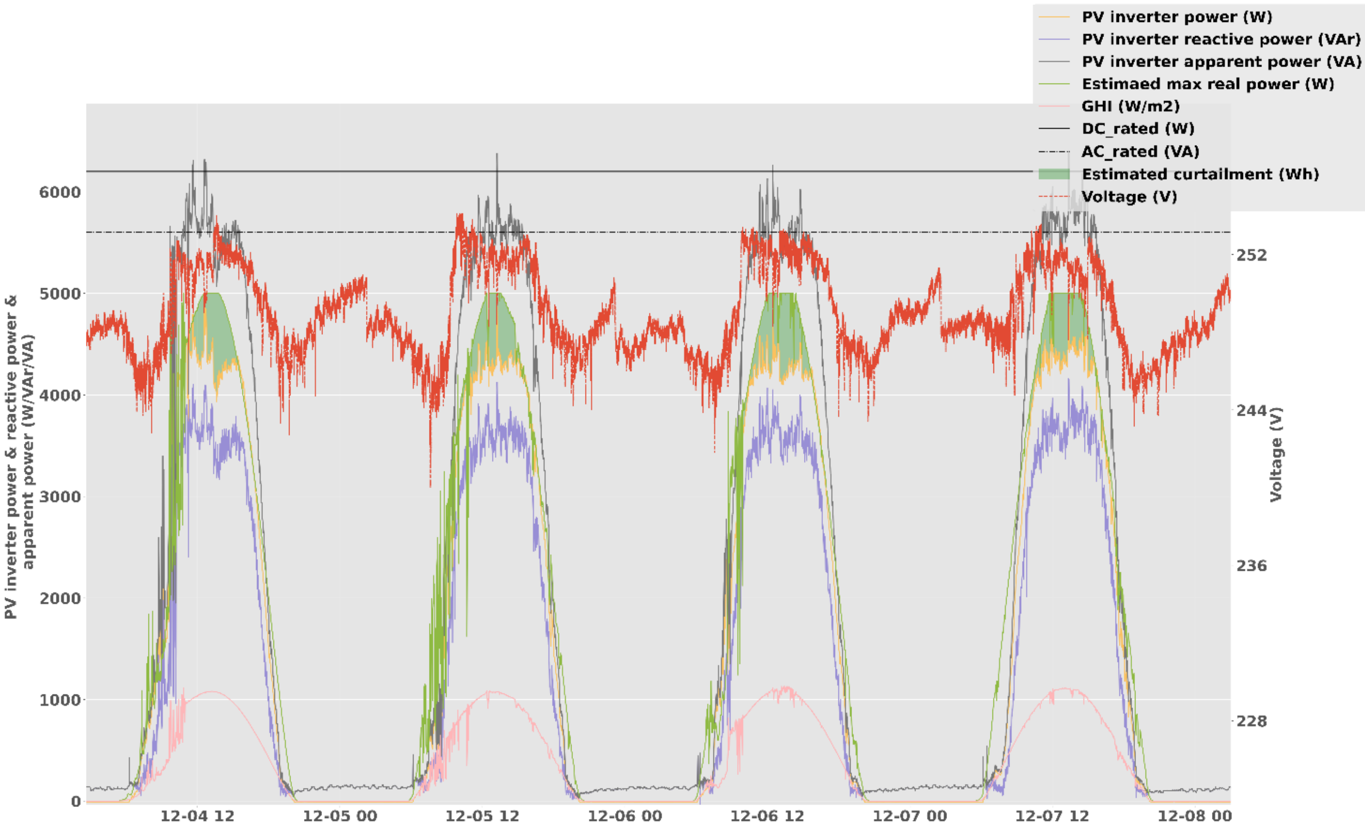


Figure 36 Example weekly operation from a sample D-PV where V-VAr curtailment instances can be observed

Figure 38 shows the percentage of total D-PV generation curtailed through V-Var response. The results are shown for 100 Solar Analytics sites which shows the most significant V-VAr response. The sites are shown in a descending order according to the percentage of lost generation. It is seen that the V-VAr curtailment is more significant for D-PV compared to BESS where the site with highest V-VAr curtailment loses 4.6 % of total generation. For the majority of sites, the lost generation is less than 1%. Like BESS, V-VAr curtailment is mostly attributed to instances of VAr absorption rather than injection.

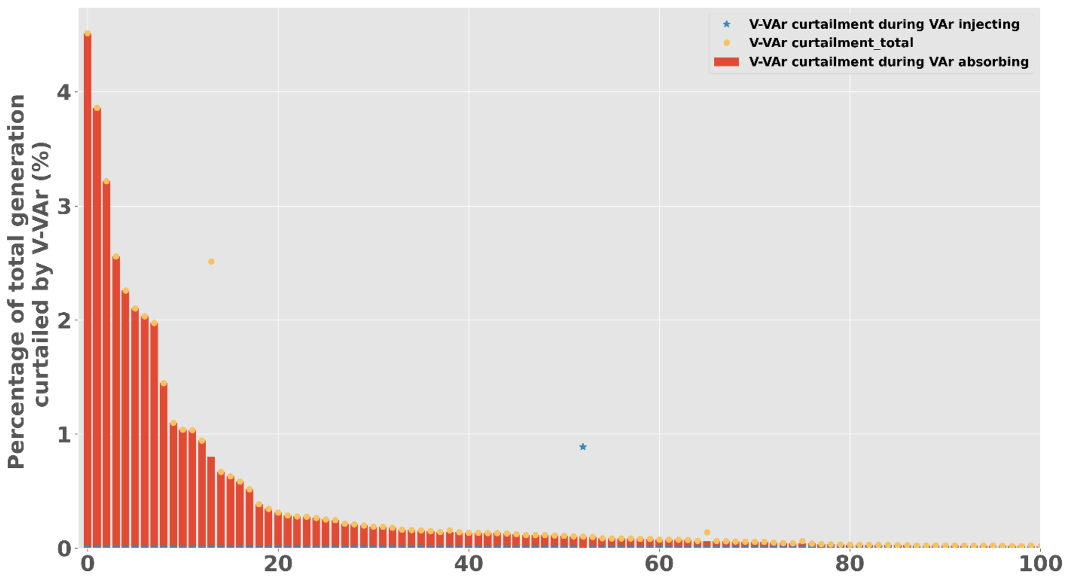


Figure 37 Percentage of total generation curtailed by V-VAr for the 100 Solar Analytics with highest V-VAr curtailment

Further examination of the sites with the highest V-VAr curtailment revealed that these sites' D-PV inverters generally operate at lower power factors during the D-PV generation window. Figure 39 presents example daily operations from the site which showed the highest V-VAr curtailment. It is seen that the D-PV inverter absorbs a higher quantity of VArs than produced real power. As a result of higher reactive power during the D-PV generation window, V-VAr curtailment was more prevalent for these sites. The sites with the highest V-VAr curtailment were also investigated for any potential relationship between voltage and reactive power, however no clear relationship was found as most D-PV inverters didn't show any V-VAr response as demonstrated in the previous section.

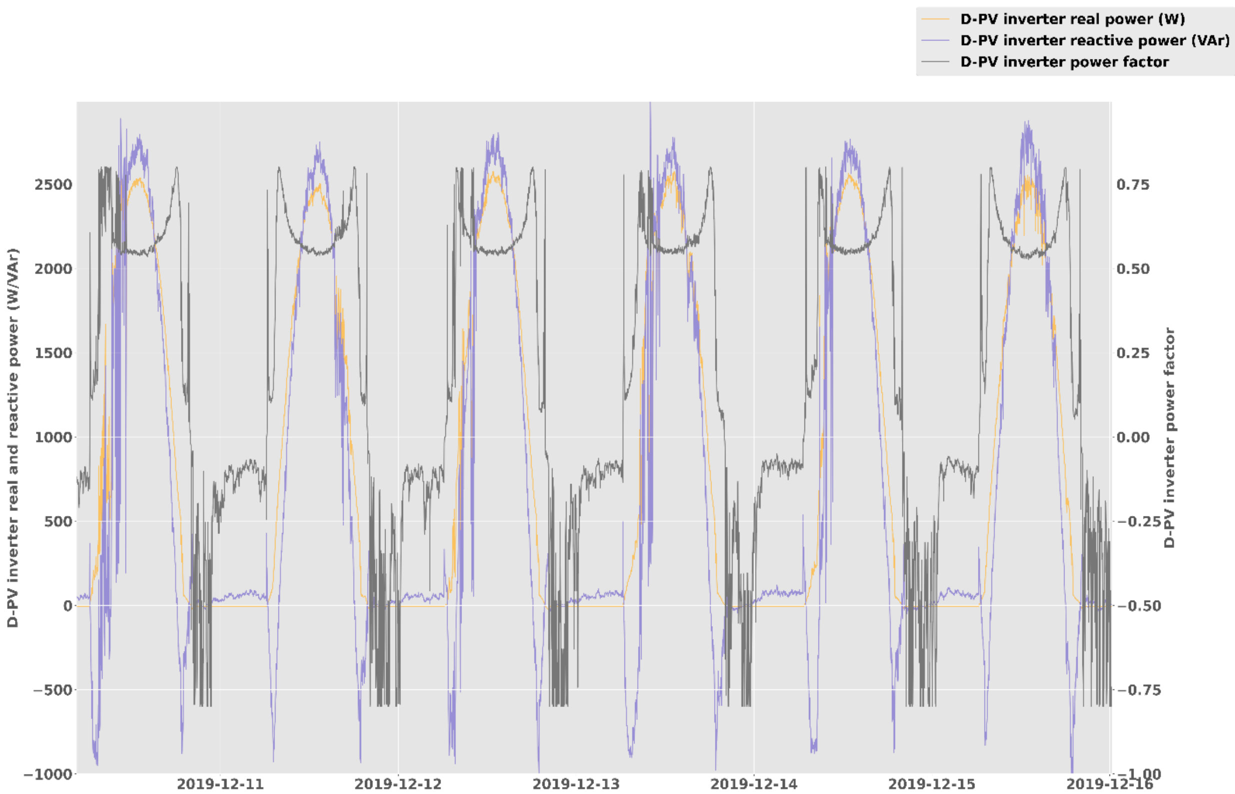


Figure 38 Example daily operations from the Solar Analytics site with highest V-VAr curtailment

Figure 40 presents the distribution of V-VAr curtailment across the 10-month period for the same 100 sites from the Solar Analytics fleet. The highest V-VAr curtailment was experienced during summer months rather than spring months which show the highest tripping (anti-islanding and limits for sustained operation) curtailment. The reason for this phenomenon may be due to higher peak sunshine hours (PSH) during summer resulting in higher and longer durations of VAr absorption causing higher curtailment.

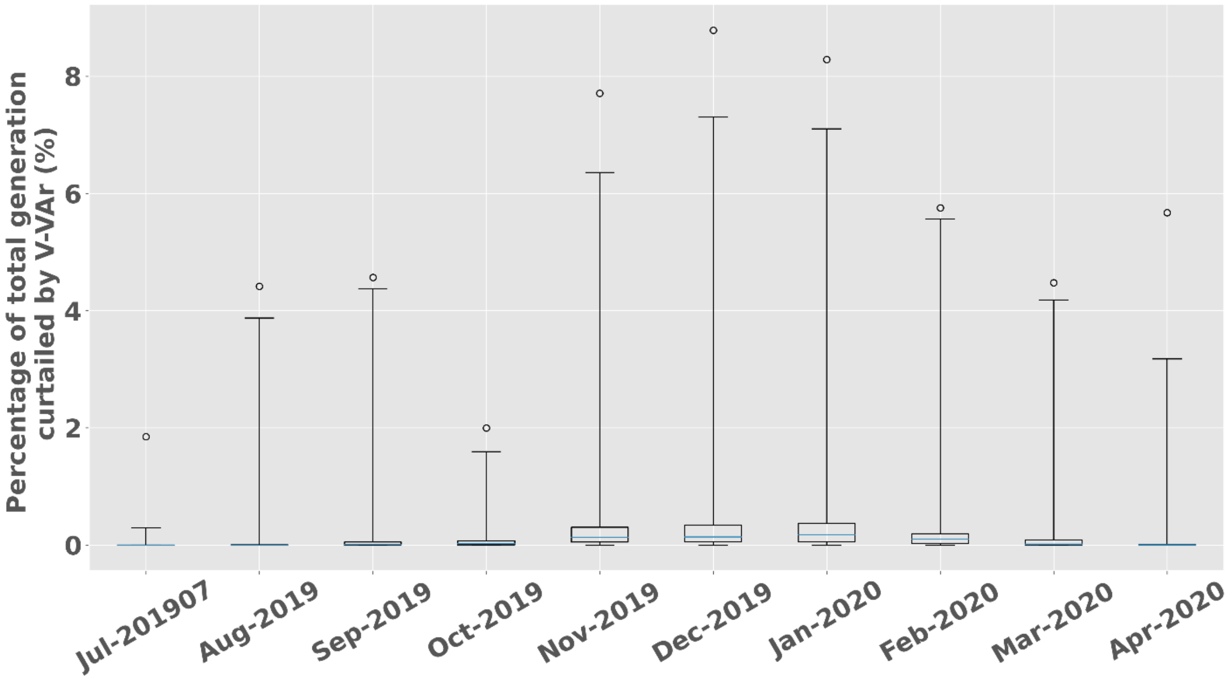


Figure 39 Monthly distribution of generation curtailed by V-VAr characteristic for the 100 Solar Analytics sites with highest VArs

6.3.4 Volt-var curtailment (scenarios)

In previous sections, it was seen that the majority of BESS and D-PV inverters do not show any V-VAr response. Therefore, the obtained V-VAr curtailment results are not representative of the ideal case where each BESS and D-PV inverter would show the required V-VAr response according to local voltage conditions and relevant standards.

The V-VAr scenario analysis conducted tries to address this point and aims to present results that are more representative of DER future where majority of BESS and D-PV inverters are installed with the respective V-VAr response mode by default.

The scenario analysis results are firstly presented for BESS systems from AGL dataset followed by D-PV systems Solar Analytics dataset.

6.3.4.1 AGL dataset

Similar to the V-VAr curtailment analysis applied on real operational data from BESS, V-VAr scenario analysis is carried from both energy user's and aggregator's perspective. Figure 41 shows the distribution of percentage of total generation curtailed by V-VAr according to the studied V-VAr curves (see Figure 9) from the energy user's perspective. The results are presented alongside the real measured data. The following Table IX presents the key summary statistics for each distribution. It is seen that V-VAr curtailment from the energy user perspective is higher under the modelled V-VAr scenarios compared to the actual case. However, V-VAr curtailment is still insignificant, less than 1% of total generation under all analysed scenarios. Amongst the four analysed V-VAr curves, the ENA recommendation results in the highest amount of V-VAr curtailment and AS 4777-2015 results in the smallest amount of V-VAr curtailment.

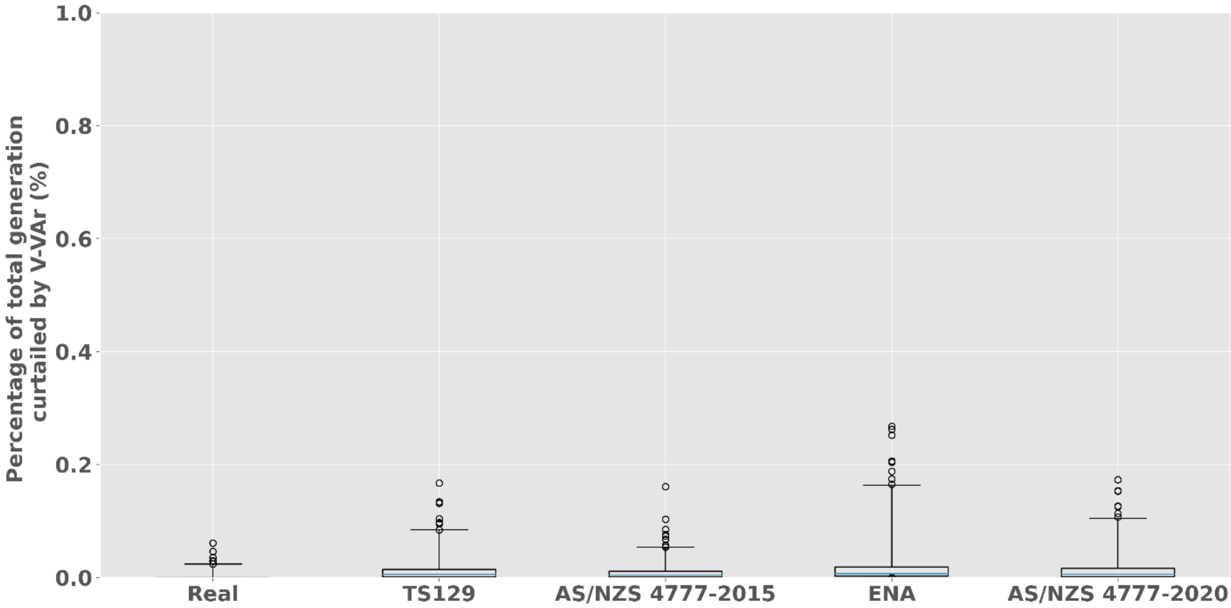


Figure 40 V-VAr curtailment scenario analysis for all AGL VPP sites (energy user's perspective)

Table IX Summary statistics for V-VAr curtailment scenario analysis for all AGL VPP sites (energy user's perspective): percentage of total generation curtailed (%)

	Real	TS-129	AS4777_2015	ENA	AS4777_2020
min	0	0	0	0	0
max	0.06	0.17	0.16	0.27	0.17
mean	0.01	0.01	0.01	0.02	0.01
median	0	0.01	0.01	0.01	0.01

Figure 42 shows the distribution of percentage of total generation curtailed by V-VAr according to the studied V-VAr curves (see Figure 9) from the aggregator's perspective. The results are presented alongside with the real case. The following Table X presents the key summary statistics for each distribution. Once again, the modelled V-VAr response results in higher V-VAr curtailment than the real case. The increase in V-VAr curtailment is higher for the aggregator's perspective (includes curtailment instances when both charging and discharging) than the energy user's perspective (only focuses on curtailment during instances of discharging and net-import). Amongst the studied V-VAr curve scenarios, the ENA recommendation results in significantly higher V-VAr curtailment. This is especially due to ENA's more aggressive VAr absorption recommendation at 60% VAr/VA_rated. The V-VAr curtailment results are very similar between TS-129 and AS/NZS 4777-2020 and smallest for AS/NZS 4777-2015.

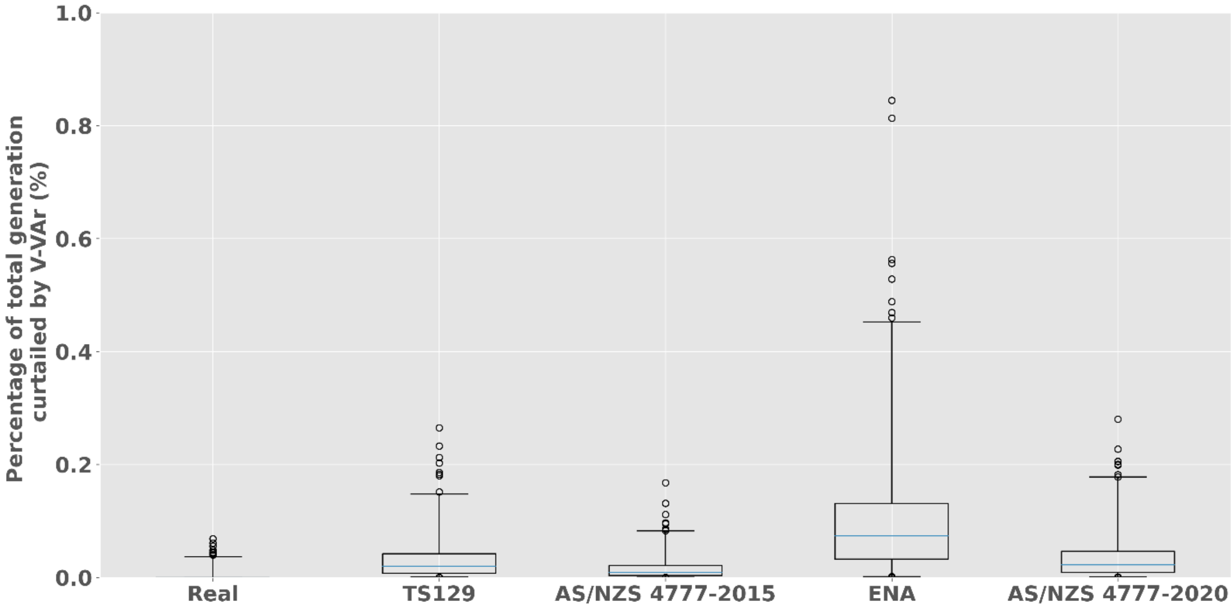


Figure 41 V-VAr curtailment scenario analysis for all AGL VPP sites (aggregator's perspective)

Table X Summary statistics for V-VAr curtailment scenario analysis for all AGL VPP sites (aggregator's perspective): percentage of total generation curtailed (%)

	Real	TS-129	AS/NZS 4777-2015	ENA	AS/NZS 4777-2020
min	0	0	0	0	0
max	0.06	0.27	0.17	0.85	0.28
mean	0.01	0.03	0.02	0.10	0.04
median	0	0.02	0.01	0.08	0.02

6.3.4.2 Solar Analytics dataset

Figure 43 shows the distribution of percentage of total generation curtailed by V-VAr according to the studied V-VAr curves (see Figure 9) from D-PV inverters. The modelled scenario results are presented alongside the data from the real case. The following Table XI presents the key summary statistics for each distribution. It is seen that average V-VAr curtailment is insignificant both for the real case and the studied scenario analysis. However, for some D-PV inverters with different VAr and PF behaviour (see Section 6.3.2) experienced curtailment was greater in real case compared to operation according to one of the reference V-VAr curves. It is also seen that when these D-PV inverters operate according to one of the V-VAr curves, the extreme V-VAr curtailment cases diminish as seen by the narrower distribution range compared to the real case. Amongst the studied V-VAr curves, the ENA recommendation causes the highest average V-VAr curtailment followed by AS/NZS 4777-2020, TS-129 and AS/NZS 4777-2015.

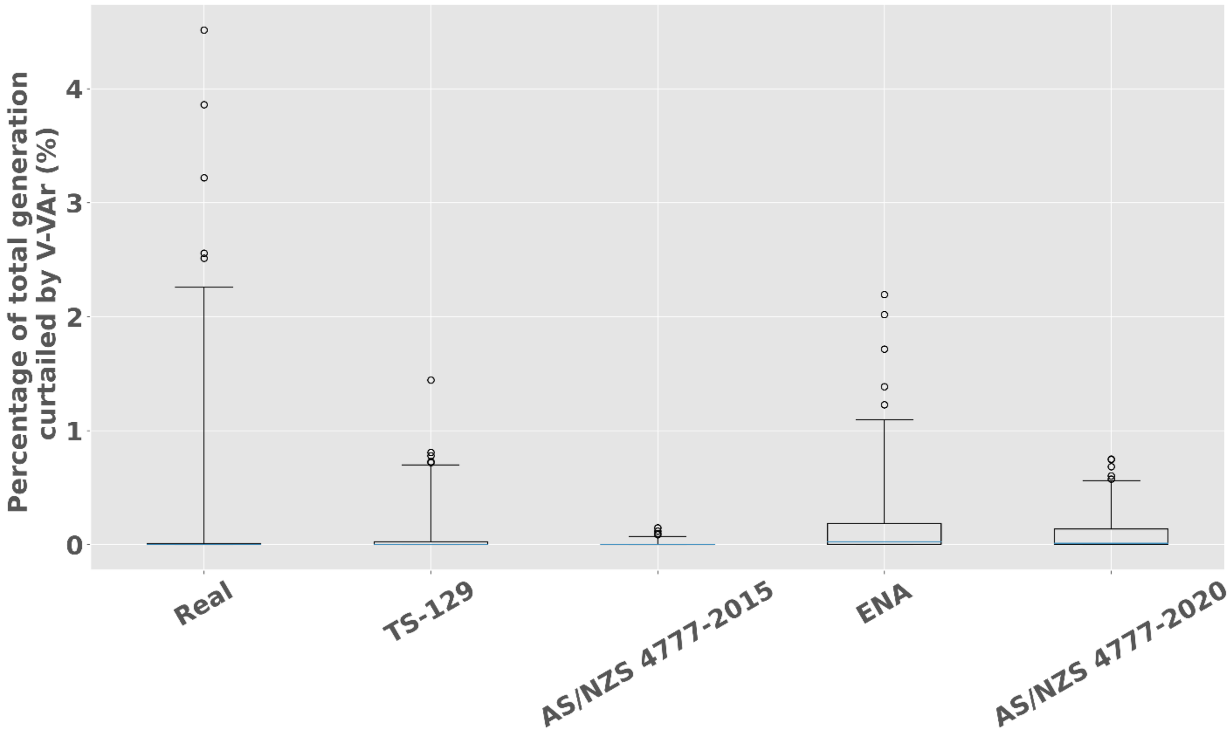


Figure 42 V-VAr curtailment scenario analysis for all Solar Analytics D-PV systems

Table XI Summary statistics for V-VAr curtailment scenario analysis for all Solar Analytics sites: percentage of total generation curtailed (%)

	Real	TS-129	AS/NZS 4777-2015	ENA	AS/NZS 4777-2020
min	0.00	0.00	0.00	0.00	0.00
max	4.51	1.44	0.15	2.19	0.75
mean	0.08	0.05	0.00	0.14	0.09
median	0.00	0.00	0.00	0.02	0.01

6.4 Summary of curtailment findings

Table XII presents a summary of tripping (anti-islanding and limits for sustained operation) and V-VAr curtailment findings (**V-Watt curtailment is not included)**. The results are based on the real measured data, rather than the scenario modelling, and the findings from D-PV sites with 10 months of data are linearly scaled to represent curtailment over 12 months. Although a direct comparison between the fleets of Solar Analytics and AGL requires caution due to many unknown differences between the sites such as energy user behaviour and net-load (Solar Analytics), geographical locations and VPP operational strategies, the results show that that D-PV systems experience higher levels of curtailment compared to BESS. Further investigation is required to identify all of the underlying reasons; however, a major contributing factor to this outcome is BESS's storage capability to soak up excess D-PV generation reducing the exported D-PV generation. Moreover, although our study has taken into account all instances of BESS's capacity being limited as a potential curtailment, in reality, this potential curtailed energy can be used later which is not a definite loss for energy users, whereas D-PV only sites lose the curtailed generation.

It is also seen that for D-PV systems, curtailment associated with tripping (anti-islanding and limits for sustained operation) and V-VAr curtailment share an almost equal proportion of total curtailment. On the other hand, for BESS, 90% of the curtailment is attributed to estimated tripping (anti-islanding and limits for sustained operation). This is because less than 10% of the studied BESS show any V-VAr response and hence the majority of the BESS have zero V-VAr curtailment

Table XII Summary of tripping (anti-islanding and limits for sustained operation) and V-VAr curtailment findings (V-Watt curtailment not included)

Tripping (anti-islanding and limits for sustained operation) and V-VAr curtailment	D-PV sites (Solar Analytics – 500 sites)	BESS sites (AGL – 996 sites)
Total curtailed energy (kWh/year)	6,301	4,434
Average curtailed energy per site (kWh/year/site)	13	5
Total curtailed energy as a percentage of total generation (%)	<1%	<1%
Percentage of total curtailment due to tripping (anti-islanding and limits for sustained operation)	48 %	90%
Percentage of total curtailment due to V-VAr	52 %	10%

6.5 Financial and emissions findings

In this section, financial loss and emissions impact are presented as a result of the analysed two modes of curtailment: tripping (anti-islanding and limits for sustained operation) and V-VAr curtailment. These results do not include losses associated with V-Watt curtailment, as it is out of scope for this preliminary study; however, it is important to remind that V-Watt losses are anticipated to be more significant than tripping (anti-islanding and limits for sustained operation) and V-VAr curtailment. V-Watt curtailment and its associated losses will be assessed in a future study.

6.5.1 Financial impact for BESS sites (AGL dataset)

For the AGL VPP sites, financial impacts are assessed separately from the energy user's and aggregator's perspective. As discussed in previous sections, the energy user's perspective considers curtailment as the limited discharged energy during net-import conditions. Due to challenges of quantifying a definite 'loss' for BESS curtailment (i.e., BESS can discharge the energy that was curtailed at a later point after the curtailment conditions), it is difficult to quantify a '$' loss value for the curtailed generation. Furthermore, VPP participants may be offered different financial incentives and tariff schemes, the financial impact of which is beyond the scope of this preliminary study. Therefore, for the brevity of the analysis, BESS energy users are assumed to have a Time of Use (ToU) tariff where the financial loss due to curtailed energy is calculated according to three scenarios using available retail rates in South Australia [47]:

- **Low loss case**: limited discharged energy during curtailment is calculated at 40 c/kWh, same energy to be discharged later is calculated at 30c/ kWh (loss is 10 c/kWh of curtailed energy)
- **Medium loss case**: limited discharged energy during curtailment is calculated at 45 c/kWh, same energy to be discharged later is calculated at 25c/ kWh (loss is 20 c/kWh of curtailed energy)
- **High loss case**: limited discharged energy during curtailment is calculated at 50 c/kWh, same energy to be discharged later is calculated at 20c/ kWh (loss is 30 c/kWh of curtailed energy)

Figure 44 shows the distribution of revenue loss due to curtailment for energy users in the AGL VPP dataset. For each financial loss case (low, medium, high), three scenarios are shown: Real case, TS-129 and ENA. These three cases were sufficient to analyse the range of impacts because AS/NZS 4777-2020 showed very similar results with TS-129 and AS/NZS 4777-2015 showed very similar results with the real-case.

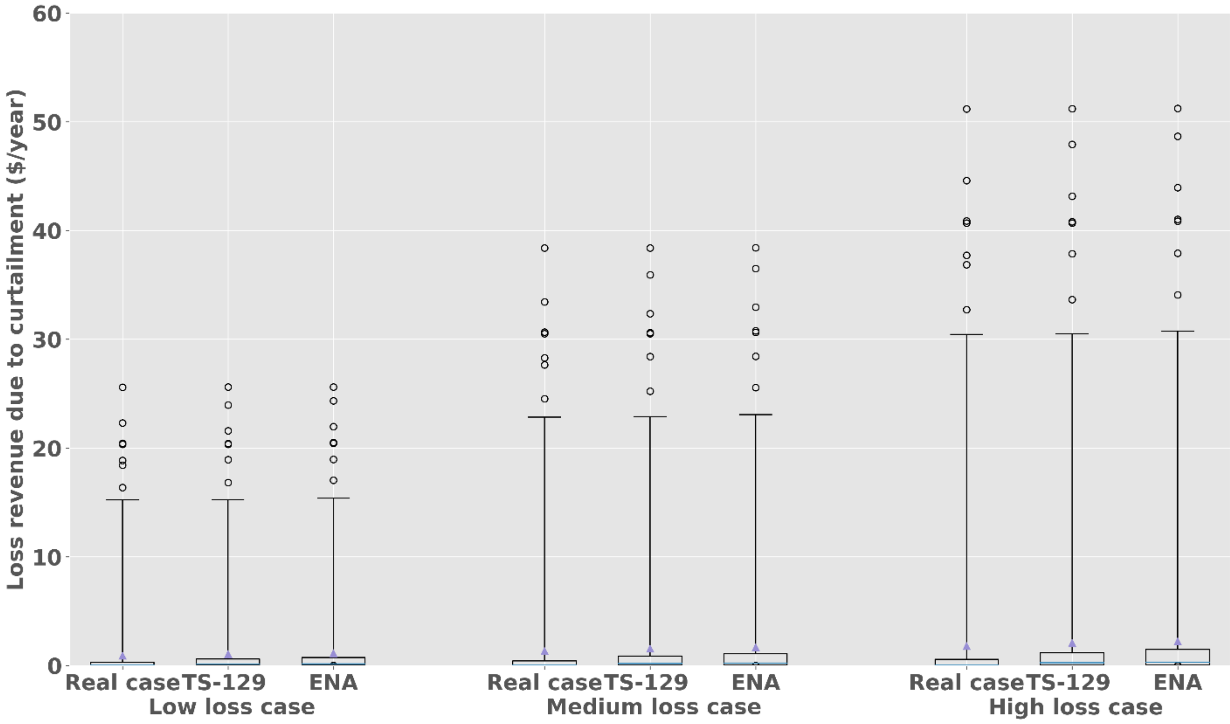


Figure 43 Financial revenue loss for BESS energy users due to tripping (anti-islanding and limits for sustained operation) and V-VAr curtailment for three tariff scenarios (low loss, medium loss and high loss) and three scenarios (real, TS-129 and ENA)

Revenue loss due to tripping (anti-islanding and limits for sustained operation) and V-VAr curtailment is not significant for the analysed BESS energy users. On average households lose less than $5 per year even in the high loss scenario. On the other hand, a small number of households lose more significant revenue as seen in Figure 40. On average, households lose more in the ENA scenario followed by TS-129 and the real case, which is aligned with the V-VAr curtailment findings. As discussed above, these losses are calculated according to sample ToU tariffs and could be much more significant depending on the VPP's incentive structure.

To quantify the potential revenue loss for aggregators, firstly total curtailed energy was calculated for the entire fleet across each half-hourly time stamp for the real case, TS-129 and ENA scenarios. Wholesale spot market price data was obtained from the National Electricity Market (NEM) website for the same analysis period (Feb 2020 – Jan 2021) [48]. When calculating the revenue loss, it was assumed that the energy that couldn't be dispatched due to curtailment could be discharged later at a range of different spot market prices. Figure 41 shows the distribution of total annual potential revenue loss due to curtailment for the aggregator for the real-case, TS-129 and ENA scenarios. It is important to emphasize that the results are only for BESS curtailment and don't include D-PV curtailment; furthermore, potential revenue losses due to V-Watt curtailment was not analysed; therefore, the result are likely to underestimate the total potential revenue loss for the aggregator. Moreover, these results are only preliminary estimates and more information needs to be obtained from the aggregator with regards to their spot price operations to obtain more accurate results.

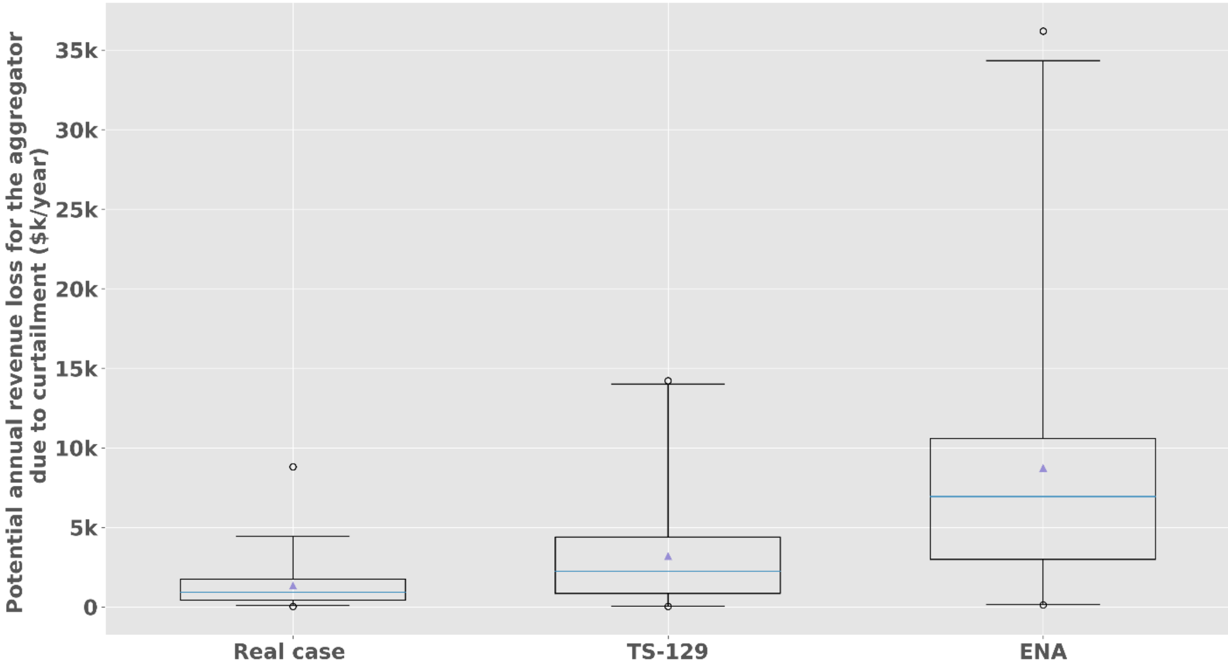


Figure 44 Total annual potential revenue loss due to tripping (anti-islanding and limits for sustained operation) and V-VAr curtailment for VPP operator with 996 BESS sites analysed for three scenarios (real case, TS-129 and ENA)

It is seen that in the real case, highest potential revenue loss is less than $10k/year which increases up to $15k/year and $36k/year for the analysed TS-129 and ENA. Table XIII presents the corresponding minimum, average, and maximum annual revenue loss for the VPP operator according to analysed spot market prices.

Table XIII Potential annual revenue loss for the VPP operator due to V-VAr and tripping curtailment: minimum, average, and maximum loss for real-case, TS-129 and ENA scenarios

	Real	TS-129	ENA
Minimum loss ($/year)	6	7	26
Average loss ($/year)	266	637	1743
Maximum loss ($/year)	9,500	14,689	36,124

Further research is needed to understand how these results may change with increasing levels of DER. On the one hand, with increasing BESS fleet, higher instances of curtailment may increase the overlap with high sport market price events. On the other hand, increasing D-PV installations may put further downward pressure on day-time spot market prices during the day. Future research aims to further investigate potential correlations between these peak spot market prices and high curtailment instances.

6.5.2 Financial impact for D-PV sites

For the Solar Analytics fleet with D-PV systems, the financial loss calculation was more straightforward as the sites did not have storage capability like the BESS. Therefore, curtailed D-PV generation was a definite loss and could not be used after the curtailment event. Because the Solar Analytics data did not include net load for the households, some assumptions had to be made for estimating the revenue loss for the energy users:

- **Low loss case:** it is assumed that all curtailed energy was during net-export conditions (energy that could be exported if it were not curtailed) and therefore, loss revenue is calculated from an average feed in tariff (FiT) rate of 10 c/kWh.

- **Medium loss case:** it is assumed that half of the curtailed energy was during net-export conditions (energy that could be exported if it were not curtailed) and other half during net-import conditions (the energy that could be self-consumed if it were not curtailed). Therefore, half of the loss revenue is calculated at 10c/kWh and the remaining half is calculated from an average import tariff of 30 c/kWh.
- **High loss case:** it is assumed that all curtailed energy was during net-import (energy that could be self-consumed if it were not curtailed) and therefore, loss revenue is calculated from an average import tariff of 30c/kWh.

The average FiT and import tariff rates were selected according to rates available for South Australian energy users [47] and the distribution of loss revenue due to curtailment is shown in Figure 46 below.

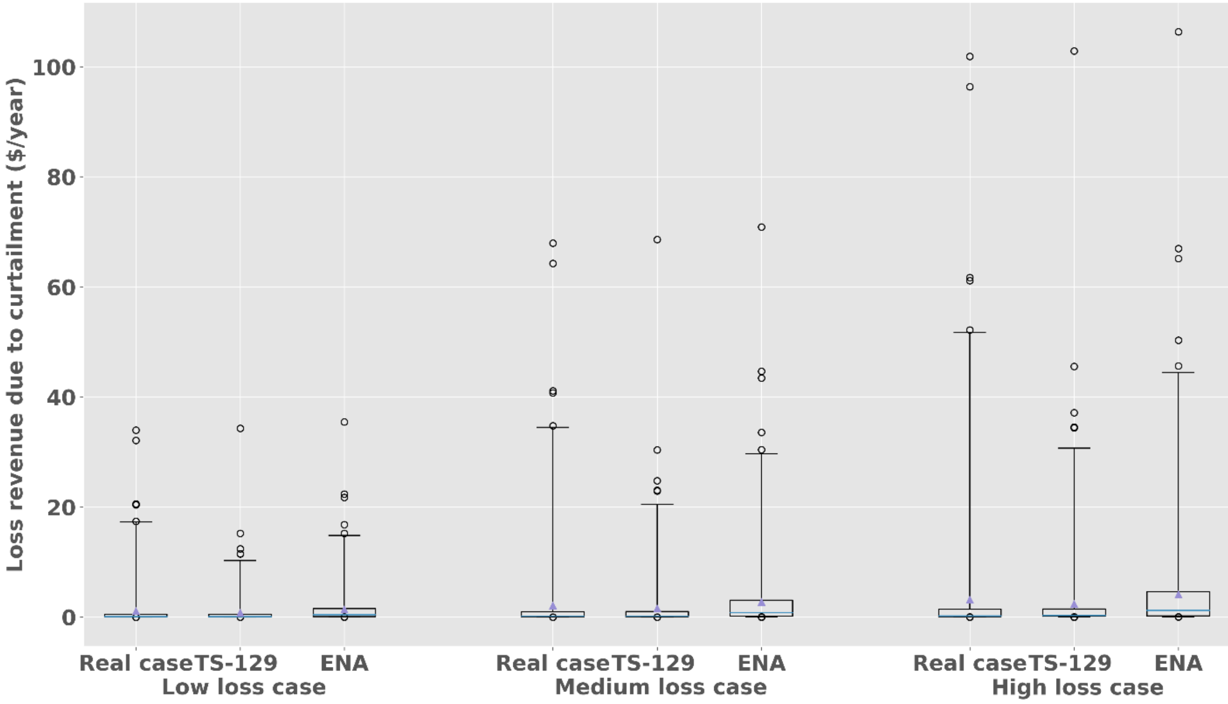


Figure 45 Financial revenue loss for D-PV owner energy users due to tripping (anti-islanding and limits for sustained operation) and V-VAr curtailment for three cases (low loss case, medium loss case, and high loss case) and three scenarios (real, TS-129 and ENA)

Revenue loss due to tripping and V-VAr curtailment is not significant for majority of the D-PV system owners as per the analysed Solar Analytics fleet. On average, the loss is less than $5/year regardless of the analysed scenario. On the other hand, similar to the BESS results, a small number of households lose more significant revenue as seen with the outliers which can be as high as $100/year. The results show that, on average, the lost revenue due to curtailment is higher for the D-PV only sites compared to BESS sites, aligned with the results presented in Table XII. Another important point to emphasize is that most D-PV sites would lose less revenue due to curtailment if their D-PV inverters show the required V-VAr response rather than showing VAr response as a function of real power.

6.5.3 Upscaled curtailed generation & emissions impact

This section provides an estimate for the upscaled curtailed generation and its emissions impact. It is critical to emphasize that these estimates include major assumptions that limit the extent to which the findings can be generalised, one of which is the fact that the analysed sites may not be representative of the DER fleet across Australia. In particular, Solar Analytics energy users tend to have higher awareness and knowledge around DER and energy related topics than the general DER owner. It can also be assumed that households that participate in a VPP trial are likely to be more engaged in DER and energy related topics than the general DER owner. Furthermore, the majority of the Solar Analytics and AGL VPP energy users have more recent D-PV/BESS installation dates compared to general DER owner which will result in different standard settings for the inverter and impact the resultant curtailment. On the other hand, the average D-PV system size from the analysed Solar Analytics fleet is 4.6kW which is consistent with the nationwide statistics [16].

As shown in Table XII, total curtailed generation is calculated as 6,301 kWh/year and 4,434 kWh/year for the studied D-PV and BESS fleets where on average curtailment is 13 kWh/year for a D-PV site and 5 kWh/year for a BESS site (less than 1% of the total generation). As previously discussed, it is more difficult to define a definite curtailed generation loss for BESS, furthermore, BESS penetration is still very small across Australia. Therefore, we calculate the upscaled curtailed generation and emissions impact based on real D-PV curtailment results.

Based on the estimated percentage of free-standing homes with rooftop D-PV [49] and total number of free-standing households across Australia [50], the upscaled curtailed generation is in the order of 22 GWh/year. Based on the reported CO_2 emissions of the Australian energy mix [51], the upscaled curtailed generation has emissions impact of 16,5 mega-tonnes of CO_2-e. Figure 47 summarizes the findings of the upscaled curtailed generation and emissions impact. Bear in mind that, the generation and CO_2 emissions losses due to curtailment are more relevant to today's grid where energy from DER isn't sufficient to provide the network demand (except for a few instances in South Australia during Spring and Summer seasons) and hence curtailed D-PV is a lost opportunity to displace more expensive non-renewable generation. However, as we move into higher DER penetrations and determine an appropriate DER capacity for balanced outcomes across different seasons, the losses associated with curtailment may need to be re-evaluated given that at times of curtailment there may still be sufficient renewable energy to meet demand.

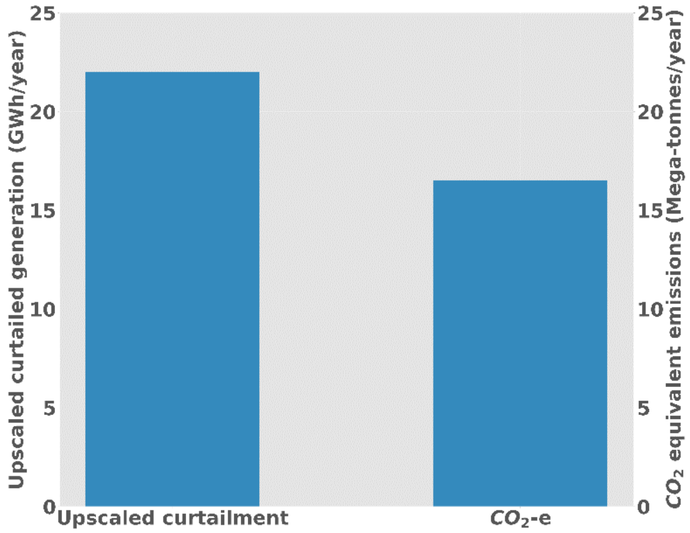


Figure 46 Estimated upscaled curtailed generation (GWh/year) and CO_2 equivalent emissions (Mega-tonnes/year)

7 Socio-technical insights

Key insights from the social and technical workstreams are compared in Table XIV, with observations grouped in terms of:

1. What is the state of curtailment?
2. What are the impacts of curtailment?
3. How could curtailment be managed?

It is important to note that the findings presented here are initial reflections, and that further work is required to consider more deeply how the social and technical workstreams can inform policy development and energy user engagement on DER curtailment.

Table XIV A summary of socio-technical insights

<table>
<tr><th>Social analysis</th><th>Technical analysis</th><th>Reflections on social and technical findings?
🟢 Align
🔴 Contradict
🟡 Require further research
🔵 Require policy action</th></tr>
<tr><td>1. What is the state of curtailment?</td><td></td><td></td></tr>
<tr><td>What have we learnt about energy users' understanding and experiences of curtailment?</td><td>What have we learnt about curtailment from the real operational data?</td><td></td></tr>
<tr><td>Based on the small sample size of this study, we can expect that most energy users have no or little awareness or experience of the issue of curtailment.</td><td>Curtailment is insignificant for the majority of energy users (less than 1% of generation is lost for majority of sites which correspond to less than $5/year revenue loss). On average, D-PV curtailment is more significant than BESS curtailment.</td><td>🟢 Align
The fact that DER curtailment has not been a major issue until more recently, and that the majority of energy users lose only a very small fraction of their generation, may explain why the awareness around curtailment is limited across energy users.</td></tr>
<tr><td>2. What are the impacts of curtailment?</td><td></td><td></td></tr>
<tr><td>How do energy users view the impacts of curtailment?</td><td>What is the distribution of curtailment across energy users and what are different impacts of curtailment?</td><td></td></tr>
<tr><td>When introduced to the issue, energy users understand that the impacts of curtailment are unevenly distributed and may vary according to location in the network, size and age of the D-PV system and inverter, and current feed-in tariff. The potential for curtailment could impede future uptake of D-PV as people view it as 'off-putting' and undermining the economic case for D-PV installation.</td><td>Even though curtailment is insignificant for most energy users, some experience much higher levels of curtailment than average.</td><td>🟢 Align
The fact that a small number of energy users experience much higher levels of curtailment raises concerns regarding the fairness of curtailment.
🟡 Further research is required to understand the reasons behind this phenomenon.
🔵 Policy action is required to ensure fairer curtailment for disadvantaged energy users</td></tr>
<tr><td>Energy users also understand that curtailment may mean that they may benefit less from electricity exports. Most view this negatively, although some may be less concerned as they view self-consumption of D-PV as its primary benefit.</td><td>Depending on the net load conditions of the household, energy users may lose revenue both as reduced exports and D-PV self-consumption.
For BESS, this can be a less significant issue as the curtailed energy output can be used later by energy</td><td>🔴 Contradict
As prior knowledge about curtailment is limited across energy users, it is expected that users may not be aware of different modes of curtailment. More transparency is</td></tr>
</table>

Social analysis	Technical analysis	Reflections on social and technical findings? ● Align ● Contradict ● Require further research ● Require policy action
	users. However, BESS curtailment can cause more significant revenue losses for VPP aggregators.	needed from retailers, installers, solar and energy companies to communicate these to energy users.
Some participants expected curtailment to occur more commonly in dense urban areas, particularly new estates with high rates of D-PV installation.	Sites that are in remote locations can experience higher levels of curtailment than sites located in urban areas. This depends on many factors such as network type, circuit X/R ratio and exact location of the site in relation to the substation.	● Contradict ● This is an important point and further research is required to investigate the impact of spatial site characteristics on curtailment.
Some participants with older D-PV systems were less concerned about the potential for curtailment as they had installed D-PV for primarily environmental reasons and considered that they had already benefitted through high FiT.	For older systems with legacy settings, tripping (anti-islanding) voltage set points are higher and limits for sustained operation requirements may not have been applied, therefore tripping (anti-islanding and limits for sustained operation) curtailment is expected to be less for these systems. Most of the older BESS with legacy settings did not show significant VAr response as they were not mandated to. Therefore, VAr driven curtailment was negligible for BESS with legacy settings. On the other hand, some of the studied D-PV systems with legacy settings showed lower power factor and significant VAr absorption compared to the required amounts given in reference V-VAr curves, therefore, for these sites, VAr driven curtailment was greater than if D-PV showed V-VAr response according to one of the reference V-VAr curves.	● Align We generally expect lower levels of curtailment amongst legacy systems. This means that more recent adopters of D-PV may perceive themselves to be disadvantaged by greater potential for curtailment, in addition to having missed out on the higher FiT available in the past. This has the potential to lead to inequity, both real and perceived, between 'generations' of D-PV owners. ● Contradict Some of the D-PV systems with legacy settings showed higher V-VAr curtailment compared to the cases analysed for the reference V-VAr response curves. ● Policy and regulations may need to consider these points in terms of equality across DER owners.
3. How could curtailment be managed?		
What are energy users' expectations regarding management of curtailment? What conceptions of 'fair' curtailment exist?	**How effective are the new inverter power quality settings in managing the impact of curtailment? How do these compare with other technical solutions available?**	

Social analysis	Technical analysis	Reflections on social and technical findings? ● Align ● Contradict ● Require further research ● Require policy action
Some people are likely to perceive curtailment as a failure of network operators and governments to plan for the rapid and widespread adoption of D-PV, and do not accept that households should bear the costs associated with curtailment. They also reject that curtailment be managed through network upgrades paid for by all energy users.	According to the scenario analysis findings, curtailment didn't significantly increase for majority of the studied sites when D-PV and BESS inverters start operating according to one of the studied V-VAr curves; however, like the real operational case, the impact was much more significant for a small number of sites. On the other hand, with increasing penetration of DER, instances of over-voltage are expected to increase, which is likely to cause higher degrees of curtailment. It is important to emphasise that V-Watt curtailment has not been assessed in this preliminary study, which is anticipated to cause more significant curtailment than V-VAr when the mode is activated at higher operating voltages. Although there are various possible solutions suggested by DNSPs to increase hosting capacity and reduce curtailment (such as network upgrades), they were out of the scope of this preliminary study.	● Further research is required to develop practical concepts of 'fair' curtailment and seek further energy user views on what is most acceptable. ● Further research is required to assess curtailment that may be caused by V-Watt mode. Moreover, other technical network solutions can be compared against the investigated inverter power quality response modes in terms of potential reduction in curtailment, improvement in local voltage conditions and reduction in revenue loss.
People are likely to hold high expectations of transparency in the location, extent, and economic impacts of curtailment.	Technical analysis revealed economic impacts of curtailment under different scenarios including real-operational case. Future research could build models that can estimate the expected amount of curtailment according to site characteristics and location of site.	● Further research is needed to understand the impact of site location on curtailment and build models that estimate the amount of curtailment an energy user may expect based on site characteristics, location, and other relevant interval data such as D-PV generation and voltage. ● Policy and regulations need to create mechanisms that can make curtailment more transparent and provide more accurate information to energy users.
People expect that battery storage will alleviate the impacts of curtailment, and that curtailment may affect D-PV owners less as battery adoption increases.	On average, curtailment was less for BESS than D-PV systems. However, it is important to emphasise that the study only considered BESS curtailment by itself and not	● Align ● Further research is required to assess D-PV + BESS curtailment.

Social analysis	Technical analysis	Reflections on social and technical findings? ● Align ● Contradict ● Require further research ● Require policy action
	in conjunction with D-PV + BESS (this was due to data restrictions regarding VPP sites' D-PV measurements). It is also useful to note that previous analysis has indicated that investment in BESS in order to avoid curtailment is not financially sound in the majority of cases [1].	

8 Concluding remarks

In this scoping study, we presented findings on the social and technical impacts of DER curtailment by running focus groups and interviews and analysing real operational data from sites located in South Australia. The results obtained from the focus groups and interviews indicate that energy users have limited understanding of the issue of curtailment and expect more transparency as the issue is anticipated to become more significant in the future. The research participants raised concerns around the fairness of curtailment and believe that it is mainly the responsibility of government and network operators to resolve the issue.

The findings from the social science analysis suggest that all three dimensions of energy justice – distribution, recognition, and process (Jenkins et al, 2019) – are relevant in considering the impacts of DER curtailment and possible measures to manage it. Prior research and this report's technical findings indicate that some energy users experience higher levels of curtailment than others, according to a range of factors such as the size, type, location and age of a D-PV or BESS system, and the research participants identified the uneven distribution of impacts as a matter of 'unfairness'. Our findings show that justice as recognition is another important dimension to be considered, by ensuring different households (including those without D-PV) and their interests are represented in decision-making around the issue of curtailment. Participants expressed that recognition of the positive role of D-PV is likely to be an important part of this. Finally, the third, procedural dimension of energy justice is at issue here too, as our research indicates that people expect transparency and information about the extent to which they are being or might be affected by curtailment, in order to make informed decisions about DER investment or management.

The technical analysis focused on two types of curtailment, tripping (anti-islanding and limits for sustained operation) and V-VAr, from both energy users' and aggregators' perspectives. Consistent with some of the prior research results, curtailment was found to be insignificant for most households. However, some households incurred significant generation loss due to curtailment, which raised concerns regarding the fairness of curtailment. The findings however have also highlighted that inverter set points are an important area for further investigation. The analysis of VAr characteristics showed that most BESS did not show a defined V-VAr response because they have legacy settings which did not mandate V-VAr response. Similarly, most D-PV did not show any V-VAr response and either operated at fixed unity power factor or increased or reduced its power factor with increasing real power. Further research is needed to investigate potential reasons behind this type of behaviour. Overall, D-PV systems experienced higher revenue loss due to curtailment than BESS, which is attributed to the storage capability of BESS, reducing the excess generation and enabling the use of the curtailed output at a later point in time.

To understand what curtailment would look like if all BESS and D-PV operated according to reference V-VAr curves, scenario analysis was carried out. Four V-VAr curves were investigated from TS-129, AS/NZS4777-2015, ENA and AS/NZS 4777-2020 and it was seen that V-VAr curtailment increased for BESS when they operated according to one of these V-VAr curves with the ENA curve resulting in the highest curtailment. On the other hand, D-PV curtailment was reduced when it operated according to one of the reference V-VAr curves, as some D-PV inverters absorbed higher amount of VArs with its default power factor and VAr settings. It is important to emphasise that the study did not investigate V-Watt curtailment, which is expected to result in higher curtailment overall than the analysed tripping (anti-islanding and limits for sustained operation) and V-VAr when it is enabled. Another limitation of this analysis is that the analysed operational voltage, BESS, and D-PV data may not be representative of a future scenario as both DER uptake and DNSP's management strategies are changing very quickly.

The study concluded with key socio-technical insights, and it was seen that there was both alignments and contradictions between the results obtained from the analysis of energy users' perspectives and the technical data analysis. These insights are useful inputs for planning future research in this area, as described in the next section.

8.1 Next steps

Curtailment is becoming more prevalent as the penetration of DER increases and this preliminary scoping study has shown that there is a lot of work to be done to improve our understanding of curtailment and the challenges and issues that surround it. The points below summarise future project and research directions.

Project directions:

- Disseminate the final project report publicly and seek broader feedback from academic and industry stakeholders. Such feedback can contribute to future research planning.
- Host a webinar to discuss the findings of CANVAS and discuss potential future collaboration opportunities with industry partners.
- Develop a RACE for 2030 standard project application which can investigate curtailment in more detail including potential research objectives listed below.

Potential research directions:

- SAPN has carried some recent upgrades across the network such as line drop compensation and advanced closed-loop voltage control, since the beginning of this study. It will be interesting to analyse DER curtailment with the most recent dataset and investigate any potential changes as a result of these upgrades.
- SAPN has made some remedial work at the energy-user sites who experienced highest curtailment according to this study. It would be interesting to investigate these highly impacted sites with most recent dataset and validate if these changes have reduced the experienced curtailment.
- Analyse the extent and impact of V-Watt curtailment.
- Investigate potential reasons behind the differences in V-VAr behaviour across different BESS and D-PV inverters. This can include working with manufacturers and conducting lab tests to get to the bottom of this different power factor behaviour.
- Improve the accuracy of the V-VAr curtailment model.
- Analyse D-PV + BESS curtailment for the VPP sites.
- Try to incorporate VPP operator decisions regarding BESS operations into curtailment analysis.
- Seek methods to investigate the impact of DER's location on the experienced curtailment. Integration of engineering and network models with big data analysis may be a potential future research direction.
- Build an open-source model that can estimate curtailment at a specific site depending on the relevant DER and location parameters and interval data.
- Further explore the conditions for what energy users would consider 'fair' curtailment, including the best ways to communicate with energy users about this issue, and their preferred scenarios for management of high network voltage.

9 Appendix

Tripping (anti-islanding and limits for sustained operation) calculation for BESS (Section 4.2.2.2)

BESS tripping (anti-islanding and limits for sustained operation) curtailment while BESS could be discharging

The tripping (anti-islanding and limits for sustained operation) curtailment when BESS could be discharging is calculated according to the steps described below:

1. Calculate BESS's storage capacity and minimum state of charge (SOC) changing over time

2. Identify instances where site is net-importing

3. Identify instances where BESS has sufficient SOC to discharge the net-imported energy

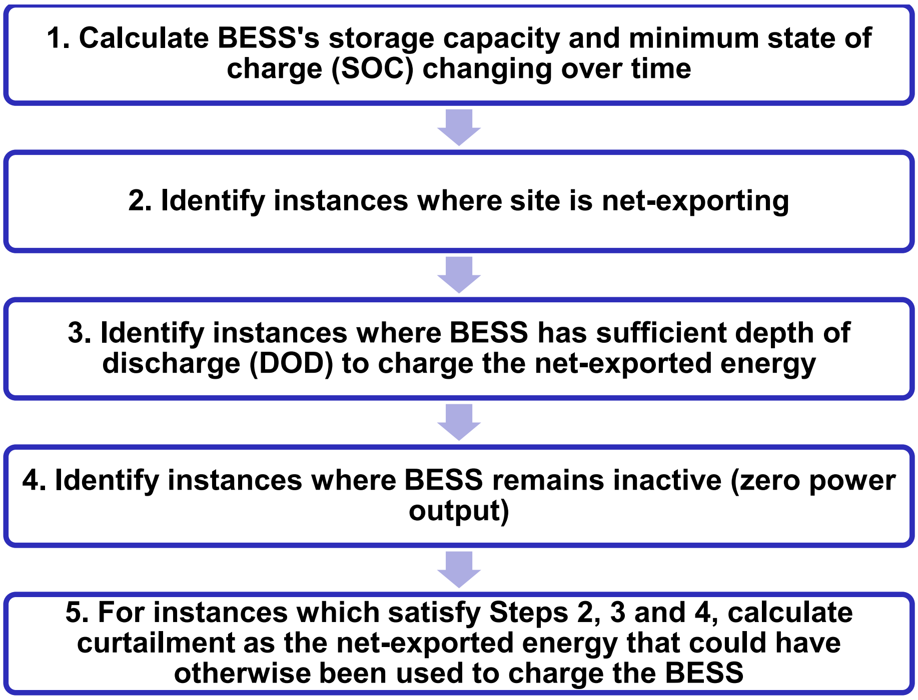
4. Identify instances where BESS remains inactive (zero power output)

5. For instances which satisfy Steps 2, 3 and 4, calculate curtailment as the net-imported energy that could have otherwise been provided by the BESS

It is important to note the VPP operator may also limit BESS discharging and choose to reserve the BESS SOC due to an operational strategy such as the anticipated high spot market price event. This strategy may cause BESS to remain inactive during these instances. Since the dataset did not include any information regarding VPP operators' operational decisions, it was not possible to separate instances of actual tripping from such operational decisions. For this reason, the method is likely to over-estimate the BESS tripping during potential discharge instances. This is a limitation of this study which should be addressed in future research.

BESS tripping (anti-islanding and limits for sustained operation) curtailment while BESS could be charging

The tripping (anti-islanding and limits for sustained operation) curtailment when BESS could be charging is calculated according to the steps described below:



Once again, the VPP operator may limit BESS charging and choose to export excess D-PV as per an operational strategy. Therefore, applied method is likely to over-estimate the BESS tripping during the potential charge instances. Another important point to emphasise is that some sites had different minimum BESS SOC values which changed over time. This could be due to change of BESS settings by the energy users, VPP operator or the BESS original equipment manufacturer (OEM). This dynamic minimum SOC created further challenges for the calculation of curtailed energy due to tripping.

V-VAr curtailment for D-PV inverters (Solar Analytics dataset) (Section 4.2.3.2)

The potential curtailment events described in Step 4 of below diagram are the instances where D-PV's real generation may be curtailed as it cannot have higher real output in the presence of VAr absorption or injection due to reaching its rated VA capacity. Note that these instances generally occur during mid-day period where solar irradiance is highest.

The preliminary D-PV generation model described in Step 5 calculated the D-PV generation using the D-PV system parameters:

a. DC rated of D-PV system
b. Minutely GHI data from BOM
c. System loss parameters assumptions:
    i. Inverter efficiencies
    ii. Model derating loss
    iii. Cable loss
    iv. Orientation & tilt

1. Calculate the operational VA of the D-PV inverter using real power and VAr data
2. Identify instances where D-PV inverter is operating at its rated VA capacity (generally peak irradiance periods).
3. Identify instances where D-PV inverter is injecting or absorbing VArs.
4. The instances which satisfy Steps 2. and 3. are the potential curtailment events which are further investigated
5. Use a preliminary the D-PV generation model to calculate power output of D-PV inverter
6. Calculate expected power output of D-PV inverter during potential curtailment instances specified in Steps 2. and 3
7. Calculate D-PV curtailment during potential curtailment events as the difference between expected power output (Step 6) and the real power of D-PV inverter

The modelled D-PV output was compared against the real operational data outside the potential curtailment times where D-PV real output wouldn't be limited by V-VAr (i.e., D-PV inverter VA is less than its rated capacity). The modelled and real D-PV outputs were checked for any discrepancies and if the modelled results were outside a 5% range of the real output, the model was re-iterated by adjusting system loss parameters.

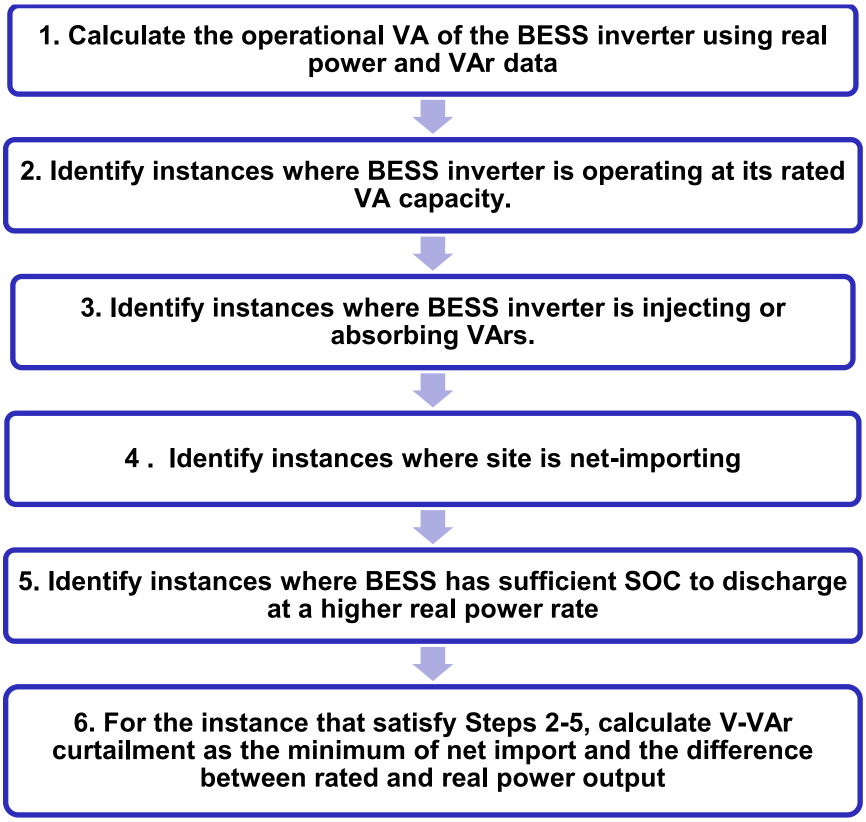
The expected power output of D-PV during potential curtailment events (Step 6) refers to the AC output from the D-PV if it was not curtailed. This was found by comparing the modelled AC D-PV power against D-PV inverter rated AC output and choosing the minimum of the two compared values. This was done because systems with high DC to AC ratio, D-PV inverter will be capped at its rated AC output.

It is important to note that the studied D-PV V-VAr curtailment model is preliminary, and its accuracy will be further improved in the following project. Due to inaccuracies between the modelled vs real D-PV output, V-VAr curtailment may be over or under-estimated depending on sites' unique D-PV system installation configurations (i.e., tilt, orientation, shading conditions etc.)

V-VAr curtailment for BESS inverters (AGL VPP dataset) (Section 4.2.3.3)

Energy user perspective

For energy users the focus was on the potential reduction of site's self-consumption rate due to V-VAr curtailment. In such instances, BESS operates at its rated VA capacity and can only discharge at a rate smaller than its rated real-power capacity due to presence of VArs. When the site is net-importing, V-VAr curtailment is the minimum of net imported power and the additional power that could be discharged (difference between its rated real power capacity and real power output). The V-VAr curtailment calculation for energy user's is summarized in the steps described below:



Aggregator (VPP operator) perspective

For aggregators, V-VAr curtailment analysis had a broader scope. In contrast to energy user's self-consumption perspective while BESS is discharging, aggregator's perspective takes all the instances into account where BESS may not be able to charge or discharge at its rated real power capacity due to injection/absorption of VArs. In such instances, the aggregator has reduced BESS capacity to charge and discharge which may is likely to impact financial returns that can be gained from different operational strategies (i.e., discharging all the BESS at its rated output during a high price event). Considering these points, the calculation of V-VAr curtailment for aggregators is described with the following steps:

1. Calculate the operational VA of the BESS inverter using real power and VAr data

↓

2. Identify instances where BESS inverter is operating at its rated VA capacity.

↓

3. Identify instances where BESS inverter is injecting or absorbing VArs.

↓

4. Identify instances where BESS has sufficient SOC or DOD to discharge or charge at a higher real power rate

↓

5. For the instance that satisfy Steps 2-4, calculate V-VAr curtailment as the the difference between rated and real power output

V-VAr scenario analysis (Section 4.2.3.4)

In the scenario analysis, new VAr values were calculated for each D-PV and BESS (which will be referred as '*ideal VArs*') using real operational voltage data and each of the respective V-VAr curve parameters presented above. The V-VAr curtailment procedure described in Sections 4.2.3.1 and 4.2.3.2 are repeated after this calculation step:

1. Calculate the ideal VAr according to real operational voltage data and V-VAr curves

↓

2. Calculate new D-PV and BESS VA (ideal VA) according to ideal VAr and real operational power data

↓

3. If ideal VA, exceeds rated VA capacity, calculate new real power output (ideal power) to give max VA at the rated capacity (real power remains the same if ideal VA is equal or smaller than the rated VA

↓

4. Calculate the differene between real and ideal power for the instances of ideal VA greater than the rated VA (V-VAr curtailment 1)

↓

5. Apply the V-VAr curtailment procedure described in 4.2.3.1 and 4.2.3.2 with the new ideal VAr, power and VA (V-VAr curtailment 2)

↓

Add V-VAR curtailment 1 (Step 4) and curtailment 2 (Step 5)

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