

N2 Fast Track

Curtailment and Network Voltage Analysis Study (CANVAS)

Succinct report 2021



RACE for 2030 Fast Track Project

CANVAS: Curtailment and Network Voltage Analysis Study Succinct Project Report

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Curtailment and Network Voltage Analysis Study (CANVAS) Public Report

Context

Australia has world leading uptake of distributed Photovoltaic (D-PV) and increasing installations of battery energy storage systems (BESS). Recent reports estimate one in four households own D-PV and installation rates are anticipated to grow in the years ahead. D-PV and BESS can provide various economic and environmental benefits to energy users, network companies and other industry stakeholders. However, integrating increasing levels of D-PV 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 D-PV. 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, D-PV exports can increase the local voltage range. To help DNSPs in managing network voltage effectively, it is increasingly required that inverter-based D-PV and BESS implement one or more of the following power quality response modes (PQRM):

1. Tripping (anti-islanding and limits for sustained operation) (**analysed in this study**)
2. Volt-VAr (V-VAr) (**analysed in this study**)
3. Volt-Watt (V-Watt) (**future work**)

The anti-islanding and limits for sustained operation were required by AS/NZS 4777.2-2015 (the latter according to the compliance specified in AS 60038-2012). V-VAr mode was not required for the legacy fleet (AS/NZS 4777.2-2005) and if available, was disabled by default for systems installed according to AS/NZS 4777.2-2015. V-VAr mode is required and enabled by default for newer systems installed according to AS/NZS 4777.2-2020. V-Watt mode was not required for the legacy fleet (AS/NZS 4777.2-2005) and if available, was enabled for systems installed according to AS/NZS 4777.2-2015. V-Watt mode is required and enabled by default for newer systems installed after AS/NZS 4777.2-2020. 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 D-PV.

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 aims to use the preliminary findings from this scoping project to inform a bigger standard-track project within RACE for 2030.

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.

Social science research stream

The social science research stream involved focus groups and the participants were recruited through a market research agency, allowing a targeted mix of demographic factors, locations in South Australia, and D-PV system ownership. A total of 20 respondents participated in the research. The composition of the focus groups and interviews are shown in Table I below.

Table I Focus groups and survey details

	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.
Focus group 4	4	2 residents of apartments and 3 residents of houses; all without D-PV 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 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 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 findings from the social science analysis suggest that all three dimensions of energy justice – distribution, recognition, and process – 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, to make informed decisions about DER investment or management. 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.

Technical data analysis stream

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 Volt-Var operation. The scope of the CANVAS technical data analysis stream is summarised in Table I. The studied datasets included 996 BESS sites from AGL’s Virtual Power Plant (VPP) trial in metropolitan Adelaide for a year period and 500 D-PV sites from Solar Analytics’ customer database in metropolitan Adelaide for 10-month period. The AGL VPP data included BESS inverter measurements captured at BESS inverter terminals whereas the Solar Analytics data included D-PV inverter measurements captured at the main switch board.

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

Mode of curtailment	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 (static/dynamic)	Future work	Future work

The study focused on the first two PQRM modes: tripping 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.

Voltages in metropolitan Adelaide

Figure 1 presents the distribution of voltages grouped by 24-hourly periods: a) 1,000 BESS sites from AGL data-set, b) 500 D-PV sites from Solar Analytics customer database. The results support the findings of our previous research in [1], as the voltages are highest during the solar window period corresponding to lower load and higher D-PV exports. Voltages are also high at late-night periods when the network load is lower. The day-time voltages are higher for Solar Analytics D-PV sites compared to the AGL data-set. This difference is mainly due to BESS’s storage capability resulting in less exports during day time. It should also 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 difference.

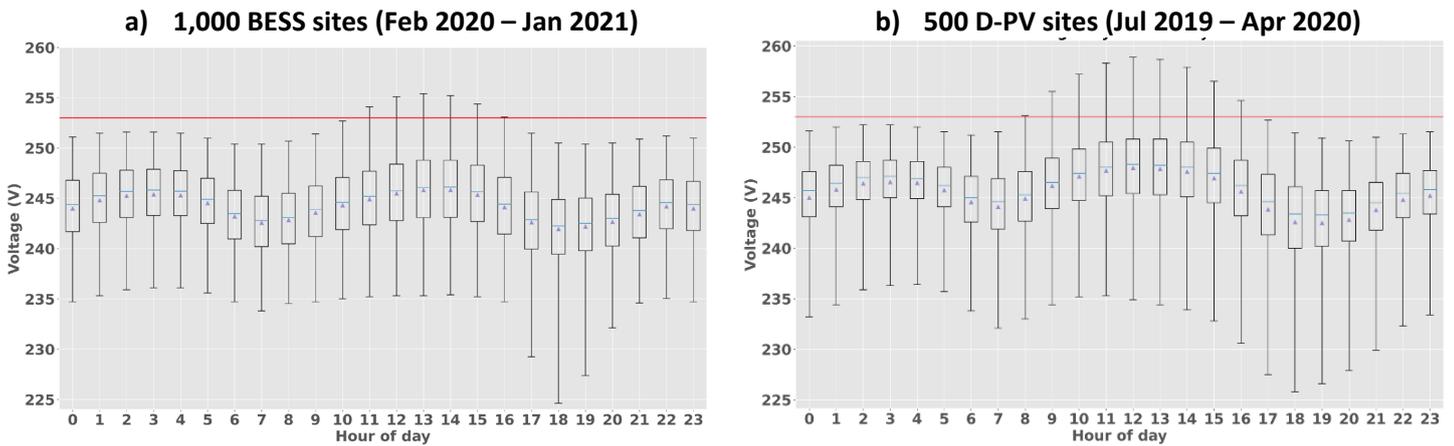


Figure 1 Distribution of 24-hourly voltages: a) 1,000 BESS sites from AGL VPP, b) 500 D-PV sites from Solar Analytics

Tripping (anti-islanding and limits for sustained operation)

Analysis of the Solar Analytics data indicates that overall, the proportion of generation lost due to anti-islanding 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 [2]. The discrepancy in curtailment on clear sky days is possibly due to differences in the sample, since large samples are more likely to capture ‘edge cases’ experiencing significant curtailment and previous work analysed over 1,300 sites whereas the work presented here analyses 500 sites within the metropolitan Adelaide. In addition, all the sites in the dataset analysed here are located in greater Adelaide, whereas previous analysis considered sites across South Australia and so it 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 III 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 2. 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 activation impacts a small proportion of overall generation, it does appear to occur very frequently.

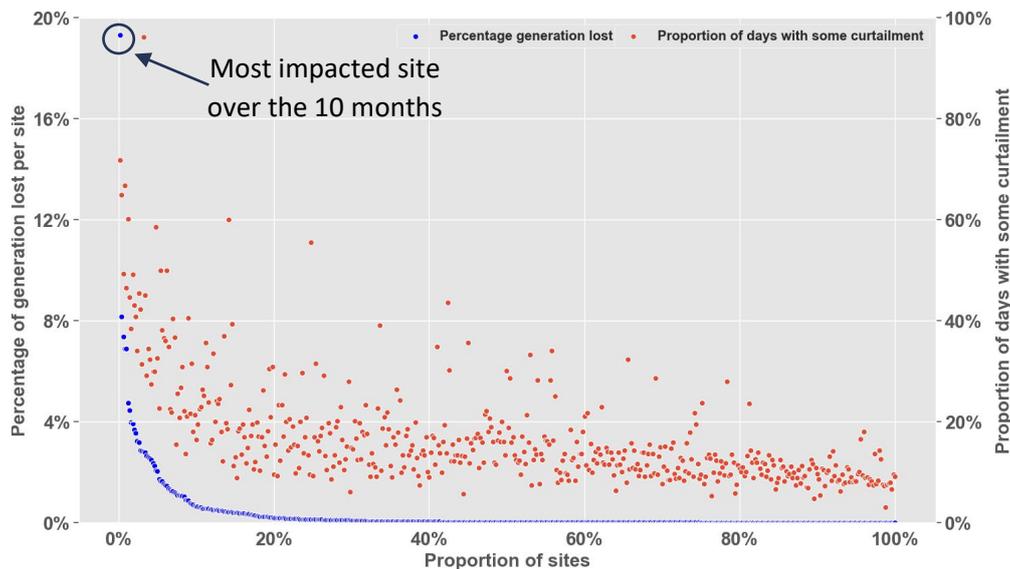


Figure 2 – Distribution of D-PV tripping curtailment: percentage of total generation being curtailed and proportion of days with curtailment occurring, 500 Solar Analytics sites from Greater Adelaide

Another important point to mention is that the majority of the anti-islanding curtailment were experienced when local voltages were lower than 255V which is lower than the specified anti-islanding set-points (260 V and 265 V) and the default limits for sustained operation set point (255 V) as specified in AS/NZS 4777.2.2015. 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.

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 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 VPP operator to stop BESS 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. During both types of events, BESS power reduces to zero and remains inactive for a period just like an actual tripping event. Therefore, it is not straightforward to differentiate these VPP decision-based events from real tripping (anti-islanding) events.

Figure 3 presents 100 AGL VPP sites with highest tripping 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 99% of the VPP fleet loses less than 1% of total D-PV generation due to tripping curtailment. Figure 3 also breaks down the curtailment into instances associated with BESS charging and discharging. It is seen that tripping curtailment is mostly attributed to instances where BESS would otherwise be discharging to avoid importing energy. On average the fleet loses only 0.06% of total D-PV generation due to tripping curtailment.

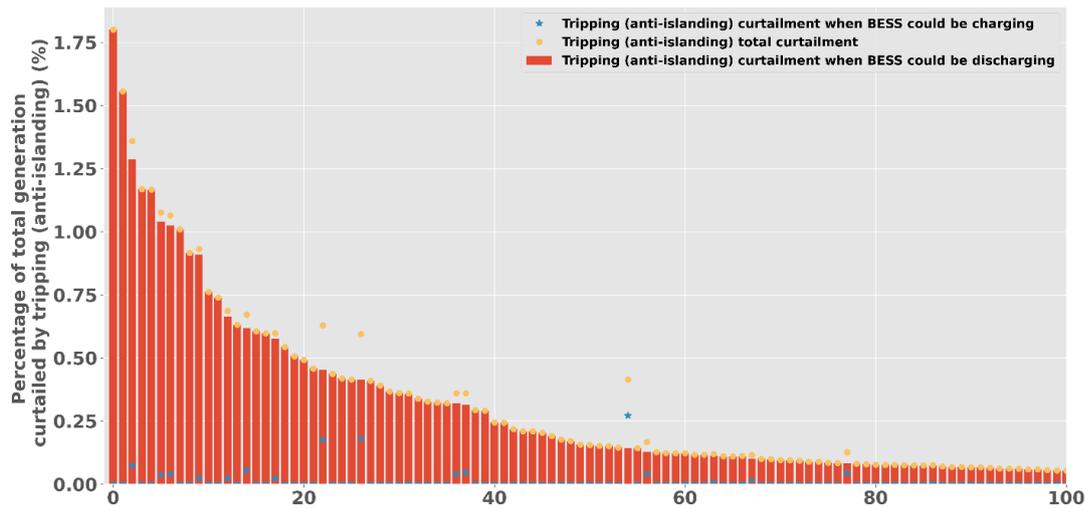


Figure 3 Percentage of total generation curtailed by tripping (anti-islanding and limits for sustained operation) for 100 AGL VPP sites with highest curtailment

Volt-VAR (V-VAR) behaviour analysis

The analysis initially investigated the V-VAR behaviour of BESS and D-PV inverters separately according to V-VAR curves specified by different standards and regulations:

- TS129 (South Australian Power Networks- SAPN) [3]
- AS/NZS 4777.2-2015 [4]
- Energy Networks Australia (ENA) recommendations [5]
- AS/NZS 4777.2-2020 [6]

The V-VAR curves for each specific standard is demonstrated in Figure 4 below.

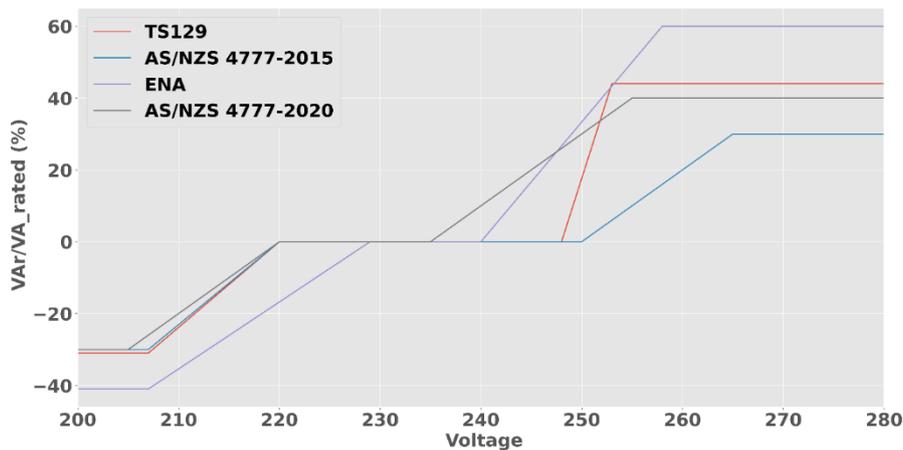


Figure 4 Studied reference V-VAR curves

The analysis found that only a small number of BESS inverters showed a clear V-VAR response according to one of the reference V-VAR curves shown in Figure 4 and the majority showed negligible VARs during over/under voltage events. After consultation with AGL, it was confirmed that most BESS were installed prior to July 2019 after which TS-129 took effect which mandates the V-VAR settings. BESS installed prior to this date were most likely equipped with the previous AS/NZS 4777-2015 V-VAR settings, and hence they were not mandated to perform V-VAR. Table IV below summarizes the results of the V-VAR curve investigation for the AGL sites.

Table IV 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 inverters showed V-VAr response according to the reference V-VAr curves. D-PV inverters showed a range of V-VAr and power factor (PF) behaviours as demonstrated in Figure 5. The figure shows scatter plots for reactive power level Q/VA_{rated} (%) vs. real power level P/VA_{rated} (%) with blue dots (left y-axis), PF vs. real power level P/VA_{rated} (%) with purple dots (right y-axis) and reactive power level Q/VA_{rated} (%) vs. voltage (bottom plots) with red dots.

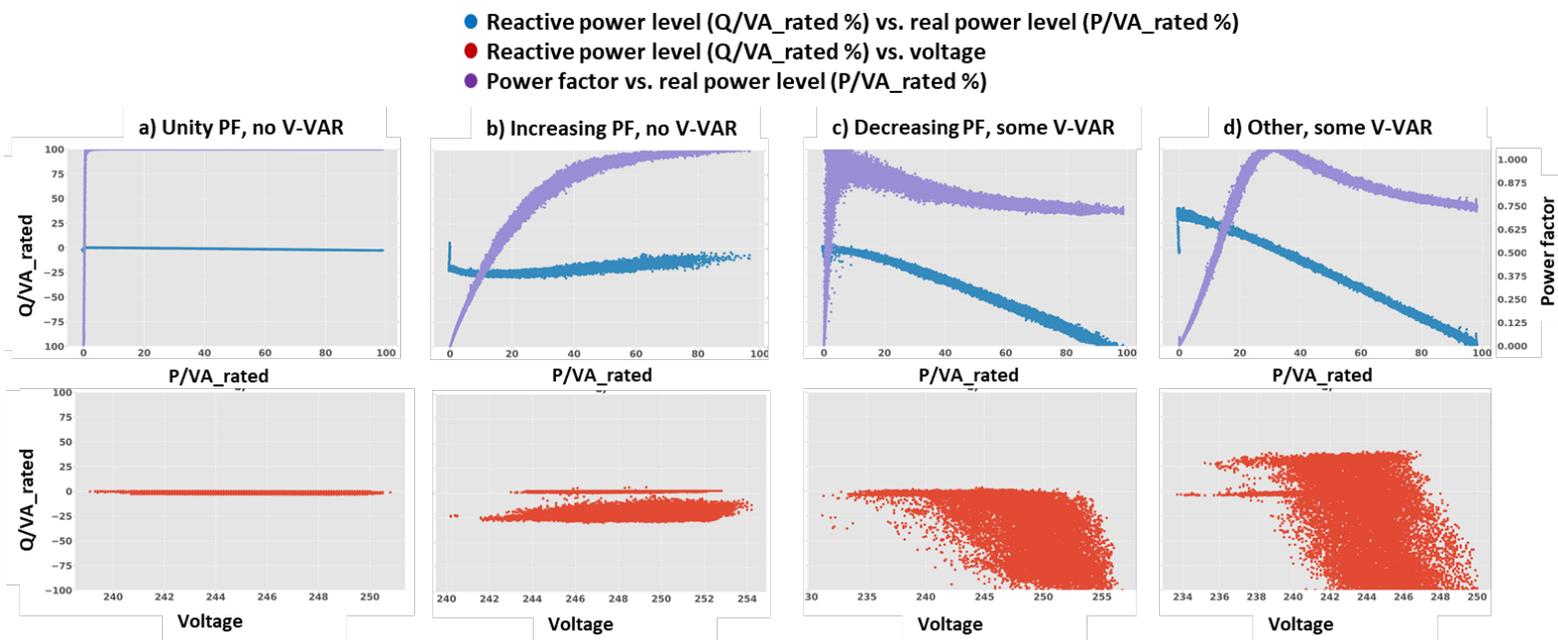


Figure 5 Different D-PV inverter V-VAr and power factor (PF) behaviours

Table V summarizes the percentage of D-PV inverters according to their V-VAr response and PF characteristics observed from the studied Solar Analytics data set with D-PV systems. It is seen that only 0.5% of D-PV inverters showed one of the reference V-VAr curves and 80% operated at unity PF with almost zero VARs across the entire voltage range. 15% of D-PV inverters increased PF with real power with limited VARs (Figure 5 b). The remaining D-PV inverters reduced PF with real power and absorbed VARs without following a clear pattern shown by the reference V-VAr curves. The behaviour demonstrated in Figure 5 b), c) and d) requires further investigation. Future research aims to conduct further lab tests and have conversations with inverter original equipment manufacturers to get to the bottom of this observed phenomenon.

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

	Reference V-VAr curves	a) Unity PF, no V-VAr response	b) Increasing PF, no V-VAr response	c) Decreasing PF, some V-VAr	Other, some V-VAr
Percentage of D-PV inverters (%)	0.5	80	15	2.5	2

Volt-VAR curtailment analysis

Figure 6 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.

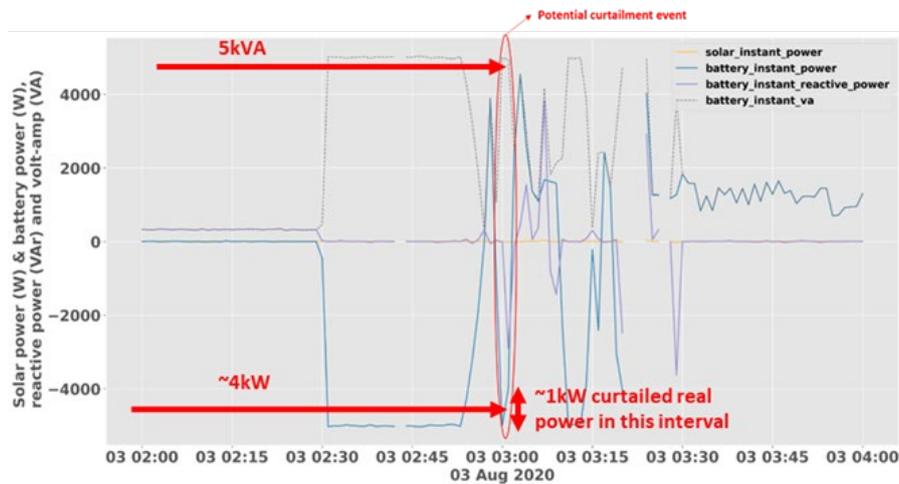


Figure 6 Example daily operation from a sample BESS where V-VAR curtailment instance can be observed

Figure 7 below presents the V-VAR curtailment results for AGL VPP sites and breaks down the curtailment in terms of injected VARs and absorbed VARs. It is seen that overall, V-VAR curtailment is negligible and the BESS that experiences highest V-VAR curtailment only lose 0.068 %. The main reason for this outcome is that most of the time BESS inverter inject/absorb VARs at a relatively small quantity which doesn't limit BESS inverter's real power capability.

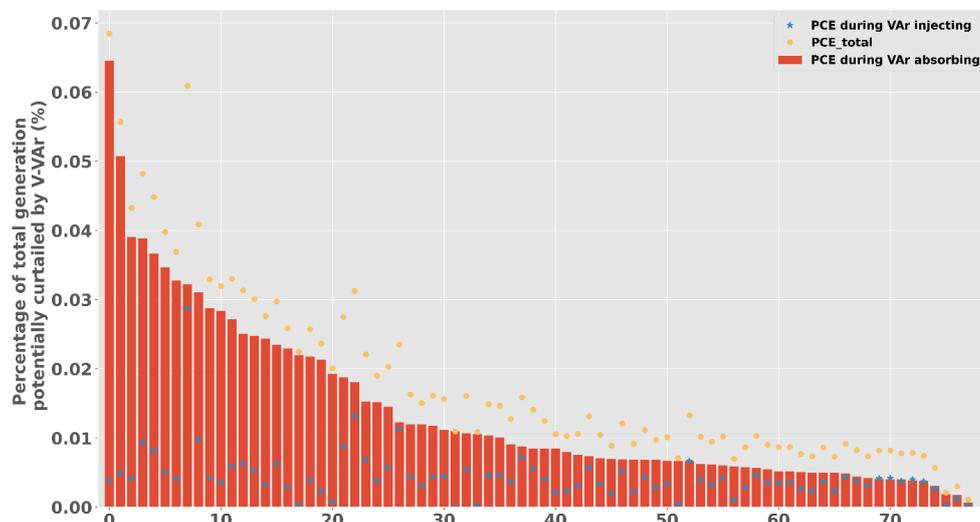


Figure 7 Percentage of total generation curtailed by V-VAR for 78 AGL VPP sites that shows some V-VAR response

Figure 8 presents an example case of curtailment from the D-PV inverter 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 D-PV inverter absorbed higher quantities of VARs during the D-PV generation window, it reached its rated apparent power capacity and as a result D-PV real power was curtailed. It is seen that the site loses a significant amount of generation during the analysed week as demonstrated by the green shaded area.

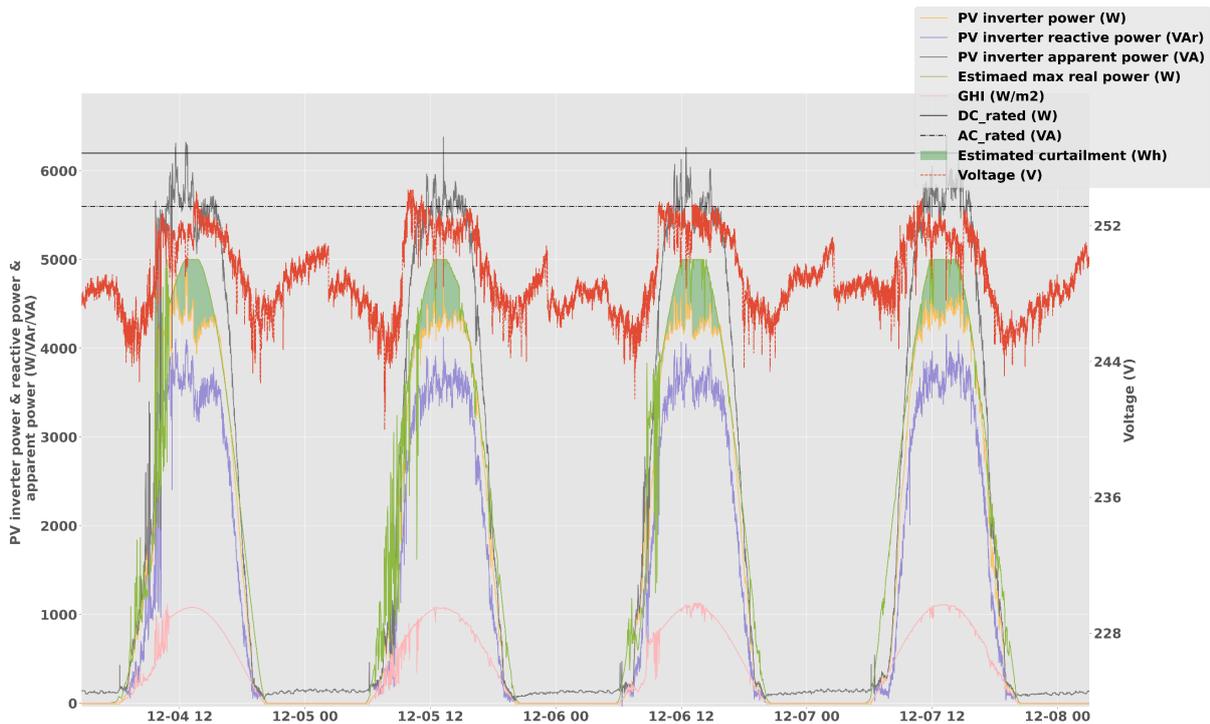


Figure 8 Example weekly operation from a sample D-PV where V-VAr curtailment instances can be observed

Figure 9 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 most sites, the lost generation is less than 1%. Like BESS, V-VAr curtailment is mostly attributed to instances of VAr absorption rather than injection.

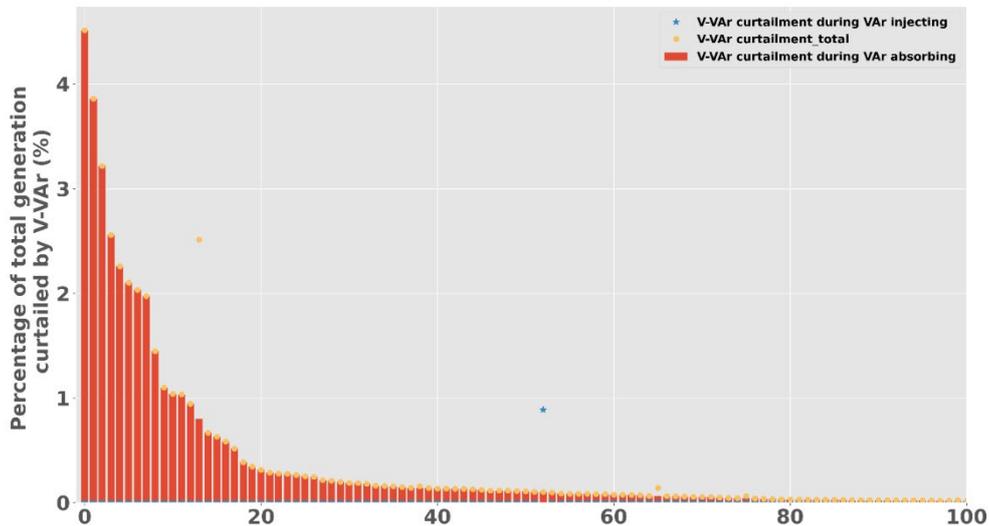


Figure 9 Percentage of total generation curtailed by V-VAr for the 100 Solar Analytics with highest V-VAr curtailment

Volt-VAr curtailment scenario analysis

In the V-VAr curtailment scenario analysis, all D-PV and BESS inverters are assumed to follow the V-VAr curves specified by the reference V-VAr curves presented in Figure 4. Table VI shows the scenario analysis results for BESS inverters presented alongside with the real case. The modelled V-VAr scenarios result in higher V-VAr curtailment than the real case. Amongst the studied V-VAr curve

scenarios, the ENA recommendation results in highest 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. The aV-VAr curtailment remains small for the BESS inverters regardless of the analysed V-VAr curves.

Table VI Summary statistics for V-VAr curtailment scenario analysis for all BESS inverters from AGL VPP sites as a percentage of total generation (%)

	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

Table VII shows the scenario analysis results for D-PV inverters, presented alongside with the real case. In contrast to BESS inverters, V-VAr curtailment is less in the analysed scenarios compared to the real case for D-PV inverters. The difference is more obvious for the maximum curtailment cases because some D-PV inverters with different VAr and PF behaviour experienced high curtailment in real case compared to operating according to one of the reference V-VAr curves. 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. It is seen that average V-VAr curtailment is small both for the real case and the studied scenario analysis.

Table VII Summary statistics for V-VAr curtailment scenario analysis for all D-PV inverters from Solar Analytics sites as a percentage of total generation (%)

	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

Summary of findings

Table VIII presents a summary for the tripping (anti-islanding and limits for sustained operation) and V-VAr curtailment findings. It is important to remind the reader that these results don’t include V-Watt curtailment which is anticipated to result in higher curtailment than these two modes. Therefore, the results don’t present the complete extent of DER curtailment. The presented 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, net-load (Solar Analytics dataset), 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 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 considered 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 and V-VAr curtailment share an almost equal proportion of total curtailment. On the other hand, for BESS inverters, 90% of the curtailment is attributed to estimated tripping. This is because only less than 10% of the studied BESS inverters show some V-VAr response and as a result, majority of the sites have zero V-VAr curtailment. Another important reminder is that even though the average curtailment per site was small, a small number of sites lost significant total generation up to 20%. This raises fairness concerns regarding DER curtailment and warrants further investigation of most impacted sites in more detail.

Table VIII Summary of tripping (anti-islanding and limits for sustained operation) and V-VAr curtailment findings

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

In the light of these findings, the financial revenue loss due to the studied two modes of curtailment were small for an average energy user (less than \$5/year). On the other hand, the most impacted site’s revenue loss was calculated to be around \$40/year based on average tariff assumptions. To quantify the potential revenue loss for the VPP 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) [7]. 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 10 shows the distribution of total annual potential revenue loss due to curtailment for the aggregator for the real-case, TS-129 and ENA V-VAr scenarios. These results are only preliminary estimates, and more information needs to be obtained from the VPP aggregator with regards to their spot price operations to obtain more accurate results.

It is important to emphasize that the results are only for BESS inverter curtailment and don’t include D-PV inverter 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. On the other hand, it is important to note that as DER penetration increases, the spot market prices go negative in the middle of the day; therefore, when all BESS are fully charged, exported D-PV generation may cause a revenue loss for the aggregator.

Another important point is that the study captured only 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 to be higher in the future.

As seen in Figure 10, 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.

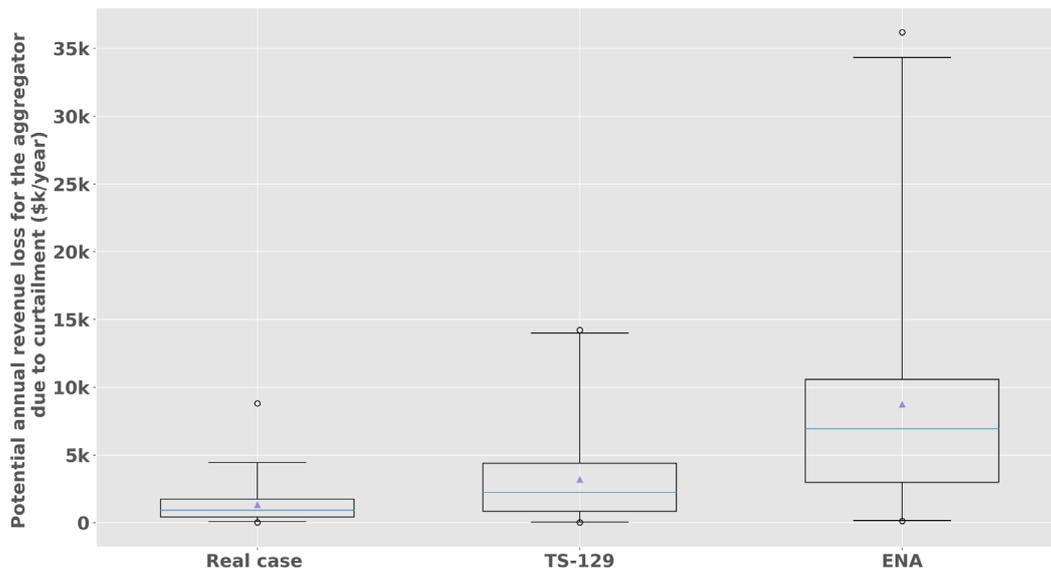


Figure 10 Total annual potential revenue loss due to tripping (anti-islanding and limits for sustained operation) and V-VAr curtailment for VPP operator with 1000 BESS sites analysed for three scenarios (real case, TS-129 and ENA)

Based on the estimated percentage and total number of free-standing homes with rooftop D-PV across Australia [8], the upscaled curtailed generation is in the order of 22 GWh/year. Based on the reported CO₂ emissions of the Australian energy mix [9], the upscaled curtailed generation has emissions impact of 16,5 mega-tonnes of CO₂-e. Figure 11 summarizes the findings of the upscaled curtailed generation and emissions impact. Bear in mind that, the generation and CO₂ 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.

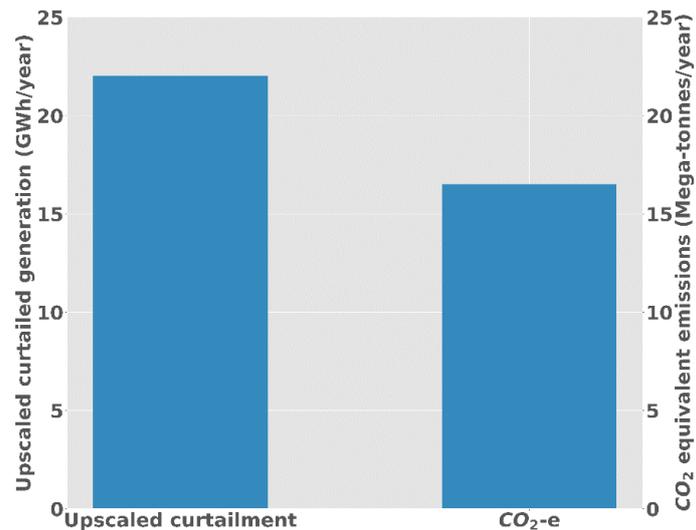


Figure 11 Estimated upscaled curtailed generation (GWh/year) and CO₂ equivalent emissions (Mega-tonnes/year)

Future research directions

Curtailment is becoming a more prevalent issue as the penetration of DER increases. 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 future project and research directions are summarized below:

- Analyse the extent and impact of V-Watt curtailment
- Analyse the extend and impact of dynamic/static export limits
- Project partner 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 because 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.
- 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.
- This study only analysed BESS inverters for the VPP sites (due to lack of voltage data from D-PV inverters of BESS sites). Future research should analyse D-PV + BESS inverters.
- Try to incorporate VPP operator decisions regarding BESS operations into curtailment analysis.
- Investigate the impact of DER's location on the experienced curtailment. Integration of engineering and network models with data-driven analysis may be fruitful for this analysis.
- Build an open-source model that can estimate curtailment at a specific site depending on the relevant DER and location parameters and interval data.
- 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.

References

- [1] Yildiz B, Stringer H, Heslop S, Bruce A, Heywood P, MacGill I, et al. Voltage Analysis of the Low

Voltage Distribution Network in the Australian National Energy Market: A report prepared for the Energy Security Board (ESB). 2020.

- [2] Stringer N, Haghdadi N, Bruce A, MacGill I. Fair consumer outcomes in the balance: Data driven analysis of distributed PV curtailment. *Renew Energy* 2021;173:972–86. <https://doi.org/10.1016/j.renene.2021.04.020>.
- [3] SA Power Networks. Technical standard - TS129: small EG connections-capacity not exceeding 30kW 2019:1–23.
- [4] Standards Australia. AS/NZS 4777.2-2015 Grid connection of energy systems via inverters. 2015.
- [5] Energy Networks Australia. Power Quality Response Mode Settings. 2020.
- [6] Standards Australia. AS/NZS 4777.2-2020 Grid connection of energy systems via inverters. 2020.
- [7] Australian Energy Market Operator (AEMO). National Electricity Market Data Dashboard n.d. <https://aemo.com.au/en/energy-systems/electricity/national-electricity-market-nem/data-nem/data-dashboard-nem> (accessed June 18, 2021).
- [8] Clean Energy Council (CEC). Solar Energy 2019.

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