Collaboration on Energy and Environmental Markets

UNSW SYDNEY

Baran Yildiz
Senior Research Associate
School of Photovoltaic and Renewable Energy Engineering

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Re: AER & EMCa feedback on Ausgrid submission

Ausgrid team has asked us to carry an independent review of the DER/CER curtailment work they have undertaken and requested us to give feedback considering the response they received from AER & EMCa.

The following review is supported by our team, Collaboration on Energy and Environmental Market (CEEM)'s previous research experience in this area. Relevant research publications can be found at the end of this report.

Item 1: Voltage thresholds for calculating curtailment

Based on the feedback received from the AER/EMCa, it is suggested that curtailment should only be calculated when the voltages measured at the inverter are over 258V for compliance with AS/NZS 4777.2:2020 and Ausgrid's voltage threshold of 253 V is found to be a conservative estimate which has caused overestimating the extend of curtailment. Below, we investigate the D-PV curtailment and inverter voltage threshold in three curtailment categories:

1) Tripping Curtailment (anti-islanding and limits for sustained operations)

- AS/NZS 4777.2:2020 defines the anti-islanding over-voltage threshold as 265 V (disconnect within 1 sec) and default set point for sustained operation as 258 V (when average voltage for a 10 min period exceeds the threshold).
- AS/NZS 4777.2:2015 defines the anti-islanding over-voltage threshold as 260 V (disconnect within 1 sec) and default set point for sustained operation as 255 V.

According to our previous analysis using D-PV voltage and power data from 1,300 residential sites in South Australia with temporal granularity ranging between 1-60 sec, we discovered that there were many sites which experienced tripping (anti-islanding and limits for sustained operation) at voltages lower than 258V or 255V. Please note that some of these measurements were taken at the main switchboard via a third-party devices (MSB) and according to AS/NZS 3000, there should be voltage rise/drop of maximum 1% of nominal voltage value (i.e., 2.3 V). Some of the site measurements were directly from the inverter terminal. Figure 1 presents an example of tripping curtailment from a sample site. Figure 2 presents voltages right before the D-PV tripped along with voltages at all other times for five sites that experienced highest amount of tripping. These figures show that the voltages can be less than 255 V or 258 V before the D-PV inverter trips, even after taking 1% max voltage rise between MSB and inverter. The reasons for this behavior may be that inverters were installed with different set-points for anti-islanding and limits for sustained operations and that they may be non-compliant.

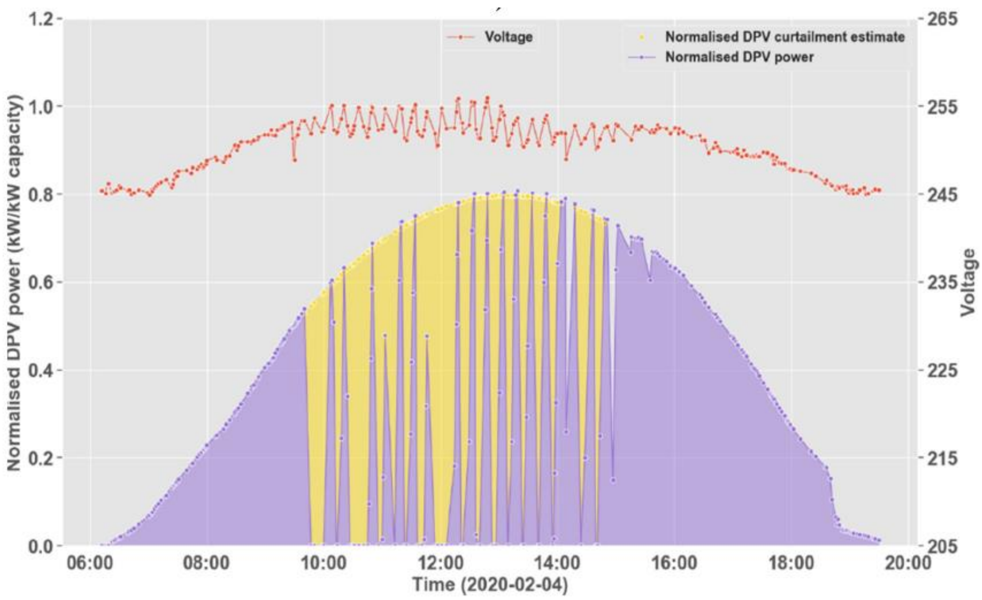

Figure 1 Example instance for tripping curtailment from a sample site

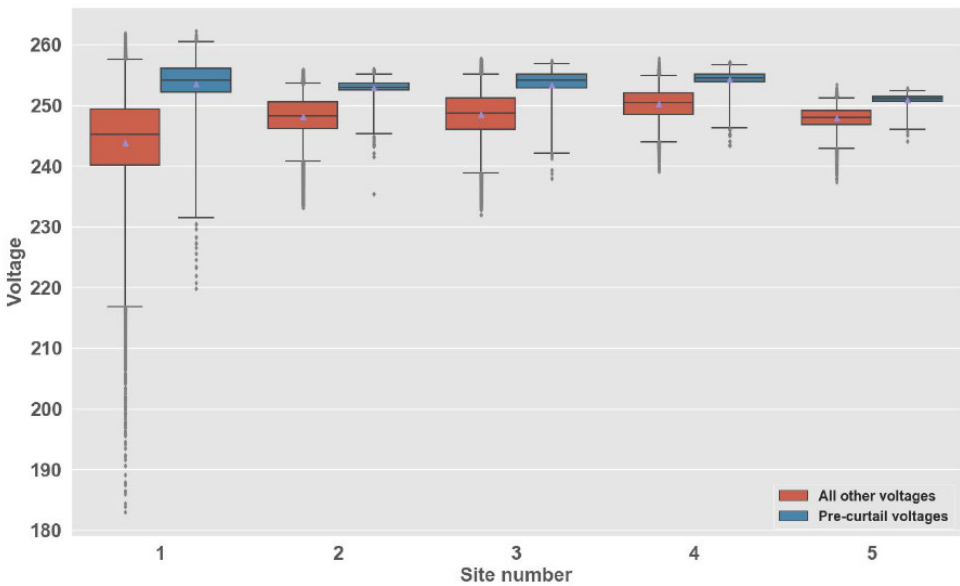

Figure 2 Distribution of voltages right before tripping and all other times for five sites with highest tripping curtailment

Besides the tripping curtailment (anti-islanding and limits for sustained operations), we have also investigated the curtailment due to inverter power quality response modes (PQRM) such as V-Watt and V-VAr as described below.

2) V-Watt Curtailment

- AS/NZS 4777.2:2000 defines the default V-Watt set-point voltage as 253 V (for Australia region A) and the cut-off voltage is 260 V.
- AS/NZS 4777.2:2015 defines the default V-Watt set-point voltage as 250 V and gives a range of possible set-point values between 235-255 V (Table 9). The cut-off voltage threshold is given as 265 V.

Our dataset didn't include the exact installation dates for the D-PV inverters although we knew all of them were installed post 2015 standard. Therefore, we investigated the V-Watt curtailment for both standards and found the inverter specific V-Watt voltage thresholds. Figure 3 shows our method of estimating V-Watt curtailment after trying to fit all possible V-Watt lines within different voltage thresholds (235 V – 255 V) to the inverter power-voltage data.

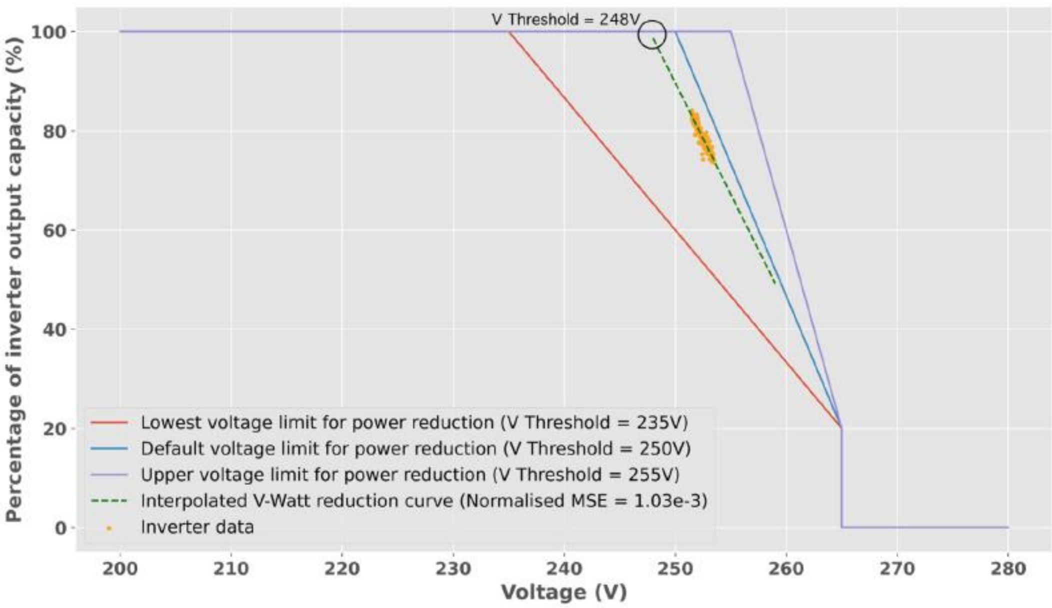

Figure 3 V-Watt power reduction line and voltage threshold identification for a sample D-PV inverter

In this example, the inverter's V-Watt voltage set-point was identified as 248 V. Figure 4 demonstrates another example for daily V-Watt curtailment where the inverter starts curtailing real power at voltages around 251 - 252 V.

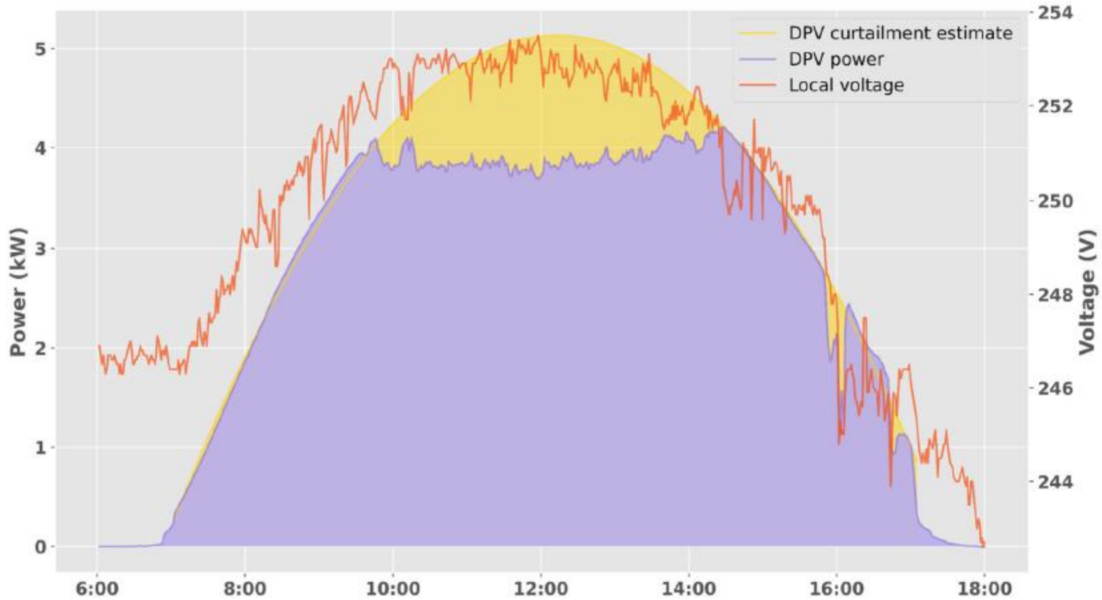

Figure 4 Example daily operation with V-Watt curtailment

3) V-VAr Curtailment

- AS/NZS 4777.2:2000 defines the V-VAr set points in Table 3.7 for different regions. For region A, the cut-off voltage threshold is 258 V at 60% absorbing VArs
- AS/NZS 4777.2:2015 defines the default V-VAr set-point voltage in Table 9 however, the standard doesn't mandate V-VAr operation for D-PV inverters.

- In addition to these two standards, we have also investigated SAPN TS 129 and Energy Network Australia recommendations for V-VAr curves all of which can be seen in Figure 5 below.

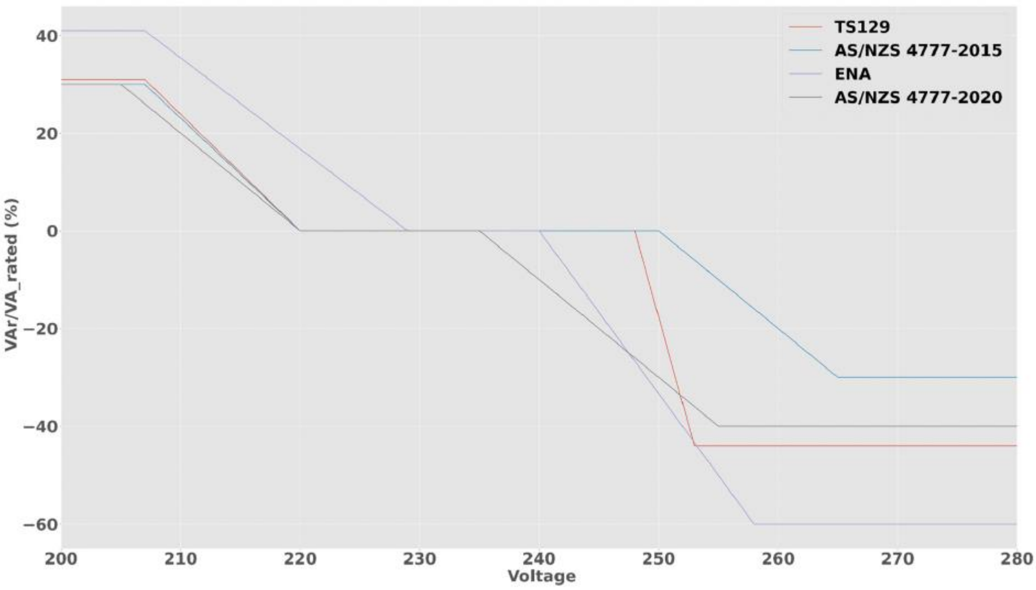

Figure 5 Studied V-VAr curves: (+) injecting VArs and (–) absorbing VArs

In our study, we have seen a low V-VAr compliance by the D-PV inverters resulting in very low levels of V-VAr curtailment (more on this in the next section). The inverters that showed V-VAr response demonstrated a range of set-point voltages one of which is shown in Figure 6 below. As seen, the inverter absorbs high levels of VAr between 249 V – 252 V resulting in curtailment of real power output.

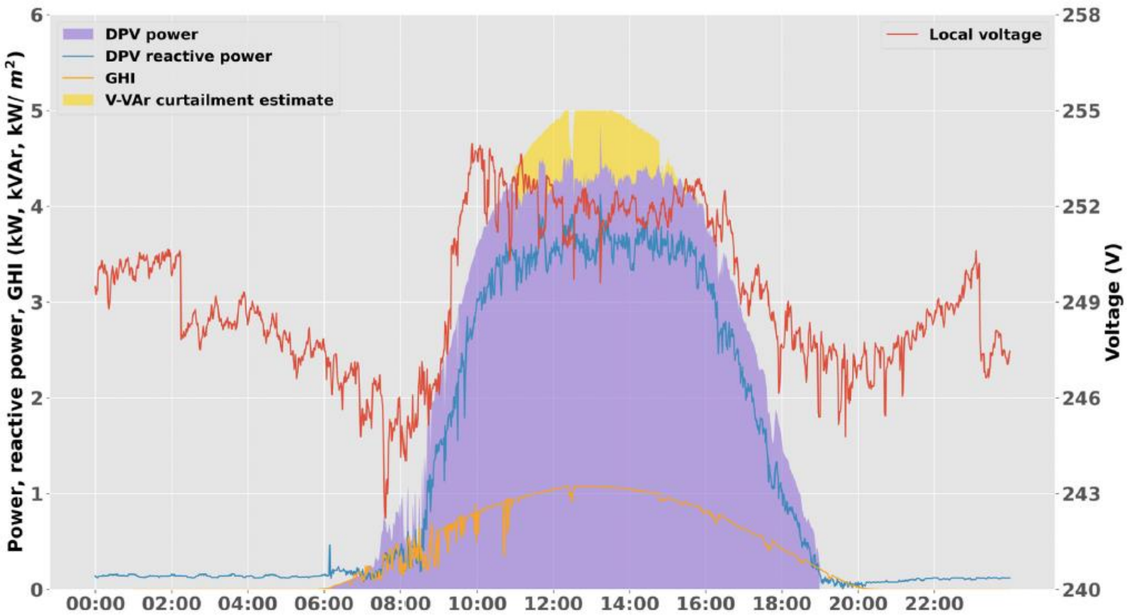

Figure 6 Example V-VAr curtailment

4) Quantification & comparison of different curtailment modes

The distribution of curtailment across the analysed sites are shown below. The results are given separately for clear-sky days and all days where curtailment is higher on clear-sky day conditions due to increased solar generation and higher voltages in the network. Our results show that curtailment due to V-Watt mode resulted in highest overall curtailment followed by the tripping curtailment (anti-islanding and limits for sustained operations) and finally V-VAr curtailment. It is seen that average curtailment loss is less than 2% of total D-PV generation however, for some sites, generation losses can be up to 25% of their respective D-PV generation.

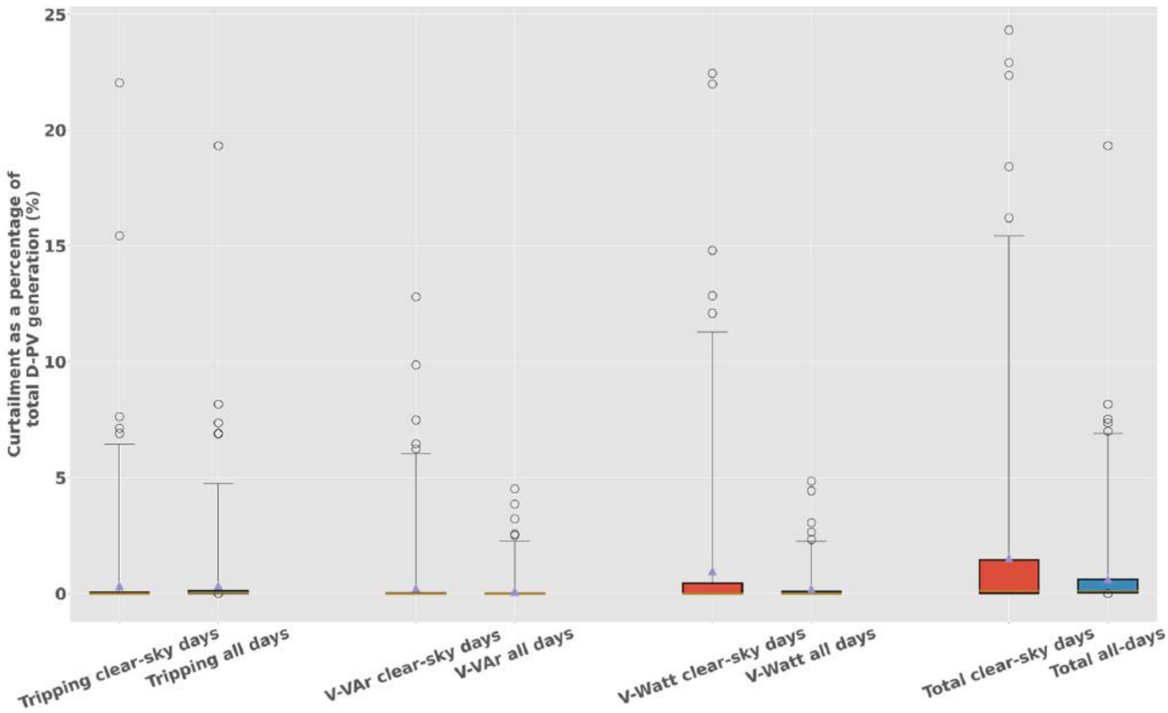

Figure 7 Distribution of curtailment results for the analyzed sites given for clear-sky days and all days

Item 2: Voltage difference between point of common coupling and inverter

Ausgrid has modelled the voltages at the point of common coupling (PCC) during the daytime minimum load conditions in Spring season when PV export is at its maximum. Ausgrid used an estimate of 3 V rise from the PCC to inverter such that when PCC read a voltage of 255 V, the voltage at the inverter was assumed to be 258 V.

In it's response, AER/EMCa suggested that AS/NZS 3000 specifies that voltage rise within an installation must not exceed 2% and 253 V is a conservative trigger for assuming curtailment for inverters installed under AS/NZS 4777.2:2020. EMCa suggest that 258 V is a more appropriate setting to be used for curtailment modelling purposes.

In item 1 above, we have shown that both types of curtailment can take place at voltages lower than 258 V according to our analysis. In terms of voltage rise/drop, Figure 8 below is taken from AS/NZS 3000 and it can be seen that, voltage rise/drop can be up to 3% of nominal voltage from the inverter to PCC which corresponds to a maximum rise/drop of 6.9 V. If Ausgrid used this maximum 6.9 V voltage rise from PCC to inverter, this would have resulted in higher curtailment estimates in their modelling. Even though the actual voltage rise/drop would change for every installation depending on where the inverter is installed (for most households between main switchboard and the sub-board), assuming 3 V rise from PCC to inverter during minimum load/maximum export conditions is more likely to be a conservative estimate, which will lead to under-estimation of modelled curtailment.

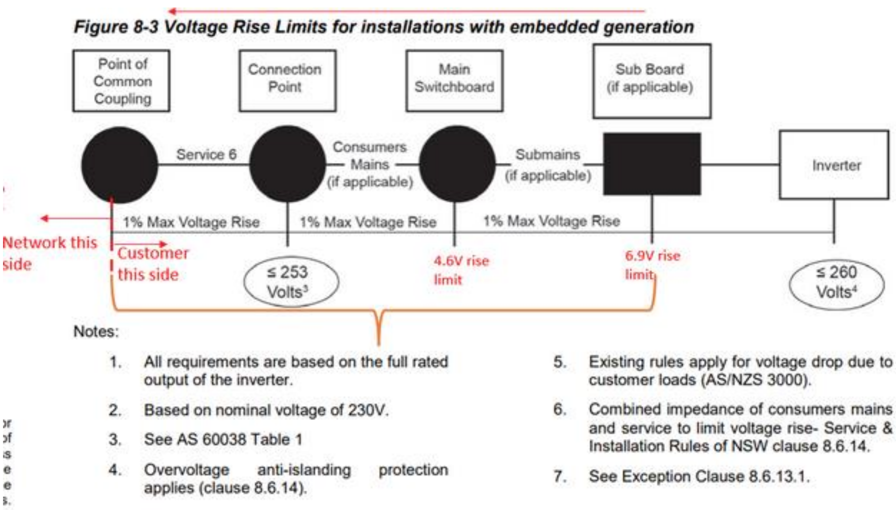

Figure 8 AS/NZS 3000 Voltage rise limits for embedded generation

Item 3: Inverter compliance

According to our study, 80% of the inverters didn't show any V-VAr response. The potential reason for this behavior is that the inverters were installed before the 2020 standard came into effect and therefore, V-VAr mode wasn't mandated. We saw various discrepancies in inverters that showed V-VAr response such that some absorbed very high levels (>60%) of VAr at relatively low voltages and some others absorbed small amounts of VAr at relatively high voltages which raises concern regarding inverter compliance. On the other hand, 35% of the D-PV inverters showed V-Watt response, for 12% of the inverters V-Watt mode was disabled. For the remained 53% of the inverters, V-Watt behavior was inconclusive simply because the inverters didn't experience V-Watt set-point voltages regularly to be able to make any conclusions. As mentioned earlier, inverters experienced tripping at voltages lower than the set-points required by the standards which also raises concerns regarding inverter compliance. Based on a recent Australian Energy Market Operator (AEMO) report which collected data from a wide range of sources across different states showed that more than 50% of D-PV inverters are not set correctly to the required standards. The issue was mostly attributed to the incorrect installer set-up and configuration rather than the OEM settings and compliance.

It is not very straightforward to make any comments on what curtailment will look like as D-PV inverter compliance rate increases. In our study, we have seen that inverters that showed V-Watt response had less tripping curtailment which is a promising finding. However, we are not able to directly compare the tripping curtailment that is avoided by V-Watt mode vs. the additional curtailment that is brought by V-Watt mode. On another note, we have seen a very low V-VAr response rate in our study and as inverters comply with 2020 V-VAr settings, they may effectively lower the local voltages which can result in reduced amount of tripping and V-Watt curtailment. However, this needs to be validated with real-world data. So far we weren't able to analyse the con-concurrent operations of V-VAr and V-Watt modes and the overall implications of V-VAr mode on curtailment.

One of the key take-aways of our study was the large variance of curtailment losses across the studied residential sites where a small number of sites experienced disproportional curtailment losses compared to other sites which needs to be considered when designing effective and equitable PQRM regulations and standards. Undertaking network expenditure to regulate LV voltages to reduce curtailment is a possible pathway moving forward, however this may be an expensive option. Other solutions include implementing dynamic network pricing, dynamic operating envelopes, and dynamic export limits to better utilize network's hosting capacity.

We expect that the issue of curtailment will become more prevalent with increasing D-PV uptake, potentially resulting in higher energy and revenue losses for the system owners and future energy users and system owners may be disincentivized to invest in D-PV unless we have effective regulations and network strategies in place around the issue of curtailment. We believe networks and researchers should be supported in their efforts to minimize D-PV curtailment moving forward.

This is a very critical area of research, and we would be happy to be involved in future discussions. Please let us know if you have any questions or feedback regarding the information presented in this document.

Thank you.

Yours sincerely,

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Dr Baran Yildiz
Senior Research Associate
School of Photovoltaic and Renewable Energy Engineering
UNSW SYDNEY NSW 2052 AUSTRALIA

CEEM's relevant publications

[1] Yildiz B, Stringer N, Klymenko T, Syahman Samhan M, Abramowitz G, Bruce A, et al. Real-world data analysis of distributed PV and battery energy storage system curtailment in low voltage networks. Renewable and Sustainable Energy Reviews 2023;186. https://doi.org/10.1016/j.rser.2023.113696.

[2] Yildiz B, Adams S, Samarakoon S, Stringer N, Bruce A, MacGill I. Curtailment and Network Voltage Analysis Study (CANVAS) Project Report. Sydney: 2021.

[3] Yildiz B, Stringer N, Adams S, Samarakoon S, Bruce A, Macgill I, et al. Curtailment and network voltage analysis study. 2021 IEEE PES Innovative Smart Grid Technologies - Asia (ISGT Asia), 2021, p. 1–5. https://doi.org/10.1109/ISGTAsia49270.2021.9715652.

[4] Stringer N, Bruce A, Macgill I. Data driven exploration of voltage conditions in the Low Voltage network for sites with distributed solar PV. Asia-Pacific Solar Research Conference 2018.

[5] 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.

[6] Stringer N, Bruce A, MacGill I, Haghdadi N, Kilby P, Mills J, et al. Consumer-led transition. IEEE Power and Energy Magazine 2020;18:20–36. https://doi.org/10.1109/MPE.2020.3014720.

[7] 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.