Voltage Analysis of the LV Distribution Network in the Australian National Electricity Market

Analysts & Authors (in alphabetical order): Simon Heslop[2], Naomi Stringer[2], Baran Yildiz[2]

Authors (in alphabetical order): Anna Bruce[2], Phoebe Heywood[2], Iain MacGill[1], Rob Passey[2]

Centre for Energy and Environmental Markets, UNSW Sydney
[1]School of Electrical Engineering and Telecommunications Engineering, UNSW Sydney
[2]School of Photovoltaic and Renewable Energy Engineering, UNSW Sydney

Corresponding authors: Iain MacGill i.macgill@unsw.edu.au
Rob Passey r.passey@unsw.edu.au

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About CEEM

The UNSW Centre for 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 CRC for Low Carbon Living, 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, entirely reenvisaged retail markets that suitably facilitate distributed resources, efficient network regulation that also supports beneficial innovation and incentivises distributed resources to provide competitive network services, and coherent and comprehensive wider energy and climate policies that can deliver the low carbon energy future required to address dangerous global warming.

Distributed Energy Resources (DERs) are a vitally important set of technologies, with vitally 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 Associate Professor Iain MacGill, Joint Director of the Centre at i.macgill@unsw.edu.au.

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Executive Summary

Introduction

Voltage is both a key measure of power system health, and a challenge to effectively manage. This is particularly the case within the low voltage (LV) distribution network where almost all consumers are connected, yet where there is currently little voltage visibility and only limited operational capabilities for its management. Both excessively high and low voltages in the LV network can adversely impact consumer, as well as network, equipment.

The key driver of voltage variations in the distribution network is changing network power flows (and hence losses and voltage drops). While varying load is the major factor here, the growing deployment of distributed photovoltaics (PV) in Australia is seeing periods of reduced or even reversed power system flows, contributing to increasing voltage impacts. Meanwhile, the distribution network service providers (DNSPs) responsible for voltage management typically have only 'coarse' voltage management options available at the Medium Voltage (MV) and LV network level. The prevalence of excessively high voltages across the National Electricity Market (NEM), the influence of PV on this, and the implications for PV curtailment due to over voltage are all areas of substantial discussion, however, detailed quantitative analysis to date has been limited.

The Energy Security Board commissioned the Centre for Energy and Environmental Markets at the University of New South Wales to undertake analysis of voltage on the LV networks within the NEM, as well as distributed PV's influence on that voltage. This work used a unique dataset of maximum and minimum voltage measurements over 12,000 sites in the LV network, provided by Solar Analytics, a company offering real-time performance monitoring for PV system owners.

Note that this work was completed on a very restricted timeline with limited resourcing, and as a result only limited analysis has been undertaken so far. Findings and recommendations in this report, therefore, need to be considered as preliminary, and there would be considerable value in further work.

As discussed in the literature review below, some analyses of LV voltage conditions have previously been undertaken in Australia. However, primarily due to lack of access to data, these efforts to date have generally been limited to small numbers of sites or limited time periods. We have not found any significant published analysis of the relationship between PV and voltage, nor of the prevalence of PV system curtailment due to voltage issues across large spatial and temporal datasets, and certainly not on a NEM wide basis.

Section 2 of the report briefly outlines the key challenge of what appears to be a growing range between maximum and minimum voltages across the LV network, and its implications for distributed PV, and consumers more generally. **Section 3** briefly reviews the literature of work to date in Australia on better understanding voltage in the LV network, possible reasons for voltage issues including the potential role of distributed PV, potential impacts on PV of high voltages including generation curtailment, and trials underway to not only better understand these issues, but investigate different options for managing them. **Section 4** presents an overview of the data used in the analysis. **Section 5** presents the analysis of voltage conditions currently seen on the NEM LV network, highlighting the fact that voltage levels are generally high across the NEM in all regions, all seasons and at all times of the day. **Section 6** presents analysis that seeks to better understand and quantify the relationship between periods where PV system generation exceeds site demand and hence is exporting to the grid, and voltage rise at those sites; and does find evidence for PV exports increasing voltage during peak PV hours. **Section 7** presents an assessment of potential curtailment using voltage measurements, to identify the proportion of sites seeing sufficiently high voltages that curtailment may be occurring, and how often this may be happening. In **Section 8** we present some detailed curtailment analysis based on earlier work using Solar Analytics voltage and PV generation data for South Australia over 24 days across a year. Finally, **Section 9** summarises some key findings from this preliminary analysis and considers possible next steps both for extensions to the analysis undertaken so far, but more generally for improving voltage visibility and management in the LV network of the NEM.

Voltages are rising: Why does it matter?

Distribution Network Service Providers (DNSPs) are required to maintain voltages at customer premises within an acceptable range in order to ensure safe, reliable and efficient operation of their appliances and equipment. It is difficult to quantify adverse impacts of poor voltage management as they depend on the nature of both the voltage excursions (duration and extent) and different end-use equipment, particularly, whether the loads are primarily resistive, motor or power electronics. Still, this equipment is generally designed around an 'accepted' voltage range and it should be assumed that voltage excursions impose some level of costs on consumers. Inappropriate voltage excursions can also adversely impact network equipment.

However, distribution networks service providers (DNSPs) have had very little voltage visibility, and only limited operational means to manage these voltages, in the LV network. Key options are 'on-load' tap changing transformers, generally only available at MV and higher voltages, and manually adjusted 'off-load' tap changing transformers in the LV network. Historically the greatest voltage management challenge for DNSPs was managing peak demand conditions, driven in recent decades particularly by growth in air-conditioning, that reduce voltages. A key management approach, therefore, has been to increase network voltages towards the upper acceptable range.

More recently, Australia has also experienced world-leading uptake of distributed rooftop solar photovoltaics (PV) with over 20% of suitable houses now having a PV system, and both South Australia and Queensland having around 35% residential penetrations. PV systems can reduce or even reverse (net negative load) network flows, driving up voltages. Where there are already high voltages, this can drive voltages above the range at which PV inverters are required to curtail their output. In this case, the PV system reduces its output and so assists in managing these high voltages but generates less electricity that can be used to meet household loads or to export excess electricity. Consequently, consumers lose any savings from self-consumption or potential revenue from a solar feed-in-tariff (FiT) on exported electricity. Electricity sector climate emissions will also be increased.

For DNSPs, the net result of increasing peak loads and PV export over the past two decades is an increased voltage range that they need to manage. DNSPs have a range of approaches for addressing high voltages from operational changes through to network strengthening and, in recent years, new voltage regulating technologies for the LV network. Alternatively, they may prevent new customers from connecting PV systems or introduce limits on PV exports. Consumers with PV also have growing technology options that can assist in addressing these challenges including Battery Energy Storage Systems (BESS) and smart load control including for electric vehicles (EVs). Voltage management in the presence of distributed energy resources (DERs) therefore poses challenges yet also opportunities for broader decentralisation and decarbonisation of the Australian electricity sector that goes beyond just rooftop PV. An effective and efficient framework for managing voltage in the LV network should, therefore, not just address immediate concerns with PV, but facilitate appropriate deployment of other emerging DERs.

Literature Review

What is known about current voltage conditions?

Australian voltage standards specify a preferred range of 230V +6%/-2% or 225-244V, and acceptable voltage range of +10%/-6% or 216-253V, At present, however, the level of compliance with these standards is difficult to assess given limited visibility of voltage conditions in the LV network, the very specific measurement requirement within the Standard, and a range of State level interpretations for their DNSPs. There is widespread agreement that improved visibility is required, and its absence is one of the key reasons for limited analysis of voltage conditions to date. Nevertheless, a number of previous analyses of voltages in the LV network, albeit over limited sites or time periods, have indicated that:

- Overall LV voltages are high with the mean voltages occurring overnight not much lower to that occurring during the day, and often near the upper acceptable limit of 253V.
- Over voltages are more prevalent than under voltages.
- A key variable impacting local voltage conditions is load.
- While time of day has an obvious relationship with PV generation, there is also a relationship between demand and time of day as well, raising some complexities for analysis.

A Solar Analytics analysis of 1000 sites across 2018 used the most comprehensive data set to date prior to the work undertaken here for the ESB, and showed that around 85% of their customers' PV sites experienced over-voltage at least once in 2018 and more than 25% of sites saw over-voltage on more than half of the days in the year. Significantly fewer instances of under voltage were recorded.

Finally, it should be noted that there are particular challenges in determining compliance from such analysis given that the relevant Australian standard has very specific measurement requirements that lie beyond the capabilities of Solar Analytics, or indeed most other, 'external' monitoring equipment. However, the high voltages seen in work to date certainly should raise concerns.

Impact of voltage on PV

Anecdotally, the primary means by which networks are made aware of PV curtailment is through consumer complaints when their PV system is not performing as expected. There remains limited visibility of PV operation and therefore limited visibility of the degree of curtailment occurring. The impact of local voltage conditions on PV largely depends on the PV inverter settings, including 'limits for sustained operation' functionality introduced in the current standard to reduce over voltages caused by high levels of PV export triggered at over 255V, and disconnection with 2-3 seconds at a limit of 260V, although the limit can be up to 270V for older inverters.

Recently adopted aspects of the AS4777 standard for small PV inverters in Australia require proportional reduction in real power output (Volt-Watt mode) or reactive power absorption (Volt-VAR mode) capabilities. The latter is preferable in that less real power is lost, but absorbing reactive power will increase losses in the network and may have only a limited capability to reduce voltages in many areas of the distribution network. These modes are now being required by a growing proportion of Australian DNSPs

Voltage management

A range of techniques for voltage management are available. In their recent Distribution Annual Planning Reports, nearly all of the 13 DNSPs in the NEM report issues with power quality and specifically voltage fluctuations in areas with high penetrations of distributed solar PV and identify possible options for voltage management, including:

- Managing distribution transformer tap settings and rebalancing across phases are relatively low-cost options, but are only applicable where voltages are generally high and no or very limited low voltage excursions are experienced, or phase imbalance exists
- Network augmentation options can reduce the impedance from the distribution transformer and narrow the voltage range, but are a more expensive option
- More advanced voltage management via various types of power electronics equipment can dynamically manage voltages at the transformer or other locations on the network
- Requiring advanced PV inverter functionality can take advantage of inverter capabilities to better manage voltages through Volt-Var and Volt-Watt responses, and perhaps 'external' control signals.
- Load management including controlled load shifting and tariffs to incentivise loads to shift to solar times can help address both low and high voltages at peak 'net' load and 'peak' solar times.

ARENA-sponsored pilot projects and trials to improve DER integration have also explored smart demand side management, dynamic network hosting capacity and operating envelopes, as well as integration of DER into the electricity market, including demand response and Virtual Power Plants (VPPs). All of these capabilities can assist in managing LV voltages.

Broader investment and operational implications of voltage

Effective voltage management in the distribution network will likely become more important as the Australian power system further decentralises. As the levels of DER grows system security challenges are emerging. There is likely to be an increased need to manage DER feed-in including PV exports. A review of a number of international PV feed-in management strategies performed by EPRI for AEMO found that these schemes typically do not provide compensation, but the amount of reduction is limited by some factor such as number of curtailment occurrences, cumulative duration or the presence of a power quality issue.

In conclusion

There is growing work in Australia and beyond on the challenges of voltage management with growing PV penetrations from stakeholders including new technology providers, DNSPs, other industry and consultant participants, the Australian Energy Market Operator (AEMO), the Australian Energy Regulator (AER), the Australian Energy Market Commission (AEMC) and the Energy Security Board (ESB). Nevertheless, there are clearly still some gaps in our understanding of actual LV voltage conditions in different regions of the NEM, and the role of distributed PV in this.

Overview of UNSW Analysis

Our analysis is based on data from 12,617 site-specific power and voltage monitoring devices deployed by Solar Analytics to assist their customers in monitoring their PV system's performance. 7,933 of the sites have single phase connections and 4,684 have three phase connections. For three phase sites, all of the phases are used for the analysis. Analysed PV systems have up to 10 kW AC-rated inverter output and the majority are installed on residential premises. The data used in this analysis is the maximum and minimum voltage seen over a five-minute period, with these voltage measurements being sampled every five seconds. The studied data-set set includes 5 minute measurements from 1/12/2018 to 30/11/2019, and hence allowing seasonal and even shorter time period (month) analysis. Of the 12,617 sites, 4,337 had data that covered the full year while the remaining had less than a full calendar year of data. Sections 5 and 7 of this report include analysis of only those sites with a full calendar year of data.

The monitored sites also record any net PV exports each 5 minutes, reported as the total kWh injected into the grid over the period. The PV systems being monitored are in almost all cases installed behind-the-meter. Any PV generation therefore first goes to supplying site load. When PV exceeds site load over the period, the net site export to the grid is recorded. For periods where there is no PV generation, or PV generation is less than site load during that period, no PV 'export' data is recorded. The analysis covers all States and Territories and their DNSPs within the NEM. Each voltage and correlation analysis is conducted across a specific area or combination of areas. An area consists of all postcodes within one of the following:

- State or Territory
- DNSP jurisdiction
- Remoteness category (using postcode categories from suburban to regional to remote)
- PV install density classification (using postcode estimates of the proportion of stand-alone housing with a PV system sourced from the Clean Energy Regulator).

Table A provides the number of monitoring sites for each DNSP. The greatest number of sites are in South Australia and Queensland which are also the States with the highest residential penetrations of PV in Australia.

Table A Numbers of Sites for Each DNSP

DNSP	Number of sites
ActewAGL	78
Ausgrid	1766
Ausnet	385
CitiPower	61
Endeavour	1236
Energex	2296
Ergon	1099
Essential	1379
Jemena	124
Powercor	241
SAPN	3718
TasNetworks	63
United Energy	171
Total	**12617**

While the dataset utilised for this study is the largest analysed to date in terms of the number of sites, their distribution across the NEM and period of collection (1 year), it cannot be assumed that Solar Analytics sites are representative of the entire 2.2 million residential PV systems across Australia, while the number of sites in some DNSPs are modest, limiting the wider validity of the findings. As always, caution is therefore required in the interpretation of our analysis findings.

Voltage Analysis

Separate voltage analysis has been undertaken for each DNSP in the NEM. Here the analysis undertaken for South Australian Power Networks (SAPN) is used to illustrate how voltage varies across the year, between seasons and across the day. South Australia, together with Queensland, has the highest penetration of distributed PV in Australia, and SAPN certainly demonstrates significant periods of high voltages. Comments for other DNSPs are included where relevant, along with several comparative figures.

Figure A shows the average maximum voltages seen by all the sites in SAPN throughout the year, as well as the South Australian net demand (demand minus distributed generation including PV). Site locations are categorised as one of ‘Suburban’, ‘Inner Regional’, ‘Outer Regional’ or ‘Remote’ across the State.

Although South Australian demand is generally higher in winter months, the State experiences its periods of peak demand in summer and these clearly drive periods of lowest maximum voltage – particularly in suburban regions. Average maximum voltages frequently sit near the upper bound of 253V over the entire year, although they are generally highest in Spring, when State demand is typically lower and PV performance is relatively high. It is unclear why voltages are generally so high in South Australia, but it may reflect some combination of the need to avoid voltages below 216V during those few periods of peak demand, and the historic 240V standard in Australia. Still, maximum voltages across the sites typically sit well above the preferred limit of 244V. The minimum voltages (not shown here) follow the maximum voltage patterns above, and particularly highlight how average minimum voltages are generally above 240V, which is around 5% above the nominal 230V.

The significant drop in voltage at high loads observed for SAPN is not seen for the DNSPs in Qld or NSW, apart from in remote areas (interestingly, the voltage drop is not particularly significant for SAPN in remote areas, although it should be noted that the number of such sites is relatively small). Average voltages are also generally not quite as high for the DNSPs in Qld or NSW, and they have a smaller spread between low and high voltages. The ACT shows a different voltage profile to Qld and NSW, being highest in November and February and lowest during the winter months, with a greater spread between low and high voltages.

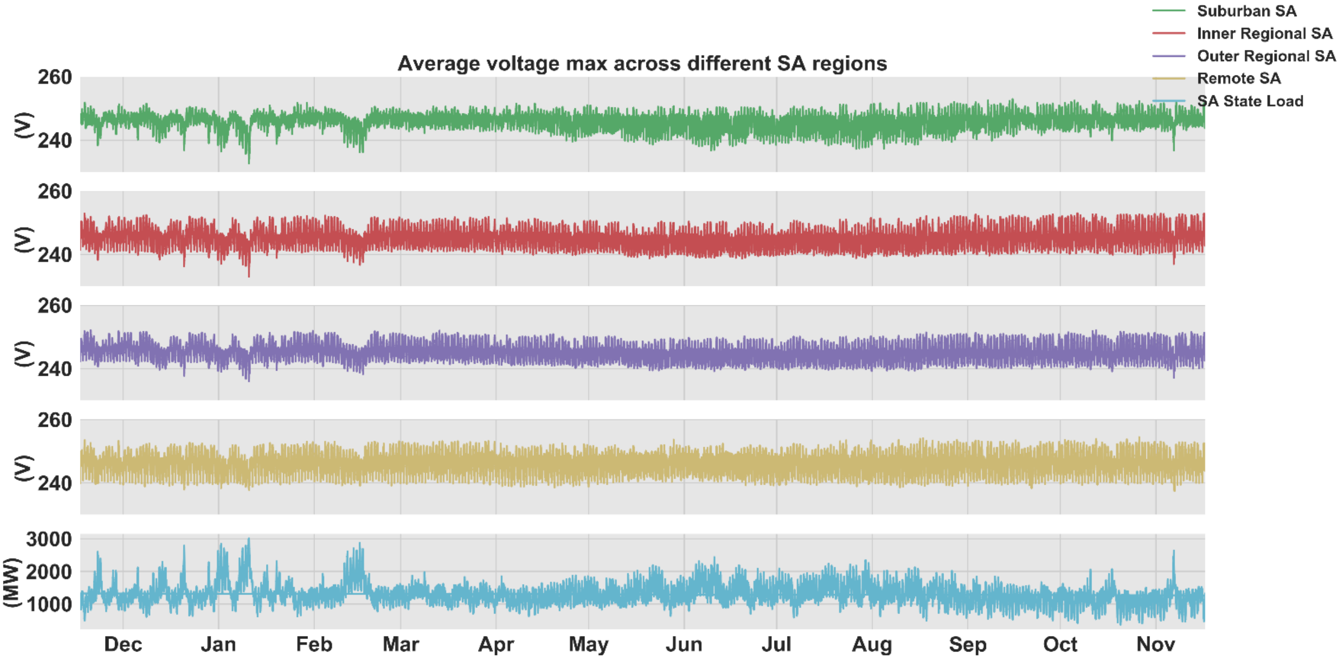


Figure A. Average voltage maximum for all PV sites in SAPN’s distribution network characterised by location from suburban to remote across the State, as well as the net state load, across the year.

Figure B.1 illustrates the distribution (1% to 99%) of maximum voltage across the South Australian regions. The Y axis shows the range of voltages whereas the X axis shows the percentage of the times a voltage value is observed. It is clear that the voltages are generally well above 230V, with an average around 245V to 250V or higher, and often closer to the upper recommended limits, especially in regional and remote parts of SA. The voltage spreads in Qld and NSW are broader and slightly lower, while Vic is also slightly lower but with a wider spread, as shown in Figure B.2 for suburban sites across the mainland NEM states.

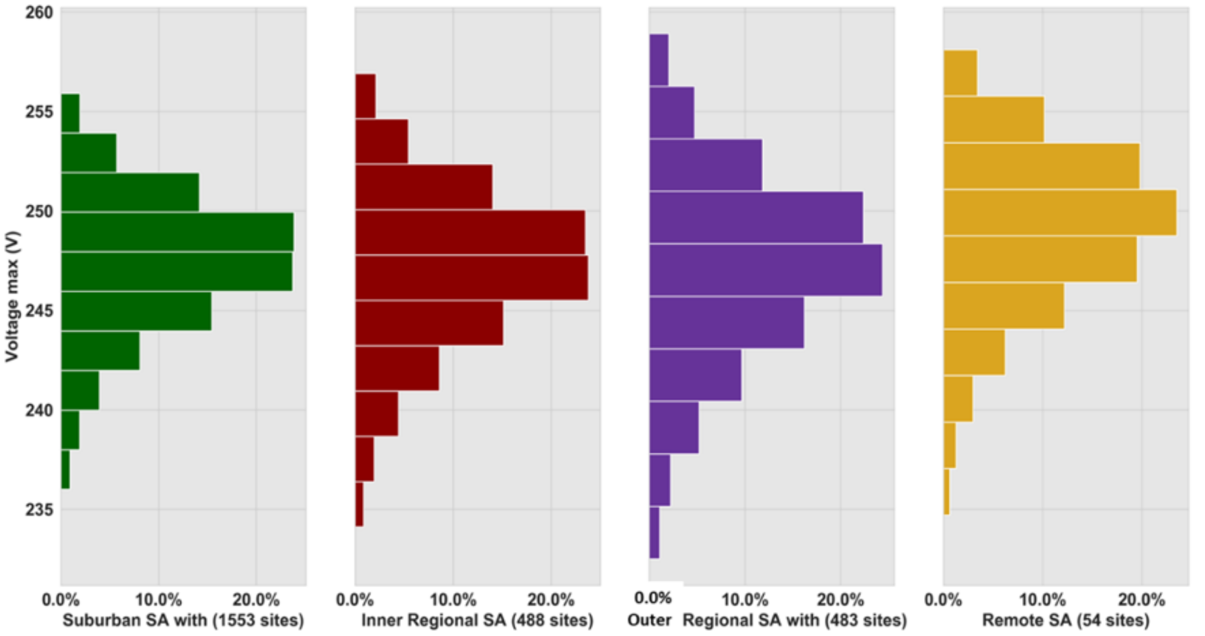


Figure B.1. Distribution of maximum voltages (1-99 percentile) across SA sites characterised by location in the State

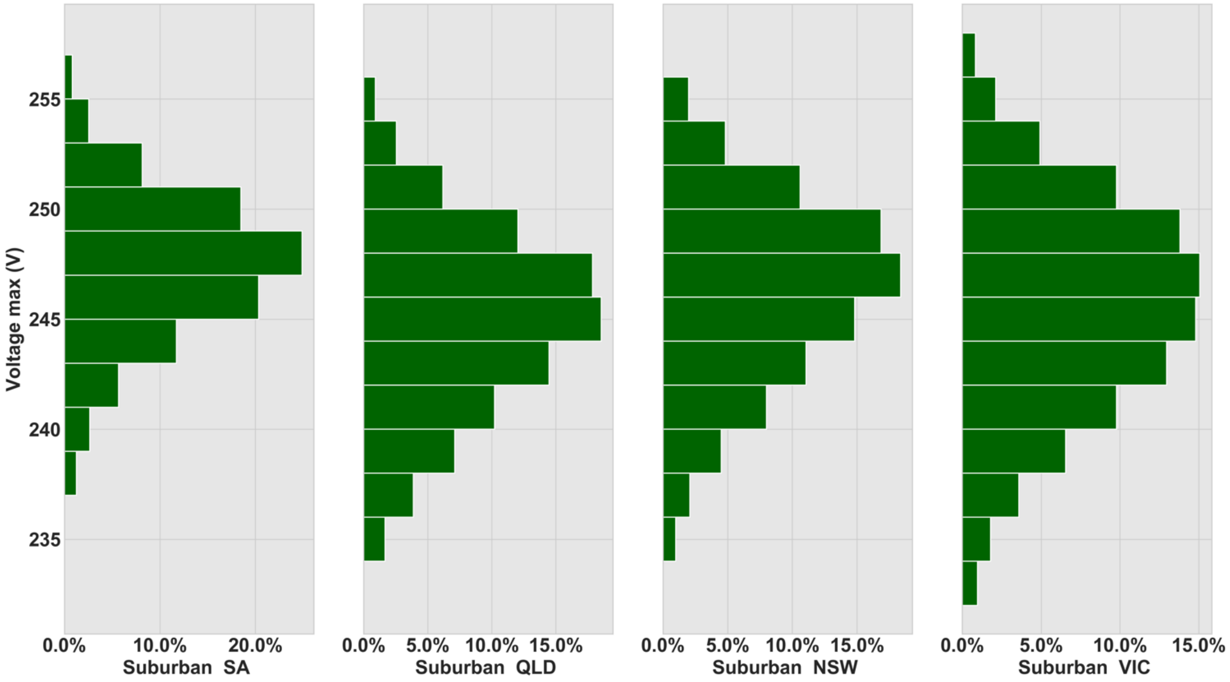


Figure B.2. Distribution of maximum voltages (1-99 percentile) for suburban PV sites across each of the NEM mainland States

Figure C shows how SAPN average voltages vary over a 24-hour period in Spring. This season is chosen because, as noted above, it is the time of maximum PV impact on voltage due to generally modest State demand and high PV performance. The red horizontal lines represent the AS/NZS standard acceptable max and min voltage levels: 253V and 216V respectively. The average maximum voltage levels are very close to the upper 253V limit rather than the lower limit, regardless of the season or time of day. During the midday and early afternoon periods (12pm-2pm) voltage levels increase, which is consistent with increasing distributed PV generation and typically reduced residential demand. During those peak sunshine hours more than 5% of the voltages recorded within that hour see maximum voltages well above 253V and above 255V for some hours. Further, late night periods that are typically also periods of lower demand also show high voltages with some 5% of voltages recorded within that hour are around the 253V limit, and above 255V for some hours. Especially in the winter and autumn seasons (not shown here), voltages observed around 4am-6am are almost as high as the midday voltages. It is also apparent that some sites experience occasional very low voltages during peak demand hours (4pm-8pm) where voltages can go extremely low, and below the recommended 216 V limit. Again, the spring voltage profiles over the day in Qld and NSW have a similar shape but are generally slightly lower.

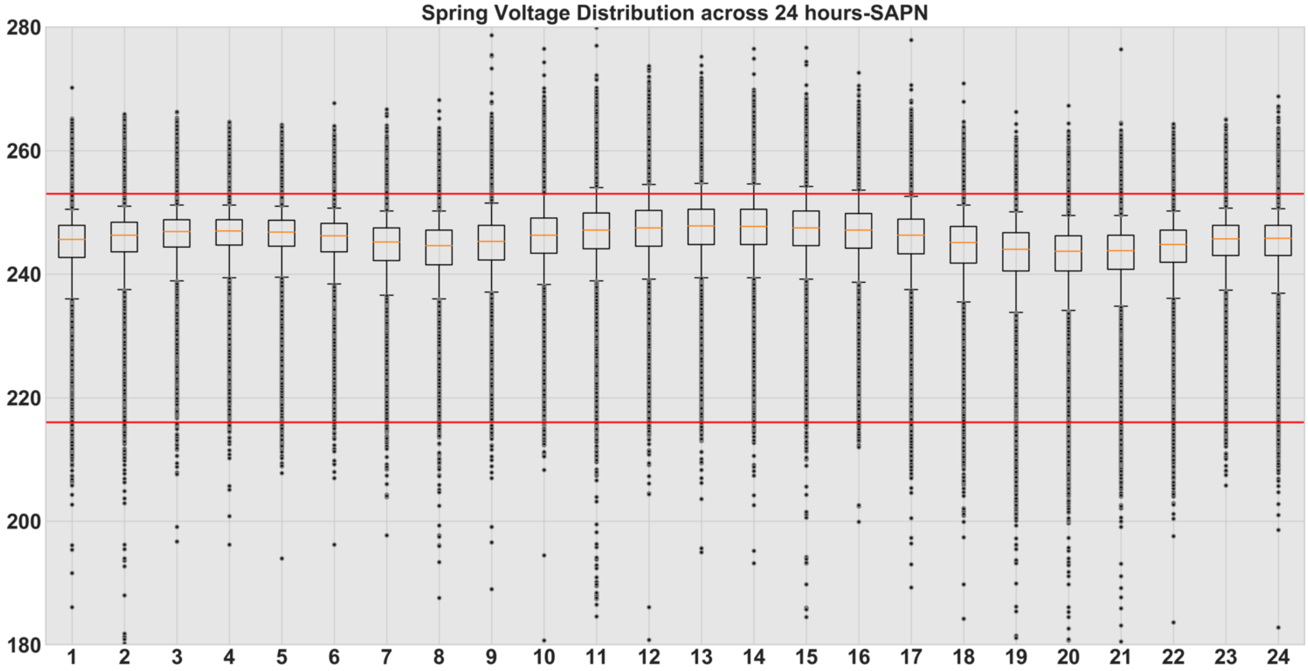


Figure C. Distribution of PV site voltages across 24 hours for SAPN for the spring season. The box whiskers represent the 5% and 95% voltage range and the red lines the upper and lower acceptable voltage range.

Given the opportunities to change the upper voltage seen in the LV network using distribution transformer tap changes, it is important to understand the range of voltages being experienced at different sites. Figure D shows the distribution of 1661 households in SAPN's area ordered by their maximum voltage values experienced throughout the year. For each household the corresponding voltage minimum and the 5th and 95th percentiles of voltage are also shown. The households that experience the highest voltages also experience some occasions of extremely low voltages, illustrating the high degree of variability even at the individual household level. Consistent with previous findings, the 95th percentile of the voltage max sits at or above the recommended 253 V limit. It can also be seen that the voltage range is much narrower for the 5th to 95th percentile, which should make it easier to keep the voltages within recommended limits for a significant number of households. Again, the voltage profile in Qld and NSW are very similar, but generally slightly lower.

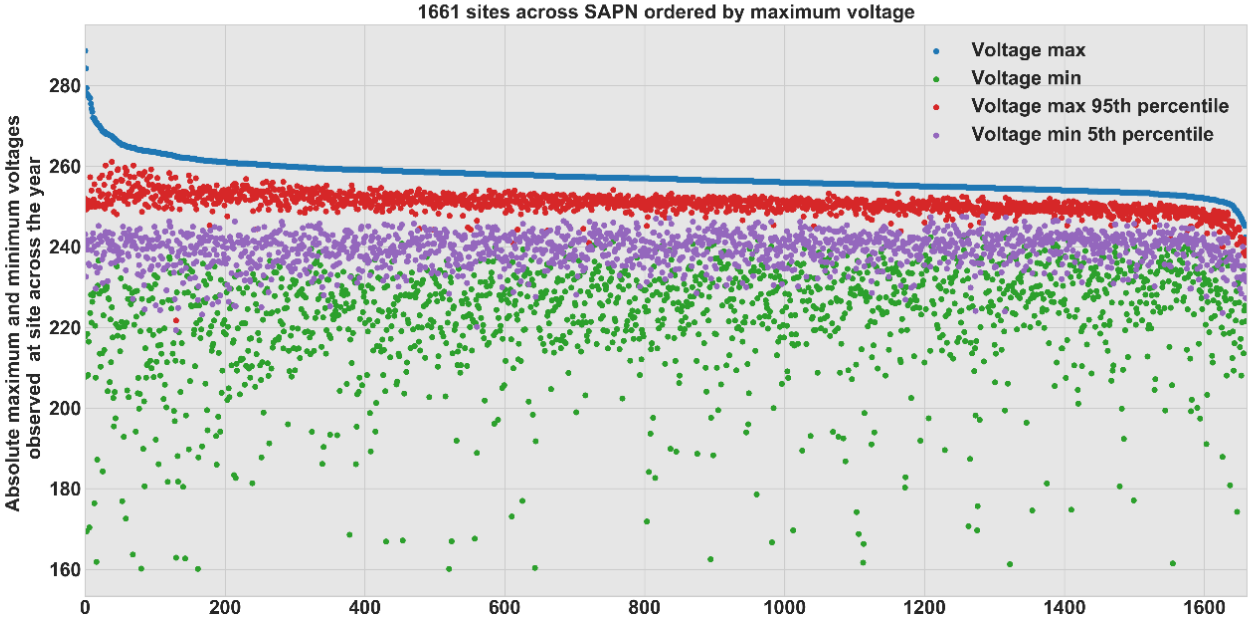


Figure D. 1661 sites from SAPN with a full calendar year data ordered by highest maximum voltage experienced over the year, as well the 95% maximum and 5% minimum voltage, and lowest observed voltage.

Correlation between solar PV export and voltage

This analysis combines the voltage data presented previously with data on PV exports from the monitored sites. Any PV exports (that is, when PV generation exceeds site load) are also recorded by the Solar Analytics equipment. Site PV exports, of course, only occur during daylight hours and captures aspects of both the profile of typical site demand (for example, lower consumption during the middle of the day while household occupants are away at work and Schools) as well as the site's PV generation.

Two methods are used to show the correlation between PV export and voltage across all States and DNSPs. The first derives a simple linear relationship between PV export and voltage by postcode. The second examines the difference in the voltage distribution when there is zero PV export and when there is non-zero PV export during the daylight hours of 10am to 4pm, representing typical hours of peak PV generation.

Method 1: Derivation of the linear relationship between PV export and voltage for an area

In this method a Least squares linear regression is used to estimate a linear equation ($y = ax + b$) associating voltage max (y) and PV export (x) during peak PV hours of 10am – 4pm. The gradient (a), with dimensions V/kW, provides a useful measure of how sensitive site voltage is to changes in site PV export during PV hours, depending on the significance of the observed correlation. It should be noted that a very wide range of voltages are seen over the year for given levels of PV exports. Still, general correlations can often be observed.

Figure E shows the range of gradients calculated for all postcodes analysed. A gradient > 0 indicates that PV systems in that postcode will typically experience voltage rise when their solar PV export is > 0 during daylight hours. Note that some postcodes include only a small number of sites (< 5), and therefore the gradient calculated may well not be representative of all sites (with solar PV installed) within the postcode. The correlation (R^2) of these lines of best fit can also vary significantly across sites. Still, it can be seen that although sites in some postcodes generally experience significant voltage rises per kW of site PV export, most are lower than 2 V/kW export.

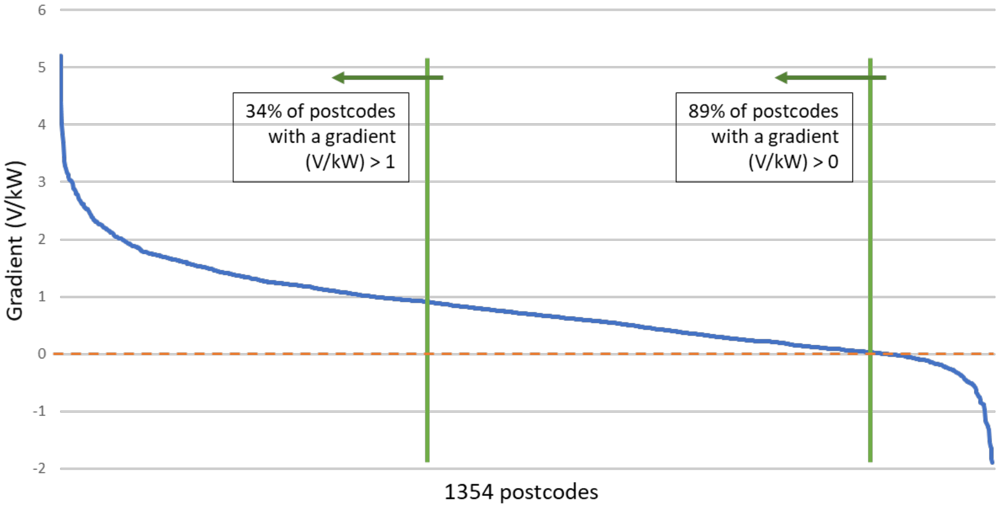


Figure E. Range of gradients for all postcodes across the NEM with PV sites, showing typical site voltage rise with respect to that site's PV exports during daylight hours 10am – 4pm.

Method 2: Voltage distribution difference for an area: Zero versus non-zero PV export

In this method, for each area, data points are divided into two segments:

1. Non-zero PV export measurements.
2. Zero PV export measurements, within the solar hours of 10 am to 4 pm.

The voltage distribution is then calculated for each segment.

Figure F and Figure G show the difference in voltage impact (between zero and non-zero PV export) for States and Territories and DNSPs. It can be seen that PV export has a similar impact on voltage for all States and Territories, with the impact in the ACT being slightly higher and the impact in Tasmania being lower (noting also that there are relatively few Solar Analytics sites in those two NEM regions). The DNSPs also all have similar impacts, with ActewAGL and TasNetworks being higher and lower respectively, as expected. The median voltage impact at both the state/territory and DNSP level ranges from 2V to 5V. Interestingly, PV generally increases the low voltage whisker more than the high voltage whisker, indicating it can be beneficial for avoiding low voltage events.

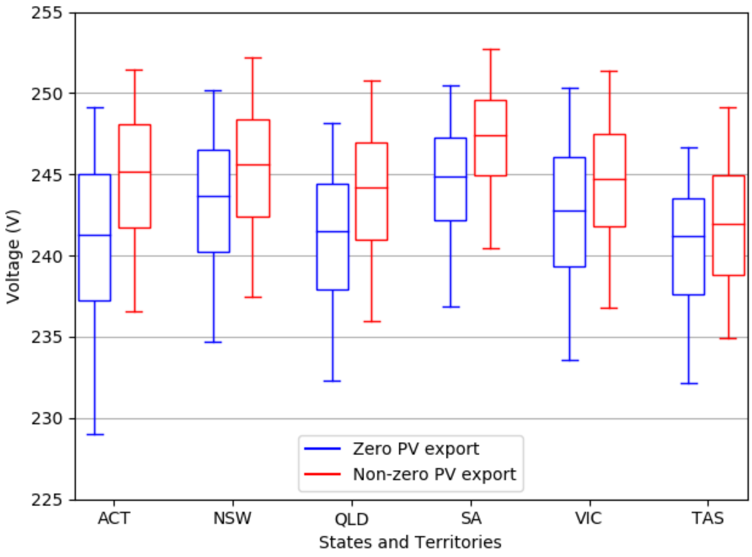


Figure F. Box and whisker plot showing Voltage distribution difference between zero and non-zero export for all states and territories during daylight hours 10am – 4pm.

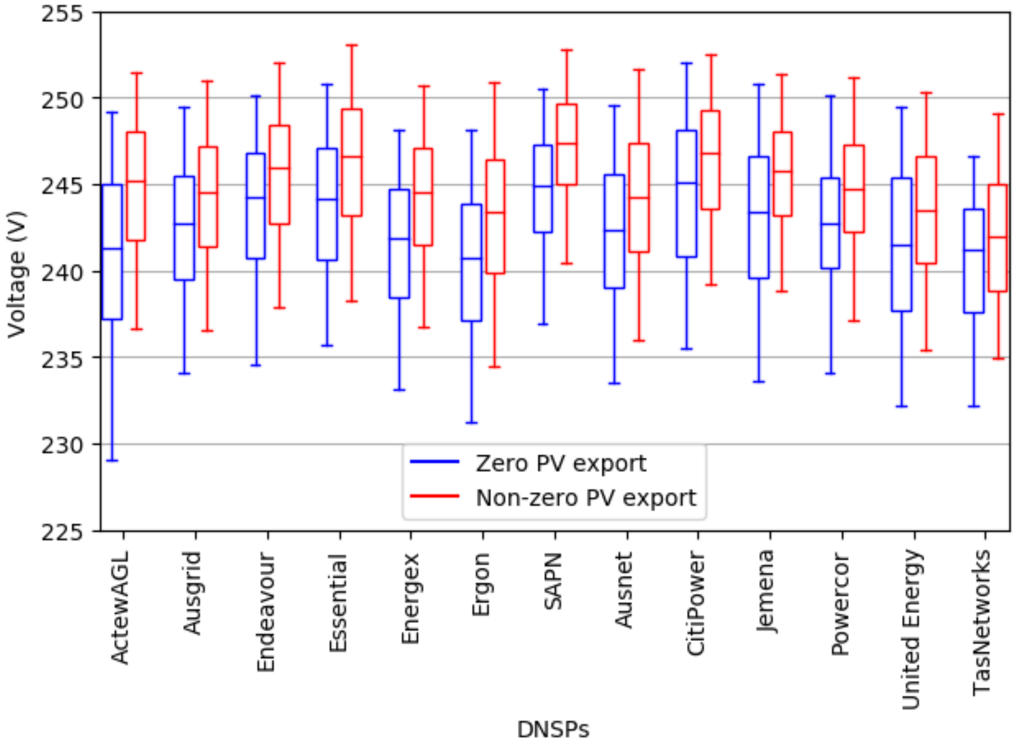


Figure G. Box and whisker plot showing Voltage distribution difference between zero and non-zero export for all DNSPs during daylight hours 10am – 4pm.

Potential for Distributed PV Curtailment

This analysis focuses on the prevalence of voltage conditions outside the present voltage Standard, and particularly high voltages at which PV inverters may see curtailment (255-258V sustained for 10 minutes, 260V for 2 seconds and 265V for 0.2 seconds for post 2015 inverters in Australia).

Separate voltage analysis has been undertaken for each DNSP. Here the analysis undertaken for SAPN is shown to allow easier comparison with the voltage analysis presented above. Again, comments relevant to other DNSPs are included where relevant.

Although the data provided were not sufficient to determine whether individual PV systems had been curtailed because of over voltage constraints, the frequency that the grid voltage at each household exceeded certain thresholds serves as a useful proxy. The analysed voltage thresholds include 253, 255, 258, 260, 265 for over voltages with respect to Australian Standards (LV voltage and PV inverter) and 216 V for the under-voltage events. However, it should be noted that the Solar Analytics voltage measurements do not comply with the Australian Standard technique for LV networks based on 10 minute average voltage rather than the highest and lowest 5 second voltage sample each 5 minutes.

Figure H shows the percentage of the SAPN sites versus the percentage of over and under voltage events. It can be seen that around 22% of the sites experience over voltage (>253V) at least 2% of the time and around 21% of the sites experience voltage >255V. Moreover, around 2% of the sites were experiencing regular over voltage events with voltages being over 253, 255 and 258 levels for 35%, 13% and 4% of the time respectively. It is important to note that the standard for upper voltage and for inverter curtailment around 255-258V is based on average voltages over 10 minutes and PV inverter connection standards have changed over time. Still, high voltages sustained over such time periods indicates that some curtailment is occurring.

In terms of the percentage of sites that experience overvoltage 2% of time, compared to SAPN these were less for Energex, Ergon, Ausgrid and Endeavour, and greater for Essential. In terms of the percentage of sites that experience overvoltage events at all, there were less for Energex, about the same for Ausgrid, slightly more for Ergon and Essential, and clearly more for Endeavour.

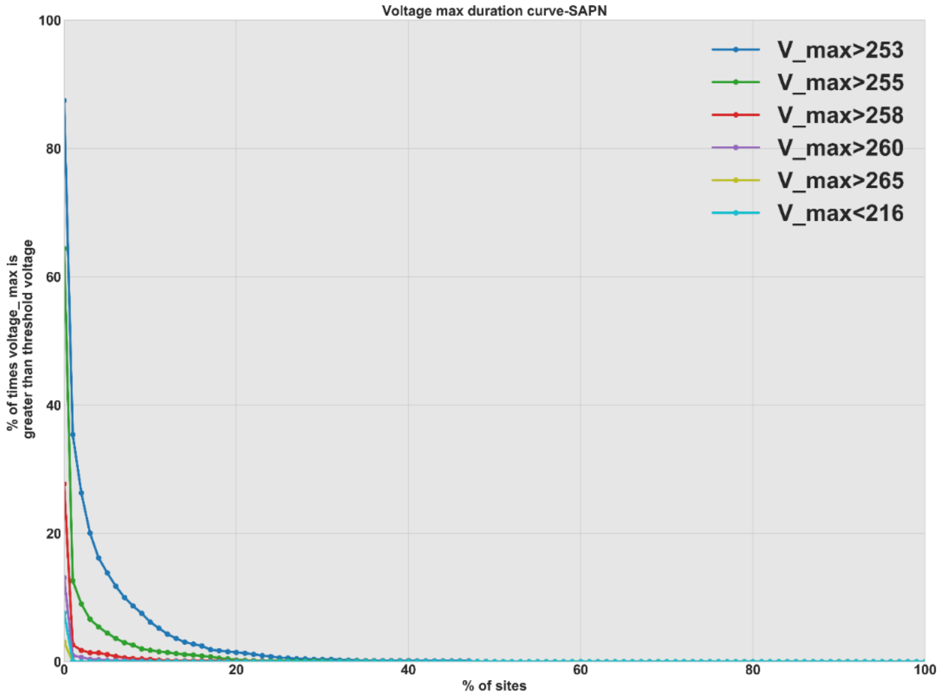
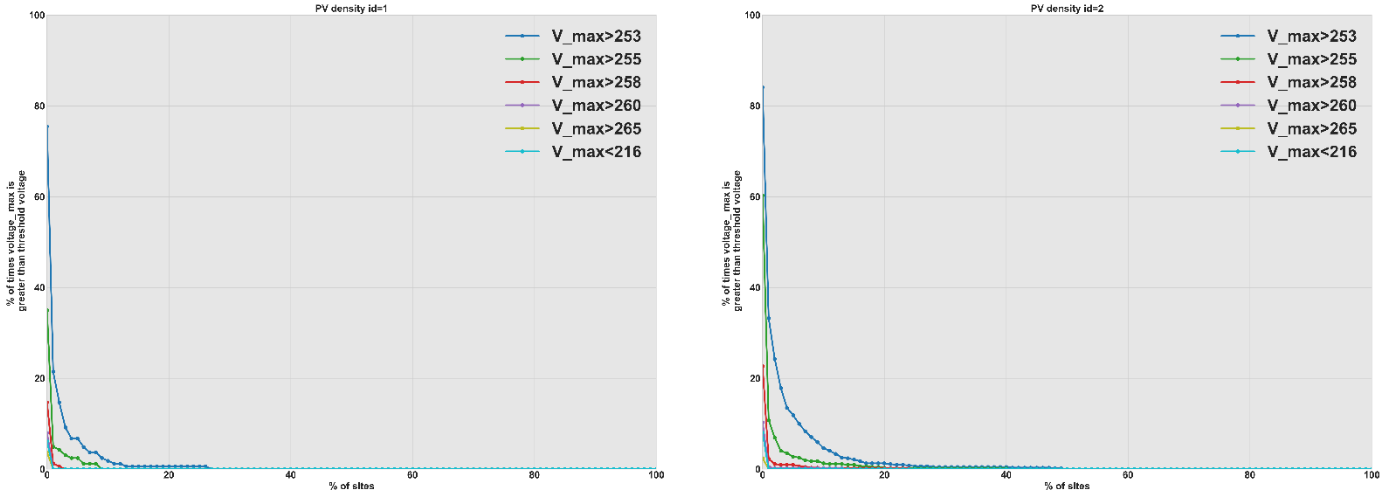


Figure H Percentage of sites vs. percentage of times of under and over voltage events based on site voltage maximum for SAPN

To understand whether the over voltage events are affected by the distributed PV penetration levels, Figure I shows the equivalent charts broken down into different PV density regions. Id1 = <10%, id2 = 10-20%, id3 = 20-30%, id4 = 30-40%, id5 = 40-50% penetration. The results show that over voltage events become more prevalent for the regions with higher PV penetration levels. For example, the percentage of sites that experience voltage greater than 253V increases from around 10% at a PV density of 1 (<10% of households) through to around 32% at a PV density of 5 (40% - 50%). The results are valid both for voltage maximum and voltage minimum analysis (not shown here), with the prior showing a stronger relationship. This relationship also applied for Qld given its similar high PV penetration to SA, but not for NSW or Victoria. There were too few sites in Tas to make a valid judgement.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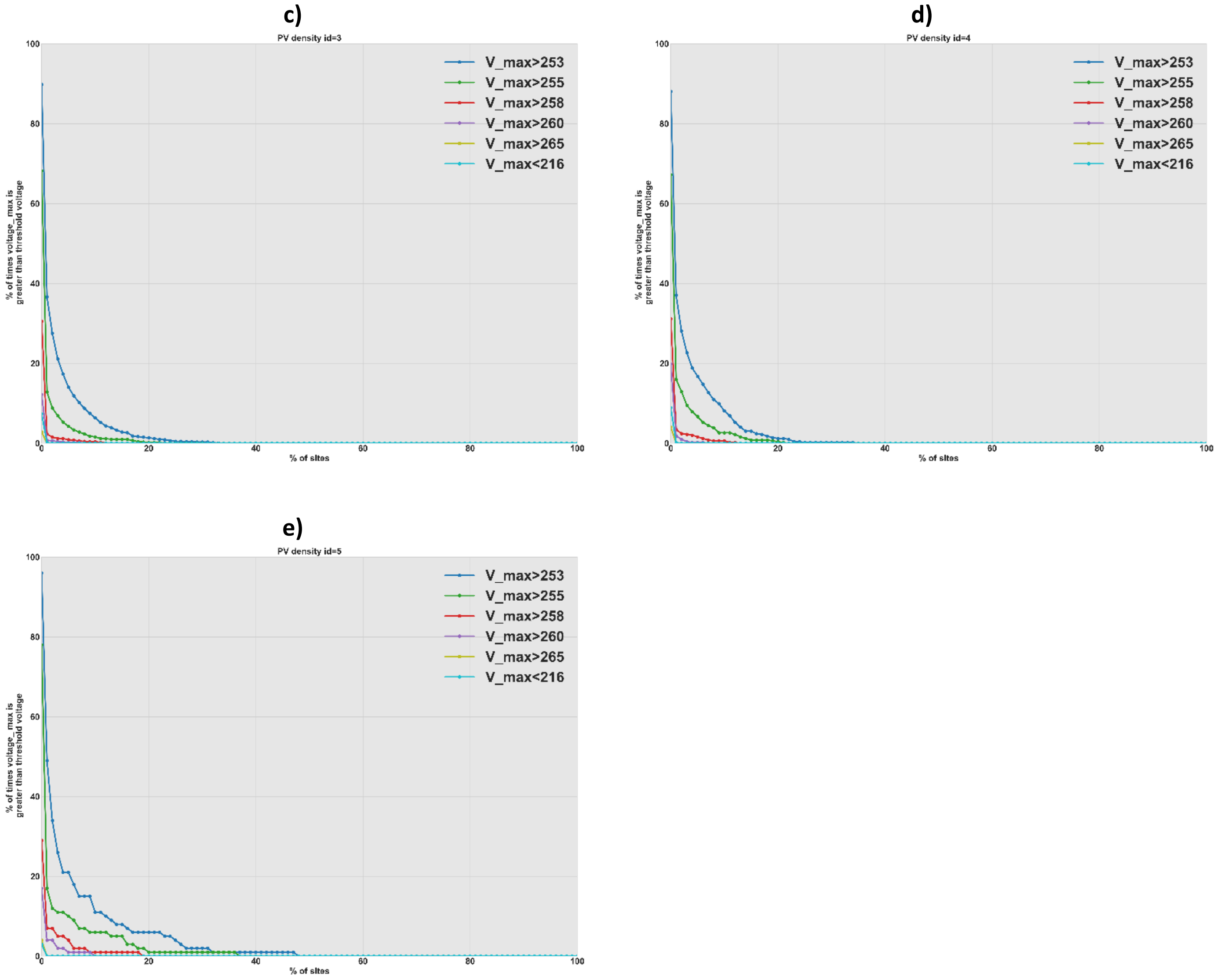

Figure I. Percentage of sites vs. percentage of times of under and over voltage events based on household region's PV density - SAPN

Figure J compares the percentage of the sites versus the percentage of over and under voltage events based on 253V for SA, Qld, NSW and Vic. It can be seen that Qld has the lowest percentage, followed by SA, with NSW having a greater percentage of sites that are affected a smaller number of times, and Vic having a smaller percentage of sites that are affected a greater number of times. Figure K shows the same chart but this time for 260V (inverter cut-off point) and the y axis is magnified. As expected, there are less 260V overvoltage problems, with Qld having the least and SA, NSW and Vic being similar.

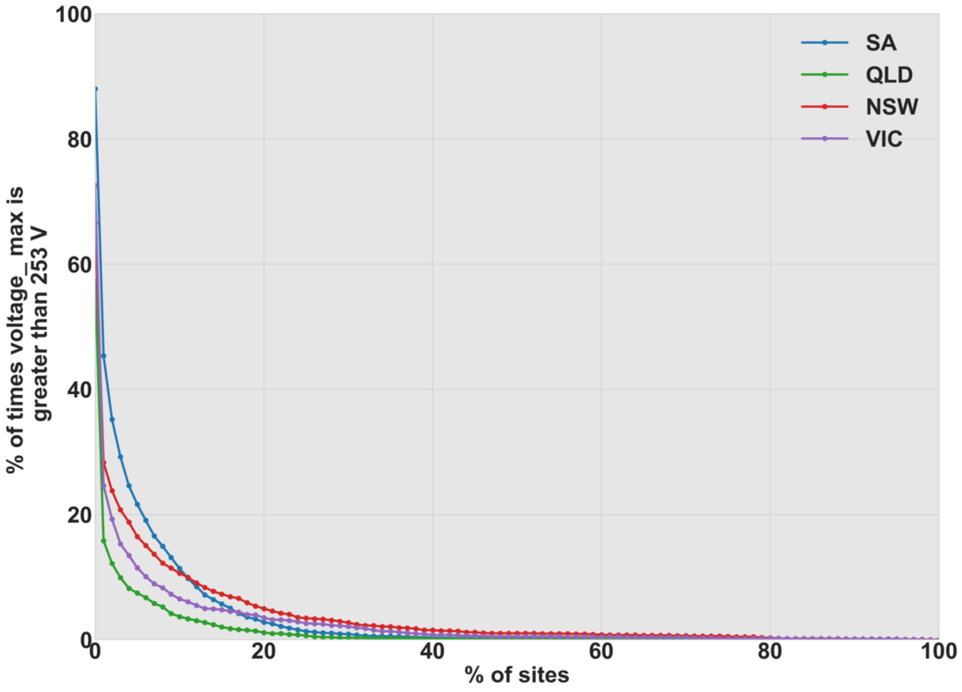

Figure J. Percentage of sites vs. percentage of times of under and over voltage events based on site voltage maximum for SA, Qld, NSW & Vic

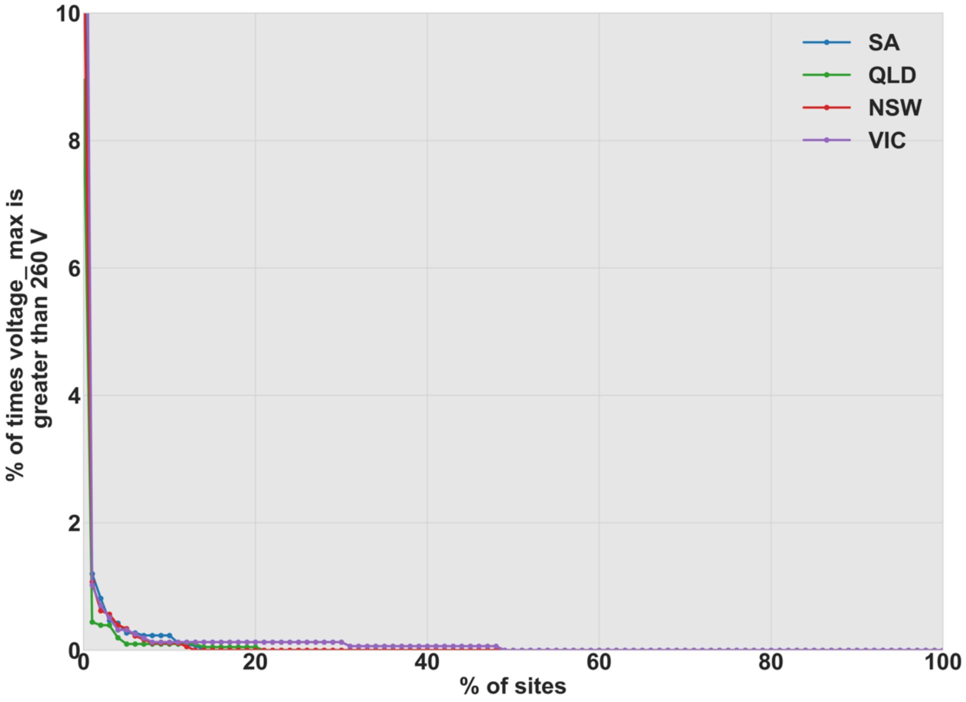

Figure K. Percentage of sites vs. percentage of times of under and over voltage events based on household region's PV density for SA, Qld, NSW & Vic – magnified y axis

Separate Work on Distributed PV Curtailment

Preliminary PV curtailment analysis undertaken by UNSW proposes and demonstrates novel techniques for analysing operational distributed PV data in order to estimate the actual volume of PV generation being curtailed, likely due to over voltage conditions, from their generation output rather than voltage. Analysis was undertaken using a data set from over 600 sites with PV (over 1,300 on some dates) in South Australia provided by Solar Analytics. The data set includes twenty-four clear sky days selected across the four seasons of calendar year 2018. Results were examined in terms of aggregate impacts and the distribution of impacts on individual consumers.

Key preliminary findings indicate that PV curtailment can significantly impact some sites with maximum daily generation loss of up to 27%-94%. However, the analysis indicates that overall curtailment over these sample days is low with an average of around 1% generation loss over the study period for all sites (including those which experienced zero curtailment losses). Upscaling the estimated generation loss to all of South Australia finds a total lost 'curtailment' value of $0.8m - $2.6m per year assuming that the sample is representative of all sites, and that the twenty-four clear sky days are representative of all days throughout the year. The use of clear sky days in particular is likely to result in an over-estimation of curtailment, and all findings are subject to key method limitations. The most significant curtailment is found to occur in spring corresponding to low load and high solar resource conditions. Investigation of whether curtailment is increasing is inconclusive and it is recommended that future work focuses on the increase in PV curtailment with increased penetration. This analysis is consistent with the above in that most sites experience little curtailment but there are some for which it can be significant.

Recommendations

Further analysis

There are excellent opportunities to extend this analysis to provide more insights into the challenges and opportunities of PV in relation to voltage management in the NEM.

- In further work, we could use the existing data set to provide more disaggregated impacts to postcode level, and particularly strengthen our findings on correlations between PV generation and voltage.
- More sites over greater time periods will assist in the analysis. So would higher resolution (e.g. 1 minute) data, particularly for the estimation of PV generation curtailment. While quite specific voltage measurement methods, and associated equipment, is required to formally assess compliance with Australian standards, there are a number of approaches we could apply to Solar Analytics data to better estimate the potential scale of non-compliance.
- Additional data points from three phase PV system sites will provide more clarity in the results and therefore more insights, but also support preliminary analysis of factors such as phase imbalance which would seem to offer low cost opportunities to improve head room for PV generation to be exported into the network.
- Additions to the available data sets, including gross PV system generation and ideally net site loads would allow more detailed assessment of correlation and causation between PV and voltage, as well as other factors including air-conditioner operation.
- We have developed particularly detailed suggestions for improved curtailment analysis, as noted at the end of the previous section. More detailed curtailment analysis is a clear priority area for future work given its importance for both consumers, but also networks given the potential expenditure involved in reducing its incidence.
- Finally, this sort of analysis will need to be continued as distributed PV penetrations continue to climb, and hence the issues that this is causing for voltage management may also increase (depending on technical standards, battery and EV take-up etc). Ongoing analysis will also support assessments of the usefulness of different voltage management approaches implemented by DNSPs.

Wider recommendations – voltage visibility

- Our analysis, and that of others, highlights both the need and opportunity for greater voltage visibility in the LV network. Distributed PV is one, but not the only factor, driving this need. Other distributed resources including battery energy storage systems and EVs may well also become significant factors while air-conditioning is already a major contributor to our voltage management challenges.
- As evident with our use of Solar Analytics data, our options for improving voltage visibility in the LV network are, fortunately, also improving. Beyond monitoring service providers, smart meters have voltage measurement capabilities that would currently appear to be underutilised, certainly in terms of publicly available data, while PV inverters measure voltage continuously as part of their operation

and are increasingly communications-enabled. There are also other consumer and network equipment that monitor voltage and might also be useful sources of real-time and historical data - including Building Energy Management Systems in the Commercial sector, Uninterruptible Power Supplies used to protect critical loads for commercial and industrial as well as sites of telecoms and other infrastructure providers. Even modern residential air-conditioners undertake real-time voltage monitoring as part of their power electronics (inverter) control systems.

- Greater coordination across key electricity sector stakeholders regarding these opportunities will likely offer relatively low cost and highly valuable improvements in voltage visibility. Arrangements for the collection and availability of smart meter power quality measurements can certainly be improved, while innovative new data provision opportunities are further explored and developed.
- These opportunities will need to be appropriately integrated into energy sector-specific consumer protections as well as wider consumer data rights provisions that are currently under development. It is important to note that voltage is a system rather than consumer-specific data stream; voltage monitoring at one location generally provides reasonably detailed information on network voltages nearby. Voltage data also has major public good aspects that need to be considered in discussions regarding data availability to a wide set of stakeholders.
- More detailed descriptions, and ideally standards, for LV voltage and associated data collection would assist in sharing and comparing analysis by different stakeholders. Again, this is primarily a coordination challenge.

Wider recommendations – voltage management

- As noted in the literature review, there is a growing body of work exploring both voltage characterisation as well as management across the NEM. There would be great value in better sharing the learnings from these efforts, as well as development of a coordination strategy to drive new work that fills existing gaps.
- A particular opportunity is to ensure better data sharing from the growing range of trials and modelling being undertaken so that a wide range of researchers, industry and other stakeholders can contribute to deriving insights from the data.
- Our range of options for cost-effective voltage management extends across PV and other DER operation, network planning and operation yet also load management. These options continue to improve, particularly those based around power electronics (from inverters to load control to network equipment) given progress in these technologies.
- The key voltage management challenge is the present wide spread of voltages, an issue of both high and low voltage excursions. Narrowing the range of low voltage excursions would allow distribution transformer tap settings that provide more headroom for PV generation. There may be many cases where these tap settings can be reduced without unacceptable impacts on low voltage extremes.
- Conservation voltage reduction trials in Victoria have highlighted opportunities to not only reduce LV voltages as a means to reduce demand during extreme demand periods; but also extend the times over which such reductions are undertaken in a more dynamic manner.
- Legacy inverters installed under earlier AS4777 versions have less strict requirements around curtailment due to high voltages. This may raise some challenges, such as more recent installations curtailing to reduce the impacts of older installations that don't. Note that BESS inverters also fall under AS4777 and there are potentially adverse situations where BESS units that could be charging and hence assisting to reduce voltages are forced to disconnect while the household's older PV system continues to generate. This highlights the importance of rapid updating of relevant Standards as PV and other DER deployment grows. Consideration should also be given to requiring inverters to be capable of having their voltage behaviour characteristics dynamically updated – a capability some models already have.
- At present, PV systems are required to curtail in response to high voltages even if they are not exporting, which prevents self-consumption of PV behind the meter. This issue deserves attention from the relevant stakeholders, given that the consumer might be being penalised for a voltage management issue they are not causing. Similarly, BESS disconnection during periods of high voltage will prevent consumers (or aggregators) from accessing the value available through charging or discharging during that period.

- Work to better understand the strengths, weaknesses and most appropriate contexts for deploying different possible voltage management options is essential. While economics will and should be a key factor in decisions regarding which methods are deployed, it is important to factor longer-term considerations into these choices as well. It seems very likely that a growing range of DER options will be deployed in our distribution networks over the medium to longer term.
- Existing frameworks for voltage management will continue to need to evolve with improvements in these options. Taking advantage of DER and load options will particularly require improved coordination and collaboration with energy consumers. Wider stakeholder consultation and engagement is therefore a key requirement for deploying the most cost-effective voltage management options.
- Some options for voltage management seem likely to require revisiting regulatory arrangements for DNSPs in terms of their obligations and allowable expenditure for cost recovery. Safe, reliable and secure provision of electricity to meet consumer demand is clearly the priority. However, a growing proportion of consumers also have the reasonable expectation that they should be able to export excess PV generation, and increasingly in the future, discharge BESS, to the grid.
- PV inverter standards for Australia are currently being revisited given growing security concerns associated with the operation of distributed PV under major power system voltage and frequency disturbances. There are opportunities to improve present curtailment and broader voltage responses of inverters for LV network management as part of this process. Other work by UNSW has highlighted some potential compliance issues that also need attention. Incorporation of remote dynamic inverter control capabilities could also be of great value, as noted in a number of DNSP proposals.
- Load management options are likely the most neglected at present, but present significant opportunities. Moving controllable loads to periods of higher PV generation (lower net loads) is a key opportunity. There are also growing opportunities to use local or remote air-conditioning load control to reduce those very infrequent low voltage excursions seen at some sites that currently drive the high voltage settings currently seen in the network. These efforts could involve development of more sophisticated standards for installation of such appliances – they could, as seen with PV, adjust their operation under certain voltage conditions, in this case low voltage conditions. They could also build upon existing programs for remote air-conditioning control as seen in Queensland, and some other NEM regions.
- A clear opportunity for early attention would seem to be Demand Response Enabled Devices on A/C units under the control of the DNSP (as already occurs for over 100,000 customers in Energy Queensland) and batteries (both owned by the DNSPs and by customers behind the meter). As well as reducing the size of network assets required to meet these peaks, this would allow the voltage to be reduced across all networks, thereby enabling greater penetration of PV, and associated benefits in terms of financial outcomes for owners of PV systems, but also benefits for non-owners through reduced wholesale spot prices through the merit order effect, reduced network costs and reduced greenhouse gas emissions.
- The growing number of residential and commercial BESS units also offer new options for reducing PV exports to the grid and the voltage challenges they pose. At present, BESS owners are generally incentivised to store their other exported PV generation in daylight hours and then discharge in the evening – operation that would seem relatively well suited to assisting in voltage management as well as reducing demand during network peaks. However, there are opportunities to better coordinate such operation for greater benefit, and Virtual Power Plant and other coordination frameworks provide one such avenue.

To conclude, the challenges yet opportunities of improved voltage management in the NEM both seem likely to grow as DER uptake continues and broadens beyond distributed PV. While there are pressing needs for early action in some cases, such actions need to support development of a longer-term, more strategic framework for distribution network management more generally. Looking beyond voltage management, there are growing concerns about peak reverse flows and security risks with DER operation. At the same time, looking beyond current voltage management frameworks toward more holistic distribution network arrangements will help us take advantage of the growing capabilities of both network as well as DER assets to assist in maximising the value of the LV network into the future.

TABLE OF CONTENTS

1 Introduction

Voltage is a key measure of safe secure and reliable power system operation. It is also challenging to manage given the inherent nature of AC electricity flows and the technical characteristics of electricity industry networks. At transmission system level, power system and network operators require and have both high voltage visibility (high speed measurements at key locations) and a range of methods for managing it within tight operational bounds (involving both large generator as well as network assets). However, both voltage visibility and management capabilities decline as you proceed further into the distribution, and particularly, the low voltage (LV) network. This has historically been largely an outcome of technology capabilities (measurement, communication and control for smaller-scale power system equipment) and simple economics - as always there is a trade-off between expenditures and returns to consumers, noting that distribution networks are often more than an order of magnitude greater in length than transmission networks. It has meant that distribution networks service providers (DNSPs) have had very little voltage visibility, and only limited operational means to manage these voltages, in the LV network where almost all of their consumers take power.

Nevertheless, DNSPs are still required to maintain voltages within upper and lower bounds for all consumers in order to ensure safe, reliable and efficient operation of their appliances and equipment. Both excessively high and low voltages are problematic in this regard, although voltage quality requirements can vary greatly across consumer equipment. The challenge is that as voltage varies considerably by location and time across the LV network driven by system-wide to local network arrangements, and particularly by changing locational consumer demand. Networks have traditionally used estimates of after diversity maximum demand to design networks that can maintain voltages within acceptable upper and lower bounds given expected consumer behaviour. By setting distribution transformer voltages near the upper limit of the permitted voltage range, these peak demand periods can be met without excessively low voltages occurring due to the voltage drops associated with higher power draws through the network. Air-conditioning uptake over the past two decades in Australia has posed challenges for this approach by increasing peak demand. And, since 2010, the uptake of solar photovoltaics (PV) in Australia has steadily increased, with over 2 million households throughout Australia now having their own PV system. These PV systems effectively extend the range of net consumer demand, reducing or even reversing it (PV exports) in periods of high PV generation.

Export from PV systems can therefore drive higher voltages, which can cause over voltages to occur, particularly in locations where there is little headroom due to existing voltage settings. For safety and security reasons, PV systems are required to reduce their output to zero when voltages go outside a defined voltage envelope, that depends on the connection standard applying at the time of installation and the extent and duration of voltage excursions. Such curtailment reduces PV generation and hence the value of the system to its owner. They may in turn, trigger a power quality complaint requiring DNSPs to change their management of voltage in that part of the network. Curtailment also reduces the environmental benefits of PV to the community, as PV power is replaced by primarily fossil-fuel generation. With high and increasing uptake of PV systems across Australian households and businesses, these factors have seen increasing interest in the degree to which voltages in the low voltage (LV) network in Australia are currently managed, the extent to which any voltage issues are caused by PV, the impacts high voltages may have on PV curtailment and hence the value, and options for improved voltage management if, where and when required.

As discussed in the literature review below, some analyses of voltage conditions have previously been undertaken in Australia, however due to lack of access to data, to date these have generally been limited to small numbers of sites or limited time periods. We have not found any significant published analysis of the relationship between PV and voltage, nor of the prevalence of PV system curtailment due to voltage issues, certainly not on a NEM wide basis.

The Energy Security Board therefore has commissioned the Centre for Energy and Environmental Markets at the University of New South Wales to undertake analysis of voltage on the LV networks within the National Electricity Market (NEM), as well as distributed PV's influence on that voltage. This work was completed on a very restricted timeline, and as a result only limited analysis has been undertaken so far. Further analysis is to be undertaken in later stages.

The analysis in this report is conducted using historical voltage and PV export measurements obtained from Solar Analytics (SolA) for 12,617 residential sites with a PV system. The data has a temporal resolution of 5 min, with 5 second sampling of voltage. Highest and lowest 5 sec voltages are recorded for each 5 minute period. There is a complete year of data for 4,337 sites, for the 12 month period from 1 Dec 2018 to 30 Nov 2019. Data from a further 8,280 sites for which a complete year is not available over this period is also included in much of the analysis. The analysis is conducted for each State and Territory and Distribution Network Service Provider (DNSP) in the NEM. By aggregating postcode data, it has also been possible to conduct separate analyses according to population density and PV household penetration levels, which can help to assess the importance of more dispersed regional and rural network characteristics, and spatial hot spots with high uptake of PV, on network voltages.

Section 2 briefly outlines the key challenge of what appears to be a growing range between maximum and minimum voltages across the LV network, and its implications for distributed PV, and consumers more generally.

Section 3 is a literature review of work to date in Australia on better understanding voltage in the LV network, possible reasons for voltage issues including the potential role of distributed PV, potential impacts on PV including curtailment, and work trials underway to not only better understand these issues but investigate different options for managing them.

Section 4 presents an overview of the data used in the analysis.

Section 5 presents the analysis of voltage conditions currently seen on the NEM LV network, highlighting the fact that voltage levels are generally high across the NEM at all times of the day.

Section 5.4 presents analysis that seeks to better understand and quantify the relationship between periods where PV systems are exporting (ie. negative net site load) and voltage; and does find evidence for PV export increasing voltage.

Section 7 presents an assessment of potential curtailment using voltage measurements, finding that overvoltage events occur a relatively small amount of the time.

Section 7.5 presents some detailed curtailment analysis based on earlier work using Solar Analytics data for a particular region over a select number of days.

Finally, **Section 9** summarises some key findings from this preliminary analysis and considers possible next steps both for extensions to the analysis undertaken to date, but also more generally for progressing voltage visibility and management in the LV network.

2 Voltage range is increasing: why does it matter?

Distribution Network Service Providers (DNSPs) are required to deliver power to consumers that meets certain power quality requirements. This includes maintaining voltage within an allowable range (typically 230V +10/-6% [1]) in order to ensure appliances function as expected and are not damaged. In practice, the standard does permit excursions outside this range 1% of the time, in part reflecting the challenges of managing voltage for all consumers within the standard at all times under all possible network operating conditions.

Voltage is influenced by a number of factors including:

- **Network characteristics**, due to impedance in the network, voltage on LV networks normally decreases between the MV connection and the last customer point of connection. Many Australian network areas include long, high impedance feeders, where voltage drop can be significant
- **Network equipment** settings, such as the voltage tapping at the nearest distribution transformer
- **The size and location of loads** at a specific point in time
- **The size and location of any distributed generation** at a specific point in time

Historically the greatest voltage management challenge for DNSPs was managing high load conditions. The uptake of air conditioning units across the Australian National Electricity Market (NEM) over recent decades has increased peak load (which typically occurs for a very small fraction of the year) and as result, minimum voltages are likely to have reduced during these peak periods.

More recently, Australia has also experienced world leading uptake of distributed solar photovoltaics (PV). Both reduction in net site load when PV generation is consumed behind the meter, and net export when generation is greater than the underlying site load, causes local voltage to be higher than otherwise. Figure 1 gives a simple illustration of solar PV exports increasing voltage. The extent to which the voltage falls or rises along a feeder depends on the amount of current flowing and the impedance of the line, a higher impedance leads to greater voltage rise.

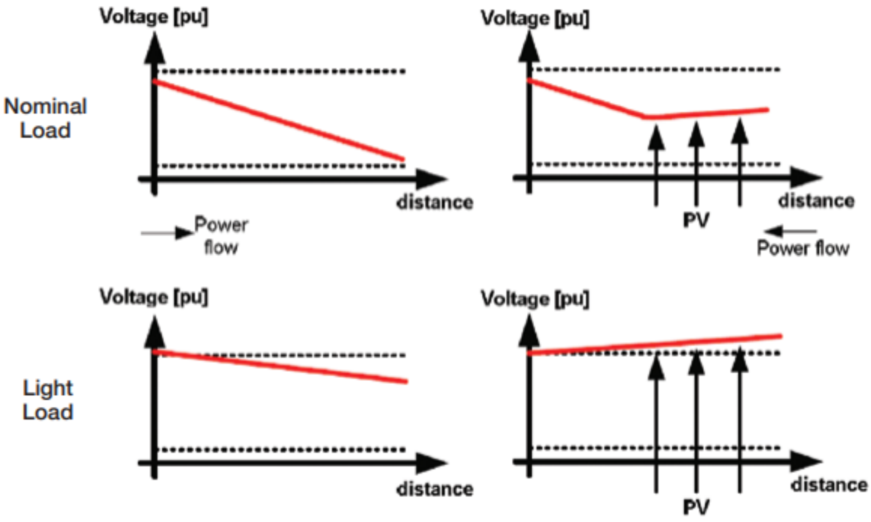

Figure 1 – Illustration showing voltage rise due to solar PV generation [2]

While PV might reduce peak loads and alleviate low voltage issues during some periods (top right of Figure 1), at other times high PV generation may occur at times of light load driving power flow back up the feeder which can result in voltages higher than at the distribution transformer (bottom right of Figure 1). The net result of the increasing peak loads and PV export over the past two decades in Australia is an increased voltage range that DNSPs need to manage. At some point excessive voltages will cause the PV systems to curtail their output in order to avoid even higher voltages.

The potential consequences of this widening voltage range for consumers are summarised in Table I. Looking forward, the challenges are likely to grow, for instance with the uptake of Electric Vehicles [3], which are likely to result in highly correlated new loads on the network.

Table I – consequences of increased voltage range

Consequence	Impacted consumer group
Household appliances are approved to operate at a nominal voltage, for Australia this voltage is 230 V. While many appliances contain power electronics that allows them to be safely used across a wide range of voltages, certain types of appliances may be damaged or have their operation affected by voltages that deviate excessively from the nominal voltage [4]. For instance, when operated at higher voltages, some appliances may consume more power, in some cases representing an energy efficiency loss.	All consumers
If the voltage at the PV system connection point rises to the over-voltage limit (defined in Australian standard AS 4777 [5]), the solar PV system is required to **disconnect** or **curtail**. In this case, the PV system no longer generates electricity to supply household loads or export any excess electricity. Consequently, consumers lose both any savings from self-consumption of PV and any potential revenue from a solar feed-in-tariff (FiT) on exported electricity.	Consumers with solar PV
DNSPs may **prevent consumers from installing a new solar PV system** if their analysis shows that over-voltage may result around the customer site or may apply zero export limits.	Consumers wanting to install solar PV
The full **potential of Distributed Energy Resources is not achieved** due to 'congestion' in the distribution network.	All consumers

Consumers may be impacted on an individual basis, however it is important to note that the increased voltage range pose challenges for decentralisation of the power system more broadly. AEMO identified in its 2018 Integrated System Plan that effective use of Distributed Energy Resources (DER)[1] could offer nearly $4 billion in reduced costs under some scenarios compared to the neutral case [6]. Curtailing distributed PV and slowing PV uptake also involves a shared loss for the community by increasing electricity sector climate emissions. Voltage is not the only issue facing DER uptake, but it is certainly a critical one. It is therefore critical that the challenges and opportunities regarding the widening voltage range are understood and addressed.

3 Literature review

3.1 Voltage conditions

This section reviews work examining the prevalence of under or over voltage issues in the NEM, and the approaches to managing voltage currently being used. Generally, there exists limited visibility of conditions in the LV network although there is widespread agreement that improved visibility is required, and its absence is one of the key reasons for limited analysis of voltage conditions to date. We therefore first review the availability of such data. DNSPs, metering companies and third party monitoring companies are the three primary entities currently collecting electricity data as set out in more detail below.

3.1.1 Availability of data

The AEMC conducted a survey of DNSPs regarding visibility in the LV network and concluded that:

"there is little direct monitoring of loads and voltages on LV transformers and circuits, and on individual phases of those circuits" [7].

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[1] Such as distributed PV, battery energy storage, electric vehicles and demand response

Findings from this survey can be found in [7] and are summarised below in Table II and Table III. Notably there is the greatest visibility at the zone substation level in the network with very limited data available at the LV or consumer connection point level, as illustrated in Figure 2. The exception being in Victoria due to existence of smart meter data. There are ongoing efforts to improve data visibility (Table III) however coverage is not universal and in fact Ergon Energy (Queensland) noted that customer connection data access is expected to reduce as ring fencing arrangements are put in place. The competition in metering rule change enables consumers to access their own data, however this provision applies only to energy measurements and does not include voltage data. Further, DNSPs must pay for access to voltage data relevant to their network. In some cases DNSPs are also purchasing data from third party monitoring companies including inverter or battery companies, aggregators and monitoring/analytics companies.

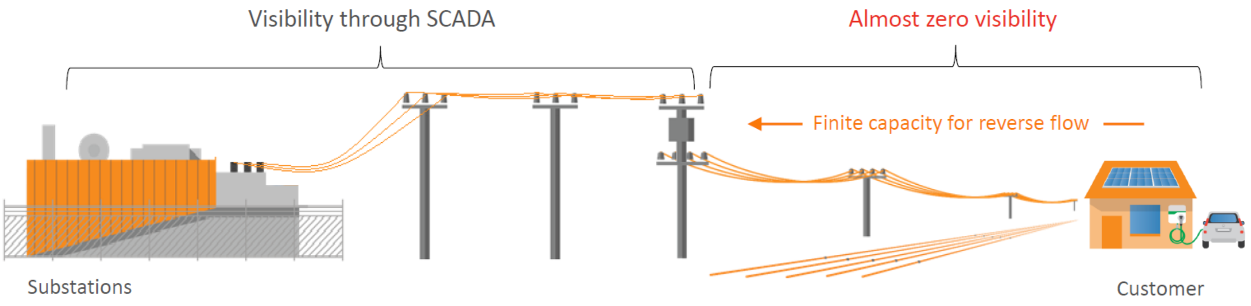


Figure 2 – Visibility in the LV network summary, SAPN [8]

Table II – Summary of data *completeness* results from AEMC DNSP survey [7]

		Part of the network					
		Zone substation feeder panel	**Distribution substation transformer**	**LV circuit**	**Customer connection**	**Inverter exports**	**Customer consumption**
Qld	**Ergon**	●	◔	○	◔	○	○
	Energex	●	◕	○	◔	○	○
NSW	**Essential**	●	○	○	◔	◔	◔
	Ausgrid	●	◑	◑	◔	◔	◔
	Endeavour	●	◔	○	◔	◔	○
ACT	**Evoenergy**	●	◔	○	◔	◔	◔
Vic	**Ausnet**	●	○	○	●	○	○
	United Energy	●	○	○	●	○	○
	Jemena	●	○	○	●	○	○
	Citipower and Powercor	●	○	○	●	○	○
SA	**SA Power Networks**	◕	◔	○	◔	○	○

Key: data availability is ● high, ◕ medium, ◑ minimal, ◔ very low, ○ limited to none.

Table III – Summary of data *trends* results from AEMC DNSP survey [7]

		Part of the network					
		Zone substation feeder panel	**Distribution substation transformer**	**LV circuit**	**Customer connection**	**Inverter exports**	**Customer consumption**
Qld	**Ergon**	→	↑	→	↓	→	→
	Energex	→	↑	→	↑	→	→
NSW	**Essential**	→	→	→	↑	→	→
	Ausgrid	→	↑	↑	↑	→	→
	Endeavour	→	→	→	↑	→	→
ACT	**Evoenergy**	→	→	↑	→	↑	↑
Vic	**Ausnet**	→	→	→	→	→	→
	United Energy	→	→	→	→	→	→
	Jemena	→	→	→	→	→	→
	Citipower and Powercor	→	↑	↑	↑	→	→
SA	**SA Power Networks**	↑	↑	↑	↑	→	→

Key: data availability is ↑ increasing, → not changing, ↓ reducing

Where smart meter data can be accessed by DNSPs, the monitoring can be more sophisticated. The AusNet Services Distribution Annual Planning Report 2020-2024 [9] states that “AusNet Services has developed a tool, known as Explore, that uses AMI data and network analytics to monitor the level of voltage compliance within AusNet Services’ distribution network. Explore provides an up-to-date view of the level of voltage compliance and stores historical data to give a view of how voltage compliance has changed over time.” Such tools highlight the opportunity to better utilise existing monitoring equipment to assess changing power quality for consumers.

3.1.2 Voltage Standards

AS61000.3.100 (Steady-state voltages) defines both an allowable operating range, and a preferred operating range. The preferred operating range is +6% to –2%, however the allowable voltage variation at the point of supply of +10% and –6%. The preferred operating range represents the 50 percentile value of voltage while the upper and lower allowed limits are the 99 and 1 percentile values respectively (Figure 3). Voltages are to be assessed on a 10 minute basis, formally the average of 3,000 measurements over 10 min (every 12 cycles or 0.2 seconds). As noted earlier, there is an appreciation that it may not be possible to always keep voltages within the allowable range given all of the potential circumstances of demand and network operation.

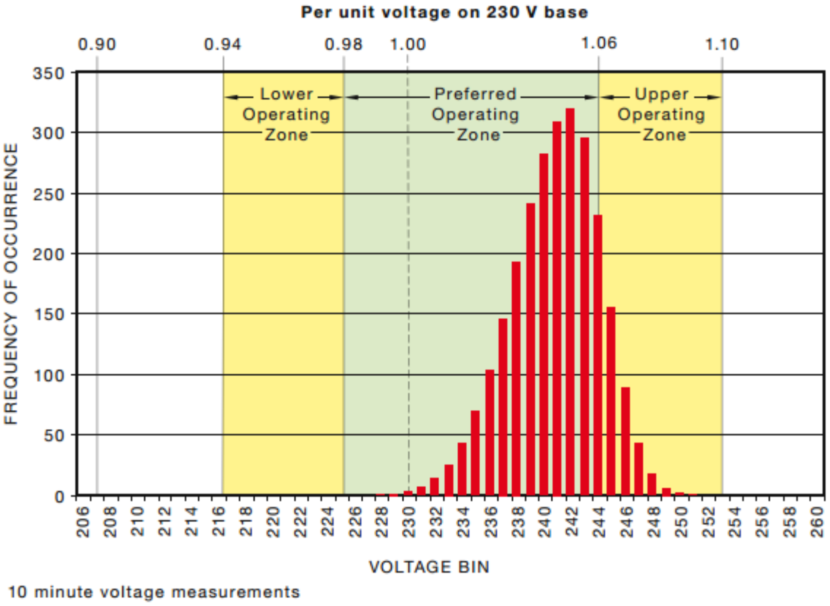


Figure 3 - Voltage operating zone specified by AS 61000.3.100

3.1.3 Prevalence of over voltage and under voltage

DNSPs are fielding a growing number of inquiries from consumers relating to PV and high voltage, however there remains limited visibility across the bulk of the distribution network. As per Australian Standard AS 61000.3.100-2011 [1], here we define:

- **Over voltage** to be voltages greater than 253V
- **Under voltage** to be voltages below 216V

Previous analysis in [10] and [11] has shown that the distribution network is typically maintained near the upper end of the allowable voltage range. In September 2019, the Australian Solar Council held a webinar entitled: “High Voltage is Stopping Solar”, which included the following presentations of analyses:

Edge Electrons

Presented analysis of voltages at 521 Victorian sites over 30 days in November-December (Figure 4). Analysis includes distribution of average, average max and overall max voltage. The report also included comparison of voltage conditions in Victorian DNSP regions. Case studies on voltages seen in 3 postcodes.

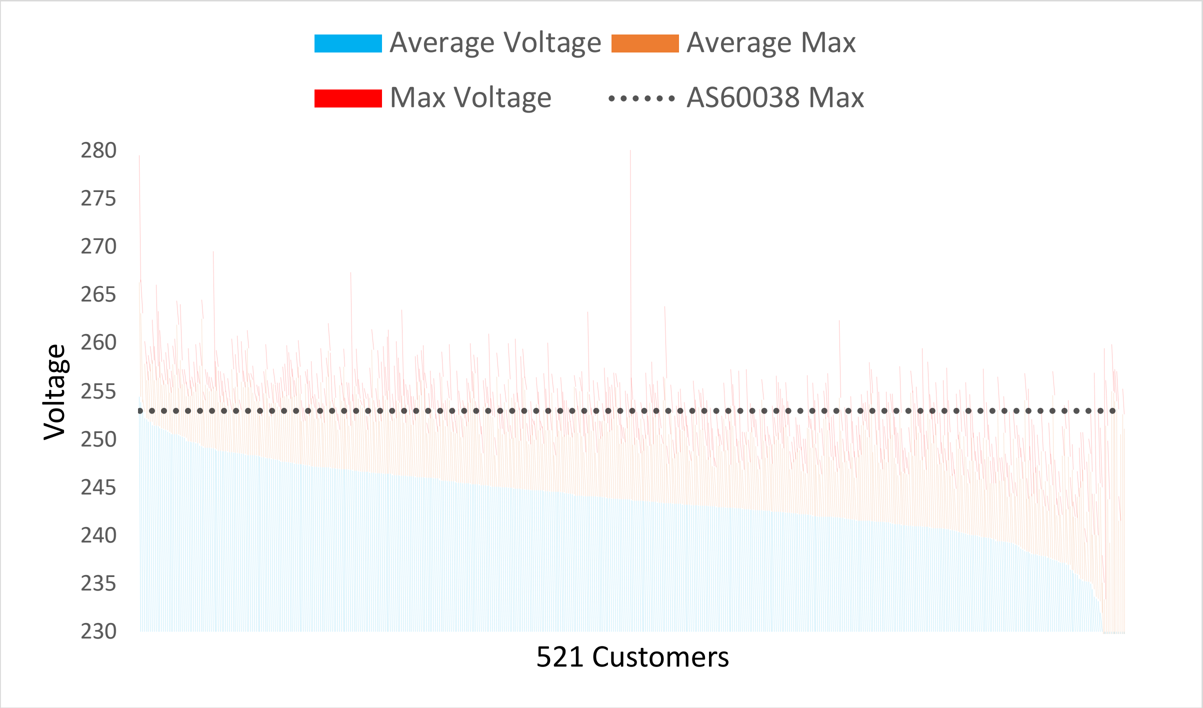


Figure 4 – Edge Electrons analysis of voltage data from 521 Victorian sites over 30 days in November-December 2018

Metropolis Metering

Presented analysis prepared for the 7:30 report using data from a large number of sites (12,000), collected at 5 specific times over 10 days. Presented distributions of average and max voltages and stated average, average_max, average_min and % voltages above compliance by state and DNSP. The analysis showed that average and maximum recorded voltages are high compared to 230V target. Highest volts were recorded at 1pm, and lowest average volts at 5pm, with only a small difference (0.7V) between the two, implying that the influence of PV on average and maximum voltages are relatively small.

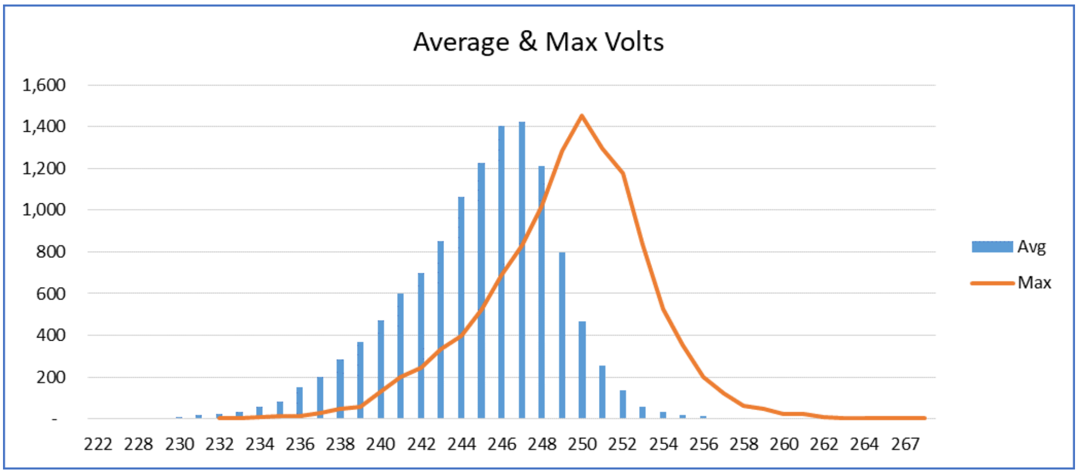


Figure 5 – Metropolis Metering analysis of voltage data from 12,000 sites collected at 5 times over 10 days

Solar Analytics:

Presented analysis based on a sample of 1000 sites during 2018 of the number of "non-compliant" sites, including a plot of % of sites vs (a) number of days that include voltage measurements above with the allowed standard (voltages above 253V) (Figure 6), and (b) number of days with voltages below standard (Figure 7). This analysis was also published in an EcoGeneration article [12] [13]. The results showed that around 85% of PV sites experienced over-voltage at least once in 2018, about 50% of the sites measured over-voltage on more than 50 days and more than 25% of sites saw over-voltage on more than half of the days in the year. Significantly fewer instances of under voltage were recorded.

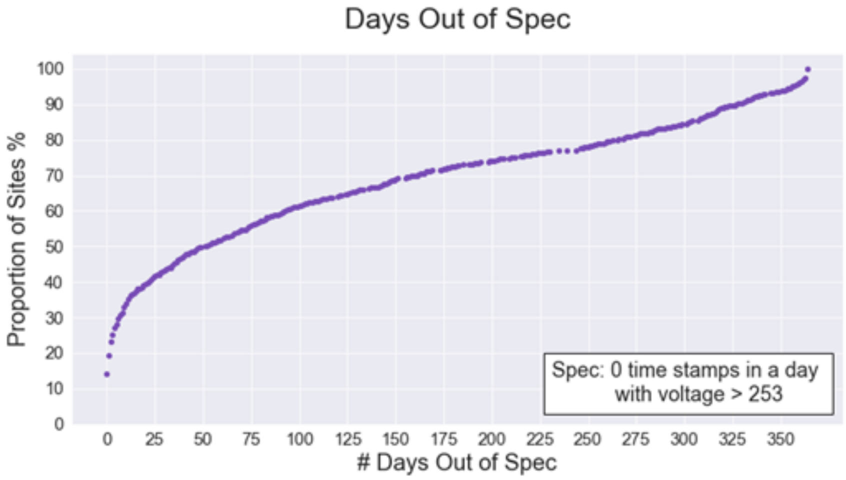


Figure 6 - Proportion of sites measuring voltage below the lower limit at least once on fewer than the given number of days, sampled from 1,000 sites spread around Australia over all of 2018

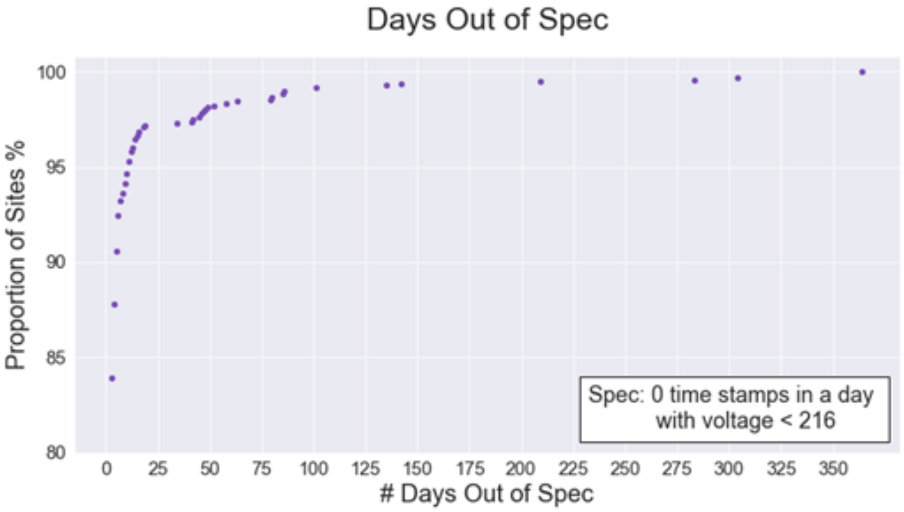


Figure 7 - Proportion of sites measuring voltage below the lower limit at least once on fewer than the given number of days, sampled from 1,000 sites spread around Australia over all of 2018.

Further analysis by CEEM, based on Solar Analytics data (Figure 8) shows the spread of voltages observed in NSW during January to June 2017 and indicates the expected voltage range. There are two key factors driving high voltages:

- historic requirements to manage peak demand (not DER exports), and
- an historic 240V nominal standard.

DNSPs are transitioning to the 230V standard and working to managing the new DER exports. Whilst this analysis indicates that over voltages are more prevalent than under voltages, the fact remains that DNSPs need to manage peak demand days and ensure consumer appliances continue to operate during these rare periods, for instance, air conditioning systems on extremely hot days.

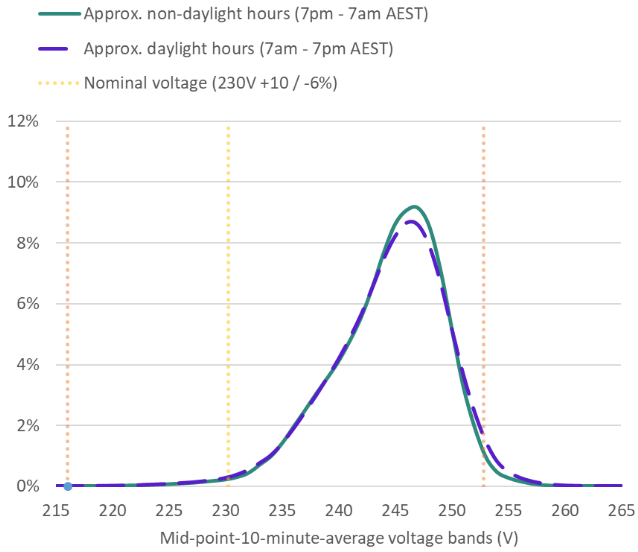


Figure 8 – NSW voltage distribution January – June 2017 [10]

Figure 9 and Figure 10 show the spread of voltages over the course of the day in summer and winter. Again, these indicate that overall LV voltages are high with the mean voltages occurring overnight similar to that occurring during the day. These plots also reflect the typical summer / winter load pattern – indicating that a key variable impacting local voltage conditions is load.

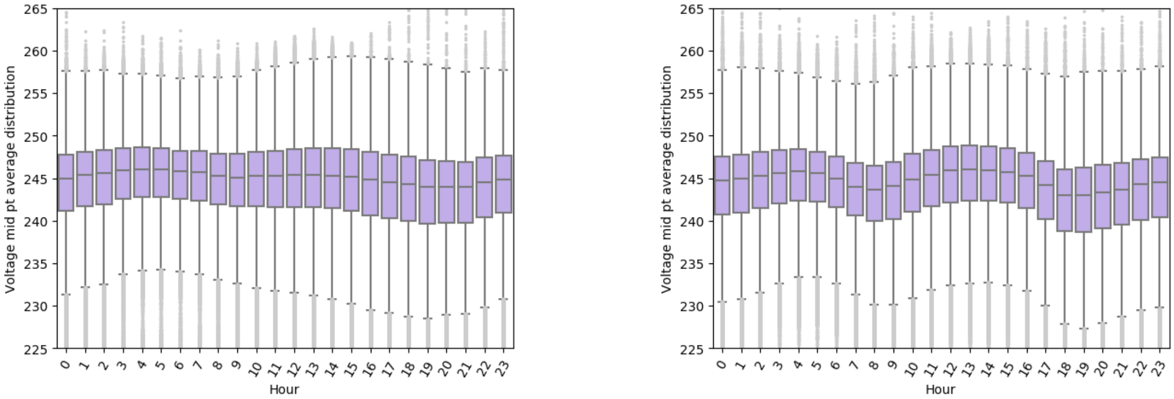


Figure 9 – NSW January daily profile [10]

Figure 10 – NSW June daily profile [10]

The AusNet Services Distribution Annual Planning Report 2020-2024 [9] states that an improvement in voltage compliance was seen between December 2014 and October 2019, with overvoltage non-compliance reducing from approximately 30% to 10%. According to AusNet, “The improvement in voltage compliance is primarily due to voltage regulator setting changes that have been actively made to improve voltage levels”. They note that compliance with the undervoltage limits have mostly been maintained. In Figure 11, the straight line between late-2015 and late-2016 is explained as being due to data that is still to be back-populated in their analytics tool.

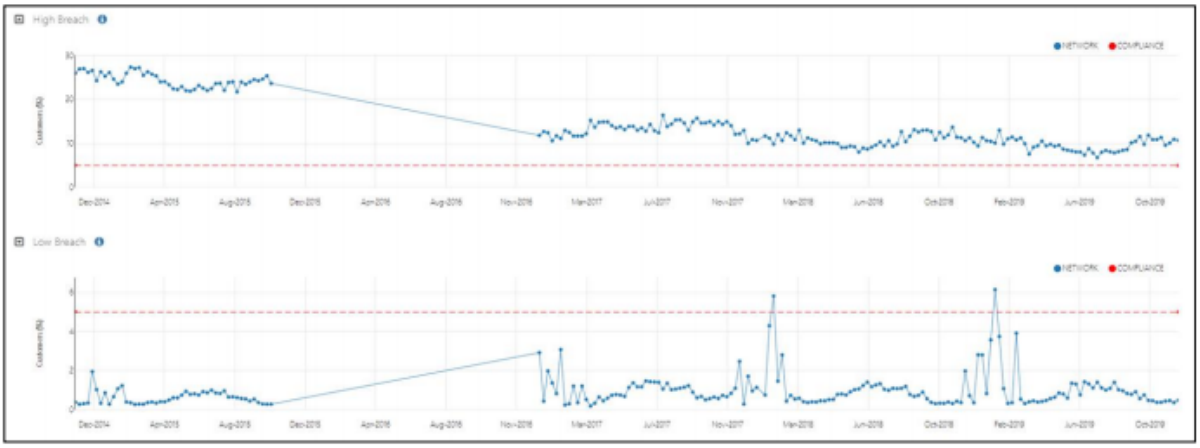


Figure 11 – Improvement in voltage compliance reported by AusNet Services from Dec 2014 to Oct 2019

Table IV – Summary of key insights with regards to voltage excursions location, frequency and duration

	Over voltage	**Under voltage**
Location	Likely to be more prevalent: • At the **end of distribution feeders**, particularly in **remote regions** with long feeders, and • In regions with **high PV penetration**	Likely to be more prevalent: • At the **end of distribution feeders**, particularly in **remote regions** with long feeders, and • In regions with **high penetration of air conditioning**
Frequency and duration	Typically voltages are ‘run high’ so over voltage in regions with high PV penetration is **likely to occur frequently**, potentially daily.	Typically voltages are ‘run high’ so under voltage is **likely to only occur during peak demand conditions**, (subject to local network configuration), potentially a few times per year.

It is worth noting that the tap setting of the majority of distribution transformers is high [7]. The regulation over-voltage limit is ~253 V, this allows for over-voltage headroom of only 3 V. Such a small headroom doesn’t allow for much solar PV installed before instances of over-voltage occur. In contrast the regulation under-voltage limit is ~216 V, a 34 V legroom. This is one of the reasons why DTx tap adjustments are a common response to customer complaints of solar PV inverters tripping due to over-voltage [7].

3.2 Interaction between PV and voltage

DERs (including distributed PV) export impacts voltage, and voltage can also impact DER operation.

PV impact on voltage

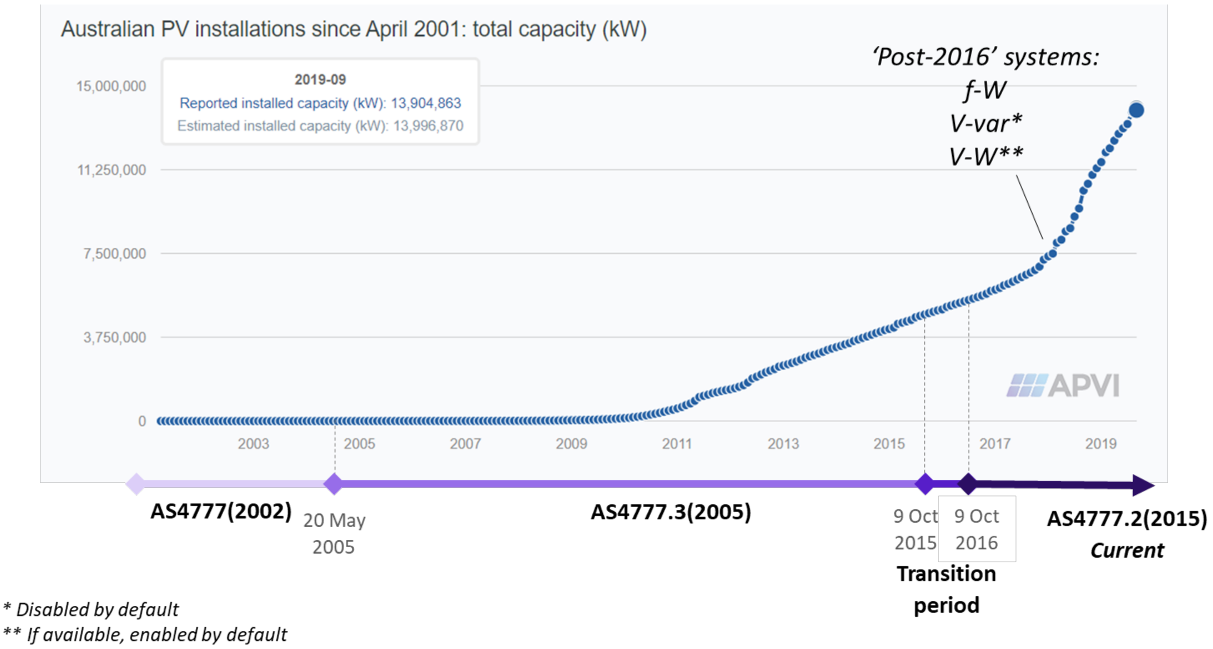
A report by Miller et al (2018) titled ‘Power Quality and Rooftop-Photovoltaic Households: An Examination of Measured Data at Point of Customer Connection’ attempted to answer whether power quality issues were caused by solar PV, however the sample was tiny (4 houses in different DSNP’s). They concluded that “the low voltage distribution networks reported in this study do not have networks that meet required power quality standards—and this cannot be attributed to the rooftop PV systems reported here.” However due to the small sample this finding would require far greater validation.

Stringer et al. characterised voltages in the LV network across hours of the day and seasons. This analysis used 2000 sites across 6 months, of which 1000 had the full 6 months of data available. While time of day has a relationship with PV generation it only captures part of the relationship. In Australia to date, analysis of correlation of PV generation or exports with voltage has been limited to results from VPPs and other trials with sample size in the order of 100 sites.

Voltage impact on PV

The impact of local voltage conditions on PV largely depends on the PV inverter (see Box 1) settings. Inverter settings are dictated by the local DNSP that largely refer to the Australian / New Zealand Standard AS / NZS 4777 [5]. This standard was updated just recently in 2015 and therefore there remains a substantial legacy fleet of inverters (with settings reflecting the superseded standard) installed across Australia.

There is an ongoing program of work to update this standard to bring it in line with international best practise [14], as well as efforts to provide nationally consistent requirements through Energy Networks Australia [15].



* Disabled by default

** If available, enabled by default

Figure 12 – Legacy and current PV fleet

Legacy inverters are allowed to have higher over voltage set points [7] compared with inverters installed under the current standard. The original intent of anti-islanding set points was to maintain safety within the distribution network, rather than to manage persistent over voltage conditions. In contrast, the 'limits for sustained operation' functionality introduced in the current standard were intended to reduce over voltages caused by high levels of PV export. In practise, both the anti-islanding settings and limits for sustained operation cause PV systems to cease operation when high voltages occur.

Table V – AS/NZS 4777 settings summary

Standard	Function	Function limit	Trip delay time	Maximum time to disconnection
AS4777.3-2005 (superseded)	Under voltage	200 – 230V	Not specified	2s
	Over voltage	230 – 270V	Not specified	2s
AS4777.2-2015 (current)	Under voltage	180V	1s	2s
	Over voltage 1	260V	1s	2s
	Over voltage 2	265V	-	0.2s
	Limits for sustained operation *(disconnect when 10min average exceeds this value)*	255V (default) 258V (maximum)	Not specified	15s
	Volt-Watt response mode	*If available, enabled by default.*		
	Volt-VAR response mode	*Disabled by default.*		

3.2.1 Volt-Watt, Volt-VAR inverter response modes

A more recent solution to prevent over-voltage is by using the solar PV inverter (See Box 1). In 2015, the option for inverters to include Volt-Watt and Volt-VAR response modes was included in Australian Standard AS 4777 [5]. Volt-Watt automatically reduces the real power output from the inverter when voltages reach a certain level, reduced real power output means less voltage rise. Volt-VAR mode can also be configured to respond when voltage levels reach a certain level. When an inverter is operating in Volt-VAR mode, it can both absorb and supply reactive power to aid in maintaining voltage at the appropriate level. Note that high levels of VAR provision by an inverter can reduce its capability to deliver real power.

Box 1. A solar PV inverter is the electronic device which converts the direct current (DC) power generated by the solar PV array located on the roof to alternating current (AC) power. All household appliances use AC power and electricity is transported throughout the NEM, aside from the DC links between states, using AC power.

According to the Clean Energy Council (CEC), Volt-Watt and Volt-VAR capability of inverters is now required as a condition of grid connection for all new solar PV system installations in 14 of Australia’s 16 DNSPs.

The drawback of Volt-Watt mode is that it is a form of curtailment, preventing clean energy generated by solar PV systems from providing power to the network. Volt-VAR mode is preferable in that less real power is lost, but absorbing reactive power will increase losses in the network and may have only a limited capability to reduce voltage in many areas of the distribution network [16].

Local [17] and international [18] analysis suggests that Volt-VAR mode is an effective option for reducing overall PV curtailment, although it does still have the potential to result in PV curtailment. Several DNSPs now require Volt-VAR response mode to be enabled in all new PV installations. Volt-VAR is included in the ENA national connection guidelines [15] and is being considered in the AS4777 review [14].

3.2.2 Evidence of PV curtailment

Anecdotally, the primary means by which networks are made aware of PV curtailment is through consumer complaints when their PV system is not performing as expected. There remains limited visibility of PV operation and therefore limited visibility of the degree of curtailment occurring.

SA Power Networks 2020-2025 regulatory proposal estimates the value of lost PV exports into the future and compares the value with various management solutions. The work involves some monitoring of representative feeders in combination with modelling and was undertaken in collaboration with EA Technology. As PV penetrations were increased, voltage emerged as the first limiting factor in this modelling (see Figure 13). The extent of curtailment of exports from new PV sites was modelled (1) if the network was augmented (2) with fixed export limits and (3) with dynamic export limits. It is important to note that this is modelled and future looking, rather than analysis of the current curtailment situation.

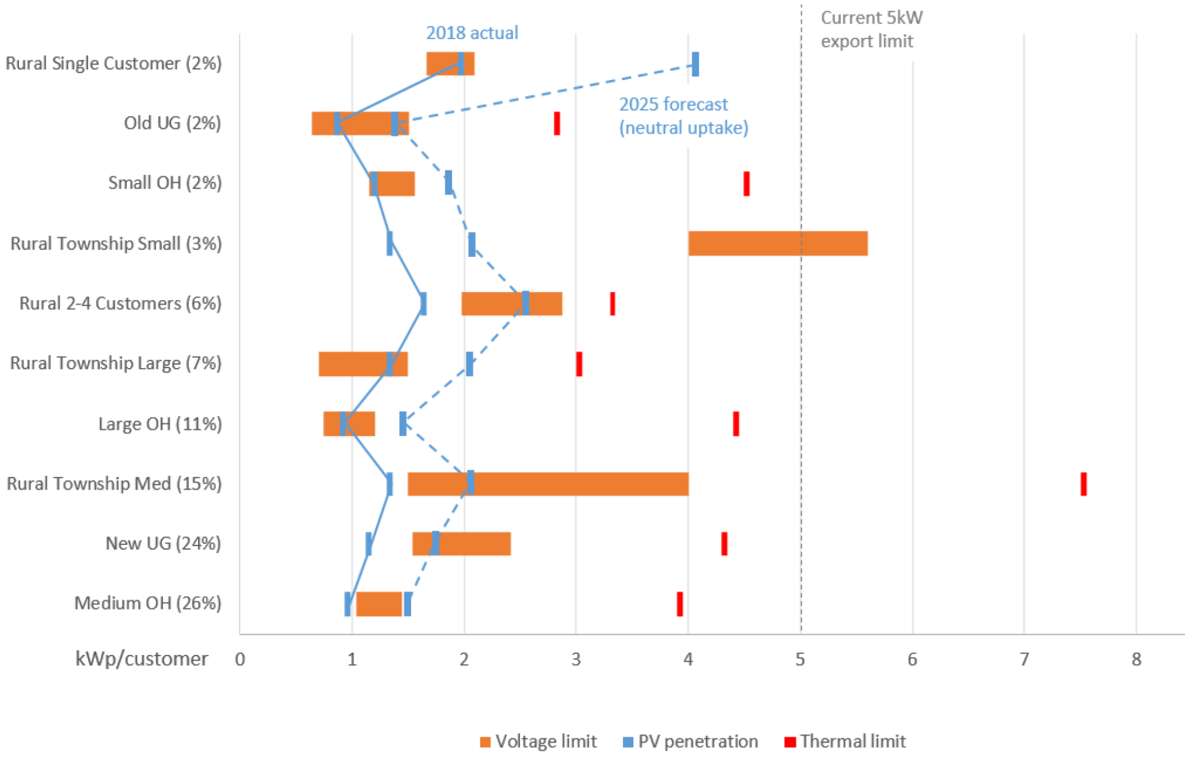


Figure 13 – SA Power Networks and EA Technology hosting capacity analysis outcomes [19]

3.3 Voltage management

3.3.1 Conventional Voltage Management Approaches

There are three conventional ways to manage over-voltage due to excessive solar PV generation in the LV network.

1. One conventional method is through network augmentation. Undertaking works to upgrade the service mains or LV feeder in an area in order to lower the impedance will decrease voltage drop/rise. In general, overhead lines are higher impedance than underground cables and can be targeted as part of overall network upgrade schedule. Where service mains are already of sufficient capacity, upgrading of the distribution transformer to a higher capacity which would have a lower impedance and less voltage drop/rise can be considered. However this approach would be expensive in comparison Network augmentation is “often costly and an inefficient solution to provide additional network capacity that is generally needed for only certain times” [16].
2. Another option is lowering the tap setting at the Distribution Transformer (DTx), the DTx transforms voltage down from 11 kV to 400 V. Households are connected to the 400 V line (but the voltage at their power outlet will be 400/√3=230 V). Lowering the tap setting at the DTx lowers the voltage at the front of the LV line. A lower voltage at the front of the LV line means solar PV can export more power before voltage levels reach over-voltage levels. This requires a network study and a small amount of hours of field staff time to change the tap. However 11 kV/415 V transformers are usually only capable of coarse adjustment and network voltages at times of peak load (and low PV generation) are commonly close to low voltage minimums allowed under network standards, as a result of the correlated operation of large loads such as air-conditioners under some conditions. Tapping down transformers could therefore cause voltages to drop below the network standards. “Lowering fixed taps on distribution transformers to increase their transformation ratio (and therefore reduce their output voltage) will increase the hosting capacity of the low voltage network. Changing the fixed tap position itself is a very simple and quick exercise, but the distribution transformer must be de-energised in order to do so. There are costs associated with notifying and interrupting consumers, or with arranging alternative supply, that are

likely to greatly outweigh the cost" [16]. (this may also cause under voltage during peak/high load periods for certain parts).

3. Where phase imbalance exists, manually switching customers across phases is an option. The National Electricity Rules require networks to maintain difference in line to line voltages across phases within 2% using a 30 minute average. Electricity is connected to residential homes to single phase residential connections, either of 3 phases (A, B, and C), and the majority of PV systems to date have also been added to single phases, so are not necessarily balanced across phases. If more solar PV (or less load) is installed on one particular phase (phase A say), then that phase is more likely to experience over-voltage than the other two phases (phases B and C). By balancing the load on the transformer the PV generation and thus voltage rise is more evenly distributed over the phases and in many cases this will be sufficient to keep the network within mandated values. Ideally the phase of connection would be chosen during installation rather than as a response to a voltage problem, however this is usually not possible due to lack of information about connection of existing loads and PV systems across phases. Changing the phase of connection is a relatively low cost option, as it only requires a network study to determine the extent of the load unbalance when PV is generating and a short amount of time for field staff to change the connection. It can also be quite effective but depends on the existing level of unbalance in the network. Networks do not typically have documentation indicating which phase customers or inverters are connected to, so these changes are generally only made in response to problems.

Several of these means of voltage management are summarised in Figure 14.

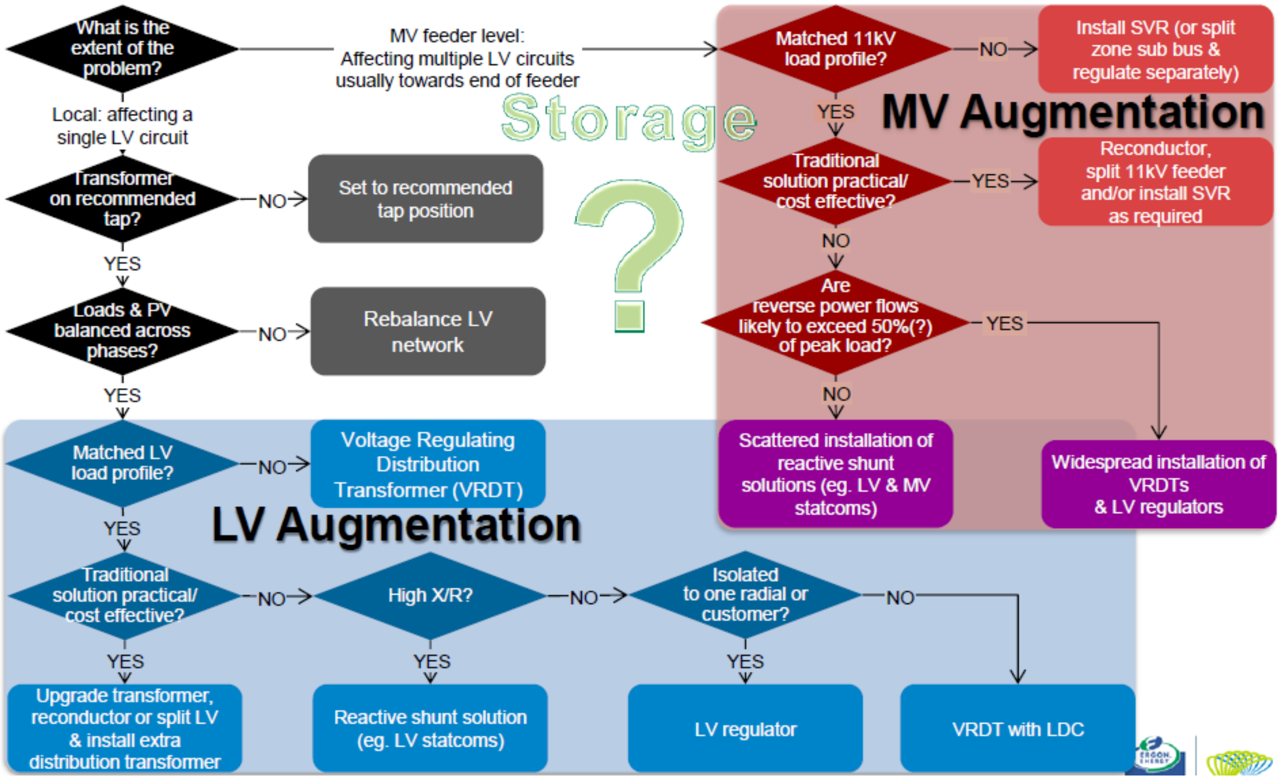


Figure 14 – Voltage management techniques, [20]

3.3.2 Advanced voltage management

Following are several examples of advanced voltage management, designed to assist in voltage management of LV networks with high levels of solar PV generation.

3.3.2.1 Voltage Regulation for Distribution Transformers

Ergon has begun trialling Voltage Regulation for Distribution Transformers (VRDT). VRDT is a potential solution for managing voltage in rural areas and locations where line impedance is higher. VRDT "decouples LV regulation from MV regulation, accommodating increased regulation on both MV and LV networks and thus increasing hosting capacity of PV (and EVs)" [21]. Figure 15 shows the application and influence of VRDT.

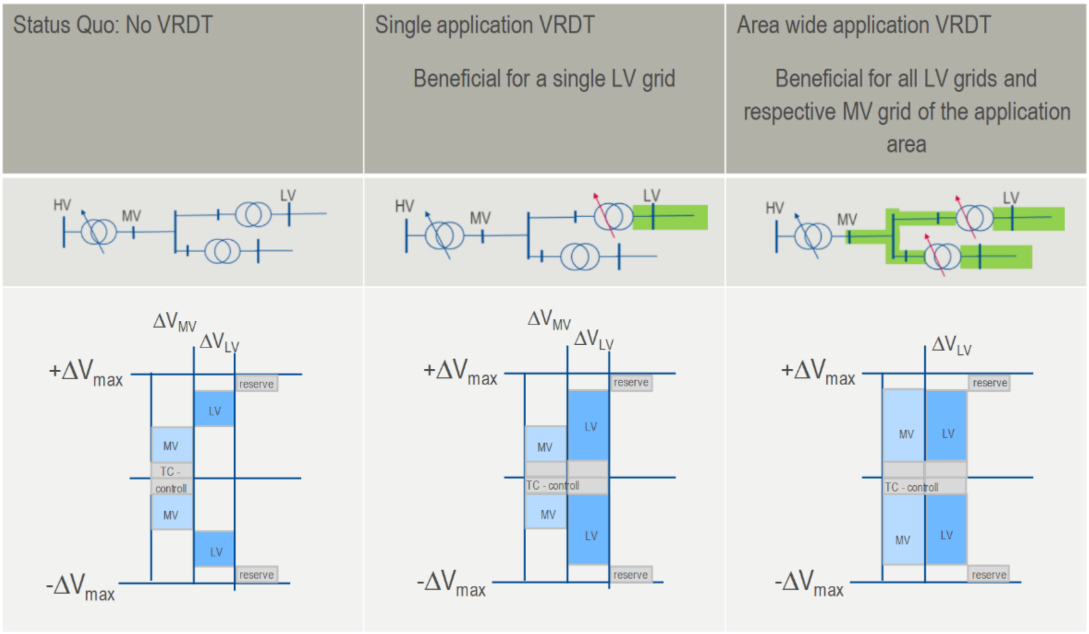


Figure 15 - Application and influence of VRDT

3.3.2.2 Dynamic Phase Balancing

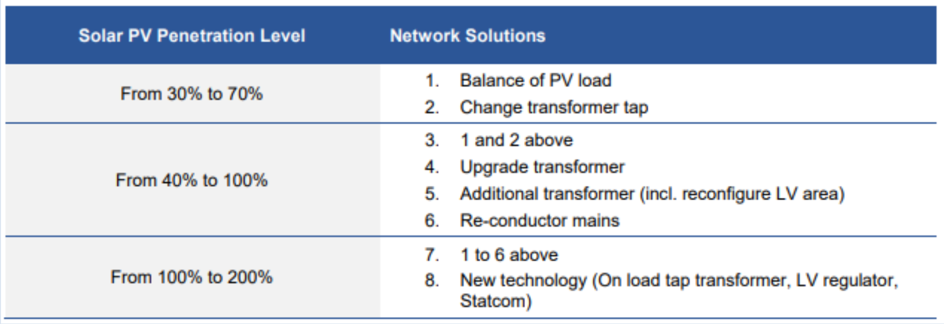
The ARENA sponsored project "The Demonstration of Three Dynamic Grid-Side Technologies" [22]–[23] will demonstrate three technologies:

1) Dynamic phase switching of customer connections. This technology allows for solar PV generation to be dynamically balanced, therefore sharing solar PV export across all phases and reducing the change of over-voltage on any one phase.
2) Dynamic power compensation. Power flow technology will be incorporated at the DTx to balance power flow across all three phases, allowing better voltage regulation, and therefore minimising the instances of both under-voltage and over-voltage.
3) Battery energy storage with Virtual Synchronous Generator (VSG) capability. This large-scale battery (100kVA/200kWh) is much larger than residential batteries; for example, a Tesla Powerwall 3 has a rating of 7kVA/7kWh. The battery will be able to absorb excess solar PV generation during the day, preventing reverse power flow and fault management issues. The energy stored can then also be reused in the evening to support evening demand.

3.3.3 Network Initiatives

In their recent Distribution Annual Planning Reports, nearly all of the 13 DNSP's in the NEM report issues with power quality and specifically voltage fluctuations in areas with high penetrations of distributed solar PV. They also identify possible options for voltage management (Table VI) which are noted to be highly consistent across the networks.

Table VI – Methods proposed by DNSPs to address voltage fluctuations

<table>
<tr><th>DNSP</th><th>Proposed methods to address voltage fluctuations</th></tr>
<tr><td>Evoenergy</td><td>Trial installation of DTx equipped with on-line tap changers (OLTC) (apparently used widely in Europe in areas of concentrated solar) [24]</td></tr>
<tr><td>Essential Energy</td><td>Plans to facilitate uptake of embedded generation by shifting from static to dynamic connection standards and implementing cost reflective pricing to drive more efficient use of the existing network [25]</td></tr>
<tr><td>Endeavour Energy</td><td>Currently attempting to better align zone substation target voltage and DTx tap settings by assessing customer complaints data, smart meter data and load flow voltage studies. They are also currently undertaking a trial of low voltage static compensator (STATCOM) technology as a lower cost alternative to LV network augmentation [26]</td></tr>
<tr><td>Energex</td><td>Installing additional PQ monitors at the terminals of DTx and the ends of long feeders. Rectification of voltage will be via installation of Statcoms, switched capacitor, LV regulators and OLTC's [27]</td></tr>
<tr><td>Ergon Energy</td><td>Plans to undertake measures as indicated in the table below, noting that as the penetration of solar PV increases, so does the cost of the associated solutions.

<table>
<tr><th>Solar PV Penetration Level</th><th>Network Solutions</th></tr>
<tr><td>From 30% to 70%</td><td>1. Balance of PV load
2. Change transformer tap</td></tr>
<tr><td>From 40% to 100%</td><td>3. 1 and 2 above
4. Upgrade transformer
5. Additional transformer (incl. reconfigure LV area)
6. Re-conductor mains</td></tr>
<tr><td>From 100% to 200%</td><td>7. 1 to 6 above
8. New technology (On load tap transformer, LV regulator, Statcom)</td></tr>
</table>
[28]</td></tr>
<tr><td>SAPN</td><td>Current reactive actions to voltage management include DTx tap adjustments, dividing the LV network between additional DTx, upgrading DTx with higher capacity transformers, upgrading LV conductor with higher capacity conductor, phase balancing [29]</td></tr>
<tr><td>TasNetworks</td><td>Corrective actions such as DTx re-tapping, circuit phase rebalancing or load shifting, transformer upgrades, installation of additional transformers and conductor upgrades. [30]</td></tr>
<tr><td>United Energy</td><td>Plans to introduce a Solar Enablement program which aims to increase the solar hosting capacity through their "dynamic voltage management system initiative", changing the tap setting of DTx, balancing the load on LV circuits, applying smart inverter settings on legacy sites, and undertaking targeted LV augmentation works in cases where it is least cost and has a net economic benefit for customers. [31]</td></tr>
<tr><td>Citipower/ Powercor</td><td>Adopting and exploring methods such as requiring changes to inverter settings and the use of smart inverters, phase rebalancing, DTx tapping and/or replacement, installing dynamic voltage controllers, undertaking conductor works and replacements, implementing network management systems to support exports and limiting/ constraining exports when network ratings are met. [32]</td></tr>
<tr><td>Jemena</td><td>On a needs basis, Jemena will change DTx tap settings, upgrade distribution substations, balance load or re-conductor LV circuits. [33]</td></tr>
<tr><td>AusNet Services</td><td>Has plans for greater monitoring, and resolves customer issues through upgrading DTx, rearranging the network for more even customer distribution, reducing</td></tr>
</table>

	circuit load through upgrading or splitting circuits and installing new distribution substations. [9]

Energex’s systematic approach to voltage management is shown in Figure 16.

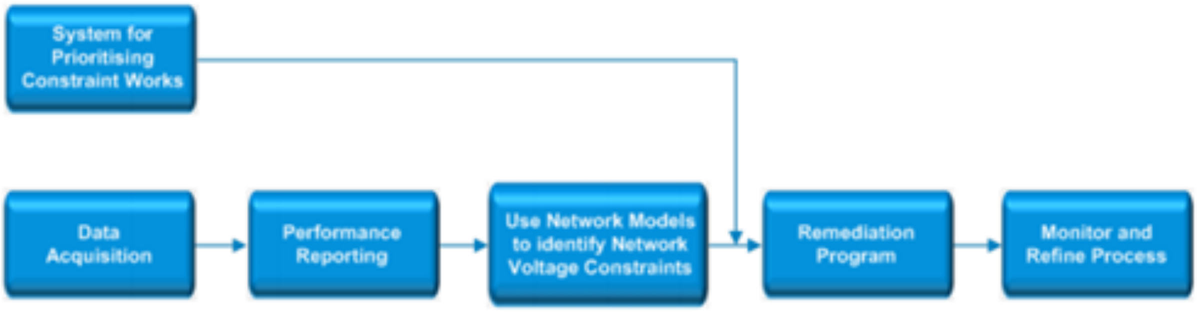


Figure 16 – A systematic approach to voltage management proposed by Energex [27]

3.3.4 Other initiatives

The Victorian Essential Services Commission conducted a review of the Electricity Distribution Code which included investigation of new voltage monitoring provisions. The review outcome requires DNSPs to measure and report on voltage conditions in the distribution network as per the concept illustrated in Figure 17.

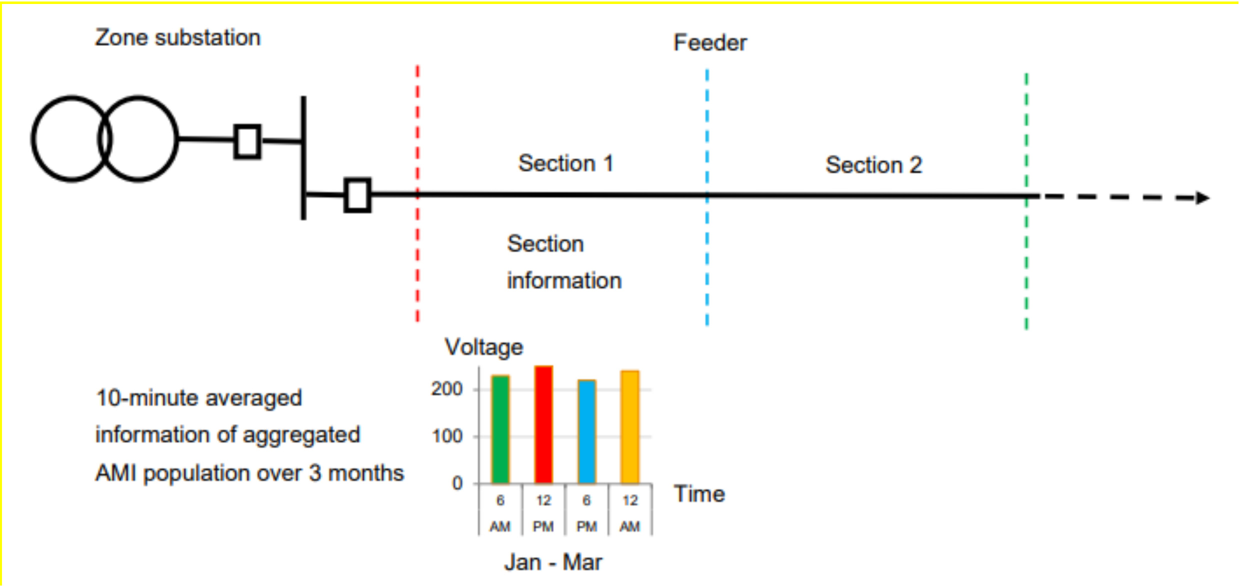


Figure 17 – Proposed voltage performance information concept illustration [34]

3.4 Broader DER Trials

This section presents ARENA sponsored pilot projects and trials. ARENA sponsored programs were selected as they are representative of the initiatives currently being undertaken internationally to facilitate the integration of DER. All programs discussed fall in one or more of the following categories:

1) Enabling and coordination of load shifting, and shedding
2) Integration of batteries
3) Smart homes
4) DER for provision of grid support

5) Increasing knowledge and visibility of our LV network
6) Integrating DER into the electricity market
7) Hosting capacity and operating envelopes
8) Demand Response (DR)
9) Virtual Power Plant (VPP)

3.4.1 Enabling and coordination of load shifting and shedding

This project "Smart Hot Water System" [35] will predict household energy usage and weather data to optimally use excess solar PV generation on Electric Hot Water Systems (EHWS) for heating water. Absorbing solar PV generation by using it to heat hot water reduces the amount of solar PV energy that is exported back into the LV network, therefore reducing the likelihood of over-voltage.

This project "Pooled Energy Demonstration Project" [36], is similar in concept to [35]. In [35], excess solar PV generation was used to heat hot water, in this project it will be used to power the pool pump.

3.4.2 Smart homes

This project "Net Zero Energy Homes" [37] involves Mirvac building 49 townhouses to demonstrate the feasibility of achieving zero energy homes. Each townhouse will have a 3.8-5 kW rooftop solar array and a 10 kWh home battery storage. Like projects [35] and [36], excess solar PV generation will be used to charge the battery. This reduces solar PV export to the grid and reduces instances of over-voltage. The stored energy in battery can then be used in the evening to reduce evening demand from the grid, this in turn will reduce the instances of under-voltage.

3.4.3 Increasing knowledge and visibility of the LV network

This project "My Energy Marketplace" [38], aims to build, operate and deploy the 'My Energy Marketplace' or MEM. The MEM will source energy data from Wattwatchers hardware, smart meters, inverters, EV chargers and sensors. The project will create large amounts of residential energy data. This data could then be used by DNSPs and aggregators (see Box. 2) for increased visibility and knowledge of DER operation and consumption behaviour within the LV network.

Box 2. In an electricity grid with large amounts of DER, an aggregator is expected to be the link between customers and their DER devices, and DNSPs and retailers. To give a simple example of how this might work – If a DNSP needs to reduce load in a certain part of their network by 500 kW, it will send out a request to the aggregators in its jurisdiction for help. Aggregators would then turn off (or reduce the consumption of) a fleet of A/C units or EHW systems or discharge some batteries under their control to contribute to the load reduction. An aggregator could be technology agnostic (have DER from different brands under its control) or associated with one brand.

A partner in the "My Energy Marketplace" is Solar Analytics, which is also involved in another ARENA sponsored project "Solar Analytics: Monitoring for Better Outcomes" [39]. One of the aims of this project was to collect data (including solar PV generation and voltage) to increase visibility in the LV network.

The benefits of this ARENA sponsored project are demonstrated by this report by the facilitation of the data provided by Solar Analytics. AEMO and various DNSPs also benefit from Solar Analytics' data, using it to gain visibility of their LV networks. Solar Analytics' data was also used to examine the behaviour of solar PV systems after two major voltage disturbances in South Australia (March 2017) and Victoria (January 2018) [40]

The CSIRO National Low-Voltage Feeder Taxonomy Study [41] aims to produce the first national low-voltage network taxonomy that outlines the real-world characteristics of the distribution system.

From [41], “Depicting how low voltage power flows through the system will help with the design and assessment of the technologies and systems that can maximise the hosting capacity of distributed energy resources (DER) across Australia”. Knowing the capacity limit of LV lines allows DNSPs to accurately know both generation (from batteries and solar PV systems) and consumption limits (from A/C units for example). Set points can then be used to limit solar PV generation (preventing over-voltage) and consumption (preventing under-voltage). Limiting A/C consumption might occur on hot days for example.

This study will also provide much needed insight into the physical characteristics of our LV network. Knowledge of our LV network, combined with knowledge of DER installations (AEMO DER register) and residential load profiles (through measurements obtained from smart meters or devices installed by companies such as Wattwatchers or Solar Analytics) allows for robust feasibility studies into all types of DER integrating technologies.

3.4.4 Integration of DER into the electricity market

GreenSync’s Decentralised Energy Exchange (deX) [42] is a digital platform that connects DNSPs and retailers with aggregators and their customers DER. The aggregators, DNSPs, and retailers communicate with the deX platform using Application Programming Interfaces (APIs) (See Box 4). The platform also includes a transactional component, allowing DNSPs and retailers to pay for services provided by customers DER (load shedding for example) through their aggregator.

“Consumer owned devices registered with deX will be visible to network and market operators and can be contracted for grid services, such as supplying energy during peak demand, managing frequency or grid voltage, and reducing network constraints” [42].

GreenSync’s aim is to become the digital platform standard for Australia, replacing existing communication links between DER and aggregator, and between aggregator and DNSPs and retailers. deX for example could be used to manage control of EHWS as in [35] or pool pumps as in [36]. Whether control comes through deX or not, the benefit of improved LV voltage management is still achieved. But deX is also an enabling technology, facilitating the integration of DER which doesn’t have an existing communication platform.

Box 3. Application programming interface (API) is a communication protocol used in computing software and hardware. In this context it is referring to an interface between a client and a server. Companies like Wattwatchers and Solar Analytics talk to their devices in the field using an API. Inverter companies and some A/C units also have an API interface.

3.4.5 Hosting capacity and operating envelopes

The evolve project aims to “develop new algorithms and capabilities to identify and ease congestion within the distribution network. This will be achieved through the calculation and publication of operating envelopes for all DER connected to the distribution network” [43].

A key part of this project is that storage (batteries or otherwise) is involved, algorithms which coordinate solar PV generation and storage allows for greater penetration of both in the LV network. The algorithms effectiveness is to be enhanced through the utilisation of “advances in data ingestion” and forecasting.

An expected outcome from the evolve project is that more sophisticated algorithms (than there are currently) are developed which can then more effectively control solar PV generation and storage. This will increase DER hosting capacity in the LV network. When control of solar PV generation and storage is coordinated, then more effective voltage management is also achieved, reducing the instances of both over-voltage and under-voltage.

There are a number of other (current and past) ARENA sponsored projects on hosting capacity and operating envelopes, including:

- Advanced Planning of PV-Rich Distribution Networks Study (University of Melbourne)

- Distributed Energy Resources Hosting Capacity Study (Powercor Australia)
- Dynamic Limits DER Feasibility Study (Dynamic Limits)
- Increasing Visibility of Distributed Networks (University of Queensland)

3.4.6 Demand Response (DR)

Under-voltage occurs during periods of high demand. In the NEM, high demand occurs on very cold and very hot days, due to heating and cooling load (i.e. A/C usage). Voluntary Demand Response (DR) is one way to incentivise households to reduce their A/C consumption on days like this. A reduction in A/C consumption will reduce the instances of under-voltage.

There has been 15 Demand Response (DR) trials conducted in the NEM over the last 10 years, involving 6 different DNSPs and 5 different retailers. Five of these trials have received ARENA funding [44]. Unfortunately, most trials encountered difficulties. A common (and crucial) difficulty was reported by EnergyAustralia [45], Jemena [46], Powershop [47] and Zen Ecosystems [48], where all had trouble accurately determining the change in A/C consumption of households during DR events – i.e. determining whether a household had used their A/C less than normal or not.

DR is an important tool, and is effective at reducing demand during peak times (and therefore reducing the instances of under-voltage). It can also result in a reduction in maximum capacity requirements of the electricity network, reducing capital expenditure. But DR won’t be embraced by customers if the transaction between themselves and the DNSP or retailer isn’t seamless. Accurately calculating change in consumption is necessary for a seamless transaction.

3.4.7 Virtual Power Plants (VPP)

A VPP consists of a cluster DERs, all located in the same geographical area. The DERs that would likely make up a VPP located in the NEM would include solar PV generation, batteries (and other forms of storage), as well as flexible loads such as A/C units and EHWS. All DERs are connected to a central control system, which controls their generation and consumption behaviour. The objective of the control can vary; it may be provide dispatchable power (thus behaving like a single power plant) or to maximise savings to customers within the VPP, or it could be a combination of both.

The VPP, along with its control objective, will also ensure that voltages within its electrical boundaries are maintained within regulation limits. The VPP is the most extensive and ambitious of technologies designed to facilitate the integration of DER in the LV network. There are a number of ARENA sponsored VPP projects currently underway, including:

- Advanced VPP grid integration (SA Power Networks)
- AEMO Virtual Power Plant Demonstrations
- Indra Monash Smart City
- AGL Virtual Power Plant
- Narara Ecovillage Smart Grid (NEV Power)
- Simply Energy Virtual Power Plant

3.5 Broader investment and operational implications of voltage

Effective voltage management in the distribution network will likely become more important as the Australian power system further decentralises. This is reflected in the ongoing efforts across the sector, including the Open Energy Networks project and various trials and research efforts to better understand hosting capacity (see section 3.4). DNSP voltage management approaches, along with inverter requirements (AS4777) will likely directly impact the ability of DERs to participate in the broader power system. For instance, VPPs may be constrained if there is insufficient head room to export.

In addition to impacts on DER participation opportunity, variation in voltage management approaches may change the efficacy of Conservation Voltage Reduction (CVR). CVR is where voltage is deliberately lowered in the distribution network during times of peak demand in order to reduce power consumption. This practise is widely accepted in the US however is relatively rare in Australia. United Energy provided Demand Response using CVR as part of an ARENA trial, including provision of Demand Response to AEMO within the Reliability and Emergency Reserve Trader panel [49].

As the levels of DER grows system security challenges are emerging. Including reduced minimum demand (poses challenges due to minimum synchronous generation requirements) and DER response to major power system disturbances. Appreciating the local voltage conditions that exist in the distribution network may become important to system operation as AEMO develops its ability to model and manage DERs. In addition, there is likely to be an increased need to manage DER feed in (that is, exports). A review of a number of international PV feed-in management strategies performed by EPRI for AEMO found that these schemes typically do not provide compensation, but the amount of reduction is limited by some factor such as number of curtailment occurrences, cumulative duration or the presence of a power quality issue [50].

3.6 Concluding comments

This review is inherently limited by the short time available for its preparation, and the speed at which relevant work is expanding. It is clear that significant work to better understand voltage challenges associated with DERs, particularly PV, and our options for managing these challenges is underway in Australia, led by stakeholders including new technology providers, distribution network businesses and the ENA, AEMO, AER, AEMC and the ESB. Nevertheless, there does seem to be a gap in our understanding of what LV voltages are actually being experienced in different regions of the NEM, and the role of distributed PV in driving any high voltages. It is this gap which the work presented in the following Sections seeks to address.

4 Overview of UNSW Voltage Analysis

The analysis presented here is based on data from 12,617 site-specific power and voltage monitoring devices that are used by Solar Analytics to assist their customers in monitoring the performance of their PV systems. Most of these PV systems are single phase, of 5kW or less, and installed on residential premises. The data used in this analysis is the maximum and minimum voltage seen over a five minute period, with these voltage measurements being sampled every five seconds. The studied data-set set includes 5 minute measurements from 1/12/2018 to 30/11/2019, hence allowing seasonal and even shorter time period (month) analysis. Of the 12,617 sites, 4,337 covered the full year, with 8,280 having less than a full year. Sections 5 and 7 included only the sites with a full calendar year of data.

The monitored sites also record any net PV exports each 5 minutes, reported as the total kWh injected into the grid over the period. The PV systems being monitored are in almost all cases installed behind-the-meter. Any PV generation therefore first goes to supplying site load. When PV exceeds site load over the period, the net site export to the grid is recorded. Periods where there is no PV generation, or PV generation less than site load during that period, no PV data is recorded.

Table VII lists the DNSPs included in the study.

Table VII DNSPs

DNSP	State
SAPN	SA
Ergon	QLD
Energex	QLD
Ausgrid	NSW
Endeavour	NSW
Essential	NSW
ActewAGL	ACT
Powercor	VIC
United Energy	VIC
Jemena	VIC
CitiPower	VIC
Ausnet	VIC
TasNetworks	TAS

4.1 Areas of Analysis

Each voltage and correlation analysis is conducted across a specific area or combination of areas. An area consists of all postcodes within one of the following:

- State or Territory
- DNSP jurisdiction
- Remoteness category from suburban to regional to remote
- PV install density classification (proportion of stand-alone houses in that area with a PV systems).

4.2 Remoteness and PV install density

There are a number of factors that influence the voltage levels and the correlation between PV export and any voltage change for a particular site beyond the load at that site, and other electrically connected sites on that feeder and wider distribution network.

a) Total solar PV export from other sites on the LV line, and electrically near LV lines and upstream feeders
b) Line impedance
c) Location of the site on the LV line (towards the front or back)
d) Mean (towards front or back) location of PV systems on the LV line

Unfortunately), the data available for this analysis doesn't include the "electrical" location (which LV line and how far along it's located) for each site, so it's not possible to examine the effects of c) or d). It is possible, however, to examine how a) and b) impact on voltage and the correlation between PV export and voltage through proxy metrics.

- **Remoteness**. LV lines in more remote locations are longer and tend to have a higher impedance than LV lines located in suburban areas. Therefore, categorising the data by remoteness allows for a proxy voltage analysis by line impedance.
- **PV install density**. Categorising the data by PV install density (proportion of standalone houses with PV systems) allows for a proxy voltage analysis by local total PV generation.

Each postcode in the analysis has been assigned a remoteness category and classified according to PV installation density, based on the AER "Values of Customer Reliability" final report for 2019 [51], which classifies each postcode according to:

- CBD
- Suburban
- Inner regional
- Outer regional
- Remote
- Very remote

The Australian PV Institutes (APVI) online solar install mapping tool [52] provides the number of PV installations for each postcode in the NEM. The tool takes data from the Clean Energy Regulator and provides an estimate on the number of PV installs and number of dwellings for each postcode in Australia. This data was used to calculate the PV install density for each postcode, each postcode was then classified according to their PV install density:

1. < 10%
2. 10% < PV install density < 20%
3. 20% < PV install density < 30%
4. 30% < PV install density < 40%
5. 40% < PV install density < 50%
6. > 50%

4.3 Dataset

All voltage and PV export measurements are taken at the household (site) level. Each 5-min data point has the following format:

- Timestamp "YY:MM:DD hh:mm"
- Site id
- Postcode
- Voltage max (V)
- Voltage min (V)

- PV export (watt-hours over the 5 minute period). This measurement is converted to the average kW over the period.

Voltage measurement. The recorded voltage is the maximum and minimum voltage seen over a 5-min interval, with voltage measurements sampled every five seconds. Therefore, over every 5-min interval, the maximum of the (60) 5 second voltage measurements is recorded as voltage max, and the minimum of the (60) 5 second voltage measurements is recorded as voltage min. The SolA equipment voltage samples are taken over 100ms just prior to collection.

Date range of dataset. The studied dataset consists of 5 minute measurements from 1/12/2018 00:00:00 to 30/11/2019 23:55:00. Some sites have less than one full calendar year worth of 5 minute data. While some aspects of the analysis can use incomplete data sets without unduly impacting results, other statistical methods require a full year of data and hence can only use full year datasets. This is noted in the respective sections.

The following tables provide the number of sites associated with each State and Territory, DNSP jurisdiction, and also for each Remoteness category and PV install density classification within each DNSP.

While the dataset used in this analysis is the largest used to date in terms of NEM-wide coverage and a year of data, there are still some DNSPs, and particularly location and PV penetration with only relatively few sites providing data. Interpretation of the findings in these cases requires suitable caution. Furthermore, SolA customers are unlikely to be a fully representative sample of all PV system sites; for example, tending towards more recent installations as well as particular NEM regions. Again, caution is required in extrapolating these findings to the overall experience of PV system sites. Finally, all monitoring equipment can be subject to occasional measurement errors – the small number of extremely high and low voltages recorded across the sites over a year may well reflect such glitches, although occasional voltage extremes in the network are also possible.

Table VIII Number of sites per State or Territory

State	Number of sites
SA	3718
Qld	3395
NSW	4381
ACT	78
Vic	982
TAS	63
Total	12617

Table IX Number of sites per DNSP

DNSP	Number of sites
SAPN	3718
Ergon	1099
Energex	2296
Ausgrid	1766
Endeavour	1236
Essential	1379
ActewAGL	78
Powercor	241
United Energy	171
Jemena	124
CitiPower	61
Ausnet	385
TasNetworks	63
Total	12617

Table X Number of sites per DNSP according to PV install density (pvd)

			PV density (pvd)			
DNSP	pvd<10%	10%<= pvd <20%	20%<= pvd <30%	30%<= pvd <40%	40%<= pvd <50%	50%<= pvd
SAPN	0	181	883	1831	678	143
Ergon	1	37	498	410	153	0
Energex	1	36	321	964	676	296
Ausgrid	280	1154	318	13	0	1
Endeavour	19	665	537	11	4	0
Essential	0	405	437	321	209	7
ActewAGL	4	62	11	0	1	0
Powercor	2	112	93	30	0	3
United Energy	20	138	13	0	0	0
Jemena	22	41	60	0	0	0
CitiPower	48	13	0	0	0	0
Ausnet	0	145	188	46	6	0
TasNetworks	2	53	7	1	0	0

Table XI Number of sites per DNSP according to Remoteness

		Region name					
State	DNSP	CBD	Inner Regional Australia	Outer Regional Australia	Remote Australia	Suburban Australia	Very Remote Australia
SA	SAPN	0	702	585	65	2359	5
Qld	Energex	1	180	0	2	2110	0
	Ergon	0	565	491	34	0	9
NSW	Ausgrid	1	112	1	0	1652	0
	Endeavour	0	231	5	0	1000	0
	Essential	0	908	307	10	153	1
ACT	ActewAGL	0	0	0	0	78	0
Vic	Powercor	0	134	31	0	75	0
	United Energy	0	2	0	0	169	0
	Jemena	0	2	0	0	121	0
	CitiPower	4	0	0	0	57	0
	Ausnet	0	178	30	2	175	0
Tas	TasNetworks	0	44	18	1	0	0

5 Voltage Analysis

In this section we present voltage analysis for the DNSPs in South Australia, Queensland, New South Wales, the ACT, Victoria and Tasmania. This analysis focusses on:

- the max and min voltage distributions seen over the year at sites, categorised by DNSP and according to geographical region and PV install density,
- the seasonal daily profile of max and min voltages by DNSP showing the mean yet also distribution (25-75% and 5-95% variation experienced across the sites as well as voltage outliers beyond these ranges, and
- the voltage spread experienced at each site by DNSP; that is, the highest and lowest voltages seen at each site over the year of data.

5.1 South Australia (SAPN)

Figure 18 and Figure 19 show the average maximum and minimum voltages seen by all the sites in SA throughout the year. Site locations are categorised as one of 'Suburban', Inner Regional, 'Outer Regional' and 'Remote'. In addition to the voltages, the SA net demand (total State electricity demand minus any small scale hence not directly monitored distributed generation including PV) is also presented.

The variation in average maximum voltage seen across the year highlights systemic drivers of voltage across the state, and periods of higher SA demand are clearly associated with lower voltages. SA demand is generally higher in winter months, however, the State experiences its periods of peak demand in summer and these clearly drive periods of lowest maximum voltage and minimum. Voltage variations throughout the year increase slightly going from Suburban to Remote locations, reflecting the customer density and other characteristics of the distribution network that impact on voltage swings as changes in network load occur (although note that the smaller sample size in more remote regions may also be a factor). It is also notable that average maximum voltages frequently sit near the upper bound of 253V over the entire year, although they are generally highest in Autumn and Spring, when State demand is typically lower and PV performance is relatively high (clear skies without extreme summer temperatures which reduce PV performance).

The minimum voltages largely follow the maximum voltage patterns above, but our findings particularly highlight how high average minimum voltages generally are, noting that 240V is around 5% above the nominal 230V, while the preferred voltage range is in the relevant Australian Standard is +6% to -2%.

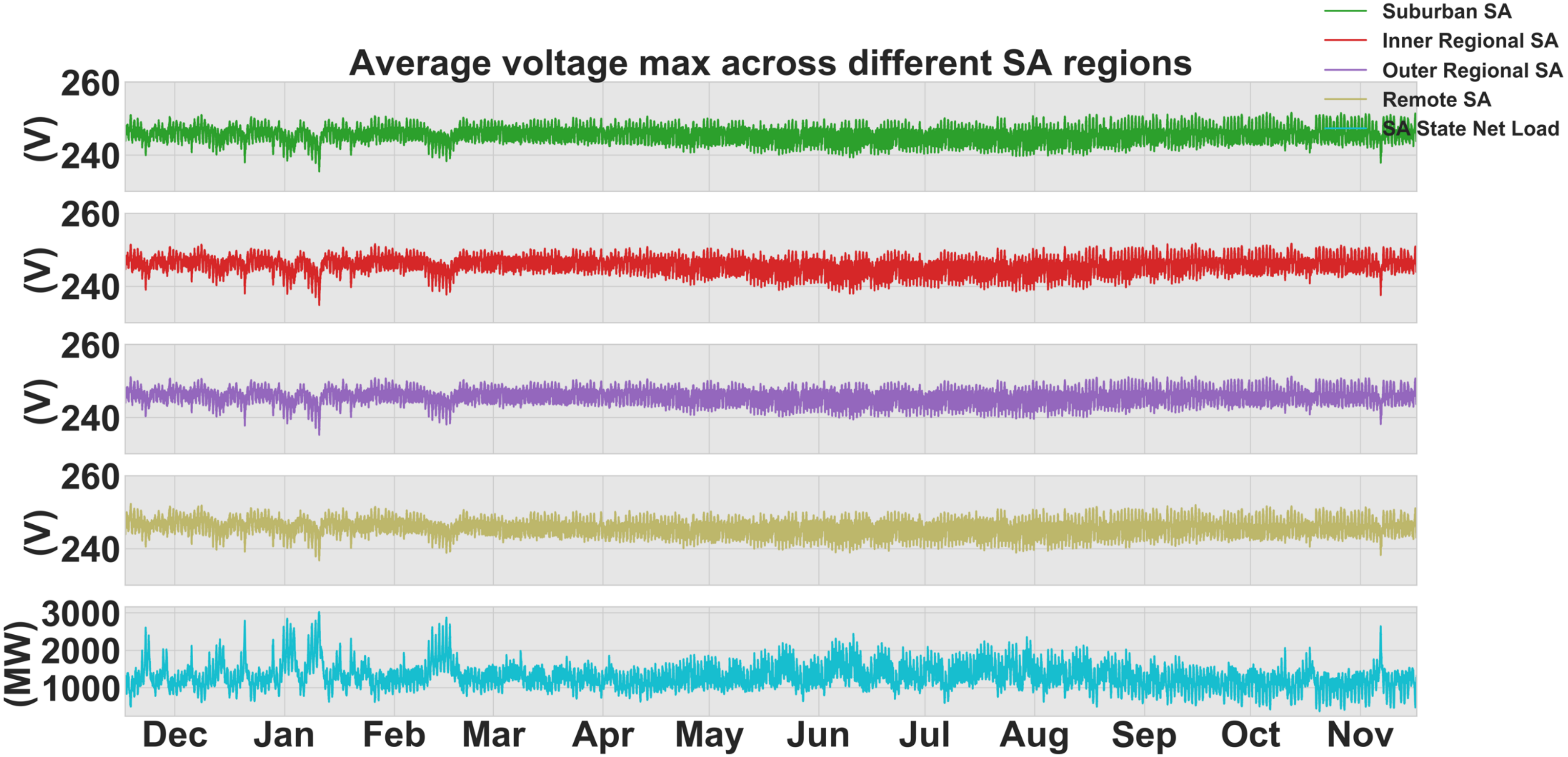


Figure 18 Average voltage maximum across different regions of SA and the net state load

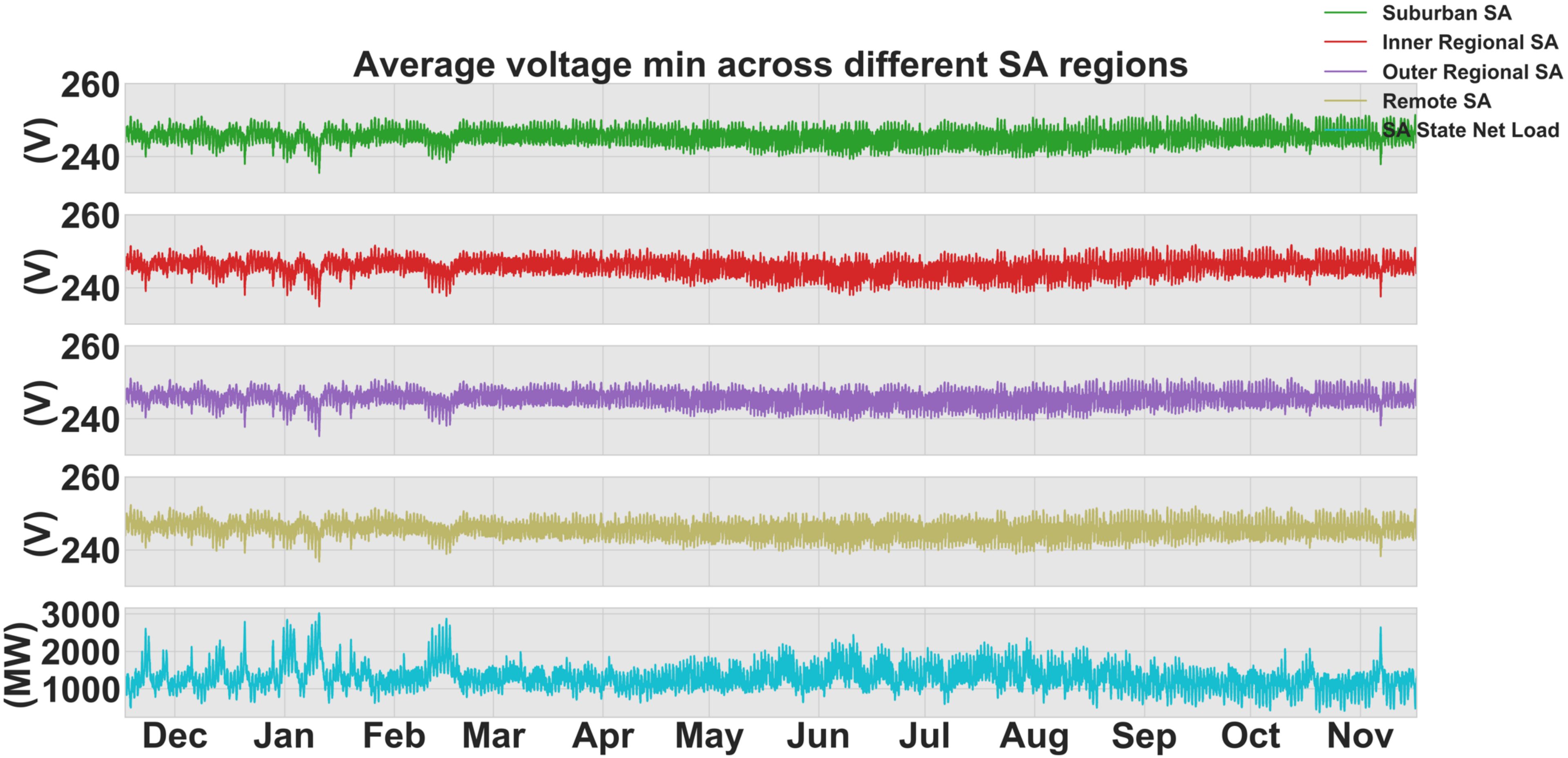


Figure 19 Average voltage minimum across different regions of SA and the net state load

Figure 20 and Figure 21 illustrate the distribution of maximum and minimum voltage across the regions. The histograms cover the 1st to 99th percentile of the voltage range so as to focus on the general distribution (the outlier voltages can be observed in the boxplots in Figure 22 to Figure 25). The Y axis shows the range of voltages whereas the X axis shows the percentage of the times a voltage value is observed. The number of households used for the analysis is shown for each region. The voltage values cover the entire yearly period of the 5 minute voltages monitored across the households.

It is clear that maximum voltages are generally well above 230V and often close to, or even exceeding, the upper Australian Standard limit of 253V, especially in regional and remote parts of SA which experience higher voltage maximums and lower voltage minimums that suburban PV sites.

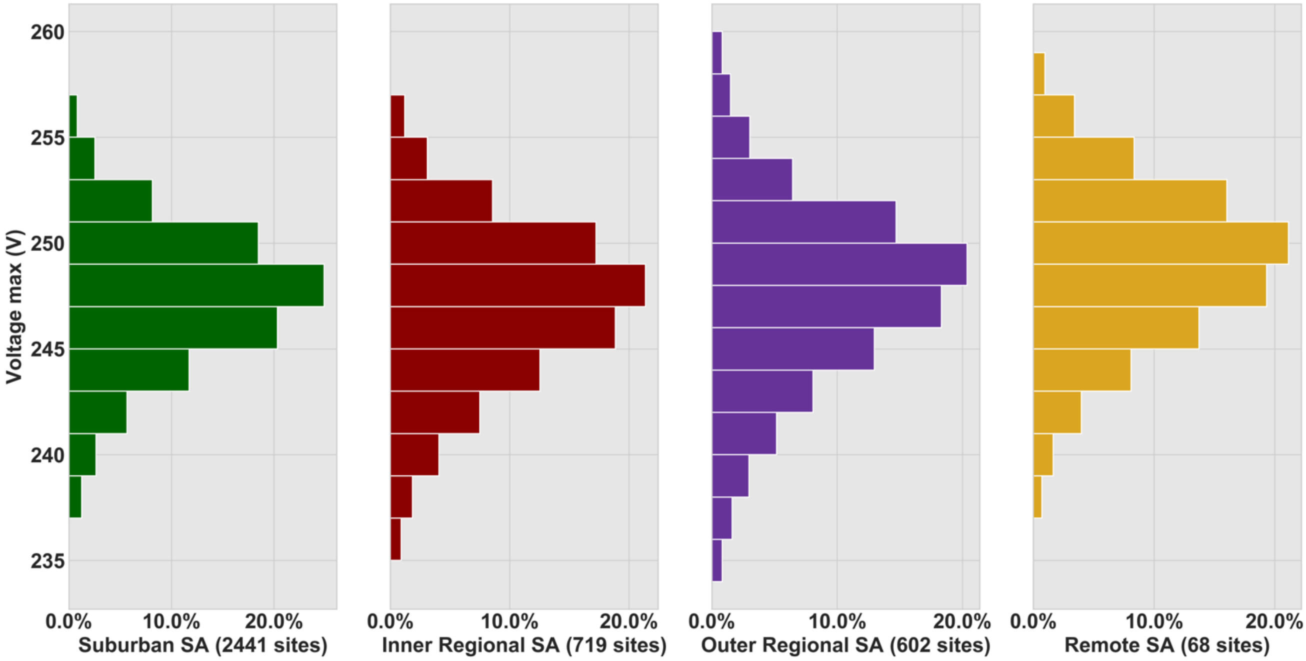


Figure 20 Distribution of maximum voltages across SA regions

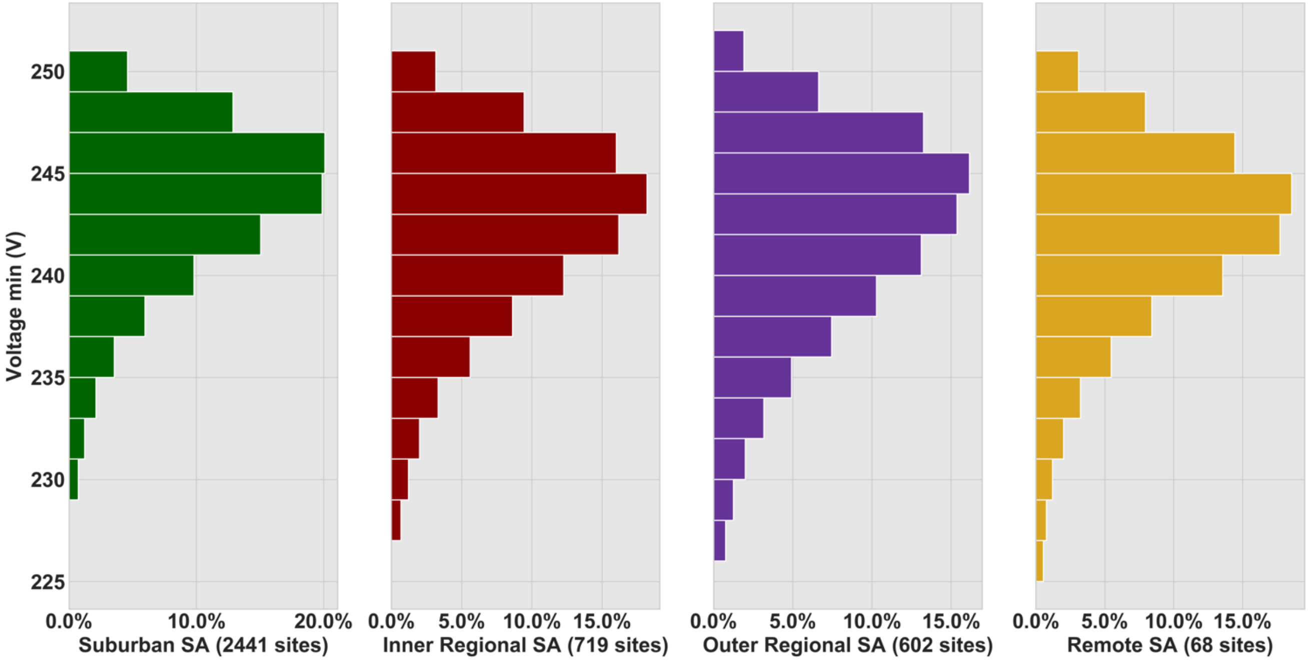


Figure 21 Distribution of minimum voltages across SA regions

Figure 22 to Figure 25 show how site voltages vary over a 24 hour period in different seasons. The plots show the distribution of seasonal minimum and maximum voltages. Each hour includes the entire dataset of monitored SAPN sites (3718 sites) voltage data across the respective season. The red horizontal lines represent the AS/NZS standard acceptable max and min voltage levels: 253V and 216V respectively. The Box plot whiskers are the 5th and 95th percentile of the voltages observed within the particular hour and the dots represent the outliers beyond this range.

It can be seen that average maximum voltage levels are closer to the upper 253V limit rather than the lower limit, regardless of the season or time of day. During the midday and early afternoon periods (12pm-2pm) voltage levels increase, especially in Spring, which is consistent with increasing distributed PV generation and typically reduced residential demand. During those peak sunshine hours more than 5% of the voltages recorded within that hour see maximum voltages well above 253V and above 255V for some hours. Sustained voltages above 255V should see post 2015 inverter curtailment begin to commence, as explored further in Section 7. Further, late night periods that typically are also periods of lower demand likewise show high voltages with some 5% of voltages recorded within that hour are around the 253V limit, and above 255V for some hours. Especially in the winter and autumn seasons, voltages observed around 4am-6am are around as high as the midday voltages. It is also apparent from the plotted voltage outliers that some sites experience infrequent very low voltages during peak demand hours (4pm-8pm) where voltages can go below the lower 216 V limit.

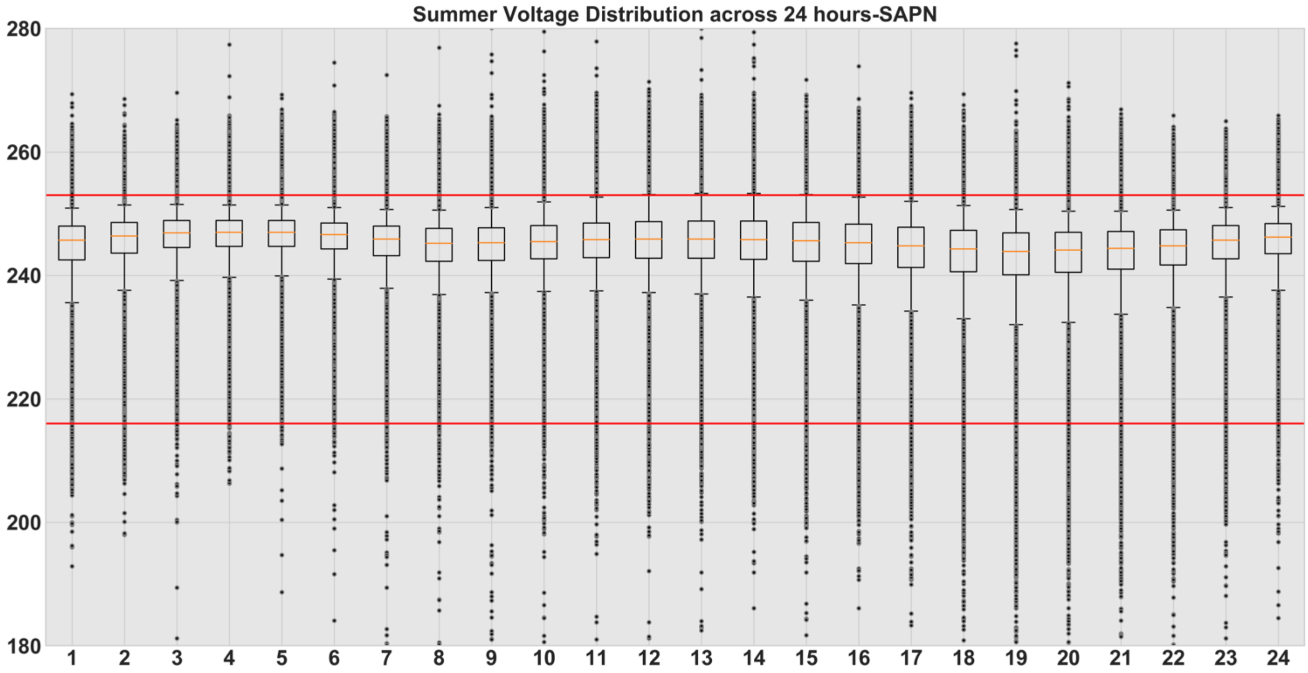


Figure 22 Distribution of voltages across 24 hours for SAPN for Summer

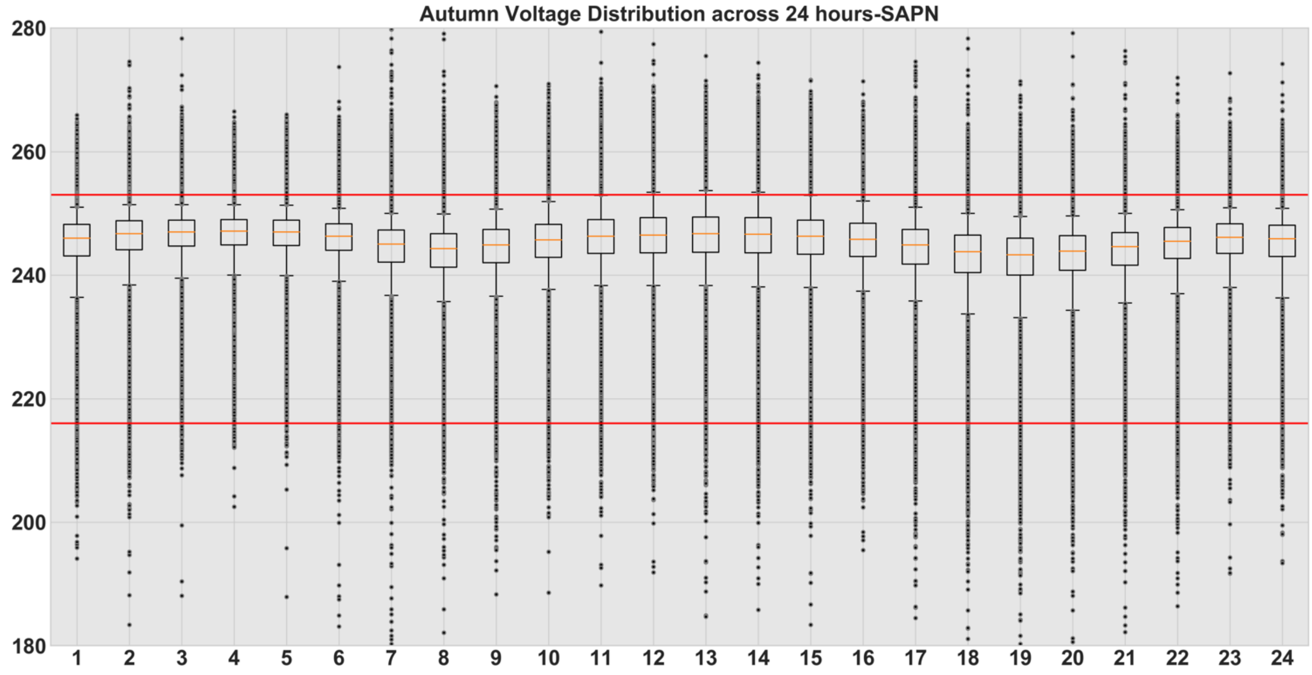


Figure 23 Distribution of voltages across 24 hours for SAPN for Autumn

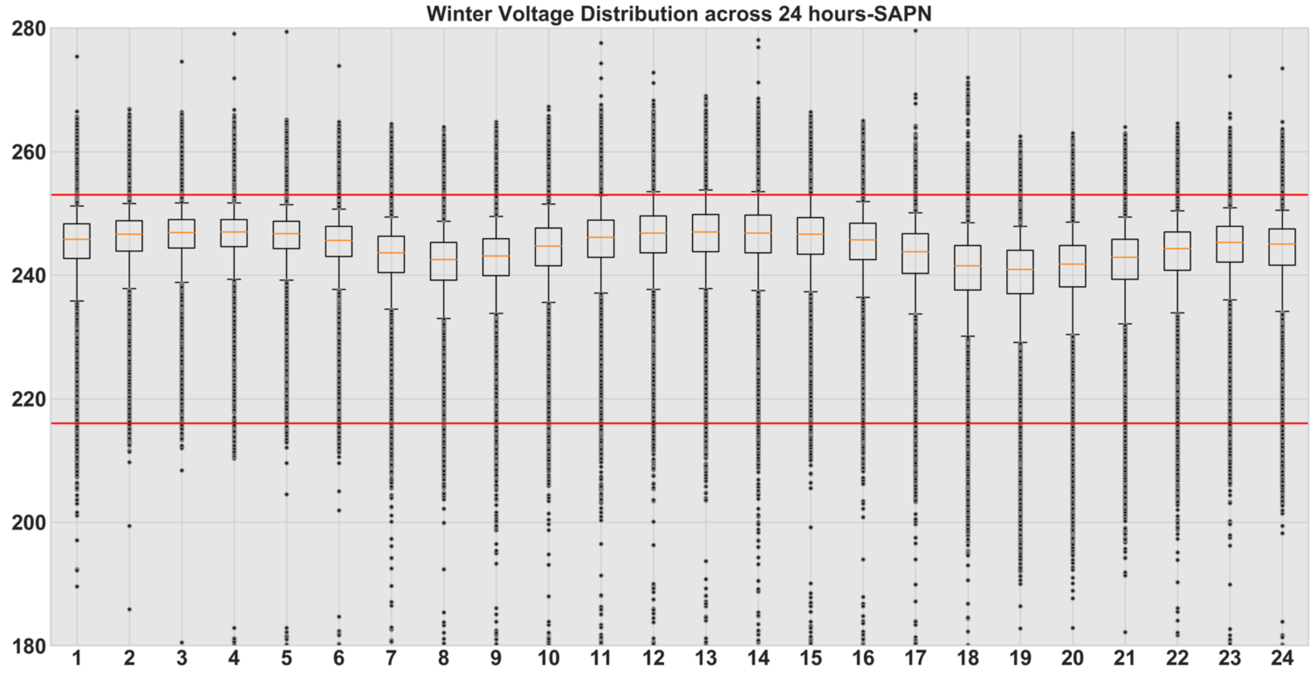


Figure 24 Distribution of voltages across 24 hours for SAPN for Winter

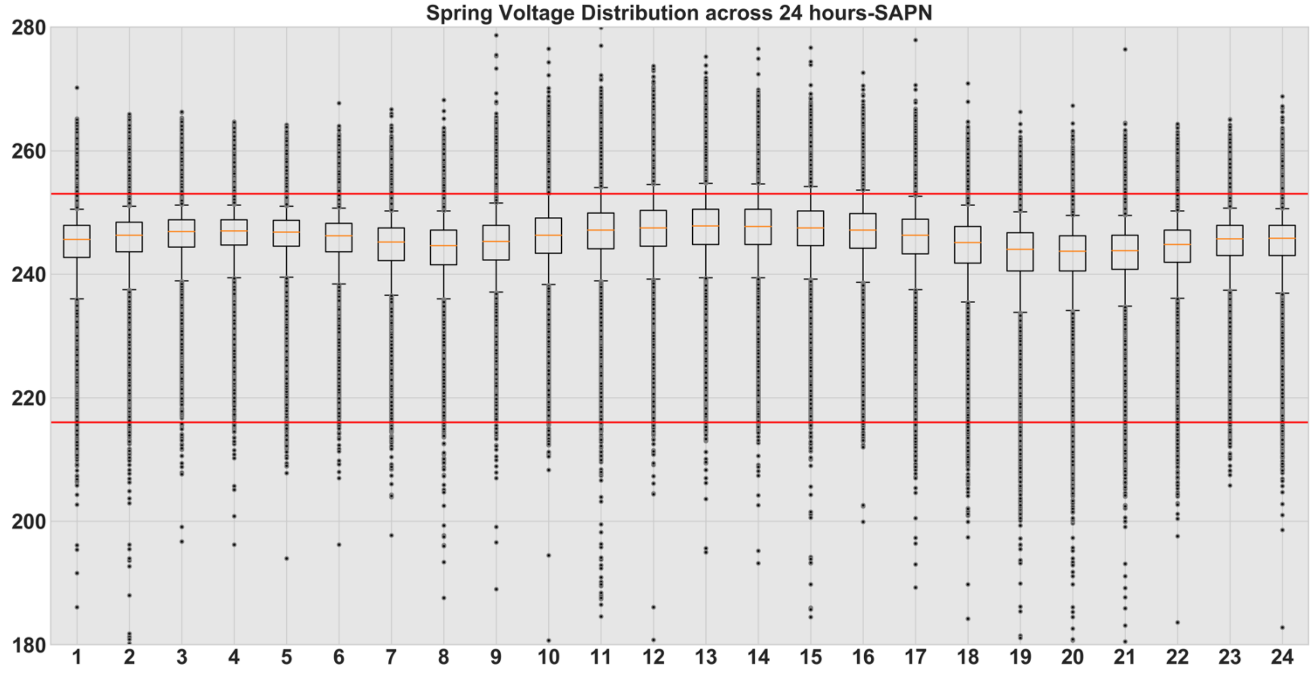


Figure 25 Distribution of voltages across 24 hours for SAPN for the spring season

Given the opportunities to change the upper voltage seen in the LV network using distribution transformer tap changes, it is important to understand the range of voltages being experienced at different sites. Figure 26 shows the distribution of 1661 households with a full year of data, ordered by their maximum voltage values experienced throughout the year. For each household the corresponding voltage minimum and the 5th and 95th percentiles of voltage are also shown. It can be seen that the sites that experience the highest voltages also experience some occasions of extremely low voltages. Consistent with previous findings, the 95th percentile of the voltage max sits near, at or above the recommended 253 V limit for many sites. It can also be seen that the voltage range is much narrower for the 5th to 95th percentile of voltages, which suggests that there may be opportunities to narrow the voltage range experienced by consumers through actions that are only required for very occasional low voltage excursions.

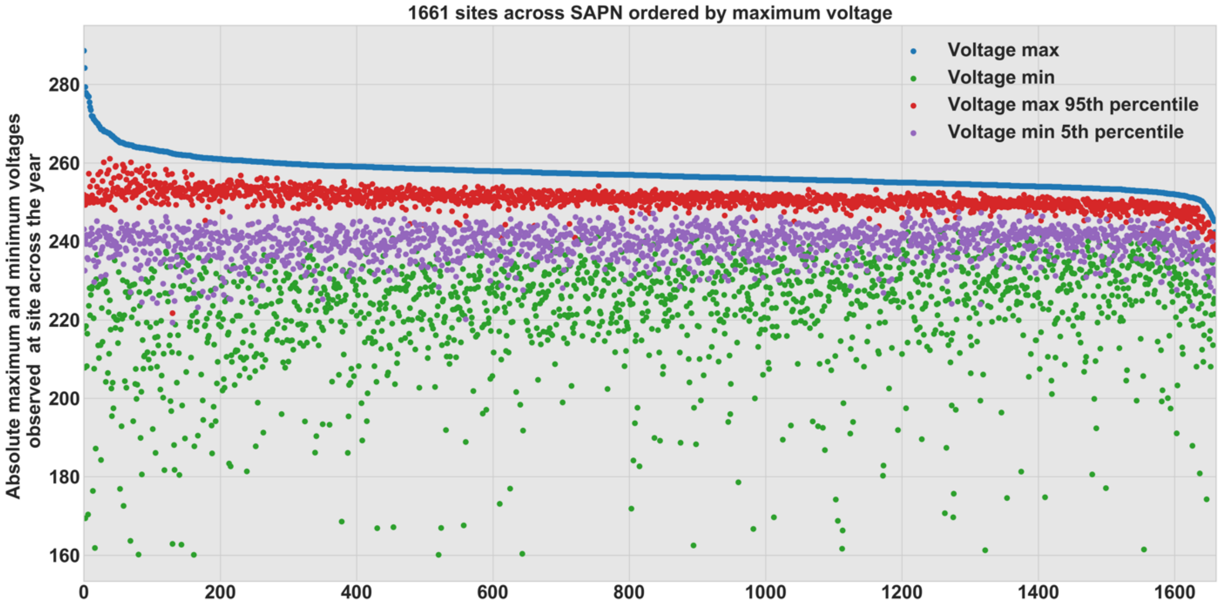


Figure 26 1661 sites from SAPN with full calendar year data ordered by highest average maximum voltages

5.2 Queensland (Energex & Ergon)

Figure 27 and Figure 28 show the average maximum and minimum voltages seen by all the sites in QLD throughout the year. Site locations are categorised as one of ‘Suburban’, Inner Regional, ‘Outer Regional’ and ‘Remote’. In addition to the voltages, the QLD net demand (total State electricity demand minus any small scale hence not directly monitored distributed generation including PV) is also presented.

The variation in average maximum voltage across QLD is less severe than observed in SA. Yet, it is still clear that the QLD demand peaks cause dips in voltage across the state. QLD demand is generally higher in summer months and the State also experiences its periods of peak demand in summer, which drives the periods of lowest maximum voltage. The average voltage is clearly greatest in Outer Regional, and lowest in Inner Regional. Voltage variations are least in Outer Regional, and similar in the other locations, with Remote having the greatest voltage spikes during Summer. It is also notable that average maximum voltages are lower than SA average maximum voltages and frequently observed around 245V most times of the year.

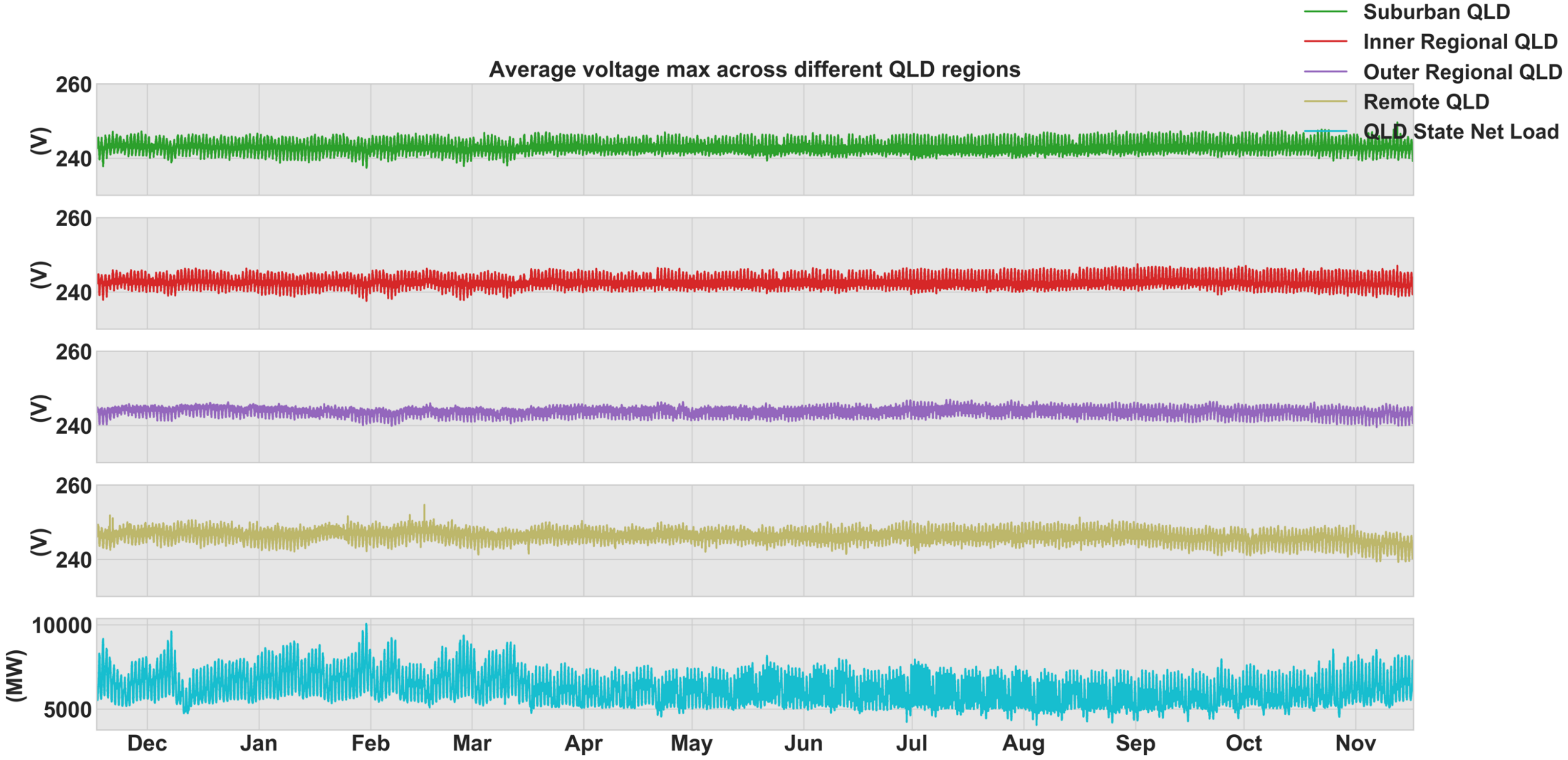


Figure 27 Average voltage maximum across different regions of QLD and the net state load

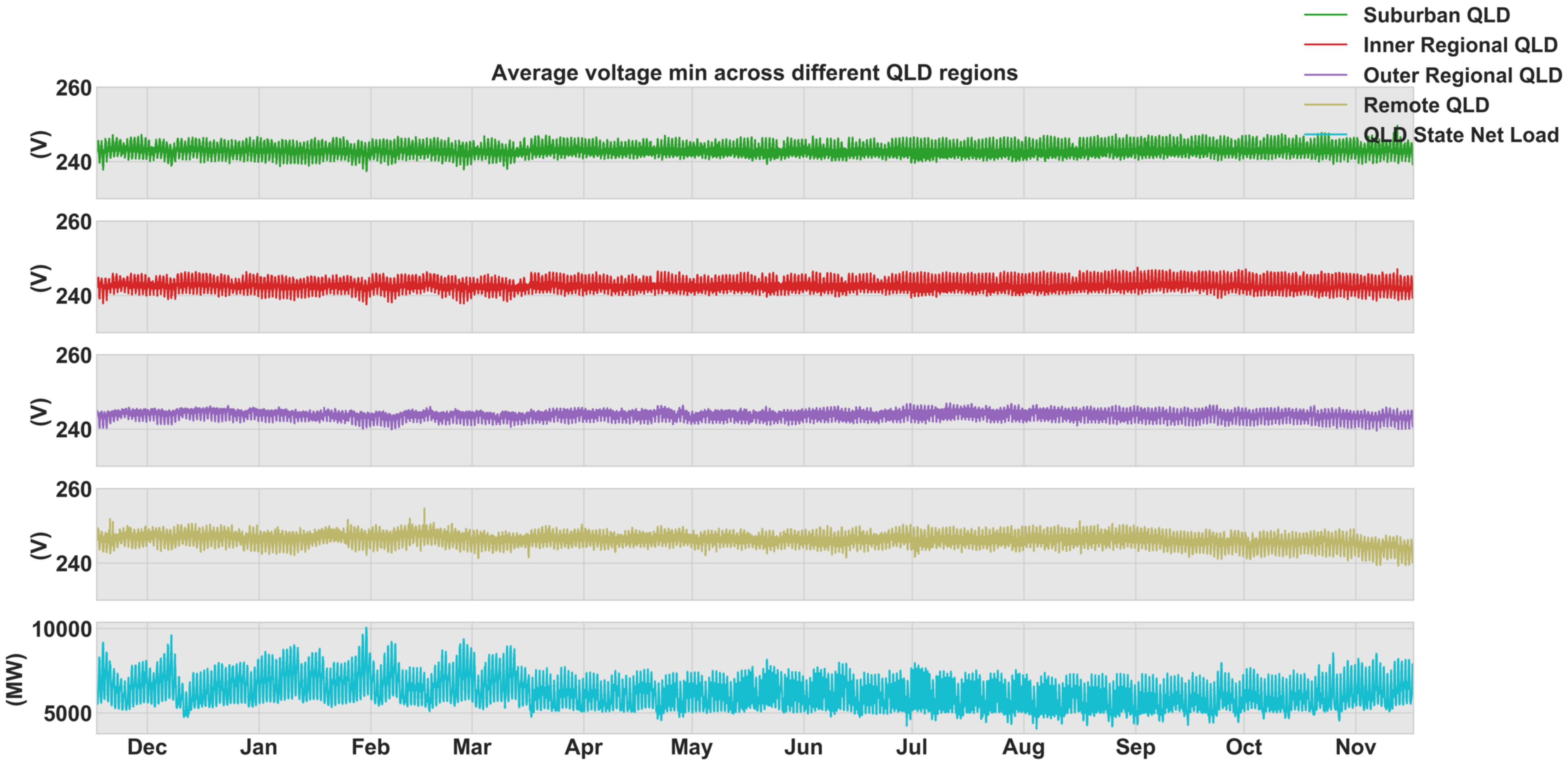


Figure 28 Average voltage minimum across different regions of QLD and the net state load

The average minimum voltages shown in Figure 28 largely follow the maximum voltage patterns above, but particularly highlight again how high average minimum voltages generally are, noting that 240V is around 5% above the nominal 230V.

Figure 29 and Figure 30 and illustrate the distribution of maximum and minimum voltage across the regions. The histograms cover the 1st to 99th percentile of the voltage range so as to focus on the general distribution (the outlier voltages can be observed in the boxplots in Figure 31 to Figure 38). The Y axis shows the range of voltages whereas the X axis shows the percentage of the times a voltage value is observed. The number of households used for the analysis is shown for each region. The voltage values cover the entire yearly period of the 5 minute voltages monitored across the households.

Once again, it is clear that the voltages are generally well above 230V and often closer to the upper recommended limits throughout QLD. Outer regional QLD has signficantly higher maximum voltages than other parts of the state, with Inner Regional being lowest. Minimum voltages generally sit between 240 and 245V noting that 240V is around 5% above the nominal 230V.

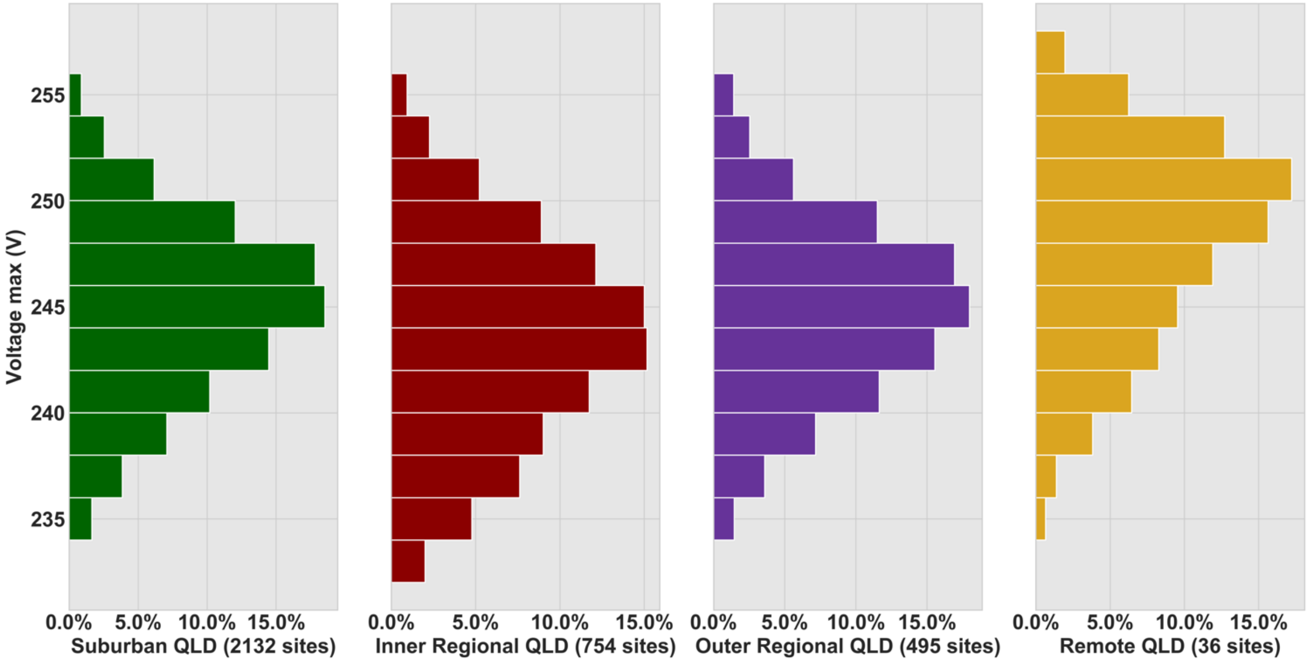


Figure 29 Distribution of maximum voltages across QLD regions

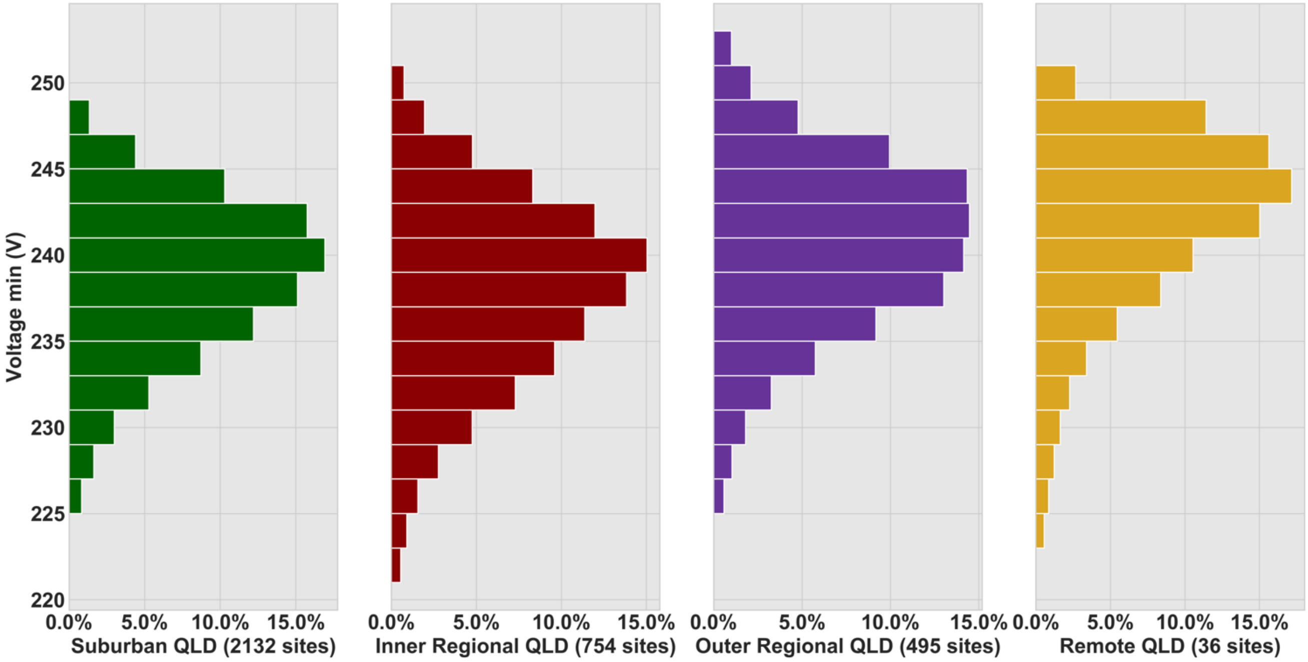


Figure 30 Distribution of minimum voltages across QLD regions

The variation in voltage over a 24 hour period for different seasons is shown for the Energex (Figure 31 to Figure 34) and Ergon (Figure 35 to Figure 38) networks. The plots show the distribution of seasonal hourly voltages including both minimum and maximum voltages. Each hour includes the respective DNSP's household stock's (2296 and 1099 sites for Energex and Ergon respectively) voltage data across the respective season. The red horizontal lines represent the AS/NZS standard recommended max and min voltage levels: 253V and 216V respectively. Box plot whiskers are the 5th and 95th percentile of the voltages observed within the particular hour and the dots represent the outliers.

It can be seen that average voltage levels are generally between 240 to 245 V for both DNSPs, which are slightly lower than SAPN voltages. The 95th percentile is very close to or above the upper 253V limit rather than the lower limit regardless of the season. During the midday and early afternoon periods (12pm-2pm) voltage levels increase, which is consistent with increasing distributed PV generation and typically reduced residential demand. During those peak sunshine hours around 5% of the voltages that sites experience are equal to or above 253V. Sustained voltages above 255V should see post 2015 inverter curtailment begin to commence. Further, late night periods that are typically periods of lower demand also show higher voltages with some 5% of sites seeing voltages around the 253V limit, and above 255V for some hours. Especially in the winter and autumn seasons, voltages observed around 4am-6am are also slightly higher. It is also apparent that the voltages significantly drop during peak demand hours, and some sites experience occasional very low voltages during peak demand hours (4pm-8pm) where voltages can go extremely low, and below the lower 216 V limit.

5.2.1 Energex

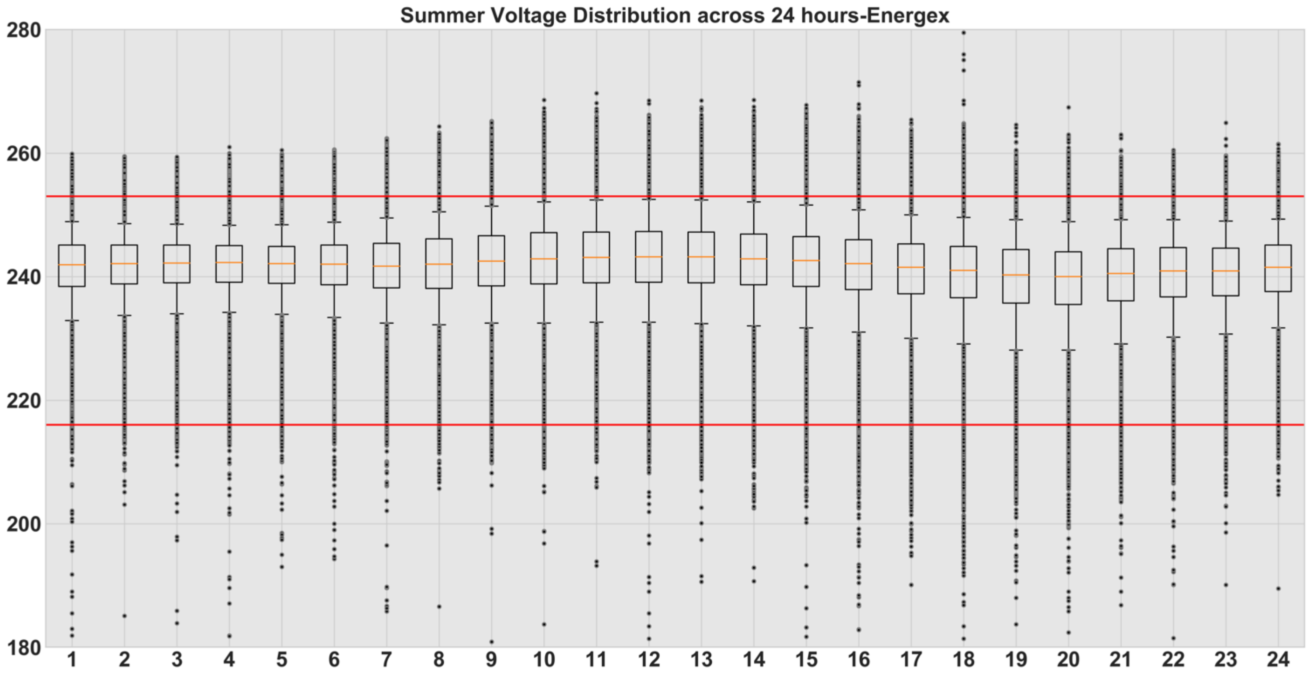


Figure 31 Distribution of voltages across 24 hours for Energex for Summer

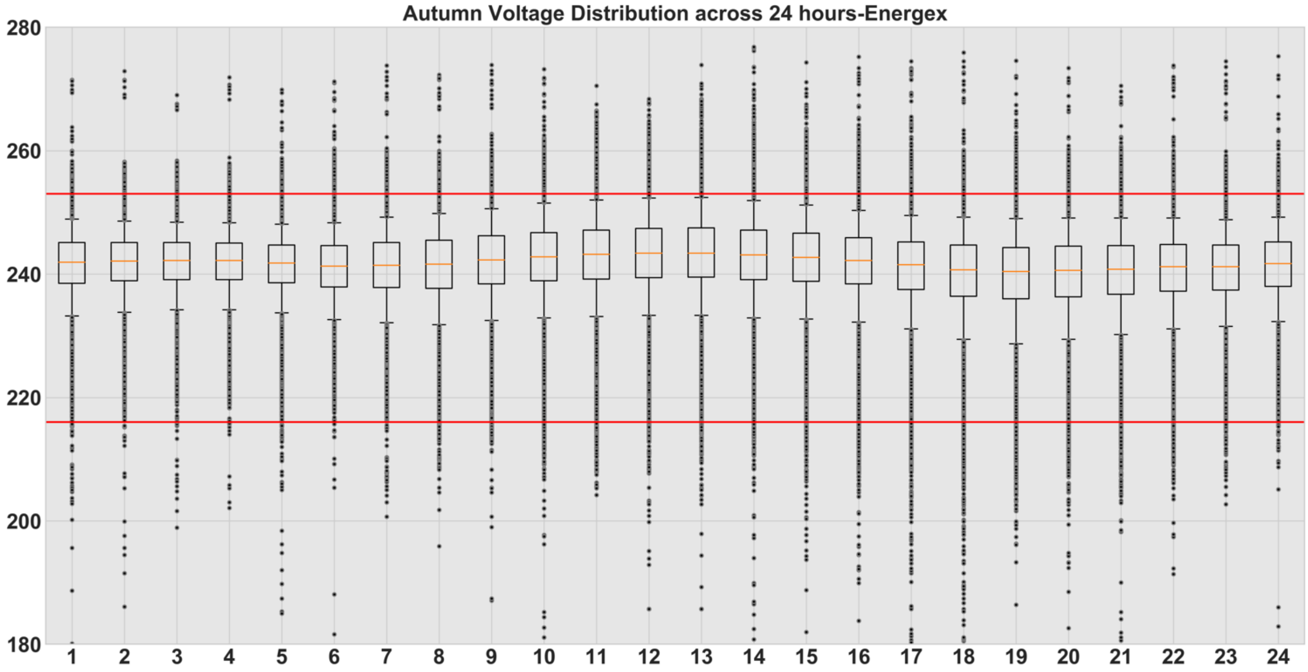


Figure 32 Distribution of voltages across 24 hours for Energex for Autumn

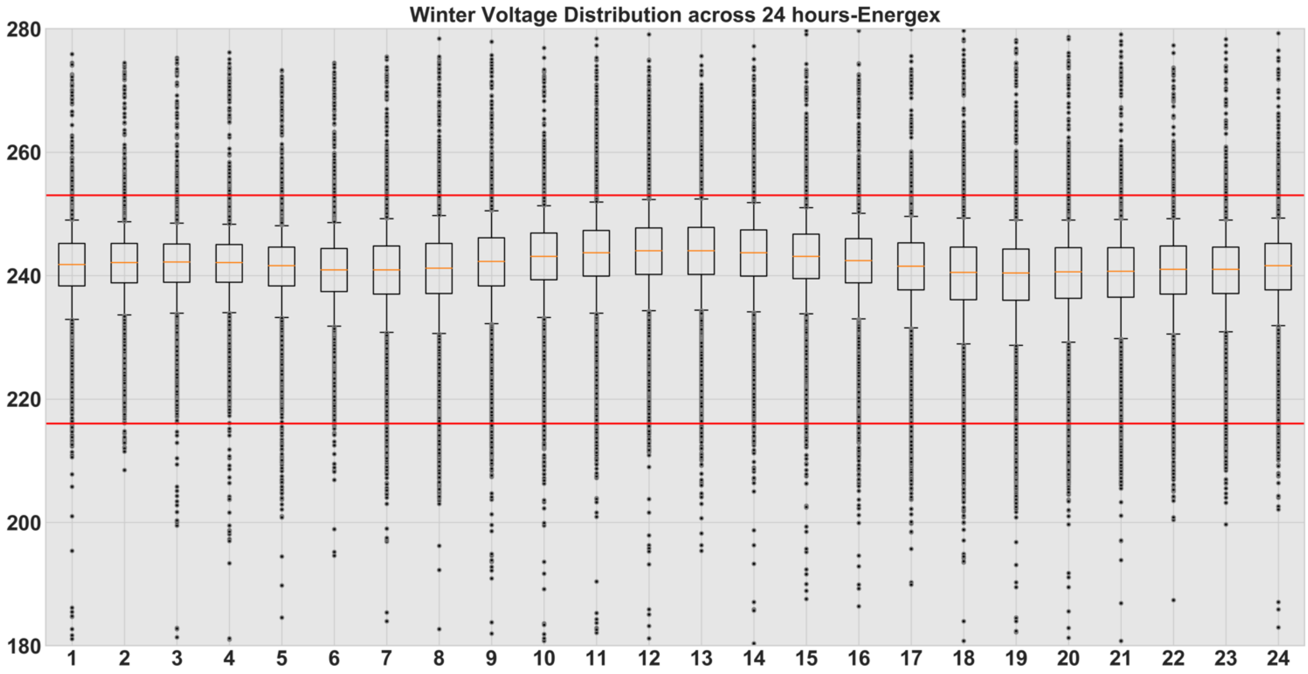


Figure 33 Distribution of voltages across 24 hours for Energex for Winter

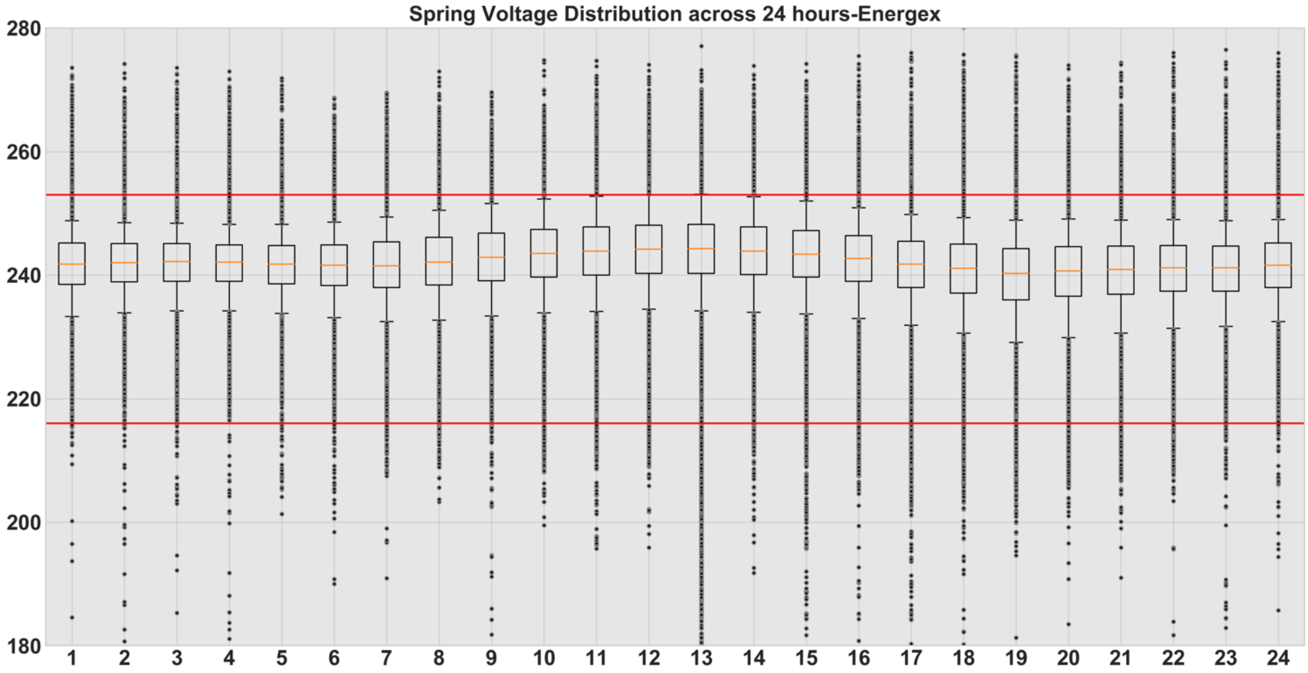


Figure 34 Distribution of voltages across 24 hours for Energex for Spring

5.2.2 Ergon

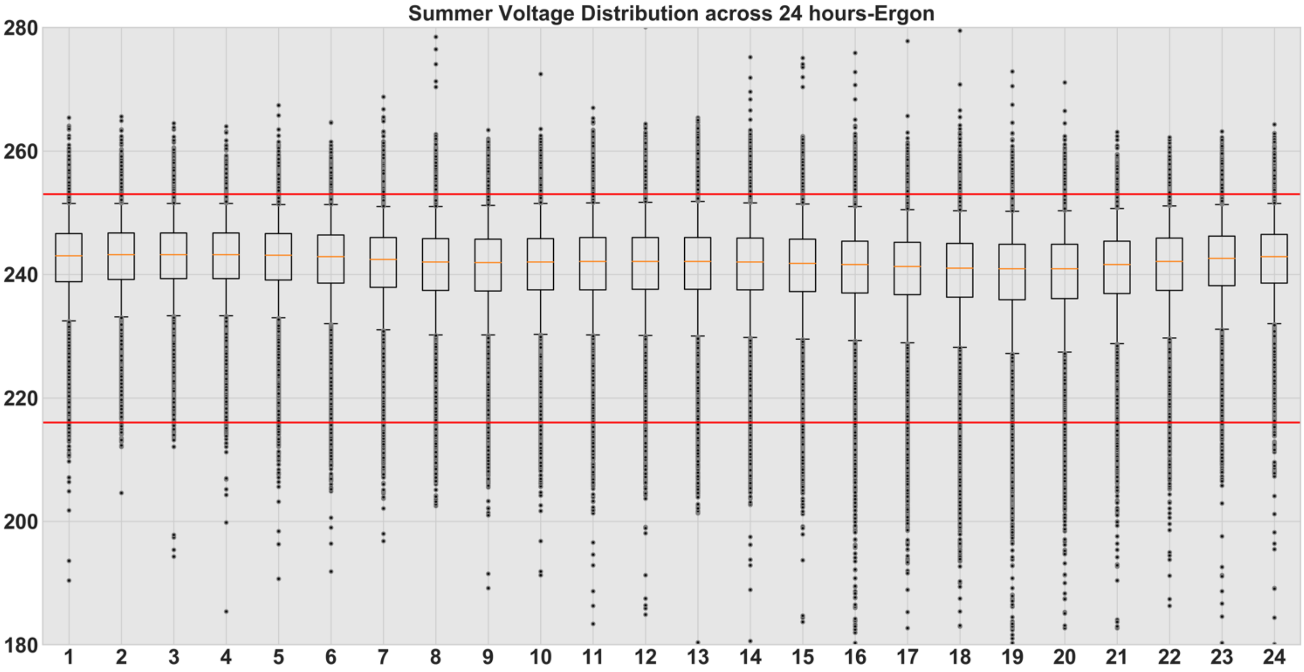


Figure 35 Distribution of voltages across 24 hours for Ergon for Summer

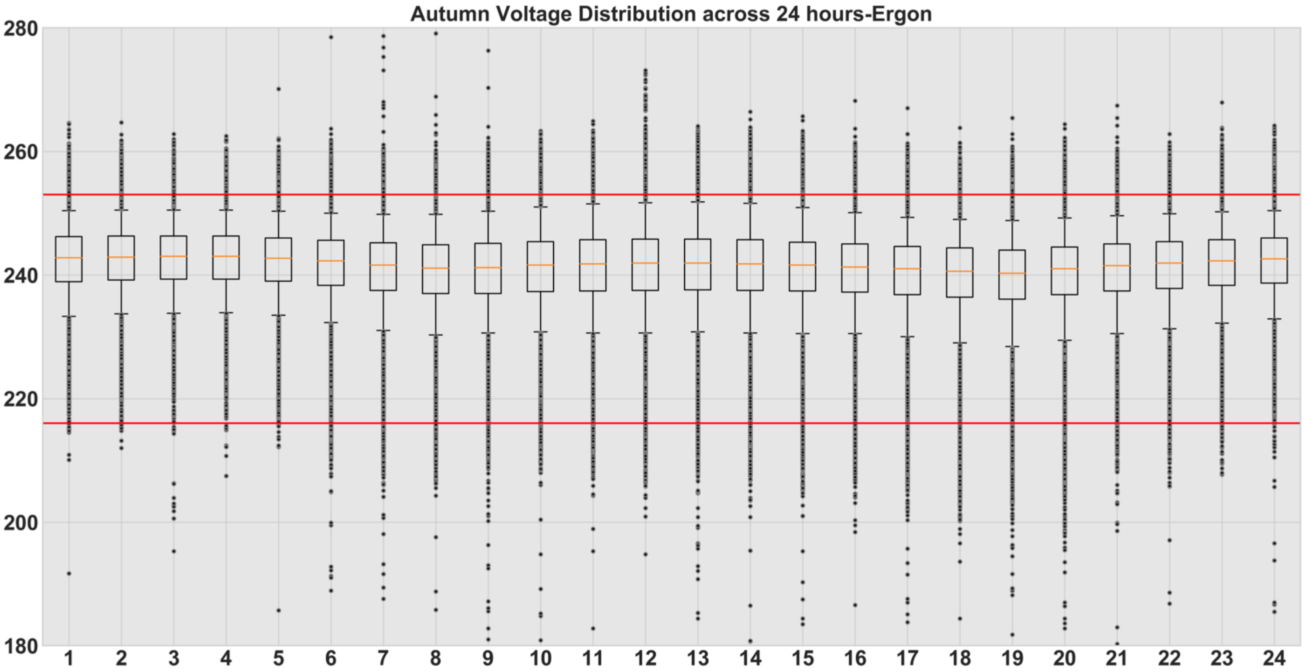


Figure 36 Distribution of voltages across 24 hours for Ergon for Autumn

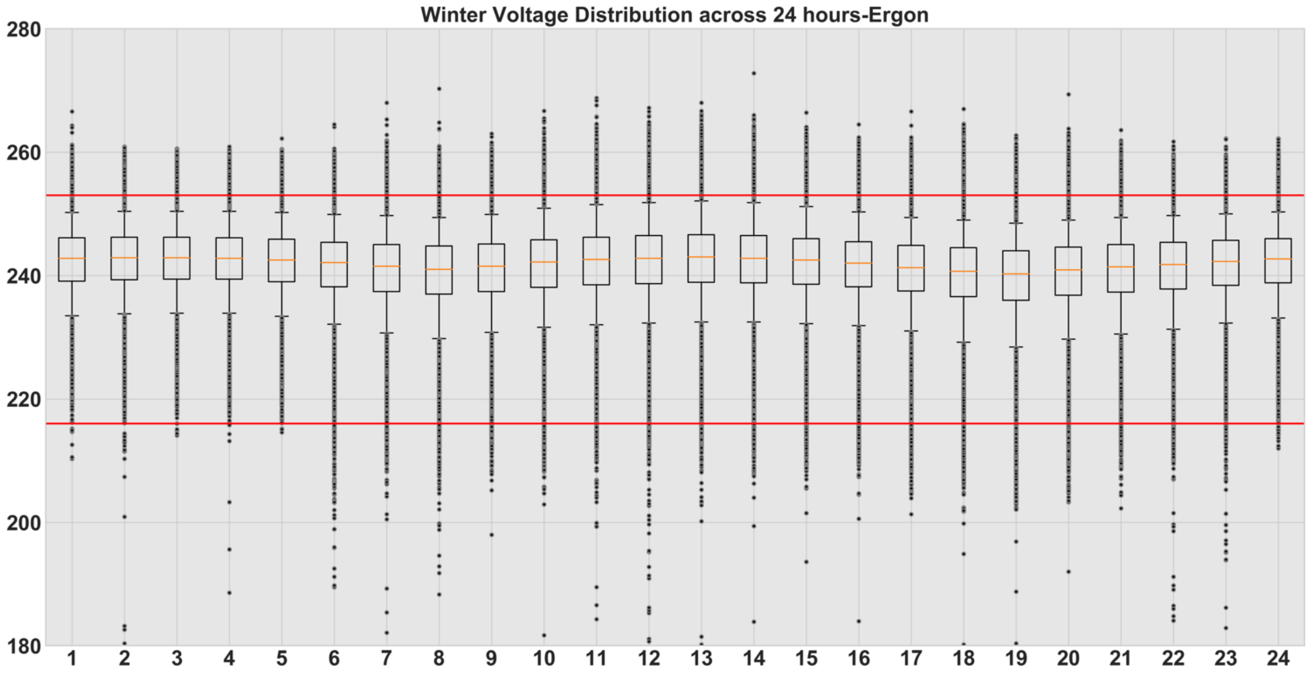


Figure 37 Distribution of voltages across 24 hours for Ergon for Winter

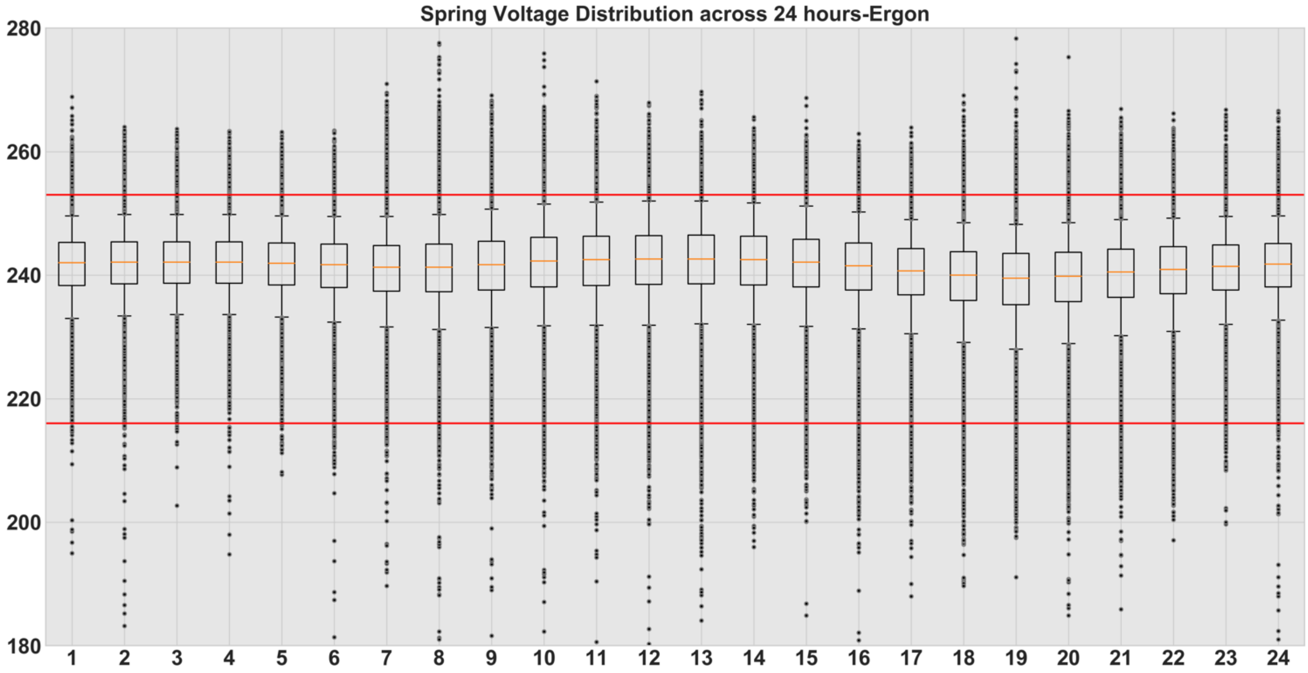


Figure 38 Distribution of voltages across 24 hours for Ergon for Spring

Given the opportunities to change the upper voltage seen in the LV network using distribution transformer tap changes, it is important to understand the range of voltages being experienced at different sites.

Figure 39 and Figure 40 show the distribution of 687 and 249 households with a full year of data in Energex and Ergon networks respectively, ordered by their maximum voltage values experienced throughout the year. For each household the corresponding voltage minimum and the 5th and 95th percentiles of voltage are also shown. Similar to SAPN, the households that experience the highest voltages also experience some occasions of extremely low voltages. Consistent with previous findings, the 95th percentile of the voltage maximum sits at or above the recommended 253 V limit. It can also be seen that the voltage range is much narrower for the 5th to 95th percentile, again highlighting opportunities for interventions that reduce the very small number of extremely low voltage occurrences.

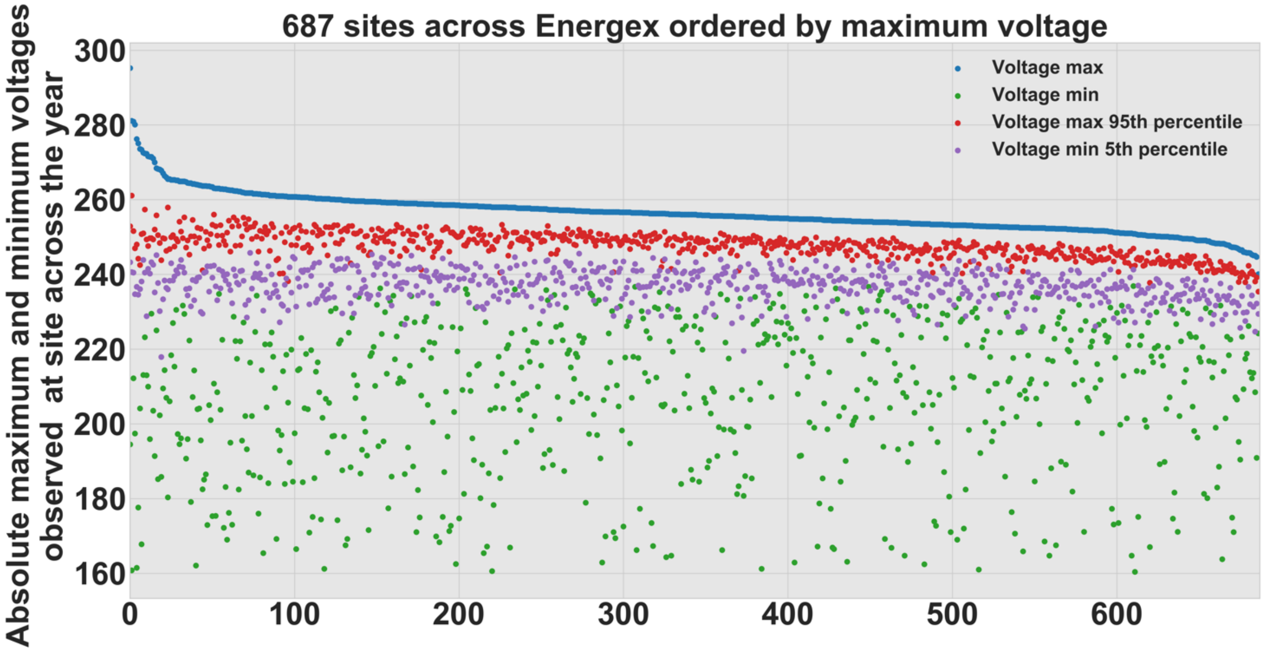


Figure 39 687 sites from Energex with full calendar year data ordered by highest average maximum voltages

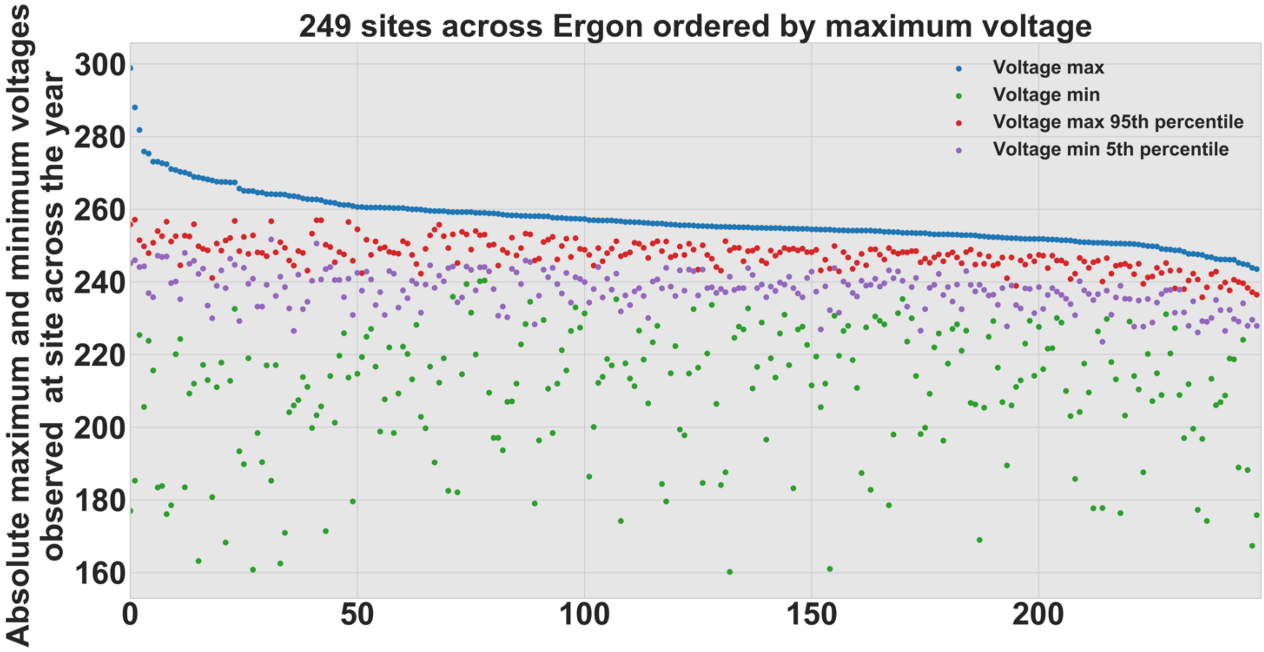


Figure 40 249 sites from Ergon with full calendar year data ordered by highest average maximum voltages

5.3 New South Wales (Ausgrid & Endeavour & Essential)

Since the dataset included only a limited number of households for the ACT, ActewAGL is analysed together with the DNSPs in NSW. Figure 41 and Figure 42 show the average maximum and minimum voltages seen by all the sites in NSW throughout the year. Site locations are categorised as one of 'Suburban', Inner Regional, 'Outer Regional' and 'Remote'. The ACT is shown separately. In addition to the voltages, NSW+ACT net demand (total State electricity demand minus any small scale hence not directly monitored PV generation) is also presented.

The variation in average maximum voltage across NSW is again less severe than observed in SA. Yet, it is still clear that the NSW and ACT demand peaks cause widespread dips in voltage. NSW/ACT demand is higher in summer and winter months, and like SA and Qld, the State experiences its periods of peak demand in summer and these clearly drive periods of lowest maximum voltage. Voltage variations are least in Suburban, and greatest in Remote locations, especially in Summer months, reflecting the customer density and other characteristics of the distribution network that impact on voltage swings as load and PV generation change. The average maximum voltages frequently sit midway between those of SA and Qld, around 245 – 250V most times of the year. In Outer Regional NSW the main periods of high voltages appear to be autumn and spring, whereas in Remote NSW it is through the winter months. In the ACT, the highest voltages occur in the warmer months, with the winter months seeing the lowest voltages, declining to around 230V.

Figure 41 Average voltage maximum across different regions of NSW & ACT and the net state load

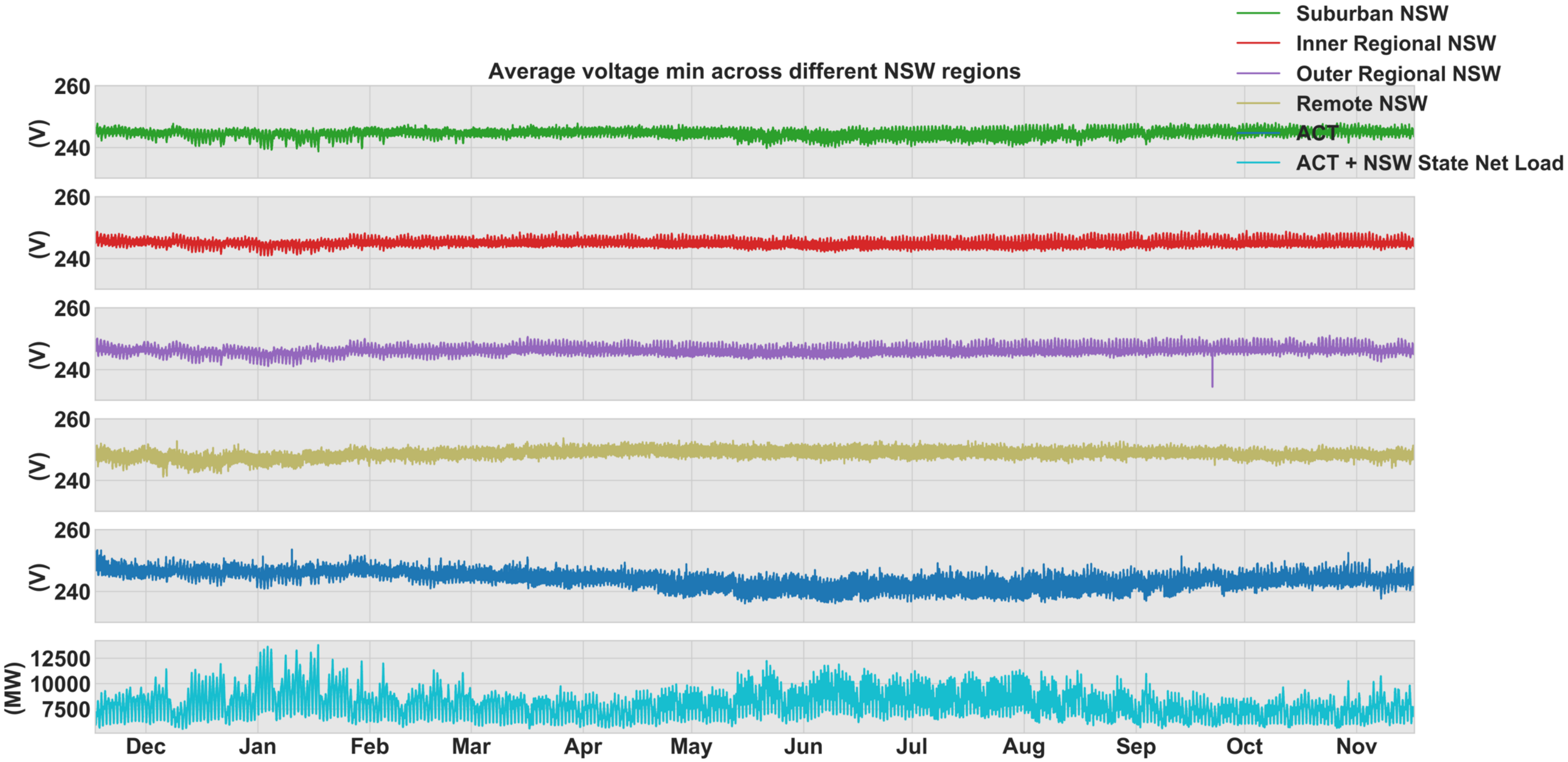


Figure 42 Average voltage minimum across different regions of NSW & ACT and the net state load

Figure 43 and Figure 44 illustrate the distribution of maximum and minimum voltage across the regions. The histograms cover the 1st to 99th percentile of the voltage range so as to focus on the general distribution (the outlier voltages can be observed in the boxplots in Figure 45 to Figure 56). The Y axis shows the range of voltages whereas the X axis shows the percentage of the times a voltage value is observed. The number of households used for the analysis is shown for each region. The voltage values cover the entire yearly period of the 5 minute voltages monitored across the households.

It is clear that the voltages are generally well above 230V and often closer to the upper recommended limits, especially in the Outer Regional and Remote parts of NSW.

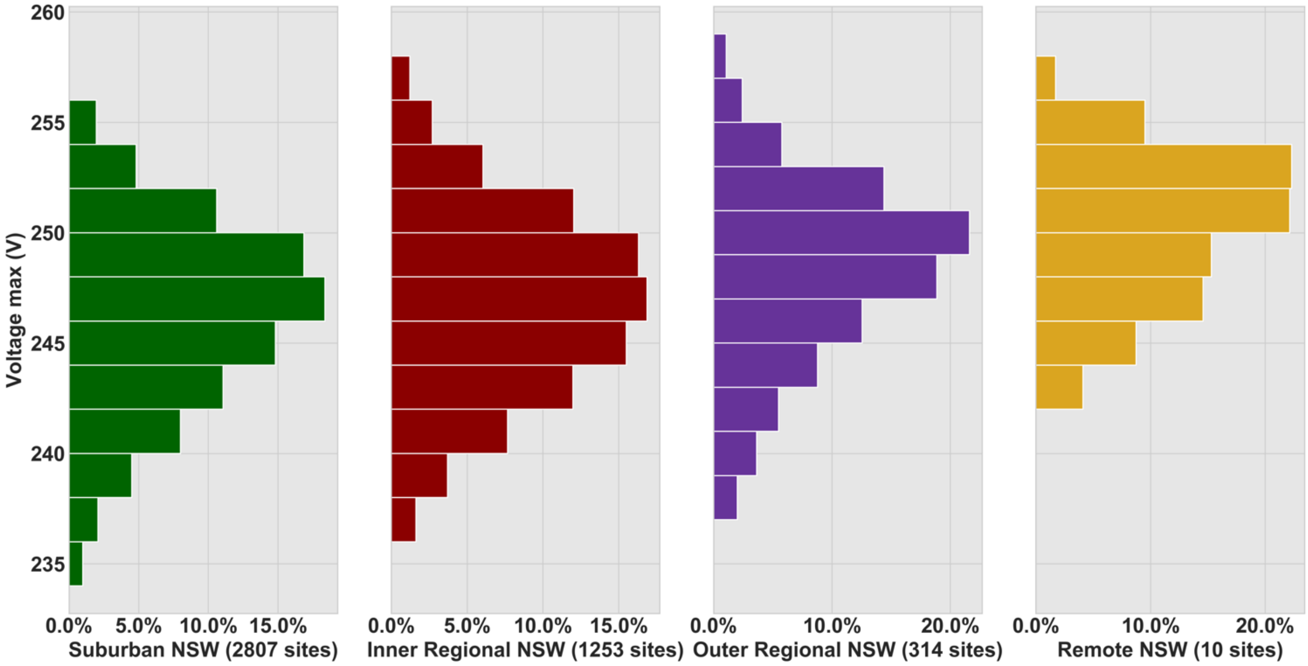


Figure 43 Distribution of maximum voltages across NSW regions

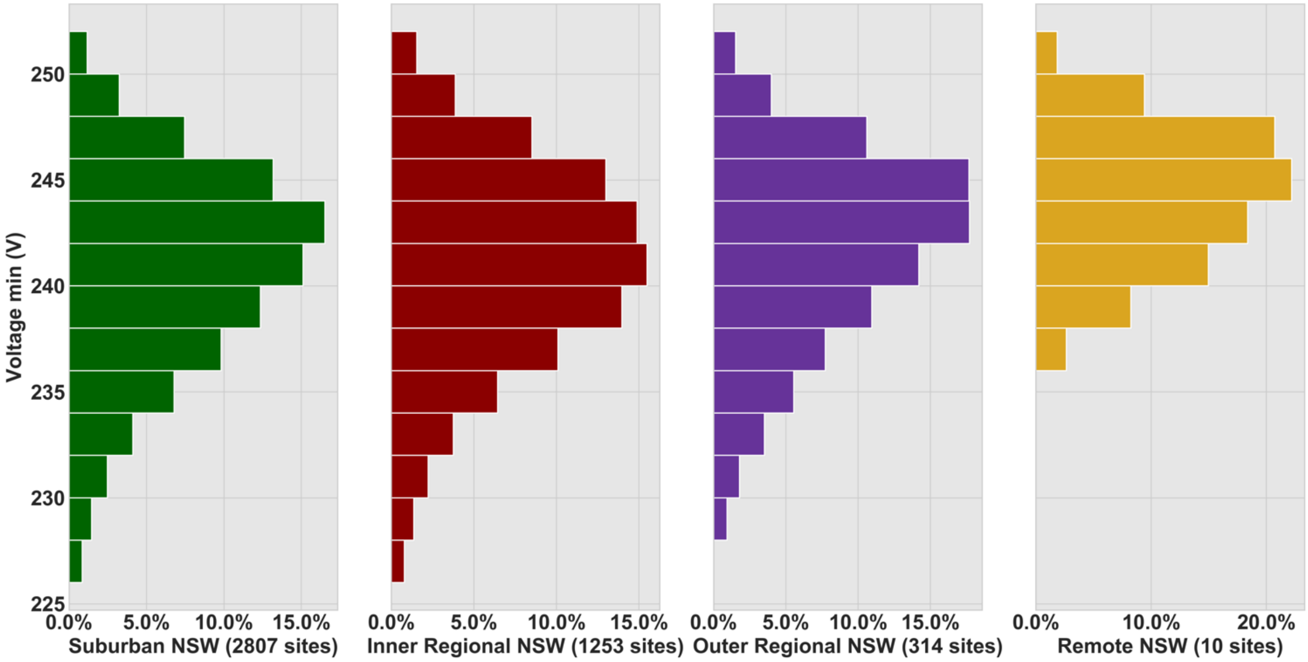


Figure 44 Distribution of minimum voltages across NSW regions

The variation in voltage over a 24 hour period for different seasons is shown for the Ausgrid (Figure 45 to Figure 48), Endeavour (Figure 49 to Figure 52) and Essential (Figure 53 to Figure 56) networks. The plots show the distribution of seasonal hourly voltages including both minimum and maximum voltages. Each hour includes the respective DNSP's household stock's (1766, 1236 and 1379 respectively) voltage data across the respective season. The red horizontal lines represent the AS/NZS standard recommended max and min voltage levels: 253V and 216V respectively. Box plot edges are the 5th and 95th percentile of the voltages observed within the particular hour and the dots represent the outliers.

It can be seen that, like Qld, the median voltage levels are generally between 240 to 245 V for Ausgrid and Endeavour, but Essential is closer to the upper 253V limit, which is more similar to SAPN. In all cases the average maximum voltage levels are closer to the upper 253V limit rather than the lower limit, regardless of the season or time of day. During the midday and early afternoon periods (12pm-2pm) voltage levels increase slightly, although the variation throughout the day is not as great as seen for other states. Sustained voltages above 255V should see post 2015 inverter curtailment begin to commence. Further, late night periods that are typically also periods of lower demand also show high voltages with some sites seeing voltages around the 253V limit, and above 255V for some hours. Especially in the winter and autumn seasons, voltages observed around 4am-6am are almost as high as the midday voltages. It is also apparent that some sites experience occasional very low voltages during peak demand hours (4pm-8pm), especially in winter, where voltages can go extremely low, and below the recommended 216 V limit.

5.3.1 Ausgrid

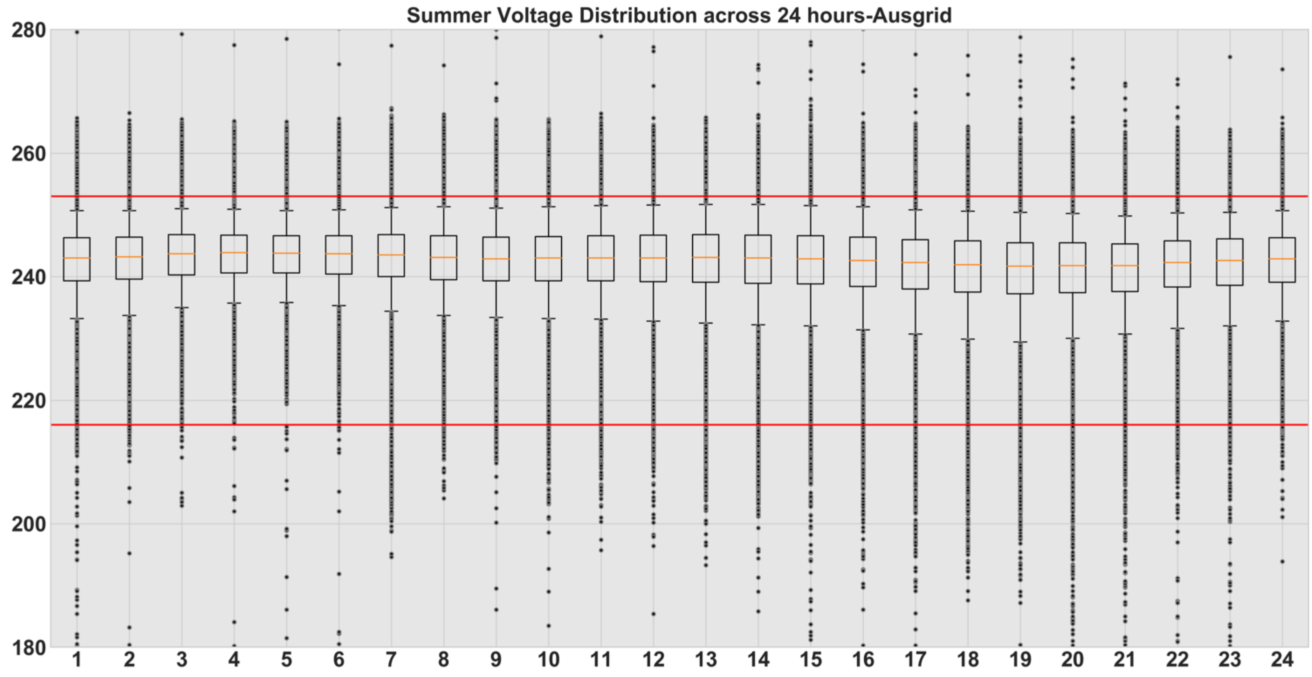


Figure 45 Distribution of voltages across 24 hours for Ausgrid for Summer

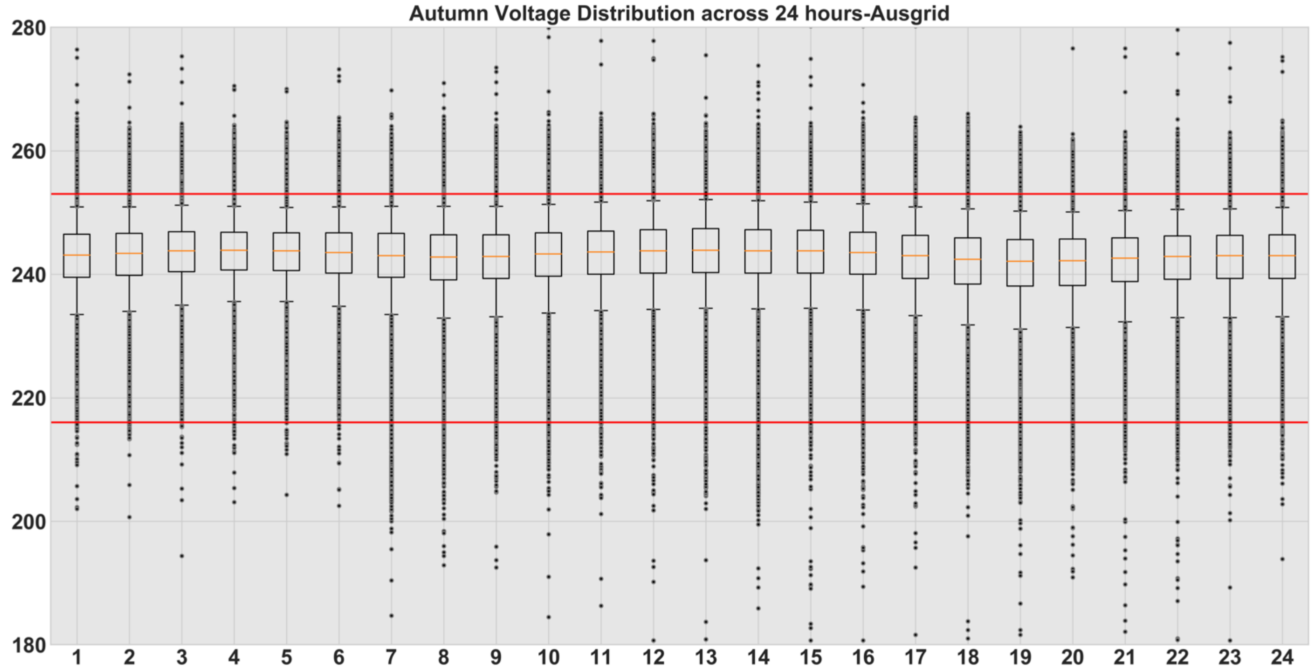


Figure 46 Distribution of voltages across 24 hours for Ausgrid for Autumn

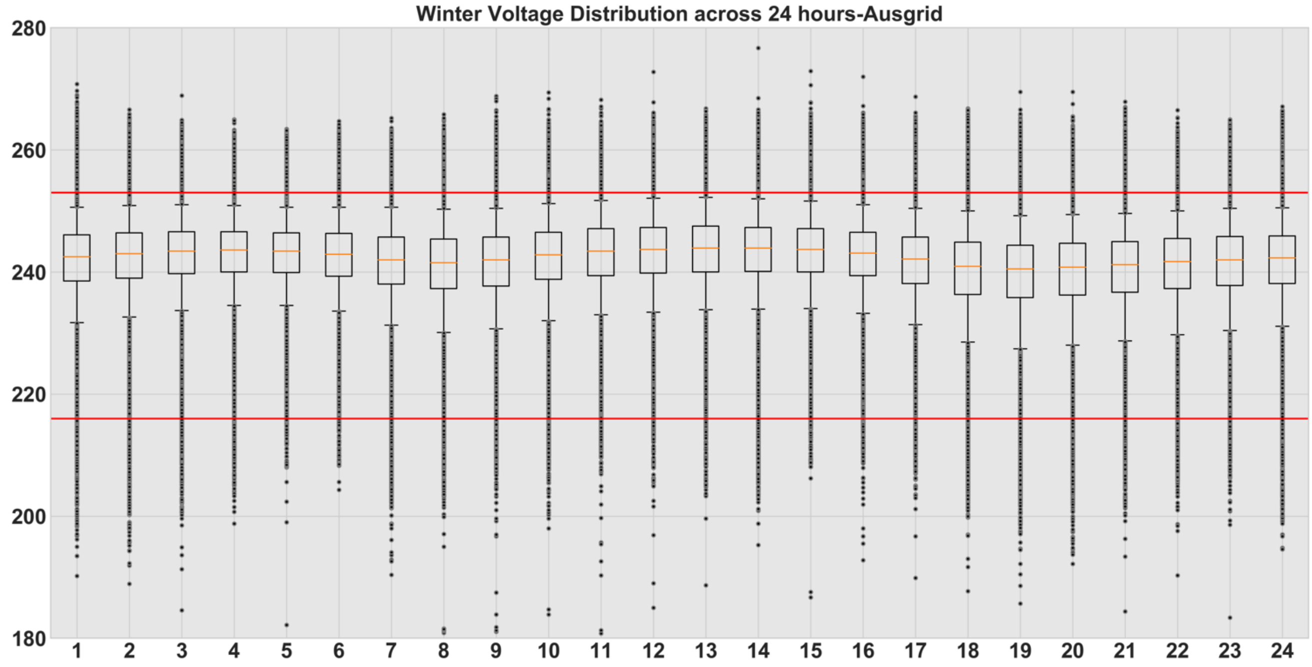


Figure 47 Distribution of voltages across 24 hours for Ausgrid for Winter

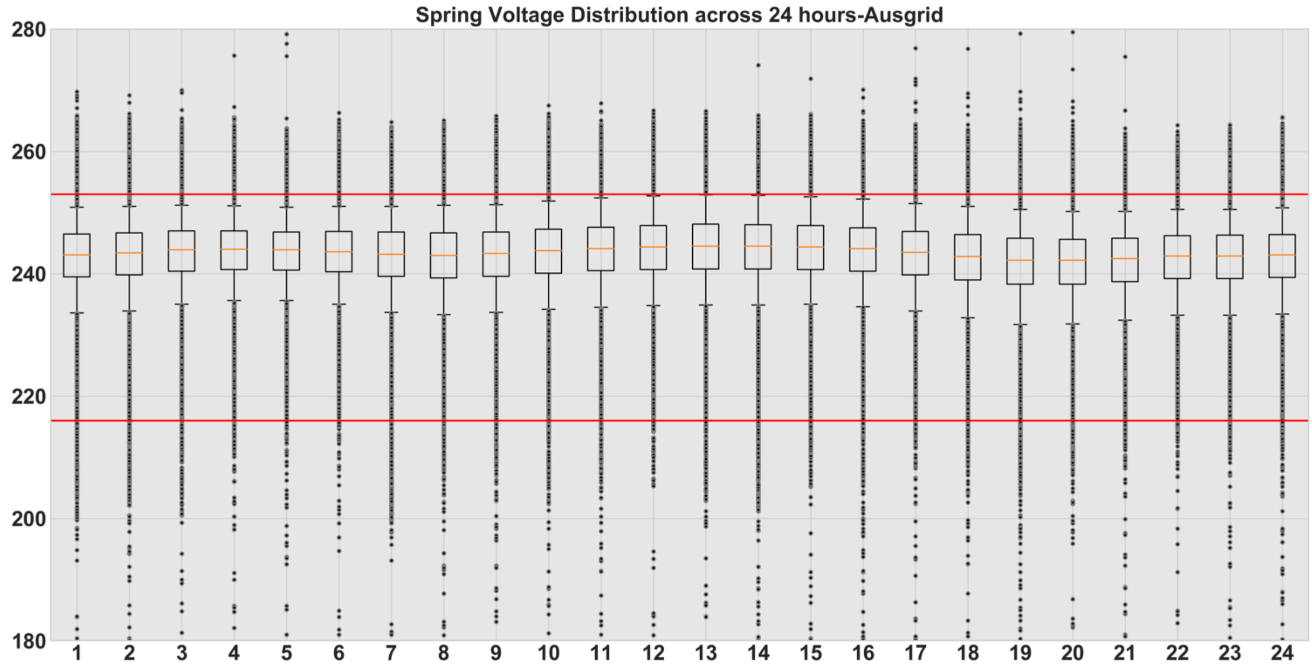


Figure 48 Distribution of voltages across 24 hours for Ausgrid for Spring

5.3.2 Endeavour

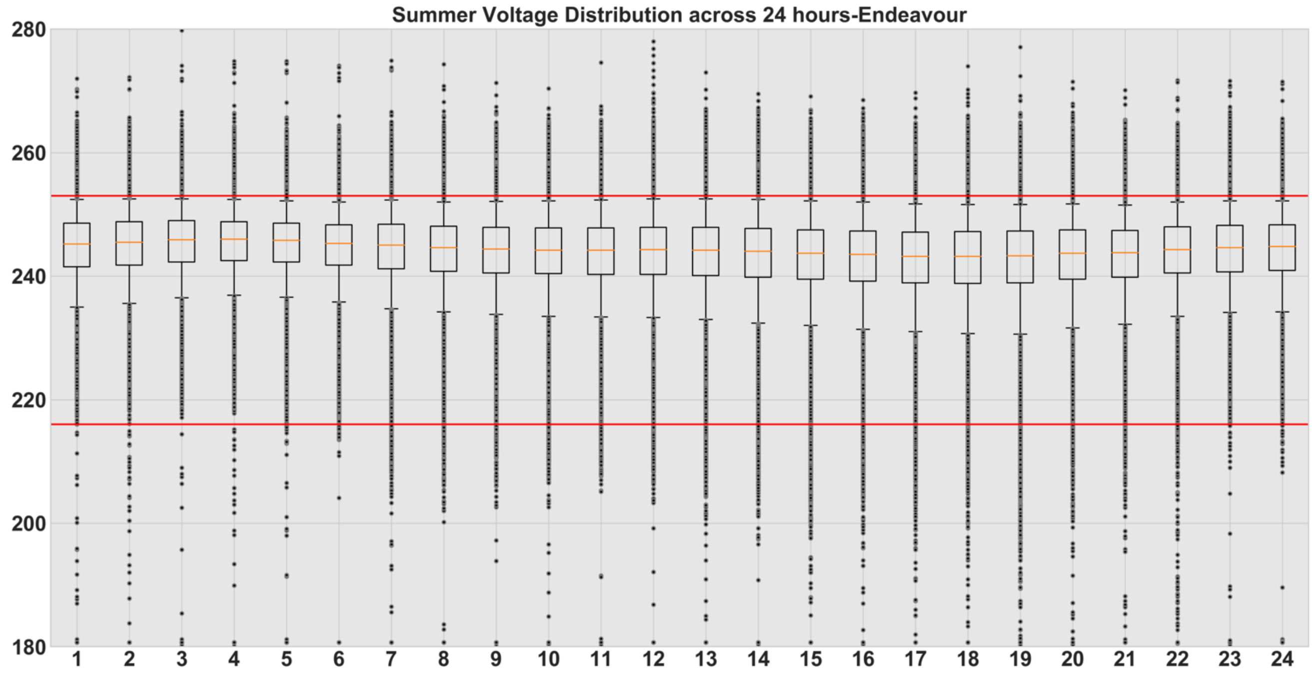


Figure 49 Distribution of voltages across 24 hours for Endeavor for Summer

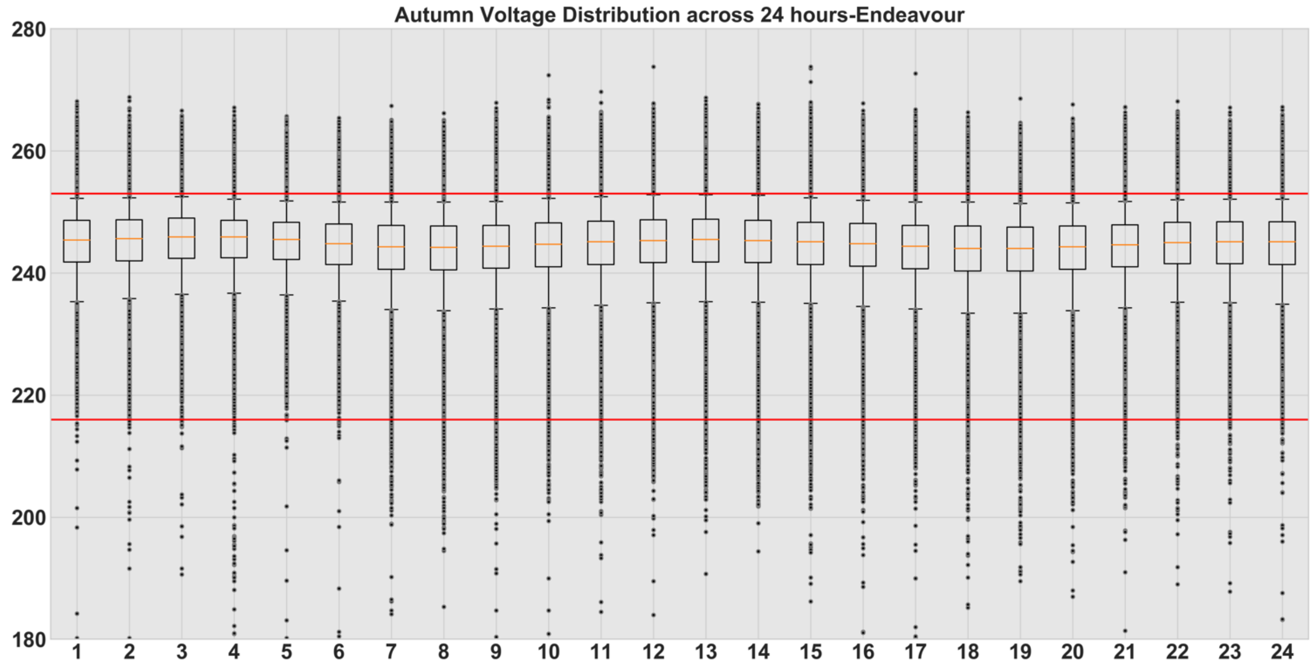


Figure 50 Distribution of voltages across 24 hours for Endeavor for Autumn

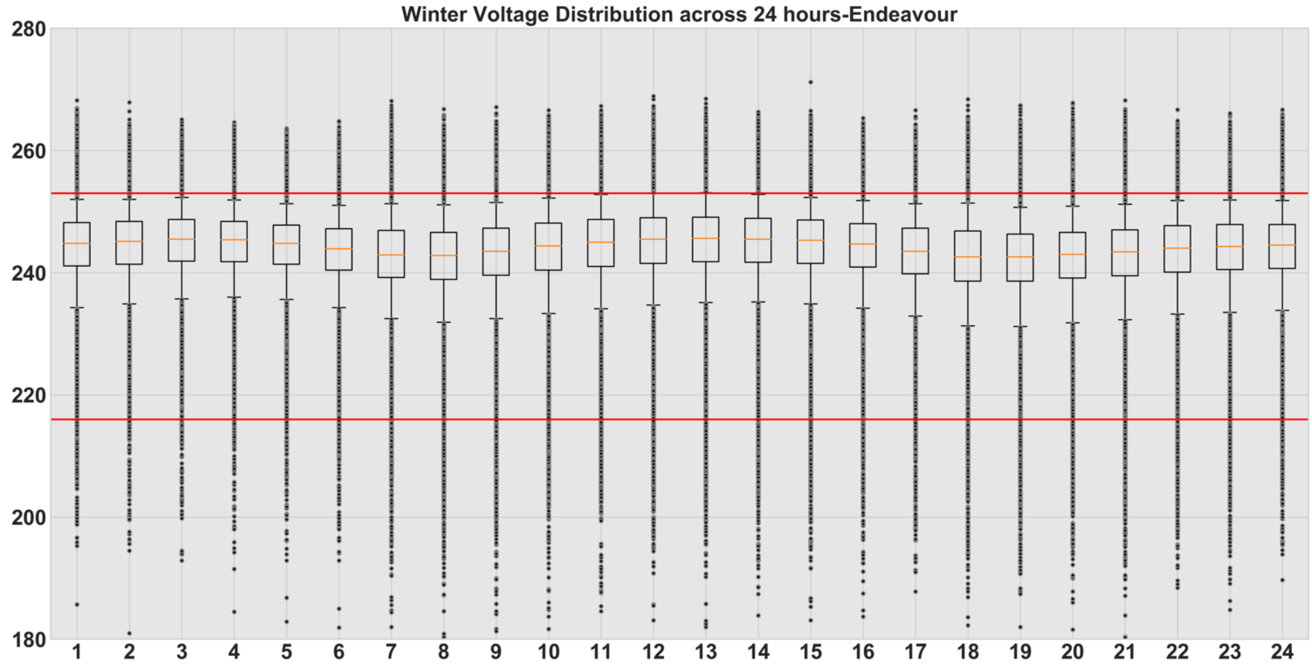


Figure 51 Distribution of voltages across 24 hours for Endeavor for Winter

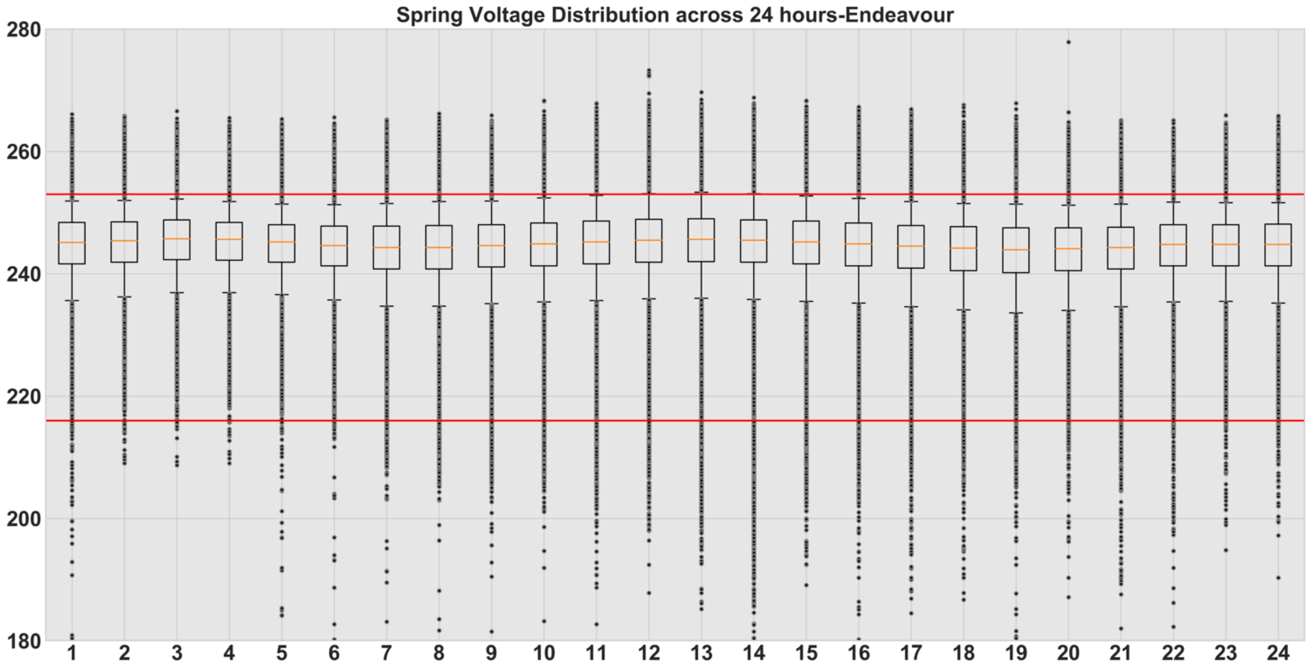


Figure 52 Distribution of voltages across 24 hours for Endeavor for Spring

5.3.3 Essential

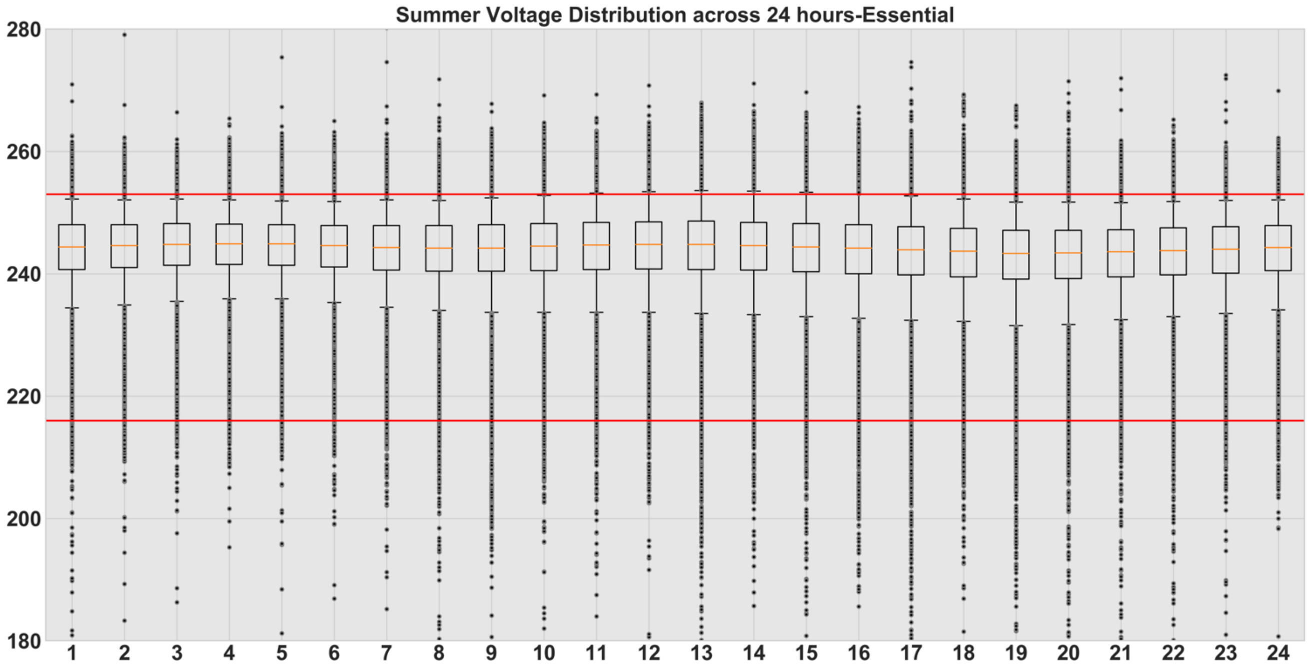


Figure 53 Distribution of voltages across 24 hours for Essential for Summer

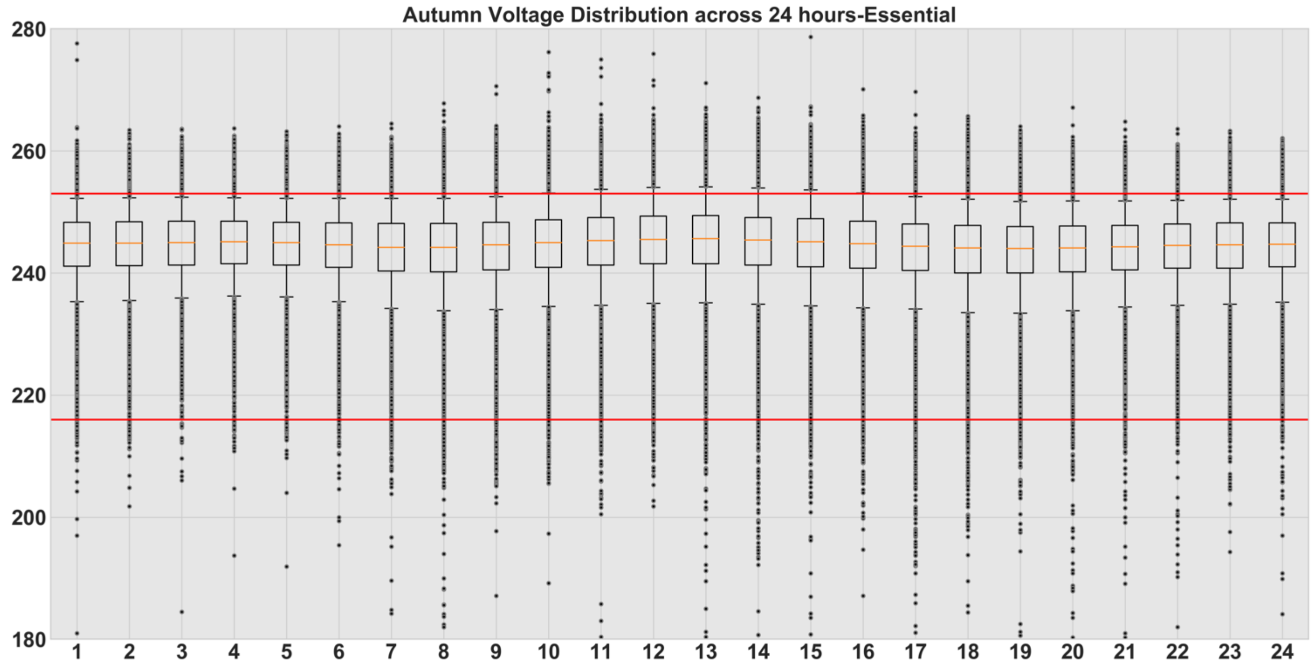


Figure 54 Distribution of voltages across 24 hours for Essential for Autumn

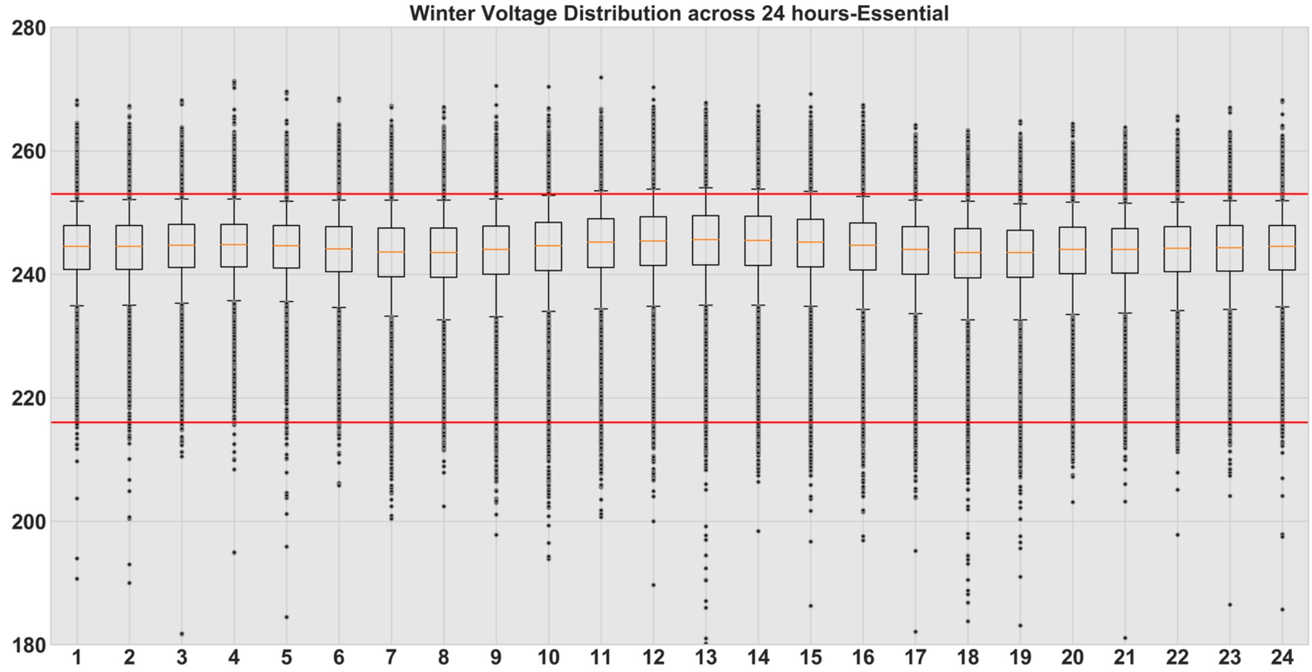


Figure 55 Distribution of voltages across 24 hours for Essential for Winter

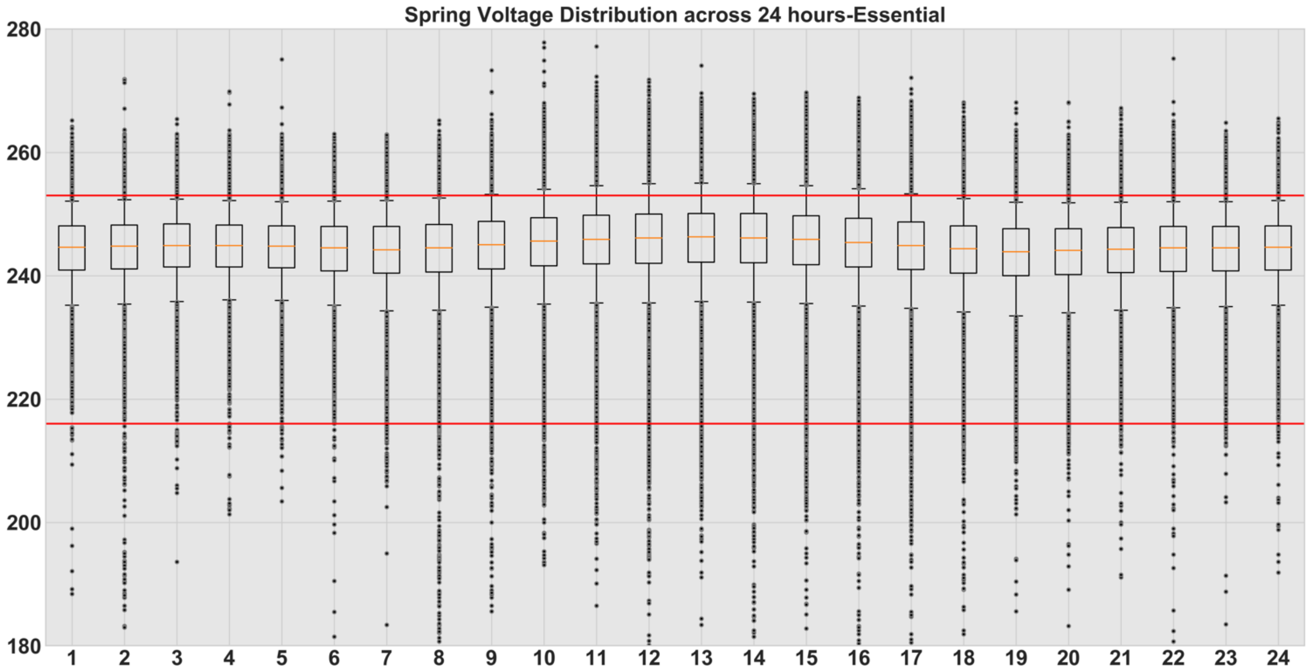


Figure 56 Distribution of voltages across 24 hours for Essential for Spring

Given the opportunities to change the upper voltage seen in the LV network using distribution transformer tap changes, it is important to understand the range of voltages being experienced at different sites.

Figure 57, Figure 58 and Figure 59 show the distribution of 654, 350 and 457 households with a full year of data in the Ausgrid, Endeavour and Essential networks respectively, ordered by their maximum voltage values experienced throughout the year. For each household the corresponding voltage minimum and the 5th and 95th percentiles of voltage are also shown. Similar to SA and Qld, the households that experience the highest voltages also experience some occasions of extremely low voltages. Consistent with previous findings, the 95th percentile of the voltage maximum sits at or above the recommended 253 V limit. It can also be seen that the voltage range is much narrower for the 5th to 95th which shows that there may not be a straightforward solution to keep the voltages in recommended limits for a significant number of households.

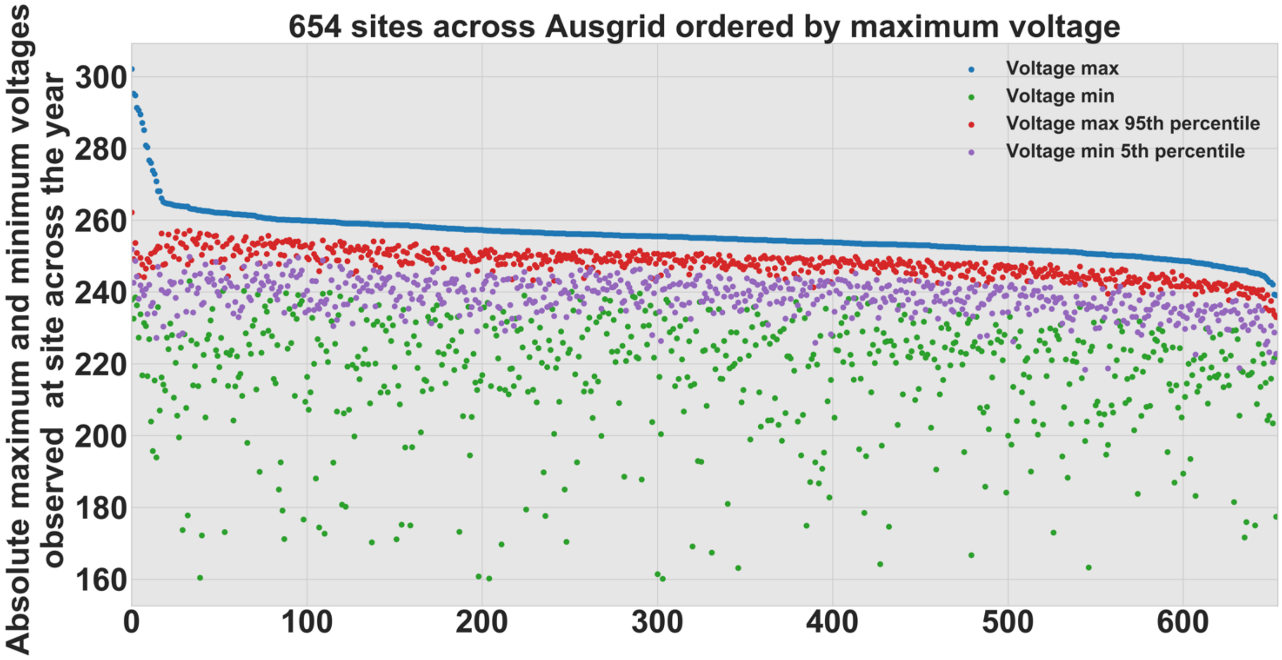


Figure 57 295 sites from Ausgrid with full calendar year data ordered by highest average maximum voltages

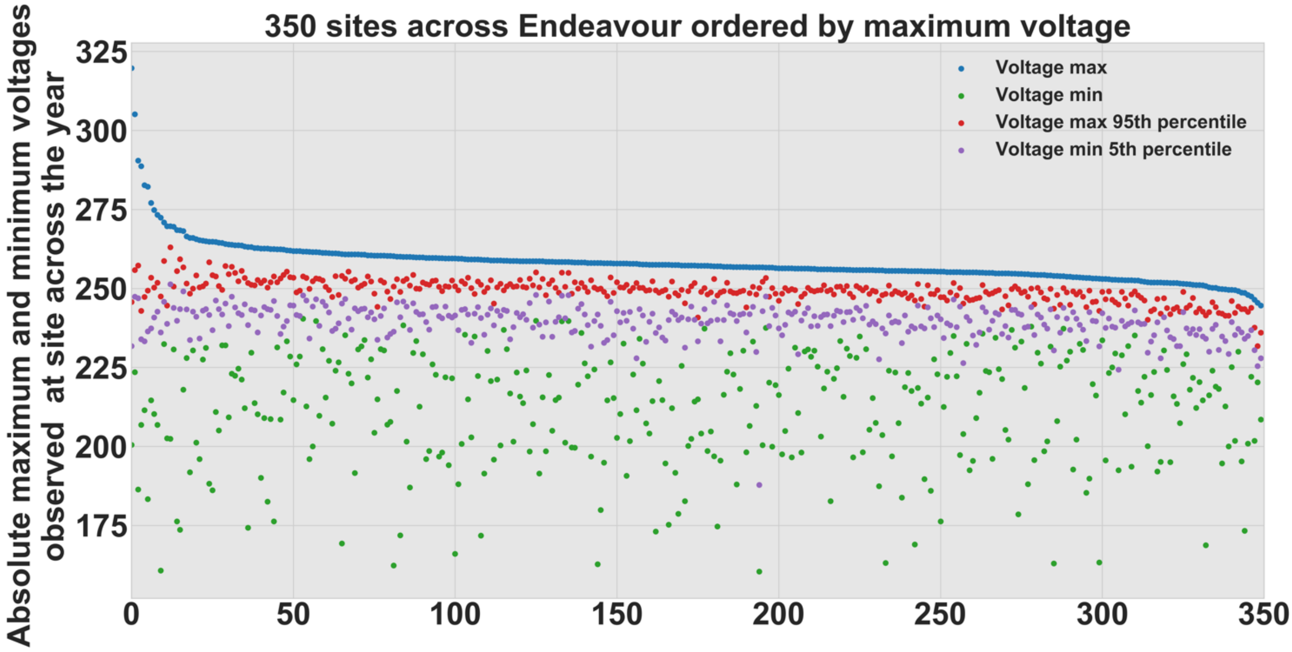


Figure 58 105 sites from Endeavor with full calendar year data ordered by highest average maximum voltages

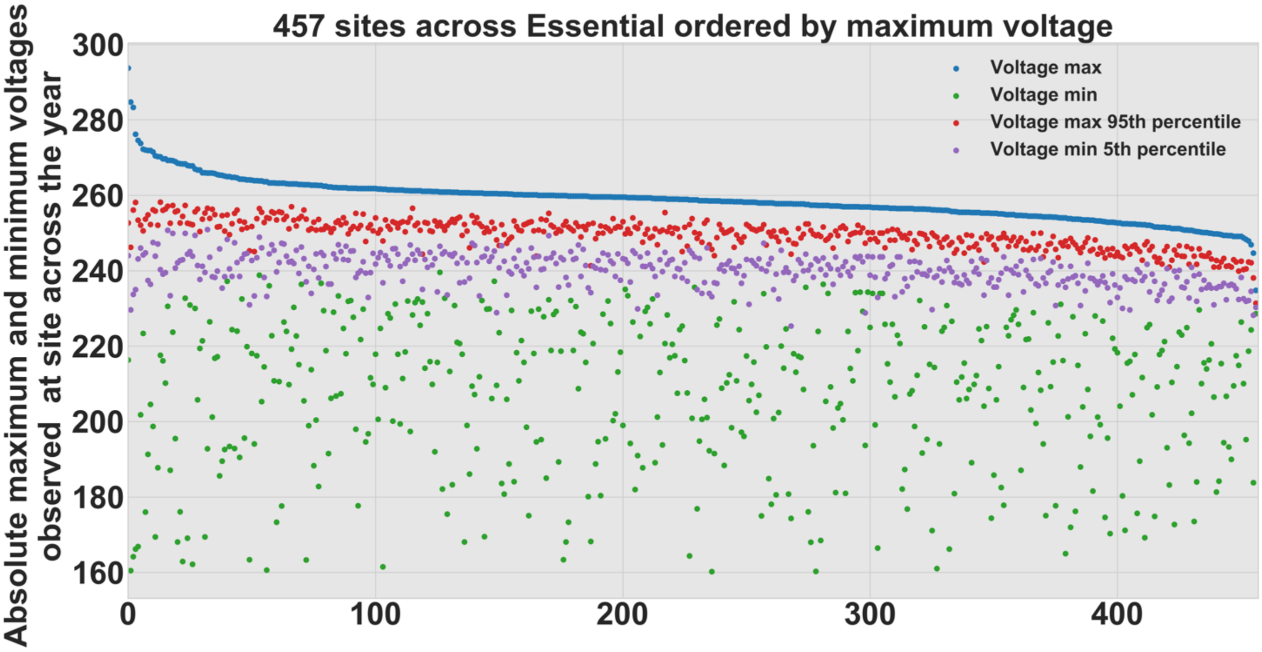


Figure 59 143 sites from Essential with full calendar year data ordered by highest average maximum voltages

5.4 Victoria (Powercor, United Energy, Jemena, Citipower & Ausnet)

Figure 60 and Figure 61 show the average maximum and minimum voltages seen by all the sites in Vic throughout the year. Site locations are categorised as one of 'Suburban', Inner Regional, 'Outer Regional' and 'Remote'. In addition to voltage, the net demand (total electricity demand minus any small scale hence not directly monitored PV generation) is also presented.

The variation in average maximum voltage across Vic is not quite as severe as observed in SA. Yet, it is still clear that the demand peaks cause widespread dips in voltage. Vic demand is higher in the warmer months, and like the other states, Vic experiences its periods of peak demand in summer and these clearly drive periods of lowest maximum voltage. Voltage variations are similar in Suburban, Inner Regional and Outer Regional, and greatest in Remote locations, especially in Summer months, reflecting the customer density and other characteristics of the distribution network that impact on voltage swings as load and PV generation change. The average maximum voltages are generally similar to those of NSW, around 245 – 250V most times of the year.

Figure 60 Average voltage maximum across different regions of Victoria and the net state load

Figure 61 Average voltage minimum across different regions of Victoria and the net state load

Figure 62 and Figure 63 illustrate the distribution of maximum and minimum voltage across the regions. The histograms cover the 1st to 99th percentile of the voltage range so as to focus on the general distribution (the outlier voltages can be observed in the boxplots in Figure 64 to Figure 83). The Y axis shows the range of voltages whereas the X axis shows the percentage of the times a voltage value is observed. The number of households used for the analysis is shown for each region. The voltage values cover the entire yearly period of the 5 minute voltages monitored across the households.

It is clear that the voltages are generally well above 230V and often closer to the upper recommended limits. In contrast to the other states, the Remote regions generally have slightly lower voltages (but still well above 230V), although note this is for only 2 sites.

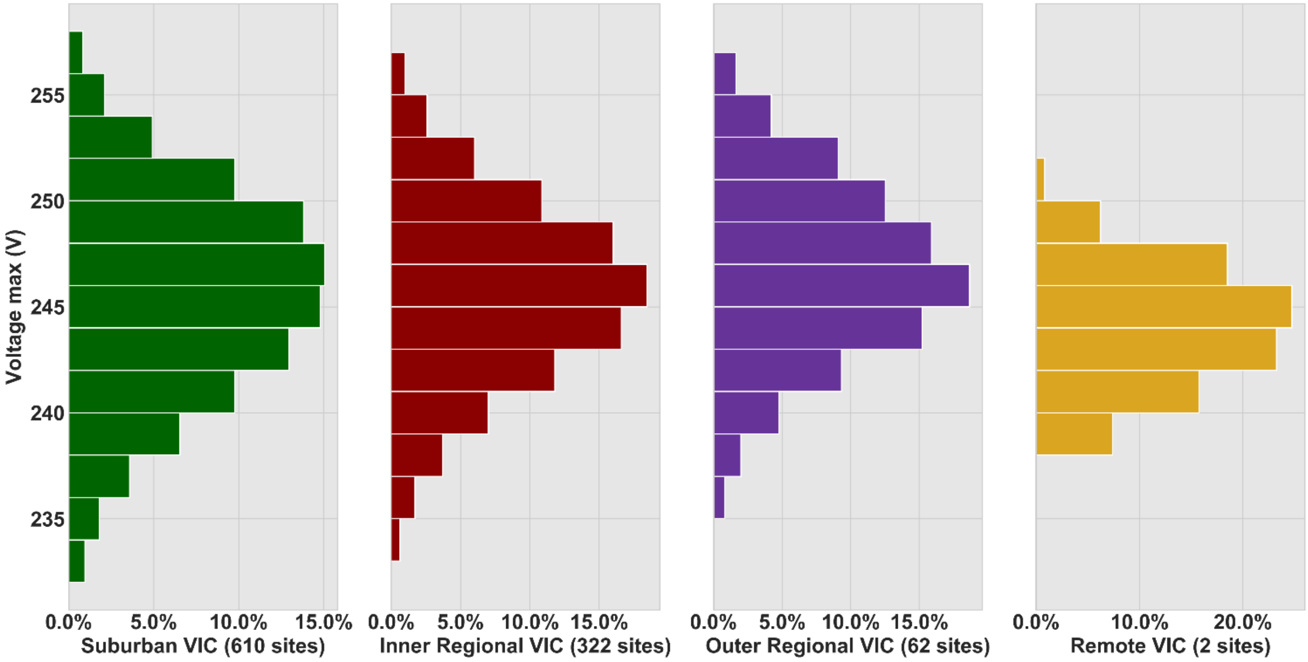


Figure 62 Distribution of maximum voltages across Victorian regions

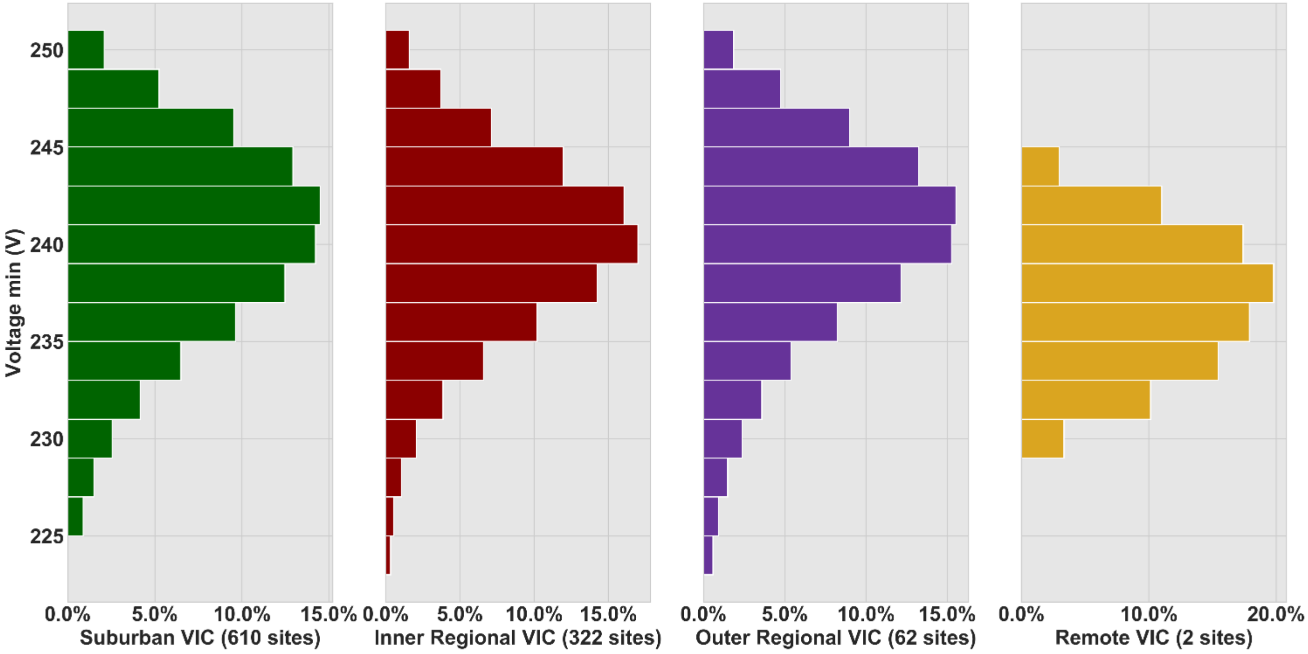


Figure 63 Distribution of minimum voltages across Victorian regions

The variation in voltage over a 24 hour period for different seasons is shown for the Powercor (Figure 64 and Figure 67), United Energy (Figure 68 and Figure 71), Jemena (Figure 72 and Figure 75), Citipower (Figure 76 and Figure 79) and Ausnet (Figure 80 and Figure 83) networks. The plots show the distribution of seasonal hourly voltages including both minimum and maximum voltages. Each hour includes the respective DNSP's household stock's (241, 171,124, 61 and 385 respectively) voltage data across the respective season. The red horizontal lines represent the AS/NZS standard recommended max and min voltage levels: 253V and 216V respectively. Box plot edges are the 5th and 95th percentile of the voltages observed within the particular hour and the dots represent the outliers.

It can be seen that, like the other states, the median voltage levels are generally between 240 to 245 V with Citipower generally being higher throughout the day. In all cases the average maximum voltage levels are closer to the upper 253V limit rather than the lower limit, regardless of the season or time of day. During the midday and early afternoon periods (12pm-2pm) voltage levels increase slightly, although the variation throughout the day is not particularly significant, except for Ausnet which shows slightly greater variation. Sustained voltages above 255V should see post 2015 inverter curtailment begin to commence. Further, very early morning periods that are typically also periods of lower demand also show high voltages with some sites seeing voltages around the 253V limit, and above 255V for some hours. For Citipower, the voltages observed around 4am-6am are higher than the midday voltages. It is also apparent that some sites experience occasional very low voltages during peak demand hours (4pm-8pm), where voltages can go extremely low, and below the recommended 216 V limit. The Vic DNSPs generally experience fewer very low voltage events compared to the other states, although Ausnet has a greater number of low voltage events, with United Energy and Jemena having more low voltage events during summer.

5.4.1 Powercor

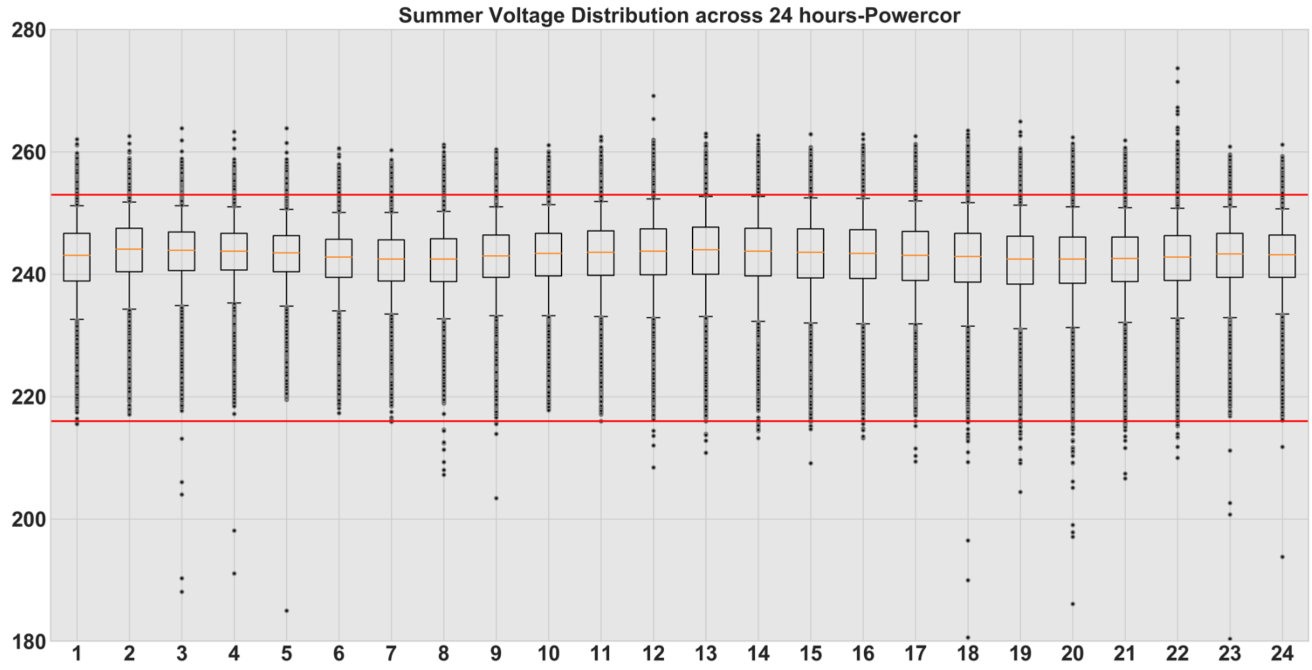


Figure 64 Distribution of voltages across 24 hours for Powercor for Summer

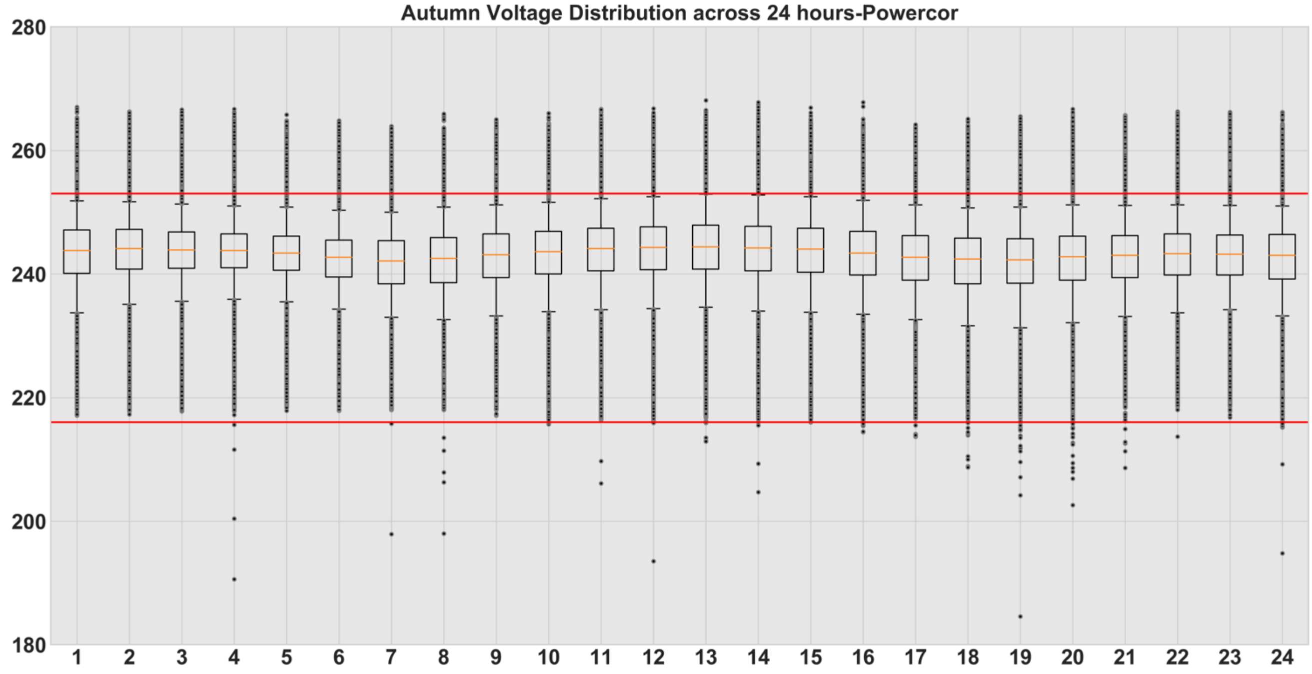


Figure 65 Distribution of voltages across 24 hours for Powercor for Autumn

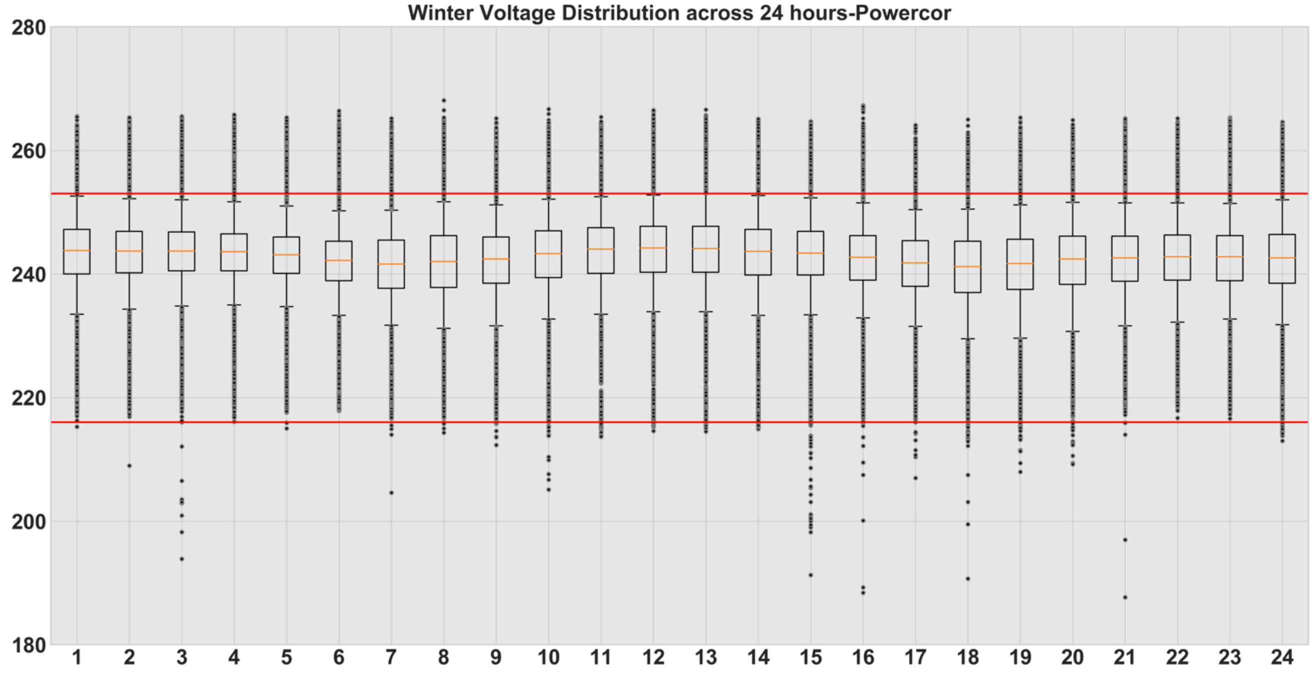


Figure 66 Distribution of voltages across 24 hours for Powercor for Winter

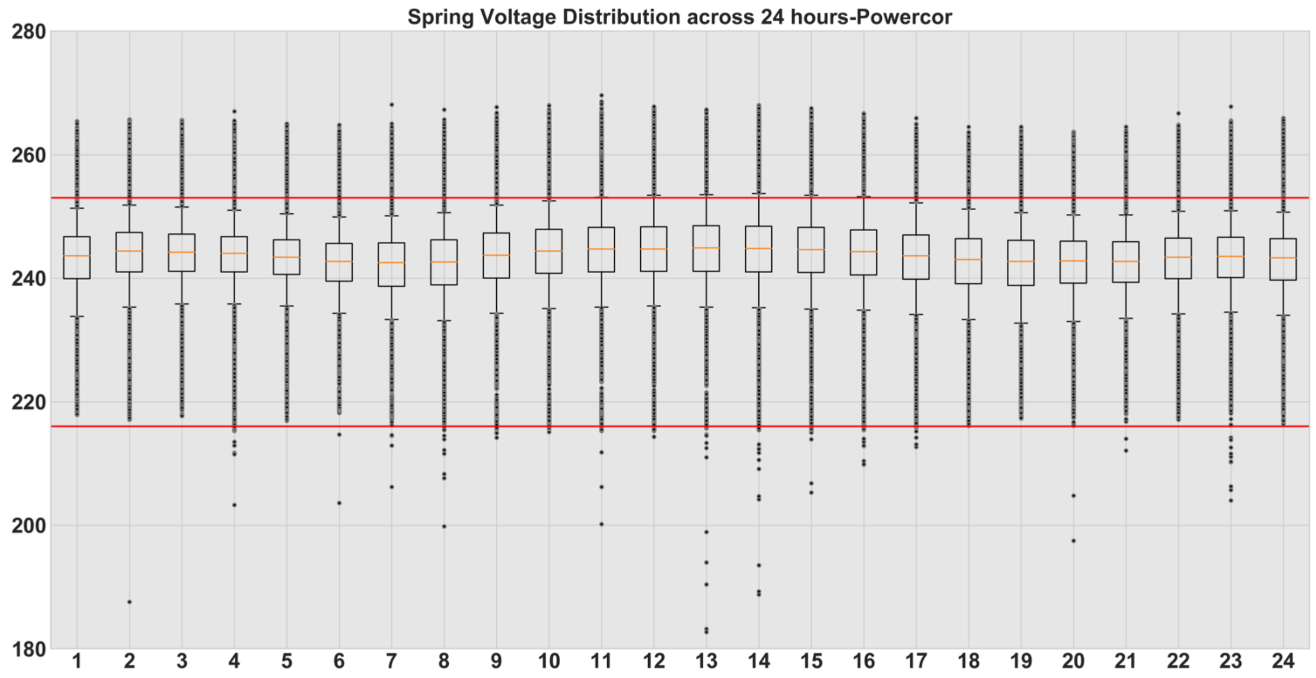


Figure 67 Distribution of voltages across 24 hours for Powercor for Spring

5.4.2 United Energy

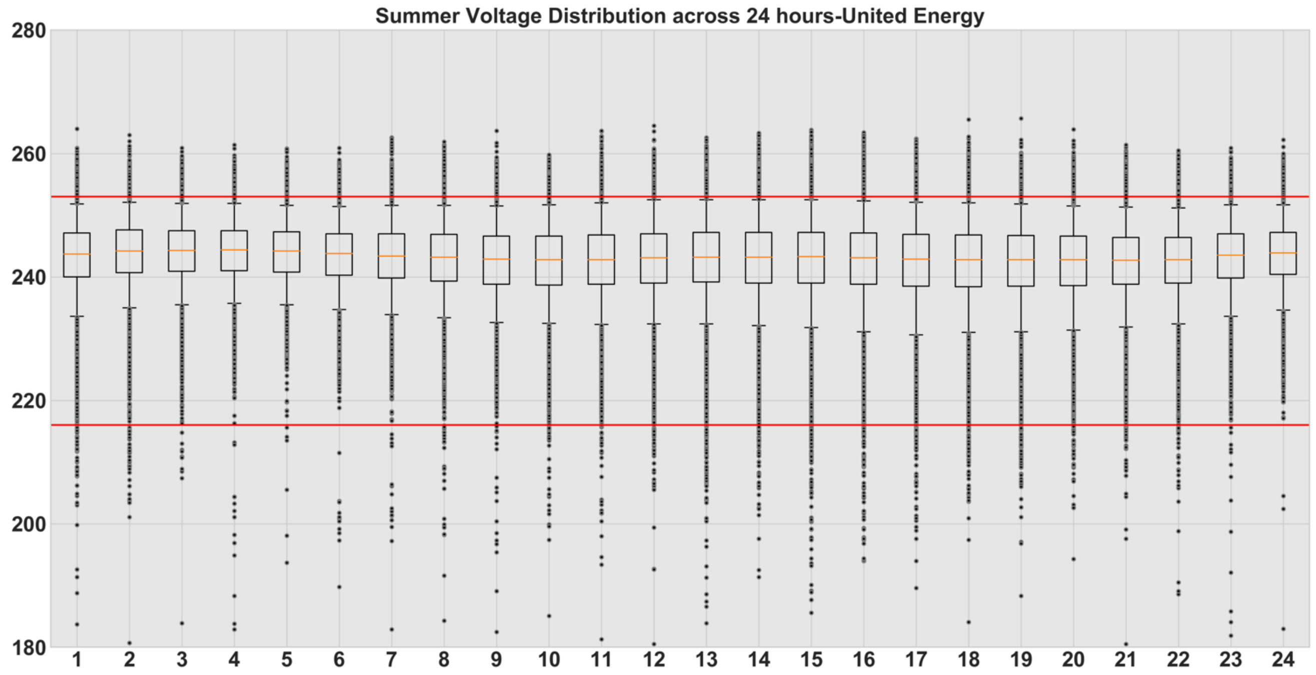


Figure 68 Distribution of voltages across 24 hours for United Energy for Summer

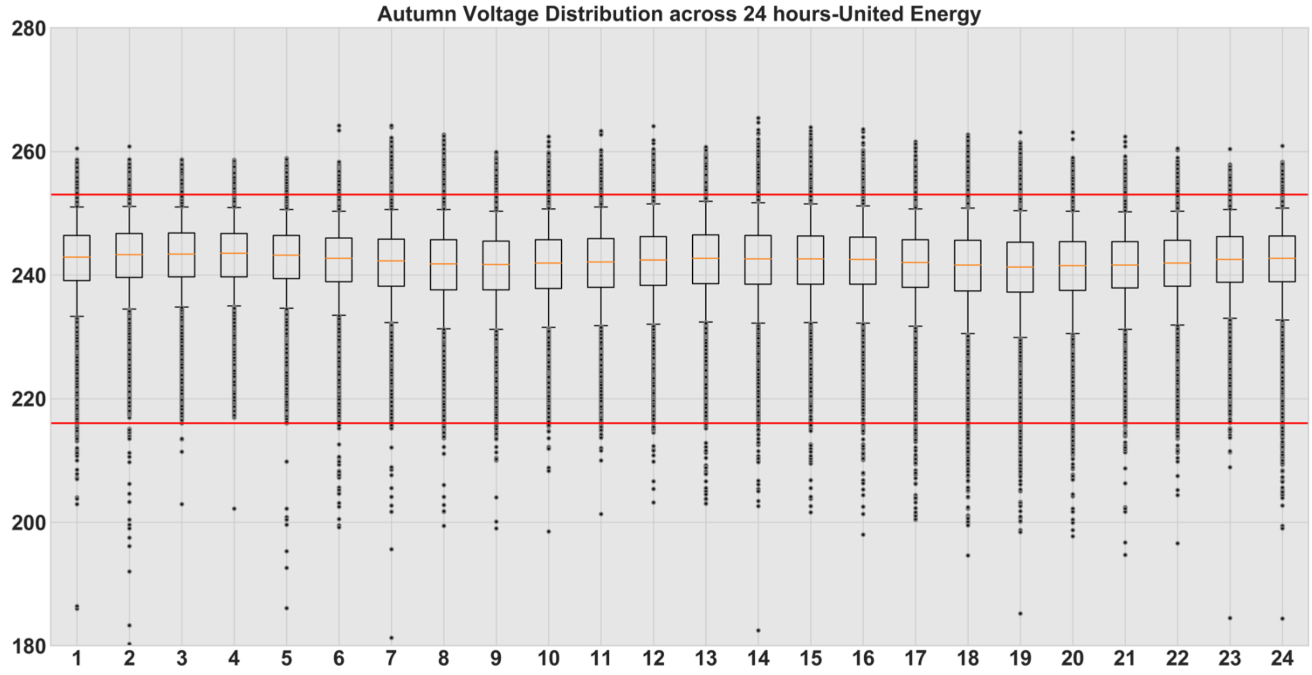


Figure 69 Distribution of voltages across 24 hours for United Energy for Autumn

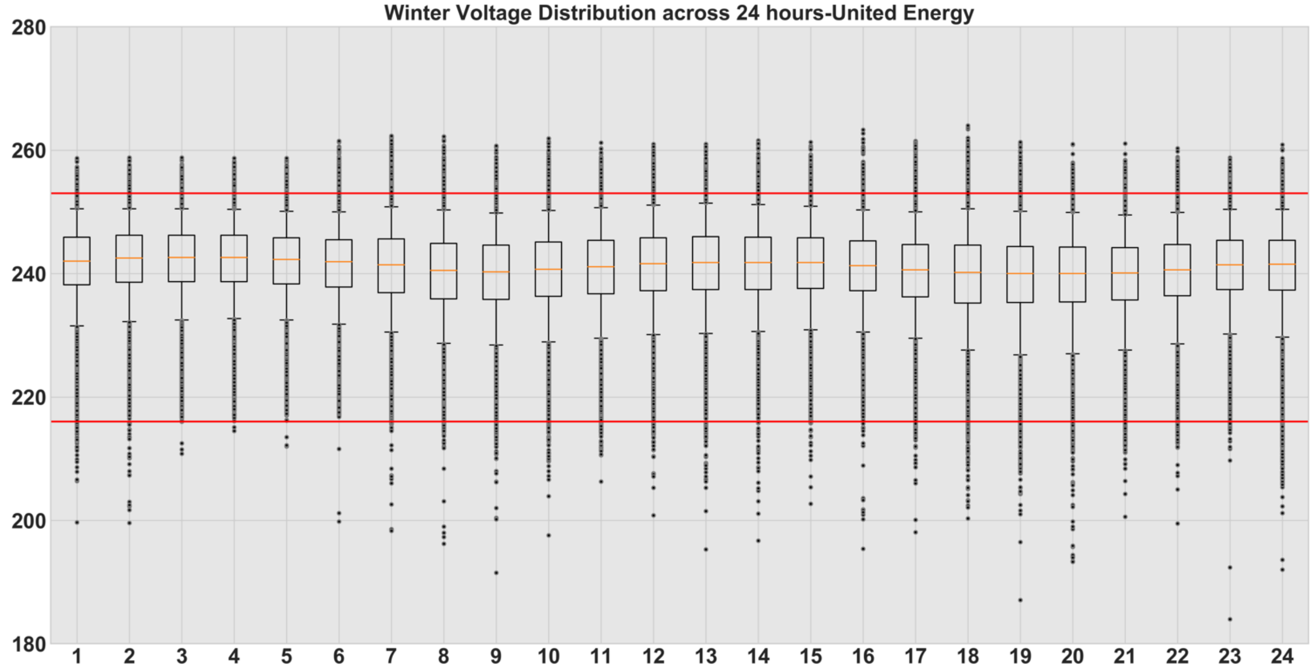


Figure 70 Distribution of voltages across 24 hours for United Energy for Winter

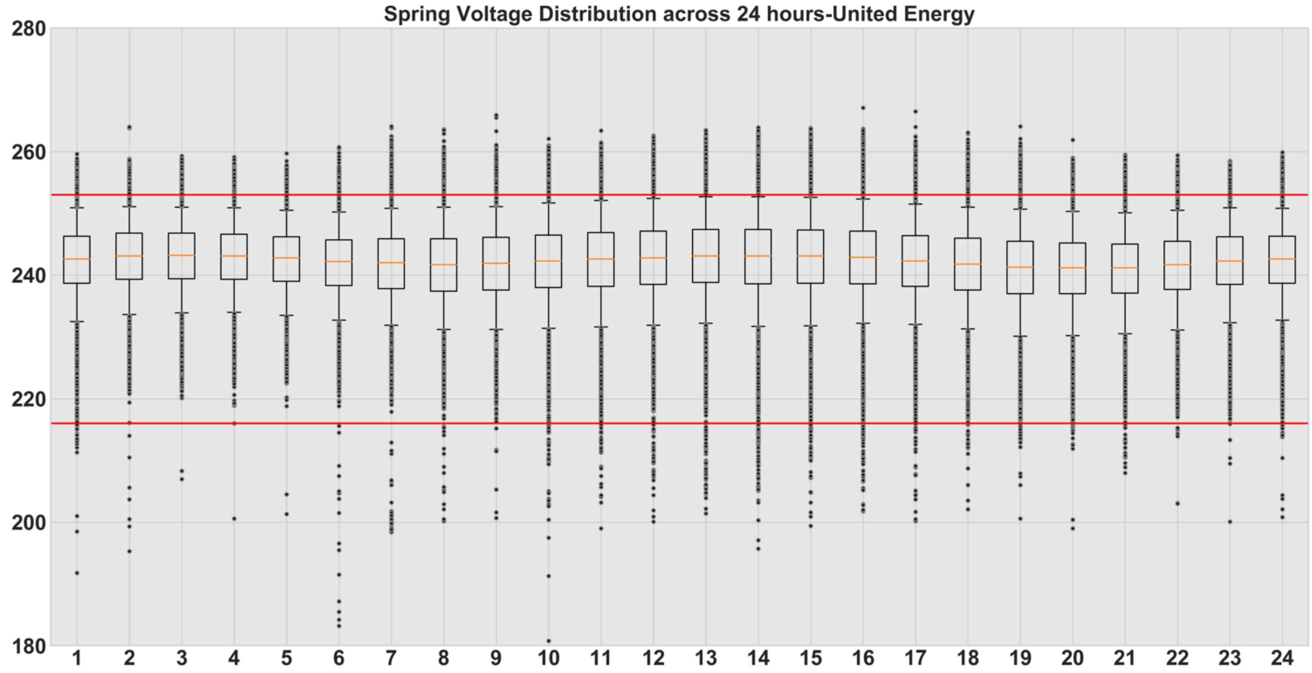


Figure 71 Distribution of voltages across 24 hours for United Energy for Spring

5.4.3 Jemena

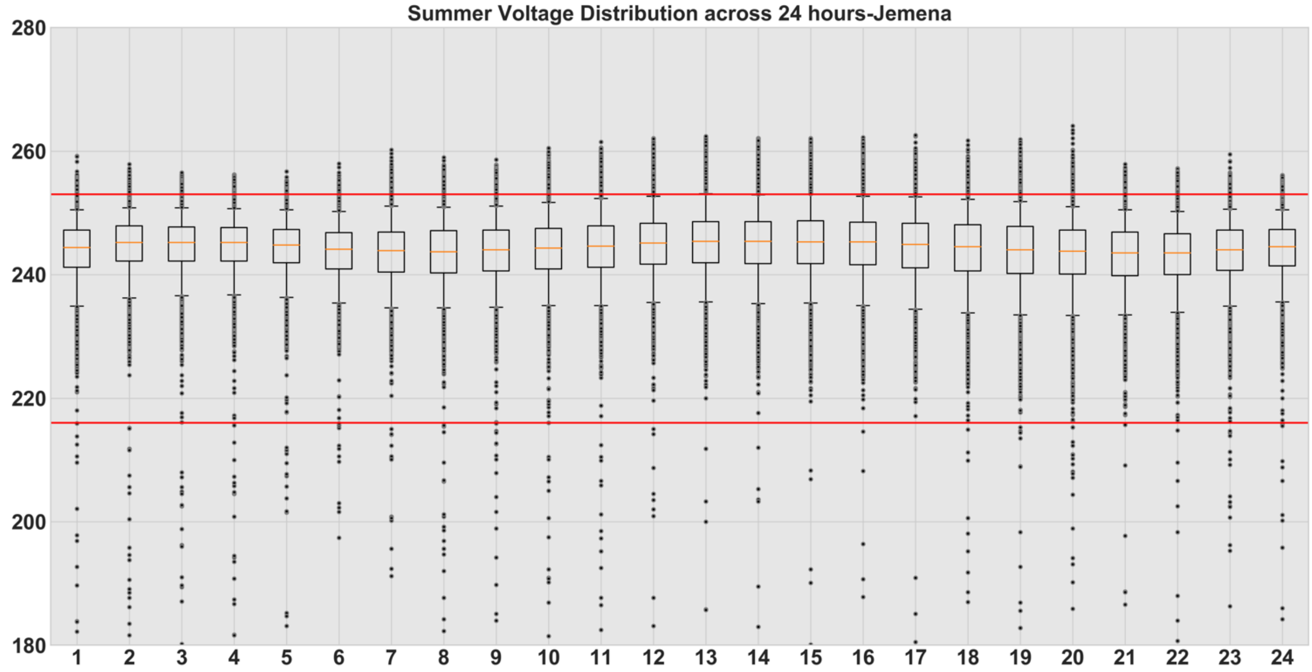


Figure 72 Distribution of voltages across 24 hours for Jemena for Summer

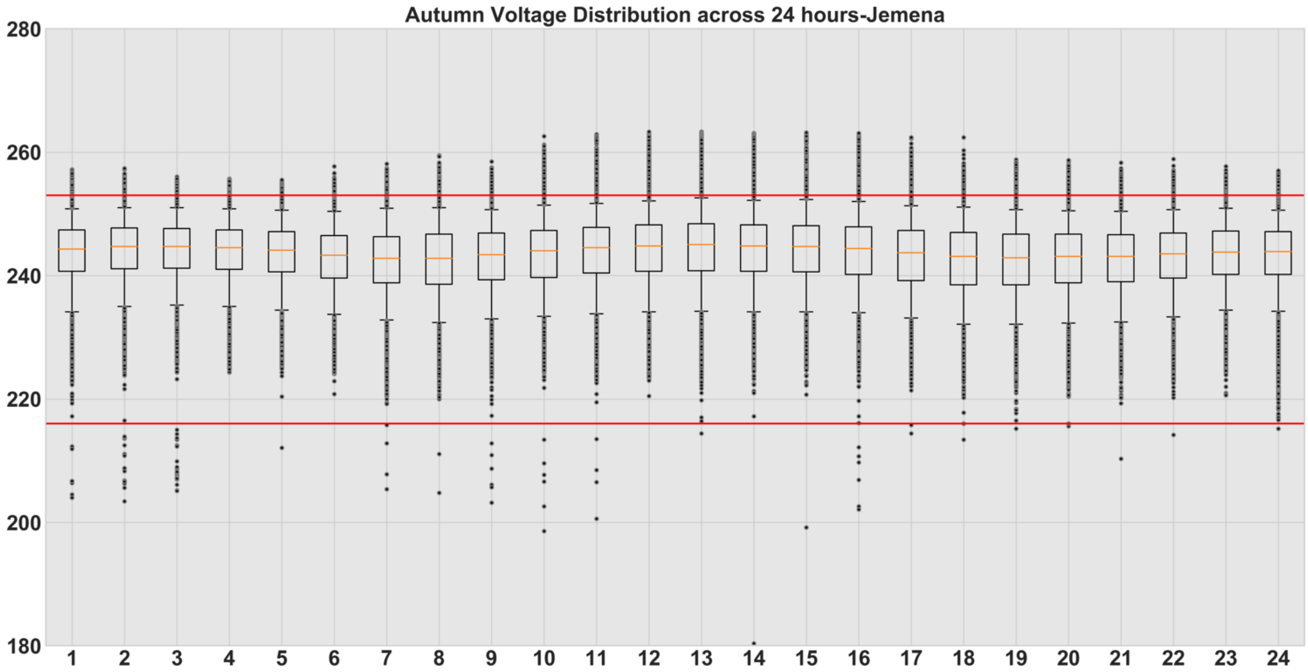


Figure 73 Distribution of voltages across 24 hours for Jemena for Autumn

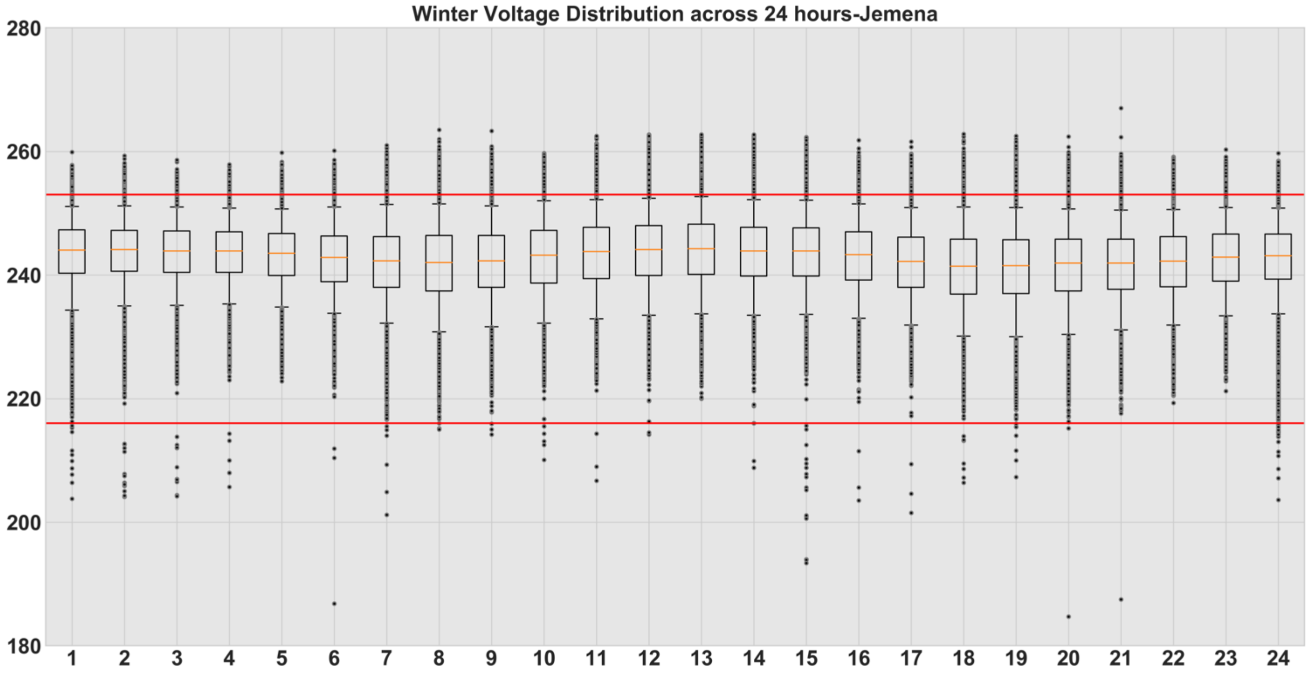


Figure 74 Distribution of voltages across 24 hours for Jemena for Winter

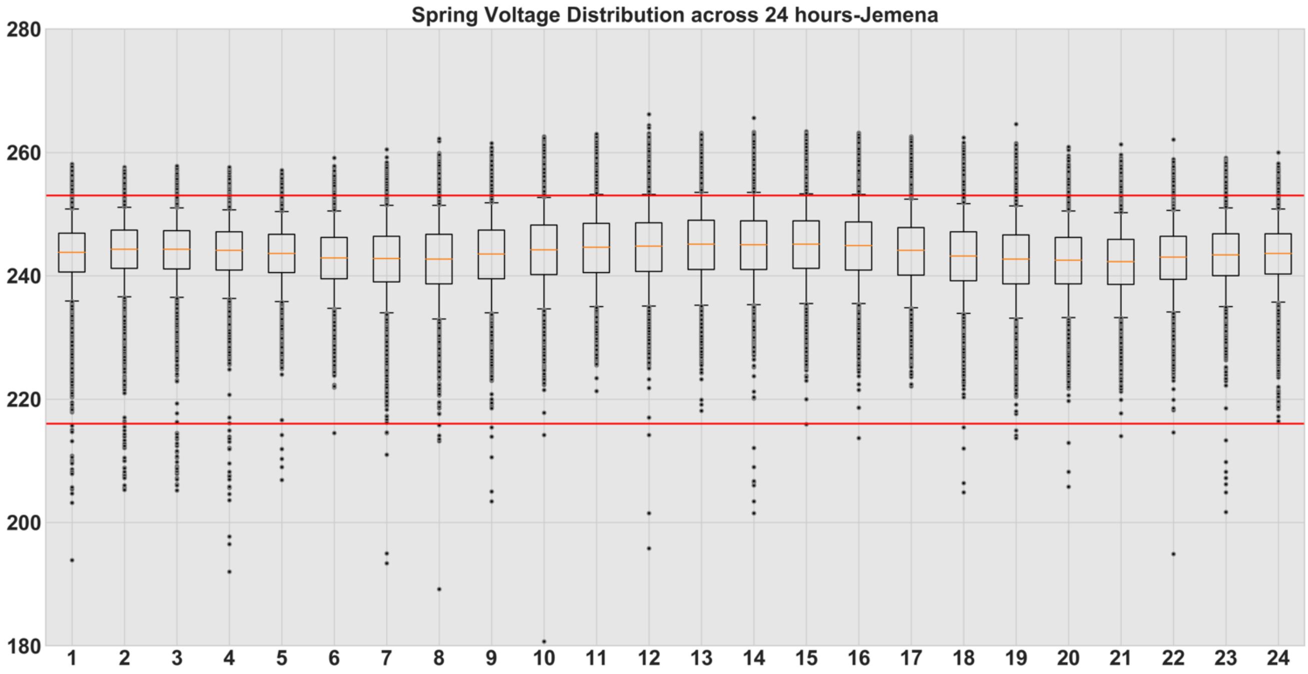


Figure 75 Distribution of voltages across 24 hours for Jemena for Spring

5.4.4 Citipower

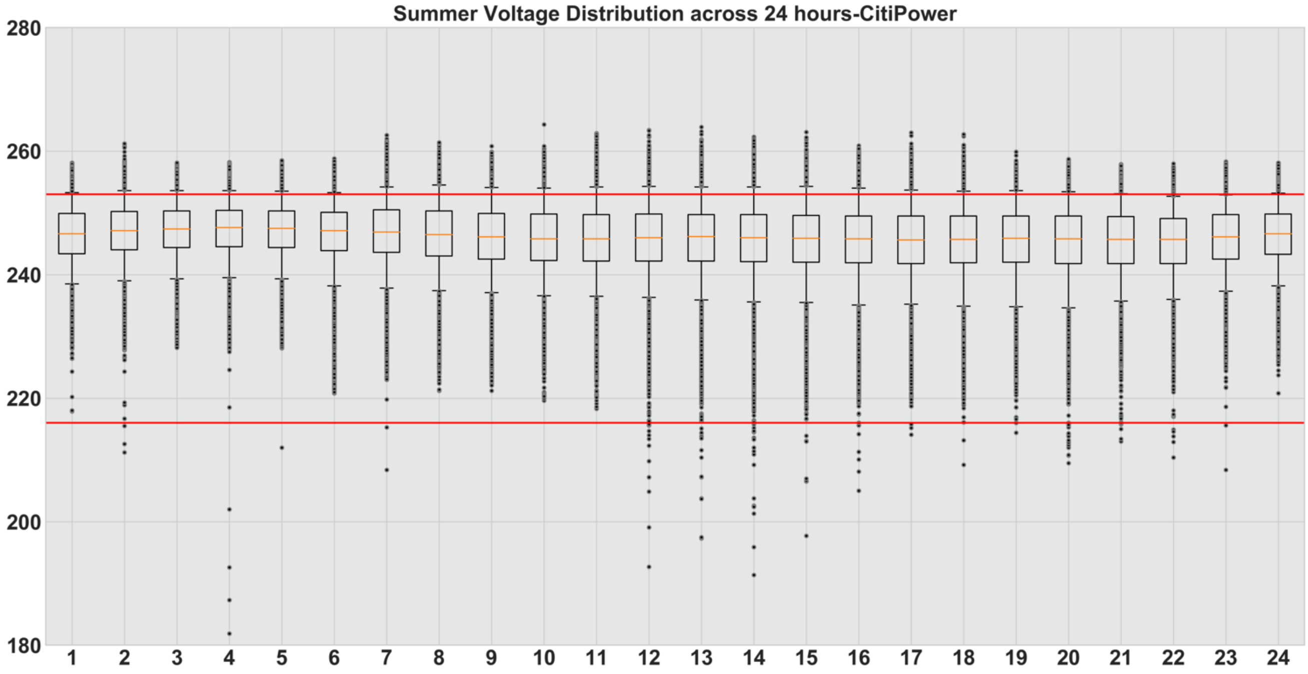


Figure 76 Distribution of voltages across 24 hours for Citipower for Summer

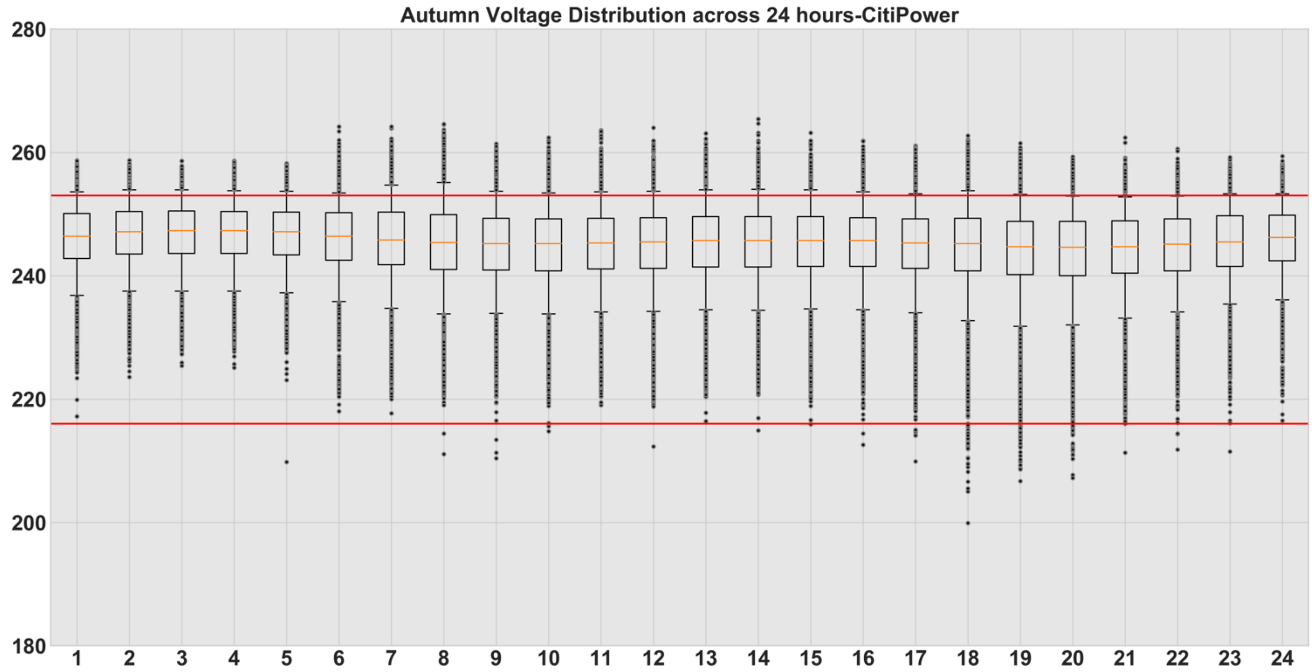


Figure 77 Distribution of voltages across 24 hours for Citipower for Autumn

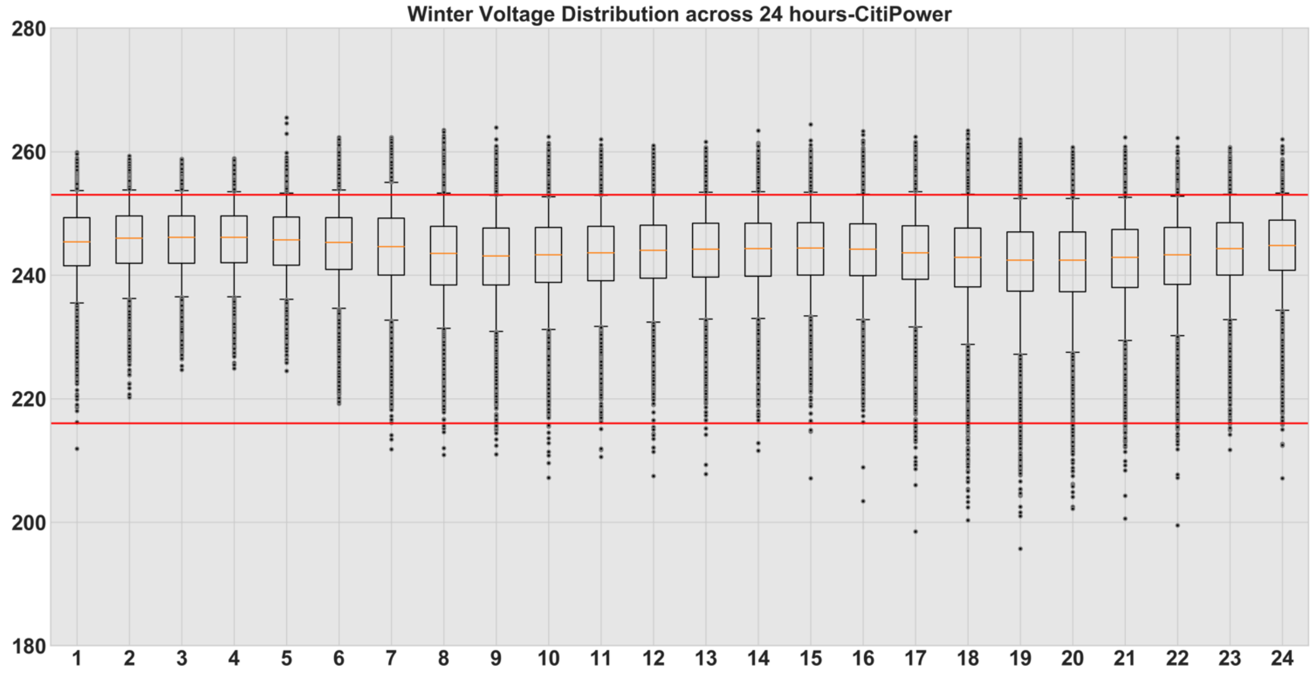


Figure 78 Distribution of voltages across 24 hours for Citipower for Winter

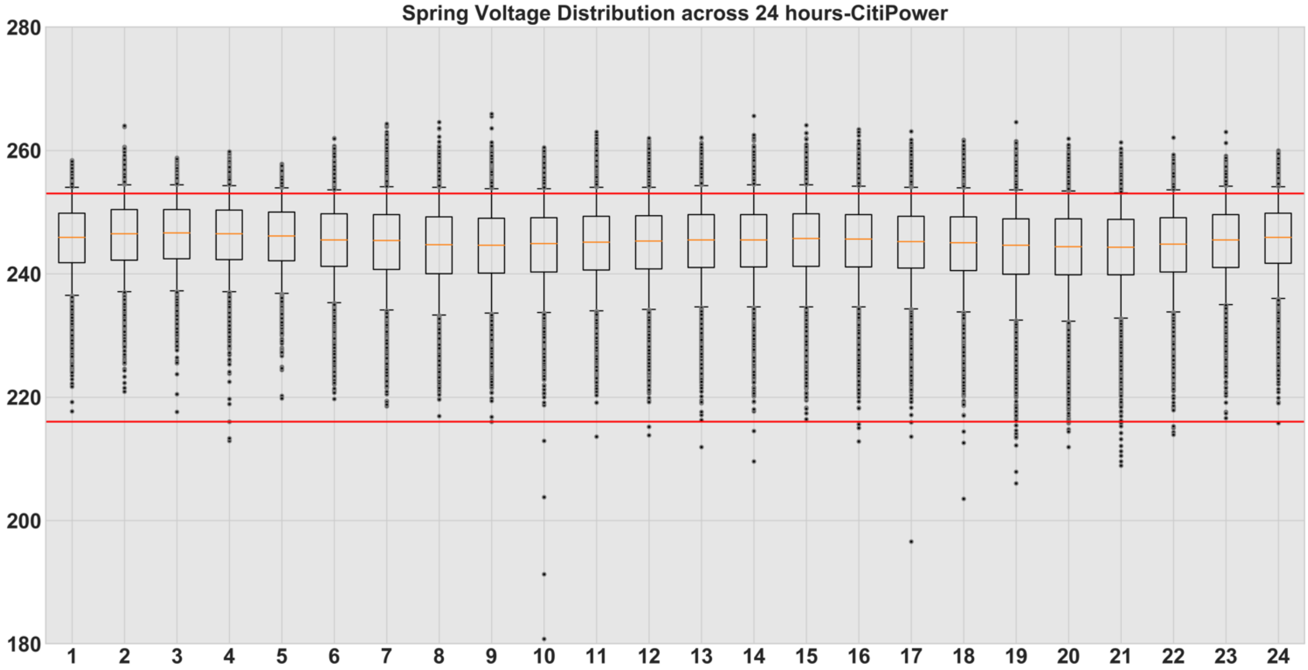


Figure 79 Distribution of voltages across 24 hours for Citipower for Spring

5.4.5 Ausnet

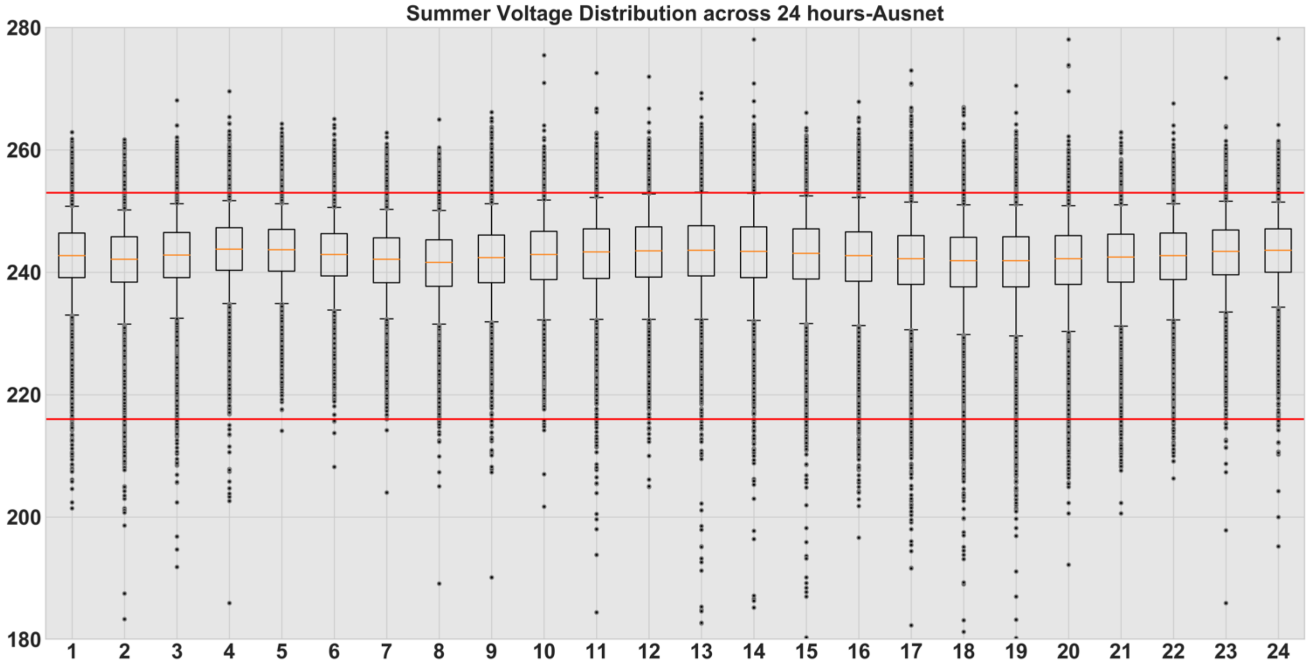


Figure 80 Distribution of voltages across 24 hours for Ausnet for Summer

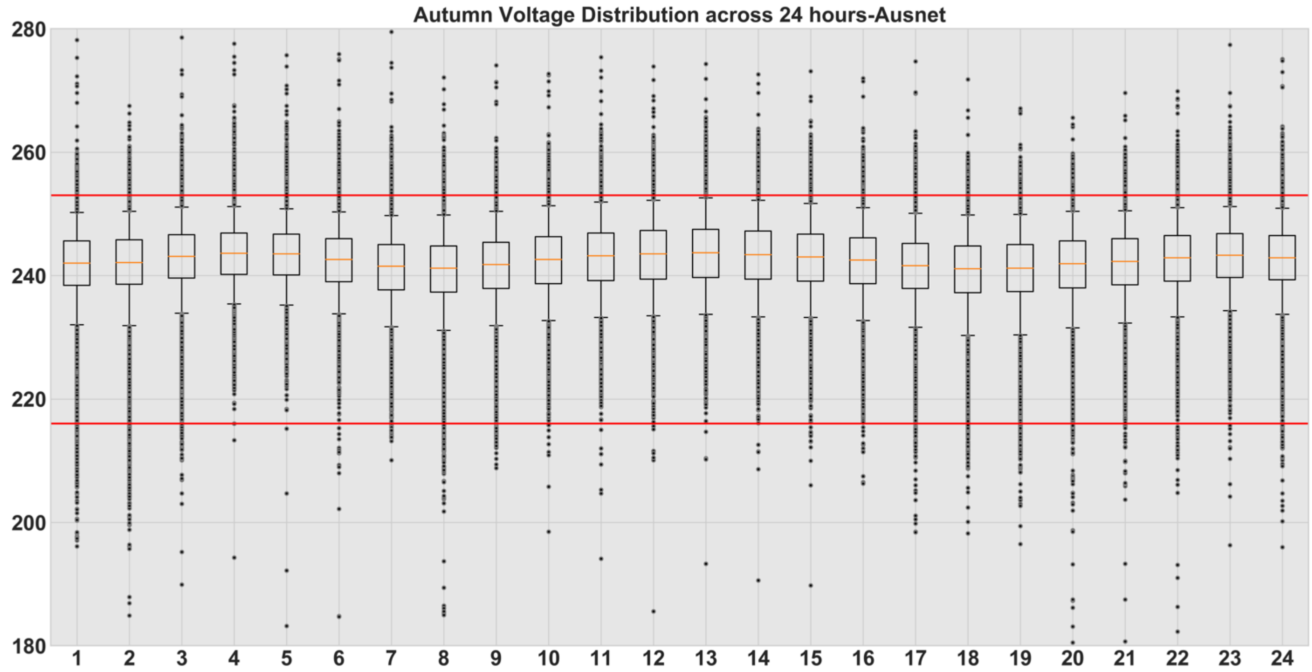


Figure 81 Distribution of voltages across 24 hours for Ausnet for Autumn

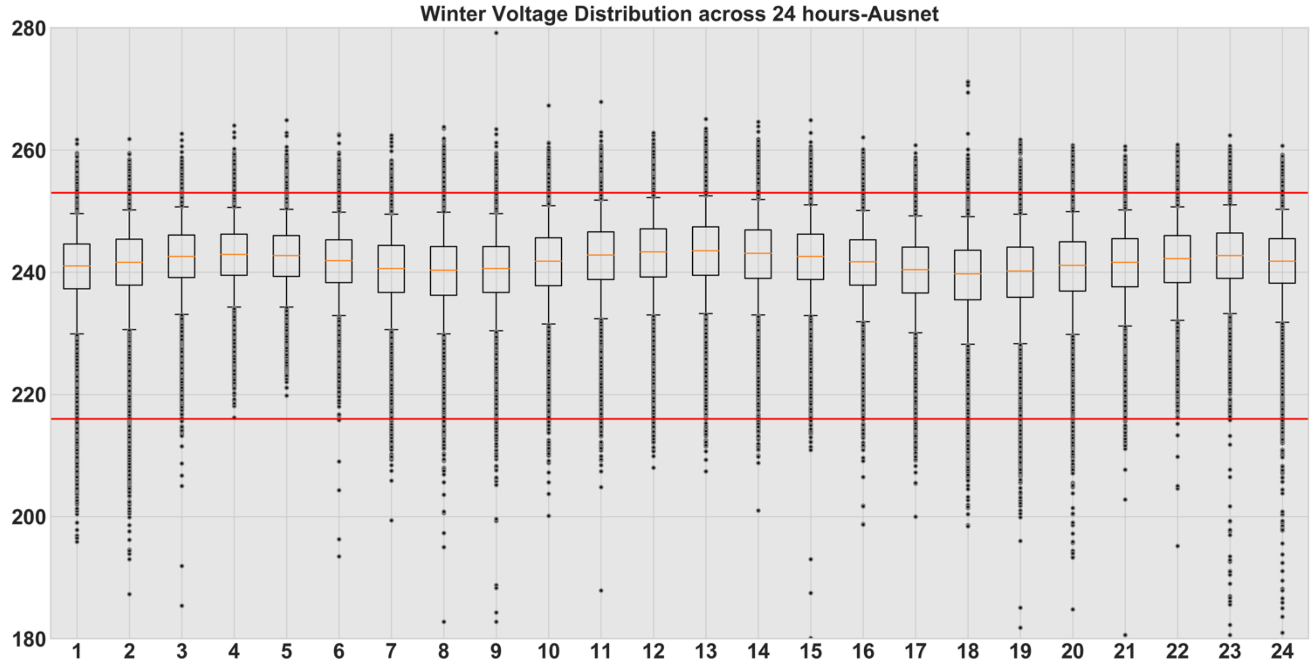


Figure 82 Distribution of voltages across 24 hours for Ausnet for Winter

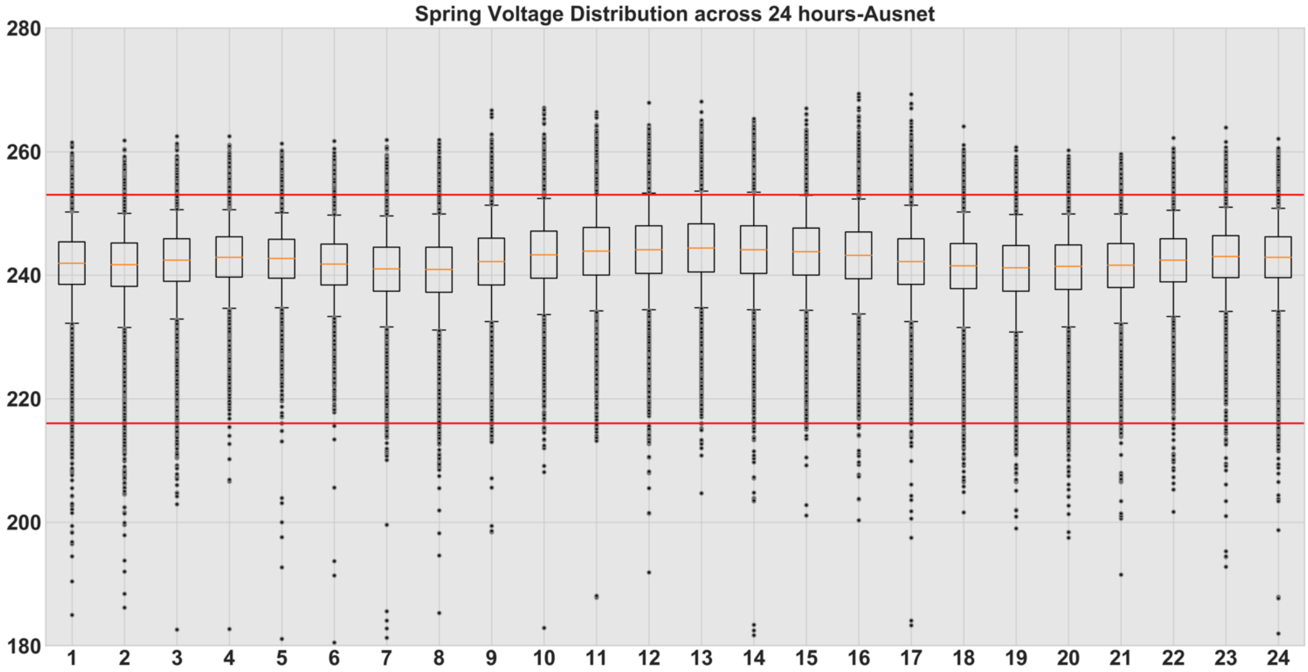


Figure 83 Distribution of voltages across 24 hours for Ausnet for Spring

Given the opportunities to change the upper voltage seen in the LV network using distribution transformer tap changes, it is important to understand the range of voltages being experienced at different sites.

Figure 84, Figure 85, Figure 86, Figure 87 and Figure 88 show the distribution of 241, 171, 124, 61 and 385 households with a full year of data in the Powercor, United Energy, Jemena, Citipower and Austnet networks respectively, ordered by their maximum voltage values experienced throughout the year. For each household the corresponding voltage minimum and the 5th and 95th percentiles of voltage are also shown. There are much fewer data points than for the other states, but as occurred for the other states, the households that experience the highest voltages also experience some occasions of low voltages. Consistent with previous findings, the 95th percentile of the voltage maximum sits at or above the recommended 253 V limit. It can also be seen that the voltage range is much narrower for the 5th to 95th which shows that there may not be a straightforward solution to keep the voltages in recommended limits for a significant number of households.

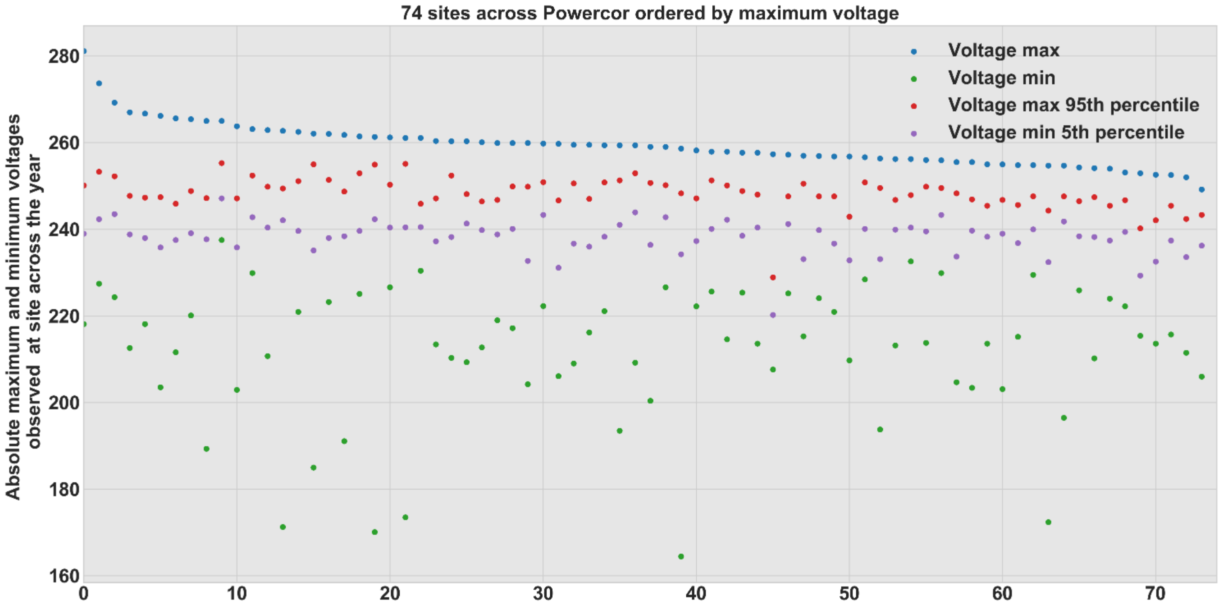


Figure 84 74 sites from Powercor with full calendar year data ordered by highest average maximum voltages

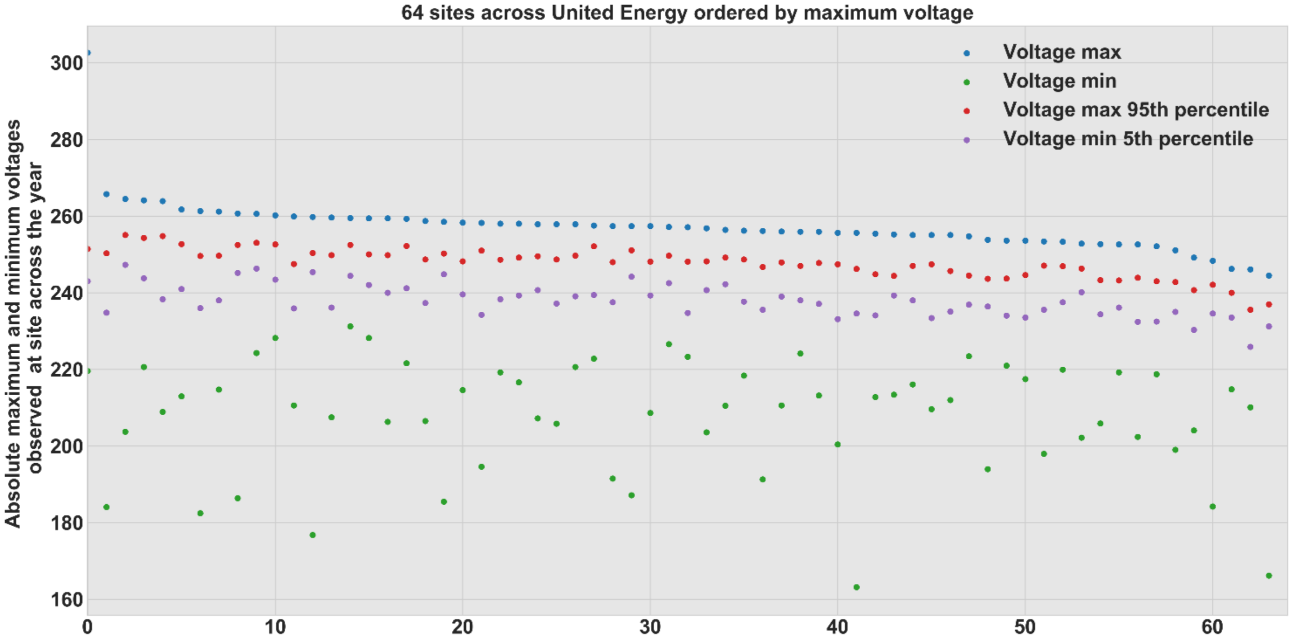


Figure 85 64 sites from United Energy with full calendar year data ordered by highest average maximum voltages

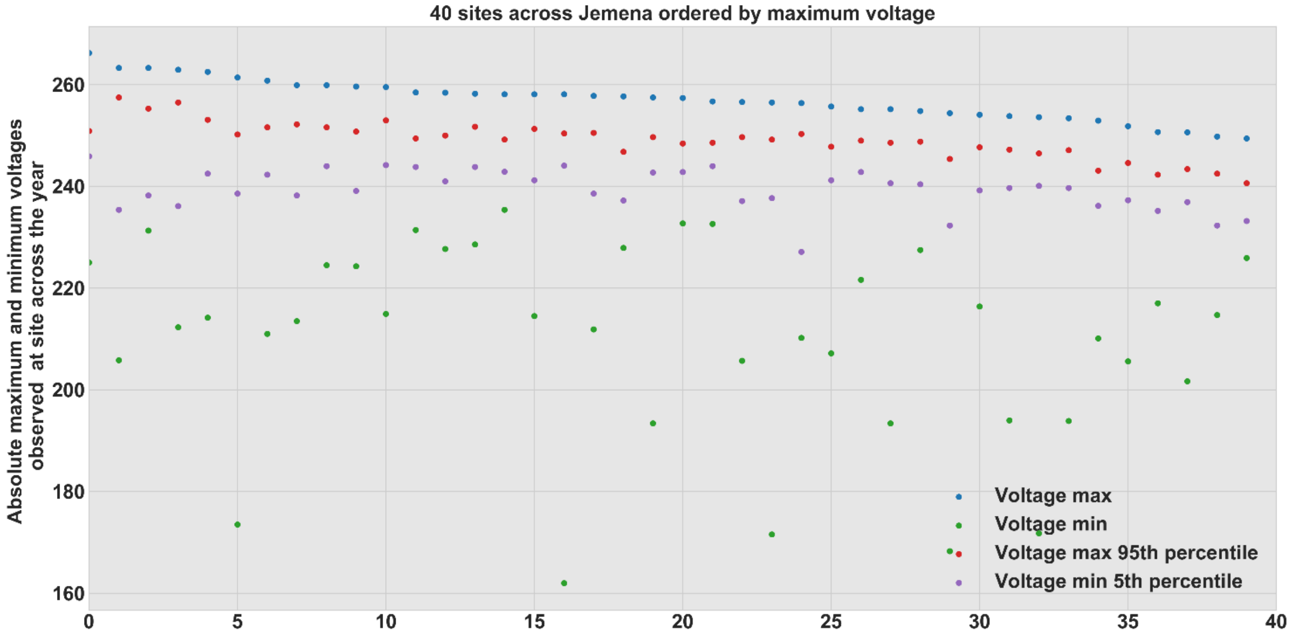


Figure 86 40 sites from Jemena with full calendar year data ordered by highest average maximum voltages

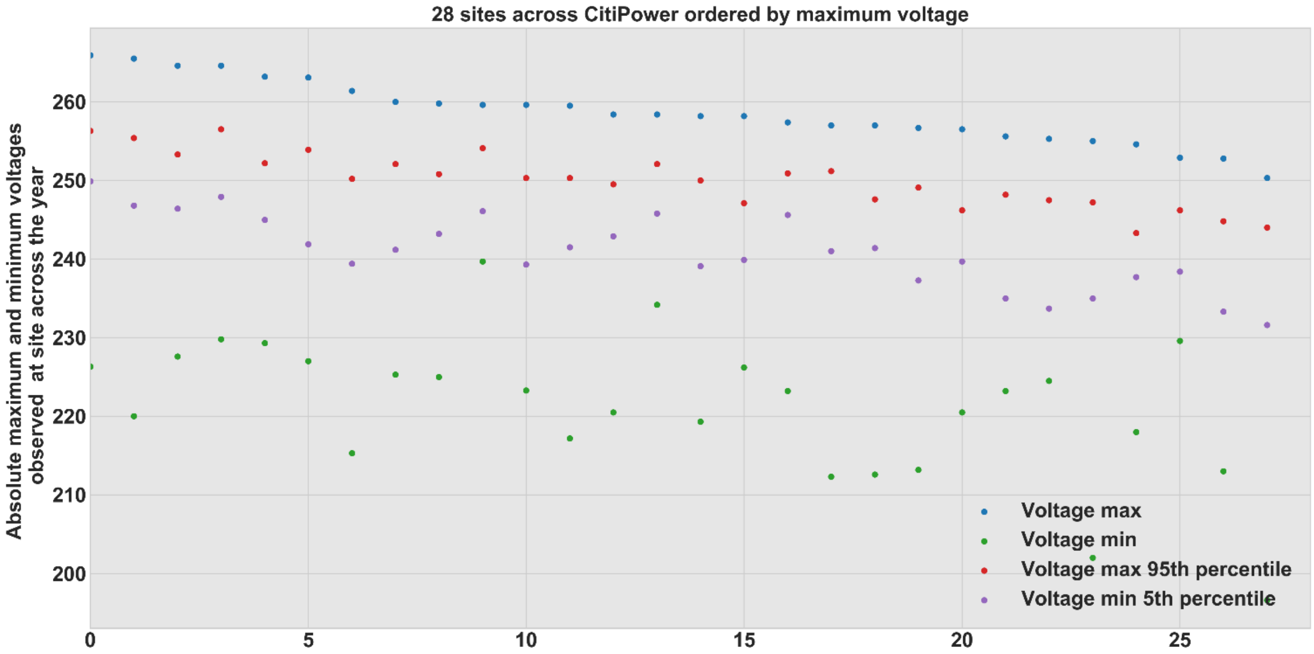


Figure 87 28 sites from Citipower with full calendar year data ordered by highest average maximum voltages

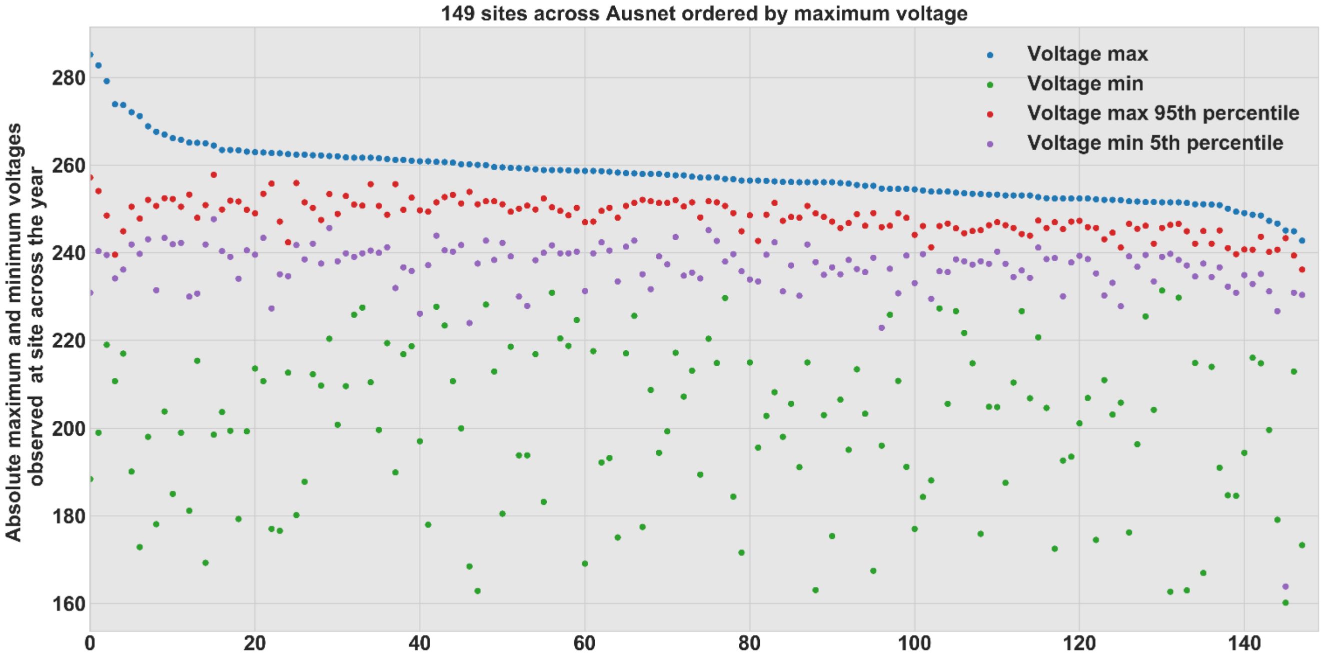


Figure 88 149 sites from Ausnet with full calendar year data ordered by highest average maximum voltages

5.5 Tasmania (TasNetworks)

Figure 89 and Figure 90 show the average maximum and minimum voltages seen by all the sites in Tas throughout the year. Site locations are categorised as one of ‘Suburban’, Inner Regional, ‘Outer Regional’ and ‘Remote’. In addition to the voltages, the Tas net demand (total State electricity demand minus any small scale hence not directly monitored distributed generation including PV) is also presented.

The variation in average maximum voltage seen across the year highlights systemic drivers of voltage across the state, and periods of higher Tas demand are generally associated with lower voltages. Tas demand is gensrally higher in winter months, and also experiences its periods of peak demand in winter, and these clearly drive periods of lowest maximum voltage and minimum. Voltage variations throughout the year increase slightly going from Regional to Remote locations (although note that the Remote values are from only 1 site). It is also notable that average maximum voltages generally sit around 240V over the entire year, although they are generally highest in Dec, March and Sept, when State demand is typically lower and PV performance is relatively high.

The minimum voltages largely follow the maximum voltage patterns above, but our findings particularly highlight how high average minimum voltages generally are, noting that 240V is around 5% above the nominal 230V, while the preferred voltage range is in the relevant Australian Standard is +6% to -2%.

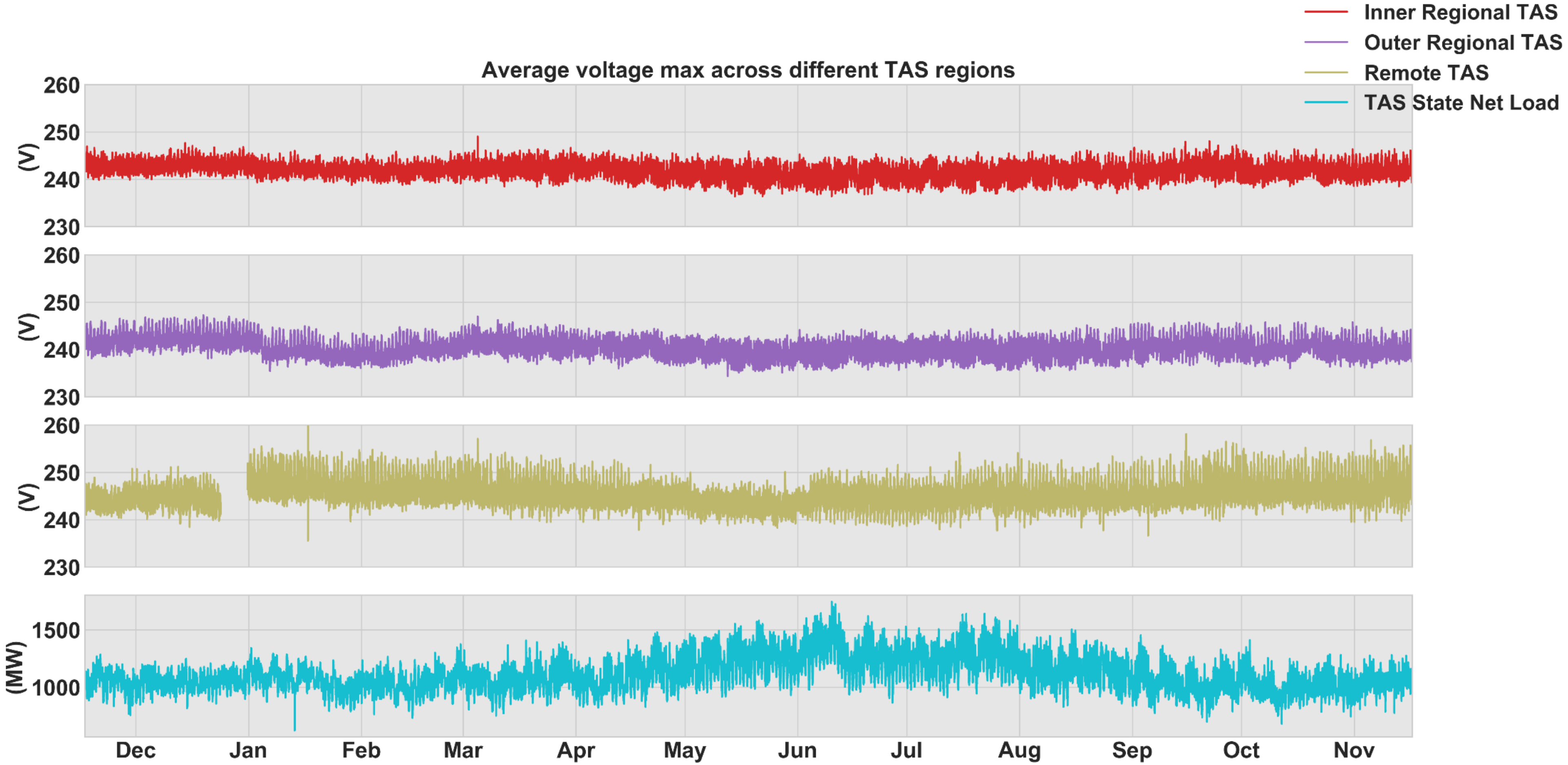


Figure 89 Average voltage maximum across different regions of Tasmania and the net state load

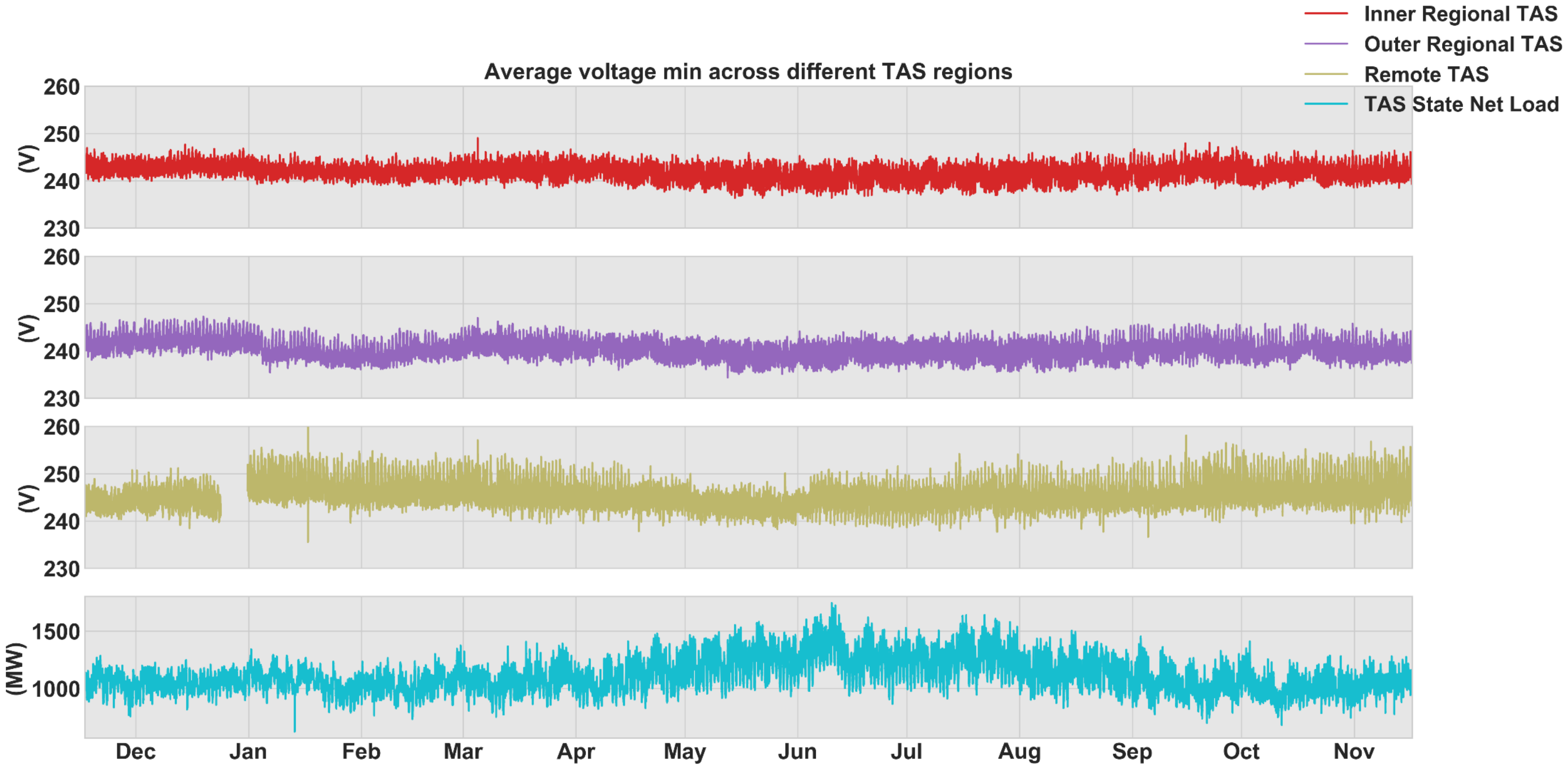


Figure 90 Average voltage minimum across different regions of Tasmania and the net state load

Figure 91 and Figure 92 illustrate the distribution of maximum and minimum voltage across the regions. The histograms cover the 1st to 99th percentile of the voltage range so as to focus on the general distribution (the outlier voltages can be observed in the boxplots in Figure 93 to Figure 96). The Y axis shows the range of voltages whereas the X axis shows the percentage of the times a voltage value is observed. The number of households used for the analysis is shown for each region. The voltage values cover the entire yearly period of the 5 minute voltages monitored across the households.

It is clear that maximum voltages are generally well above 230V and often close to, or even exceeding, the upper Australian Standard limit of 253V, especially in Outer Regional locations, which experience higher voltage maximums and lower voltage minimums than Inner Regional locations. Again, note that the Remote values are based on only one site.

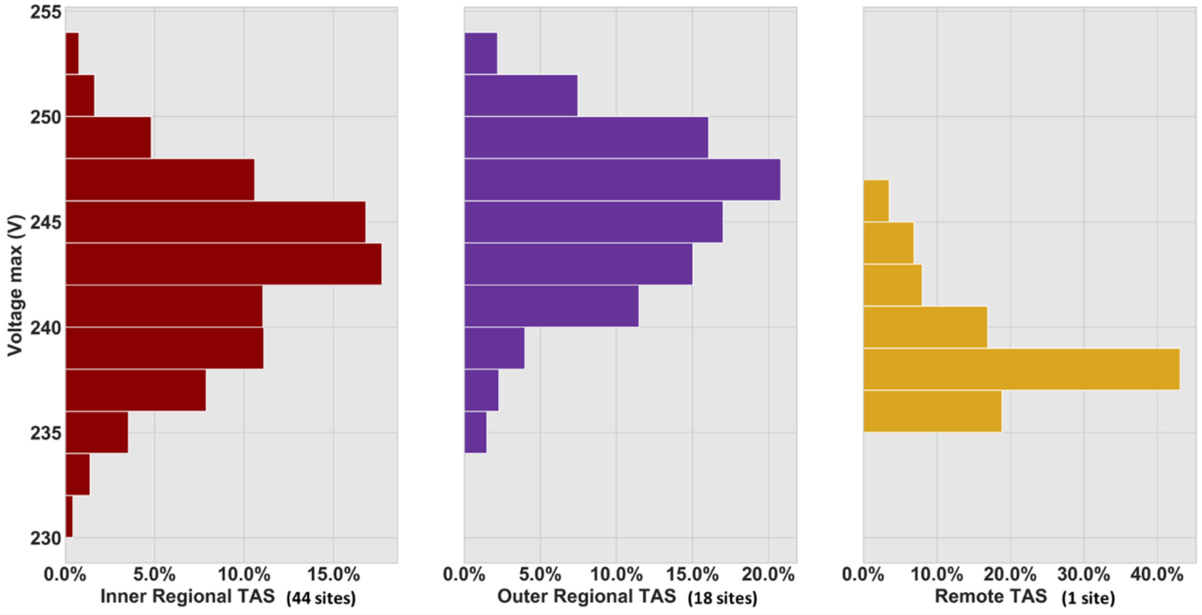


Figure 91 Distribution of maximum voltages across Tasmanian regions

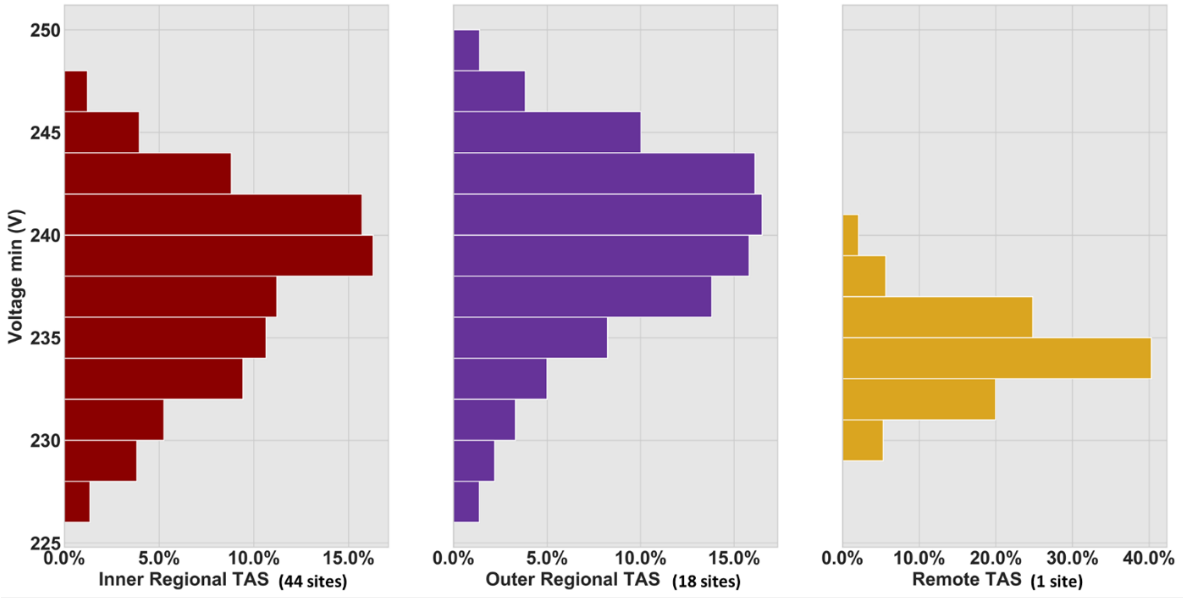


Figure 92 **Distribution of minimum voltages across Tasmanian regions**

Figure 93 to Figure 96 show how site voltages vary over a 24 hour period in different seasons. The plots show the distribution of seasonal minimum and maximum voltages. Each hour includes the entire dataset of monitored TasNetworks sites (63 sites) voltage data across the respective season. The red horizontal lines represent the AS/NZS standard recommended max and min voltage levels: 253V and 216V respectively. The Box plot whiskers are the 5th and 95th percentile of the voltages observed within the particular hour and the dots represent the outliers beyond this range.

It can be seen that the maximum voltage levels are closer to the upper 253V limit rather than the lower limit, regardless of the season or time of day. During the midday and early afternoon periods (12pm-2pm) voltage levels increase, especially in Spring, which is consistent with increasing distributed PV generation and typically reduced residential demand. Sustained voltages above 255V should see post 2015 inverter curtailment begin to commence, as explored further in Section 7. Further, very early morning periods that are typically also periods of lower demand also show high voltages, being about the same as the midday voltages. It is also apparent from the plotted voltage outliers that some sites experience infrequent very low voltages at different times of the day, where voltages can go below the lower 216 V limit.

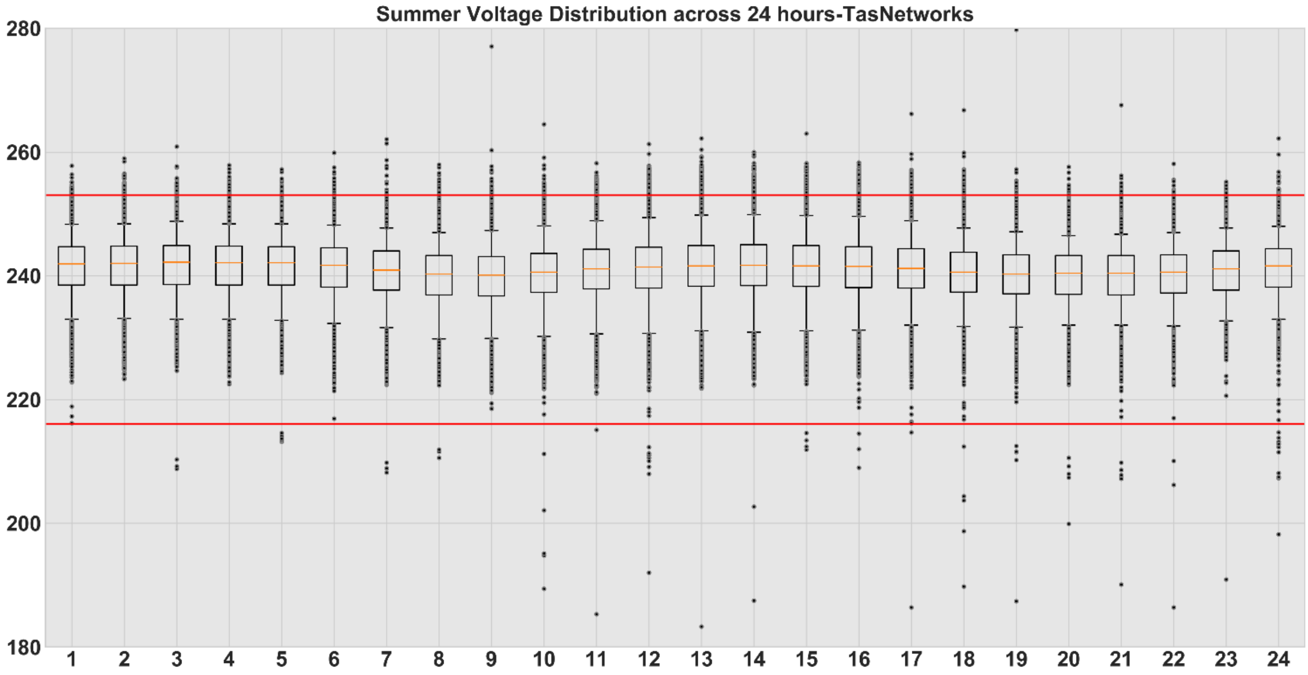


Figure 93 Distribution of voltages across 24 hours for TasNetworks for Summer

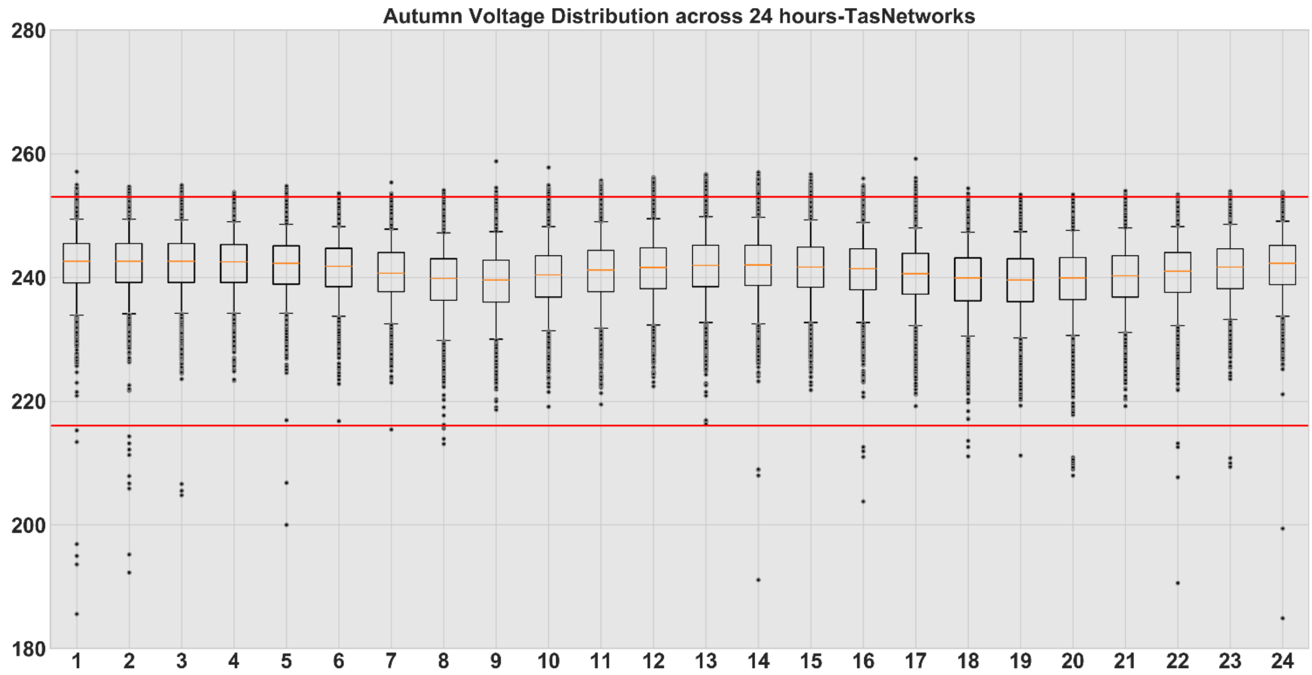


Figure 94 Distribution of voltages across 24 hours for TasNetworks for Autumn

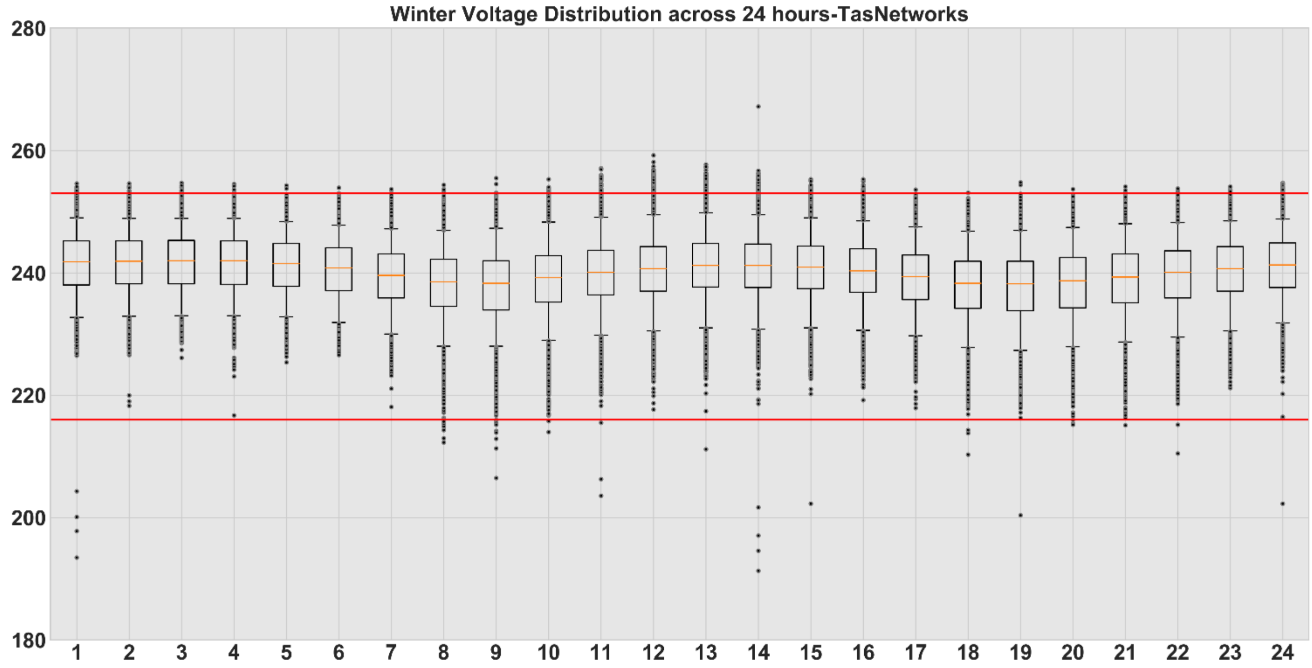


Figure 95 Distribution of voltages across 24 hours for TasNetworks for Winter

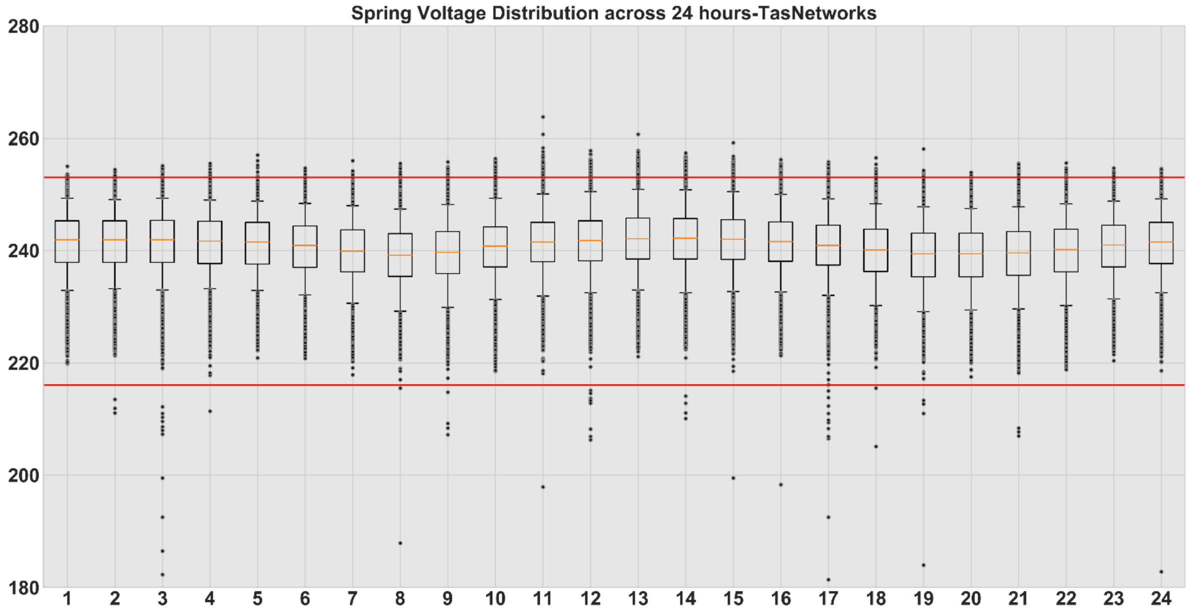


Figure 96 Distribution of voltages across 24 hours for TasNetworks for Spring

Given the opportunities to change the upper voltage seen in the LV network using distribution transformer tap changes, it is important to understand the range of voltages being experienced at different sites. Figure 97 shows the distribution of 28 households with a full year of data, ordered by their maximum voltage values experienced throughout the year. For each household the corresponding voltage minimum and the 5th and 95th percentiles of voltage are also shown. It can be seen that the sites that experience the highest voltages also experience some occasions of extremely low voltages. Consistent with previous findings, the 95th percentile of the voltage max sits near, at or above the recommended 253 V limit for many sites. It can also be seen that the voltage range is much narrower for the 5th to 95th percentile of voltages, which suggests that there may be opportunities to narrow the voltage range experienced by consumers through actions that are only required for very occasional low voltage excursions.

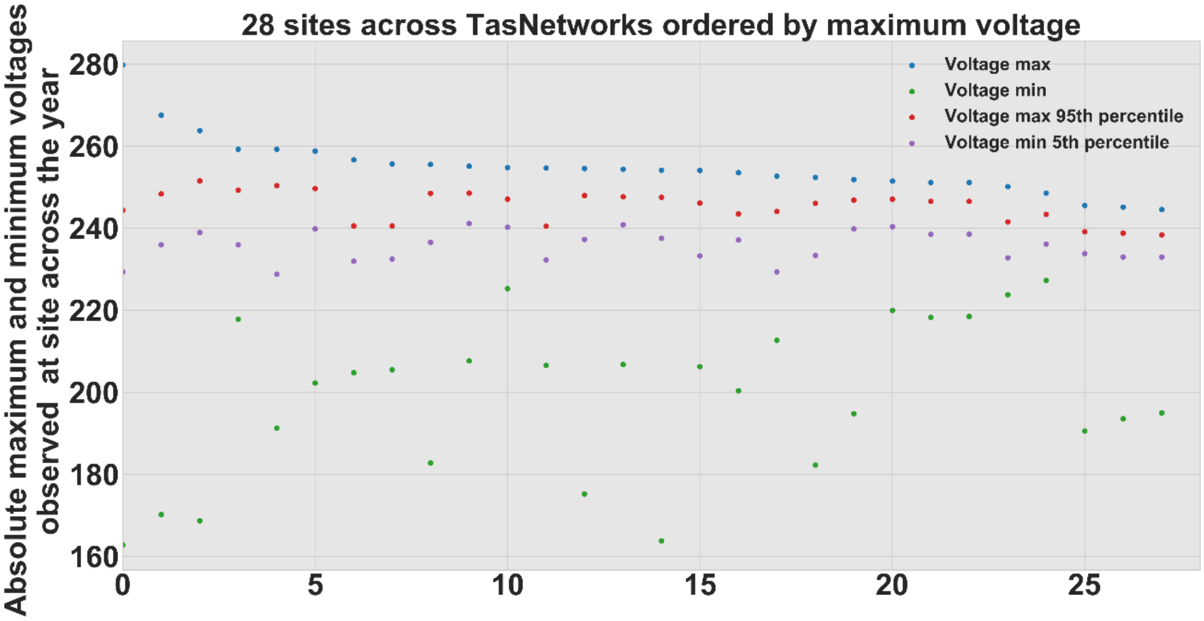


Figure 97 28 sites from TasNetworkswith full calendar year data ordered by highest average maximum voltages

6 Correlation between solar PV export and voltage

This section presents the results of the analysis regarding the correlation between site PV exports (when the generation of PV exceeds site load leading to PV exports to the grid) and voltages. All States in the NEM, and the ACT, are covered.

As noted earlier, PV exports are an outcome of site load as well as any site PV generation. Site PV exports only occur during daylight hours when the PV generation exceeds site load. As such, it captures aspects of both the profile of typical site demand (for example, lower consumption during the middle of the day while household occupants are away at work and Schools) as well as the site's PV generation.

6.1 Method

Two methods are used to show the correlation between PV export and voltage. The first derives a simple linear relationship between PV export and voltage. The second examines the difference in the voltage distribution when there is zero PV export and when there is non-zero PV export during the daylight hours of 10am to 4pm, representing typical hours of peak PV generation.

6.2 Estimating the relationship between PV export and voltage

The first method calculates the linear relationship between PV export and voltage for an area. It includes the following steps:

1. Data points with zero PV export are filtered out, leaving data points with non-zero PV export only. As such, only daytime periods with PV generation exceeding site demand are captured.
2. Least squares linear regression is then used to estimate a linear equation (y = ax + b) associating voltage max (y) and PV export (x).

The gradient (a) defines how the voltage changes with a change in PV export. The gradient and correlation coefficient (R^2) are recorded for each postcode. Figure 98 shows a scatter plot for a particular postcode, showing the relationship between PV export and voltage max. It is important to note that this model fit does not include periods of high voltages when there is no PV generation including, of course, night time hours.

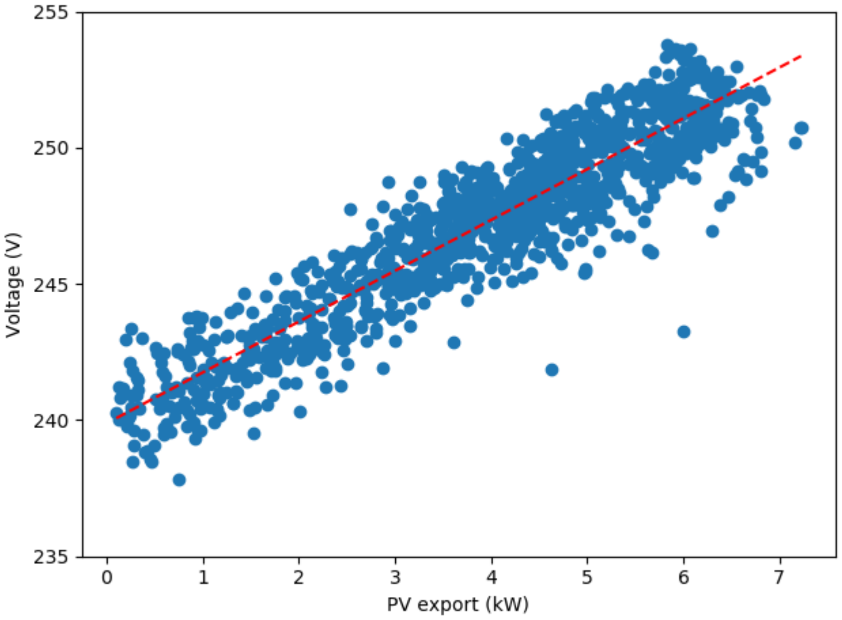


Figure 98 Scatter plot showing relationship between site PV export and Voltage max for a particular postcode. The red dashed line is the linear equation derived using Least squares linear regression.

The gradient (a) is a potentially useful measure of how sensitive voltage is to a change in PV export, depending on the significance of the observed correlation. Referring again to remoteness and PV install density, it is expected that:

- More remote postcodes will have a higher gradient, due to the higher impedance lines, and
- Postcodes with a higher PV density will also have steeper gradients, due to more surrounding PV systems exporting, pushing up the site voltage.

6.3 Voltage distribution difference: Zero versus non-zero PV export during daylight hours

For each area, data points are divided into two segments:

1. Non-zero PV export measurements.
2. Zero PV export measurements, within the typically peak solar hours of 10 am to 4 pm.

The voltage distribution is then calculated for each segment. Figure 99 gives an example of how the voltage distribution differs between zero and non-zero PV export for a single postcode area in suburban Sydney. The results produced from this method are then presented as box and whisker plots.

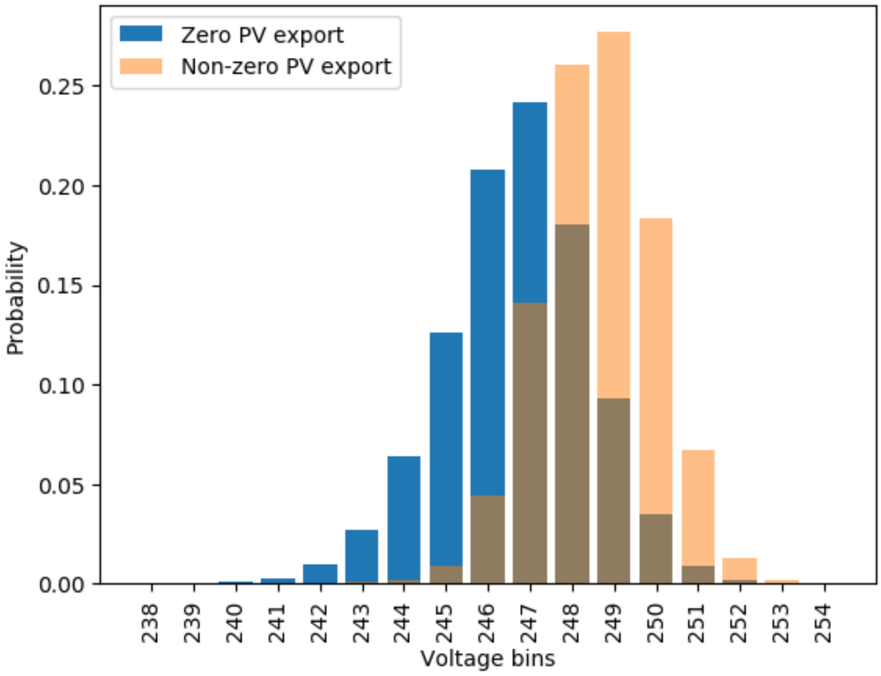


Figure 99 Voltage distribution (zero and non-zero PV export) for a postcode in suburban Sydney over daylight hours 10am-4pm.

6.4 Results

This section presents the results of the correlation analysis. The results for both methods are presented as box and whisker plots. For all plots, whisker caps are set to 5% and 95%, meaning that only 5% of the data points are below the lowest whisker and the highest whisker includes 95% of all the data points. The line in the middle of the box represents the median value. A missing box and whisker means there were no SolA sites within the DNSP for that particular PV install density or Remoteness category.

6.4.1 Linear relationship: PV export and voltage

Figure 100 presents the range of voltage rise gradients for all postcodes analysed. A gradient > 0 indicates that a postcode will typically experience voltage rise when solar PV exports are occurring. Note that some postcodes include only a small number of sites (< 5), and therefore the gradient calculated may likely not be representative of all the sites with solar PV installed within the postcode. Furthermore, the correlation between voltage rise and PV exports is in many cases not strong, meaning that PV exports has only limited explanatory power in estimating voltages. Still, if one was to assume that the SolA data for each postcode is representative of all systems within the entire postcode and correlations are sufficiently significant, then sites within 89% of postcodes will typically experience some measure of voltage rise during the peak PV generation hours of 10am-4pm when solar PV export is occurring.

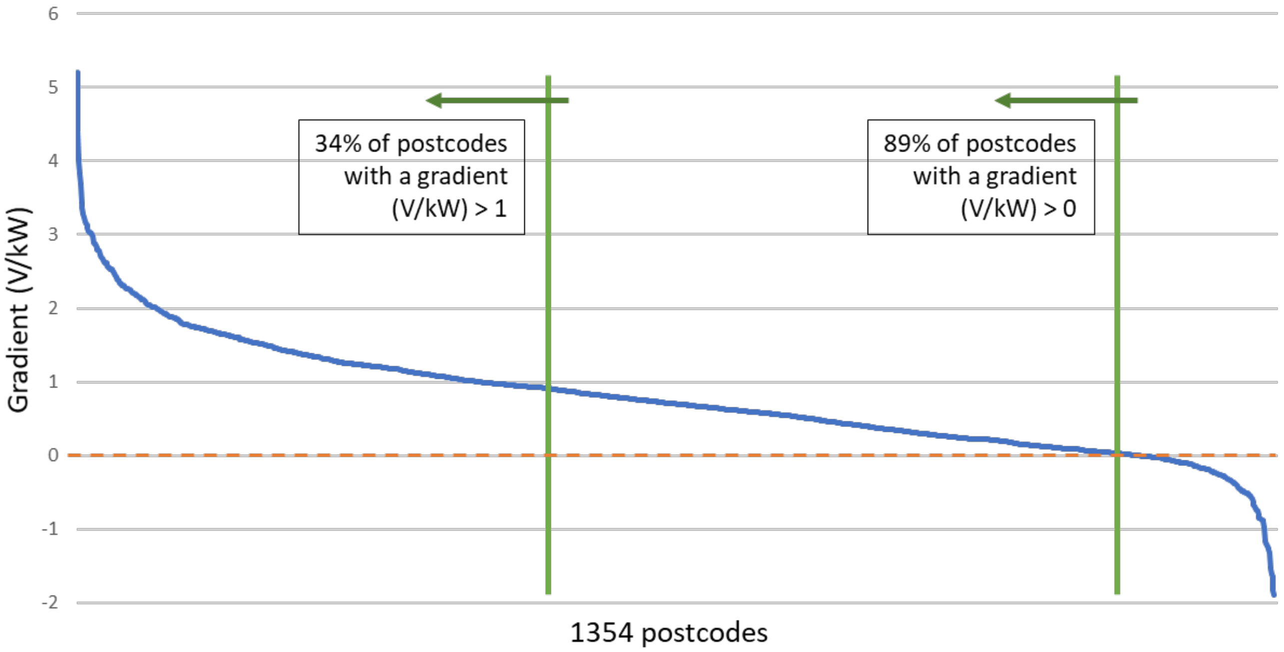


Figure 100 Range of gradients for all postcodes

Table XII provides details for the 25 postcodes which had the highest gradient (V/kW) for the linear equation estimating their relationship between PV export and voltage rise during daylight hours.

Table XII Details of top 25 postcodes which had the highest gradient (V/kW) for the linear equation estimating their relationship between PV export and voltage rise.

Gradient (V/kW)	DNSP	Postcode	Remoteness	PV install density
2.38	Ausgrid	2076	Suburban	10% - 20%
2.25	Essential	2701	Inner regional	20% - 30%
2.23	Essential	2446	Inner regional	30% - 40%
2.15	Essential	2484	Suburban	40% - 50%
2.01	SAPN	5019	Suburban	30% - 40%
1.91	SAPN	5351	Inner regional	> 50%
1.88	Ausgrid	2063	Suburban	10% - 20%
1.83	Energex	4557	Suburban	40% - 50%
1.74	SAPN	5244	Inner regional	40% - 50%
1.70	SAPN	5204	Inner regional	30% - 40%
1.69	SAPN	5152	Suburban	20% - 30%
1.64	SAPN	5608	Outer regional	20% - 30%
1.60	SAPN	5280	Outer regional	20% - 30%
1.60	Energex	4034	Suburban	30% - 40%

1.56	Ausgrid	2073	Suburban	10% - 20%
1.54	Energex	4306	Suburban	> 50%
1.52	SAPN	5255	Inner regional	40% - 50%
1.50	Energex	4152	Suburban	30% - 40%
1.48	SAPN	5093	Suburban	30% - 40%
1.48	Ausgrid	2126	Suburban	20% - 30%
1.41	Ausnet	3862	Inner regional	30% - 40%
1.40	Ausnet	3875	Outer regional	20% - 30%
1.38	Energex	4035	Suburban	40% - 50%
1.38	Energex	4053	Suburban	20% - 30%
1.37	Essential	2477	Inner regional	40% - 50%

For the top 50 postcodes with the highest gradients, Table XIII provides details on their distribution according to DNSP, PV install density and Remoteness. The postcode with the smallest number of sites was 5280 with 14, all postcodes in the top 50 otherwise met the following criteria:

- Correlation between PV export and Voltage (R^2) > 0.4 (suggesting potential statistical significance)
- Number of site days (equivalent) worth of data > 500

Table XIII Details on distribution of top 50 postcodes (highest V/kW gradients) according to DNSP, PV install density and Remoteness

DNSP	Number of Sites	PV install density	Number of Sites	Remoteness	Number of Sites
Ausgrid	6	< 10%	0	CBD	0
Ausnet	2	10% - 20%	11	Suburban	30
Energex	13	20% - 30%	20	Inner regional	15
Ergon	2	30% - 40%	11	Outer regional	5
Essential	7	40% - 50%	5	Remote	0
Jemena	1				
SAPN	19				

The following group of figures below show the scatter plot for each of the top 5 postcodes with the highest gradient. It can be seen that although voltage generally increases as PV export increases, there is significant variation, with very low PV export sites having high voltages (often above the 253V max) and high PV export sites that have voltages lower than these low PV export sites. This highlights the variety of influences on voltage that are quite separate to PV (as outlined in Section 4.2).

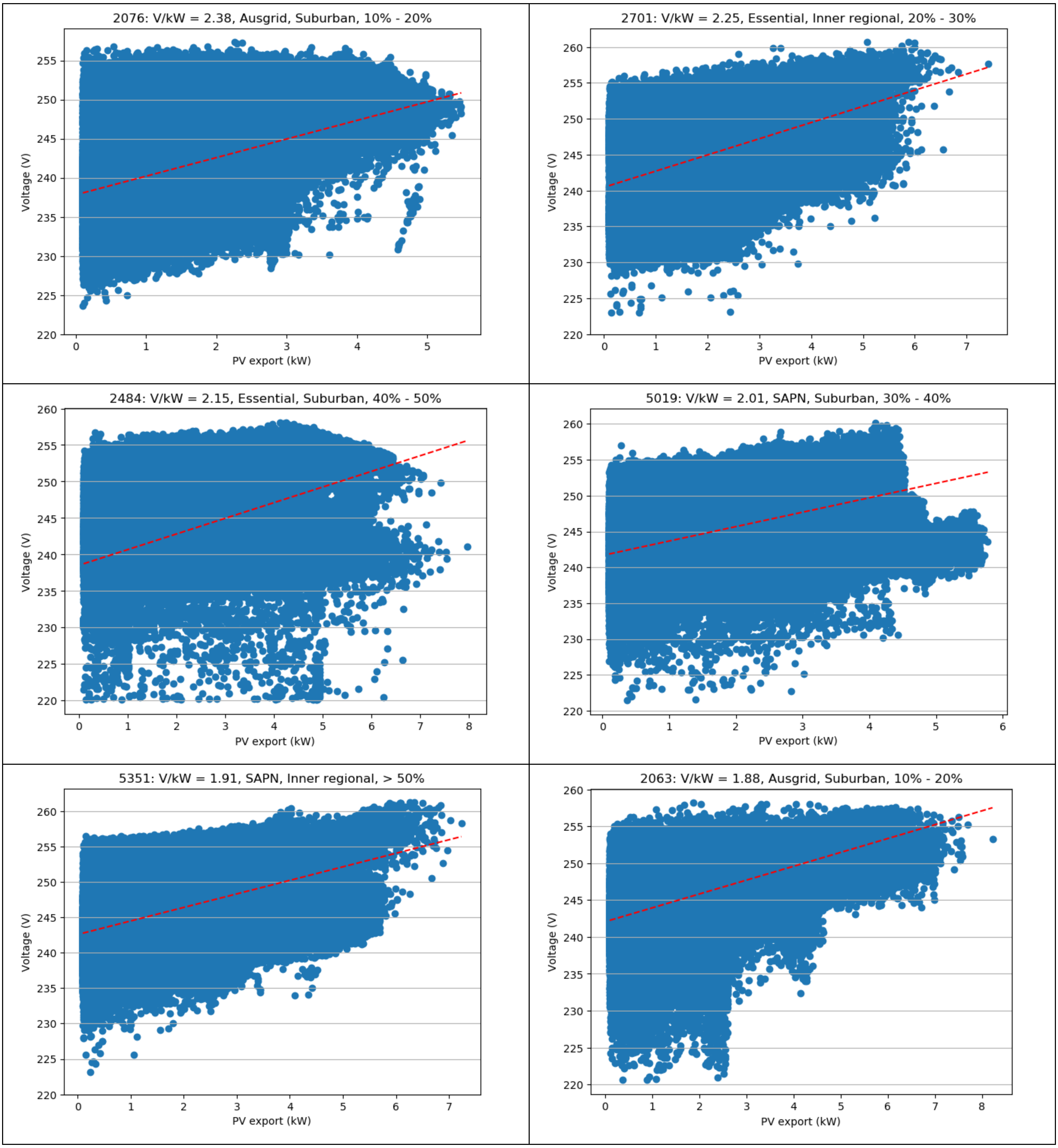


Figure 101 Scatter plots for the top 5 postcodes with the highest gradient of site voltages with site PV exports during 10am-4pm.

6.4.2 Voltage distribution difference: Zero versus non-zero PV export

The following figures present the results using the Voltage distribution difference method.

State and Territory and DNSP

Figure 102 and Figure 103 show the voltage distribution difference between zero and non-zero PV export for States and Territories and DNSPs during daylight hours. It can be seen that PV export has a similar impact on voltage for all States and Territories, with the impact in the ACT being slightly higher and the impact in Tasmania being lower. The DNSPs also all have similar impacts, with ActewAGL and TasNetworks being higher and lower respectively, as expected. The median voltage impact ranges from 2V to 5V. Interestingly, PV generally increases the low voltage whisker more than the high voltage whisker, indicating it can be beneficial for reducing the occurrence of low voltage events; that is, when high PV generation helps reduce the impact of high peak demands from air conditioning during very hot days.

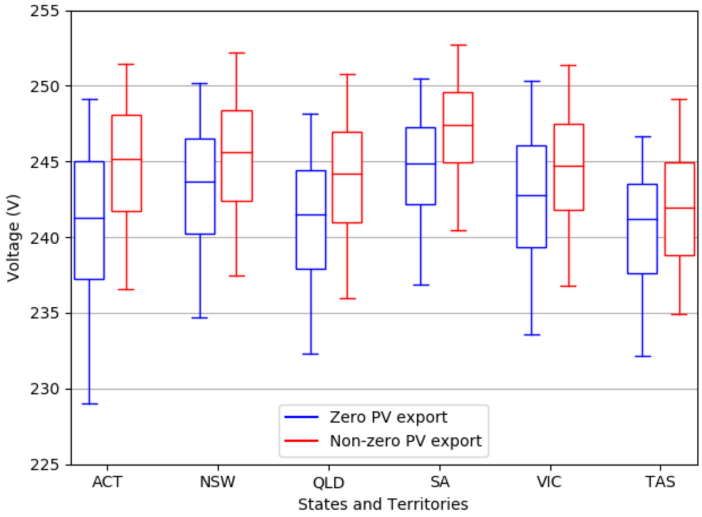


Figure 102 Box and whisker plot showing Voltage distribution difference between zero and non-zero export for all states and territories during daylight hours 10am – 4pm.

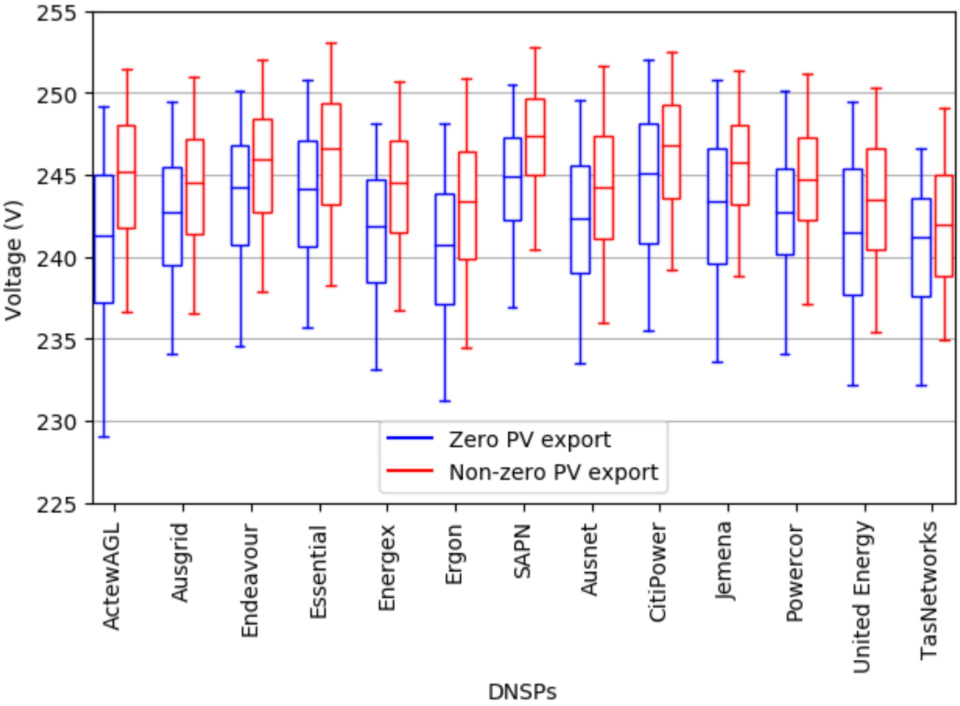


Figure 103 Box and whisker plot showing Voltage distribution difference between zero and non-zero export for all DNSPs during daylight hours 10am – 4pm.

PV install density.

Figure 104 shows the voltage distribution difference between zero and non-zero PV export when classified by PV install density, for each DNSP. It can be seen that, within a single PV density grouping there is as much variation between DNSPs as there is between different PV density groupings (i.e. as much variation within one chart as there is between different charts). The results for PV install density within each DNSP are shown in Figure 105 to Figure 118.

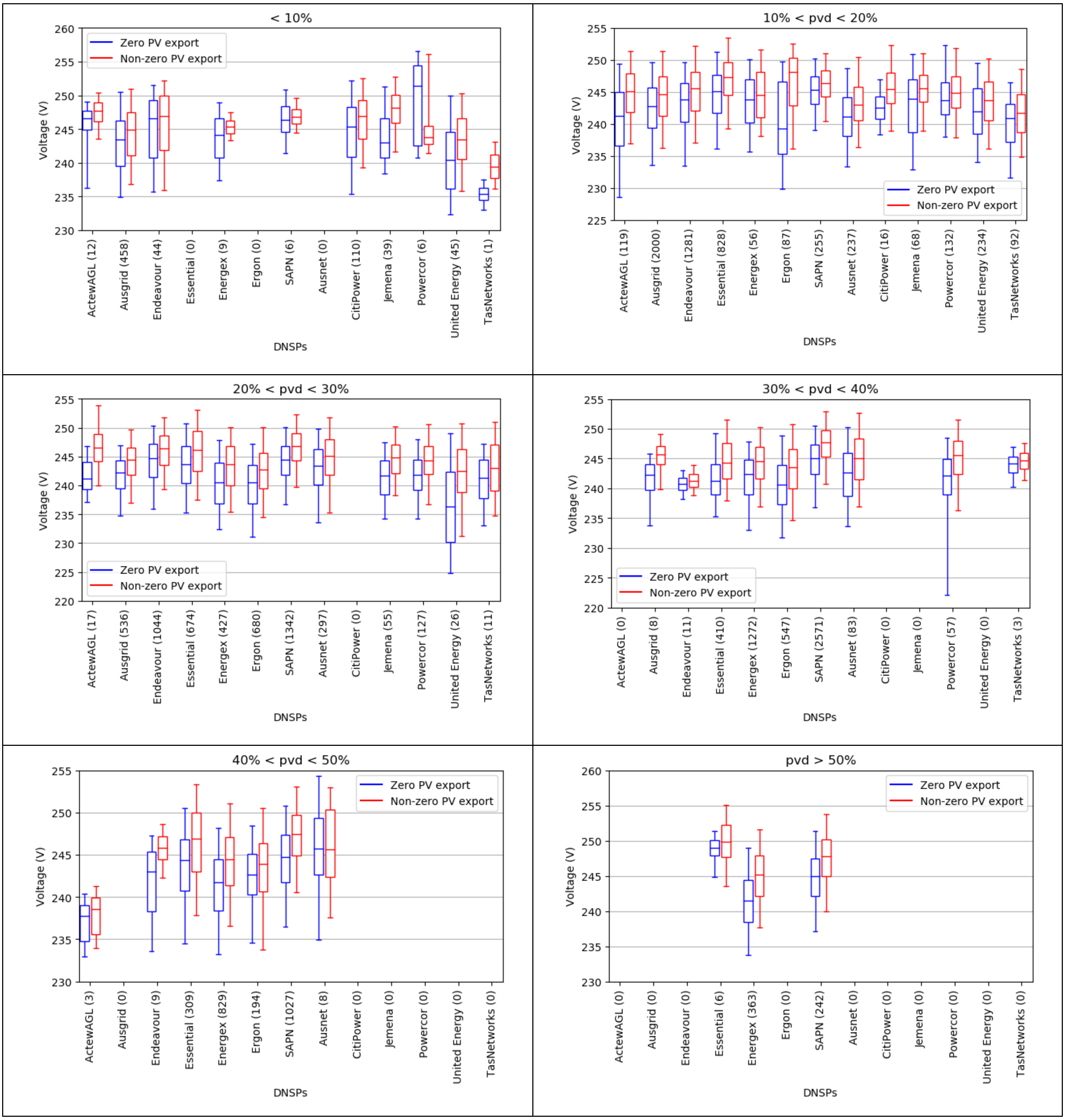


Figure 104 Box and whisker plot showing Voltage distribution difference between zero and non-zero export during daylight hours 10am – 4pm according to PV install density classification.

Remoteness

Figure 105 shows the voltage distribution difference between zero and non-zero PV export when classified by Remoteness, for each DNSP. Again, it can be seen that, within a single Remoteness grouping there is as much variation between DNSPs as there is between different PV density groupings. The results for Remoteness within each DNSP are again shown in in Figure 105 to Figure 118.

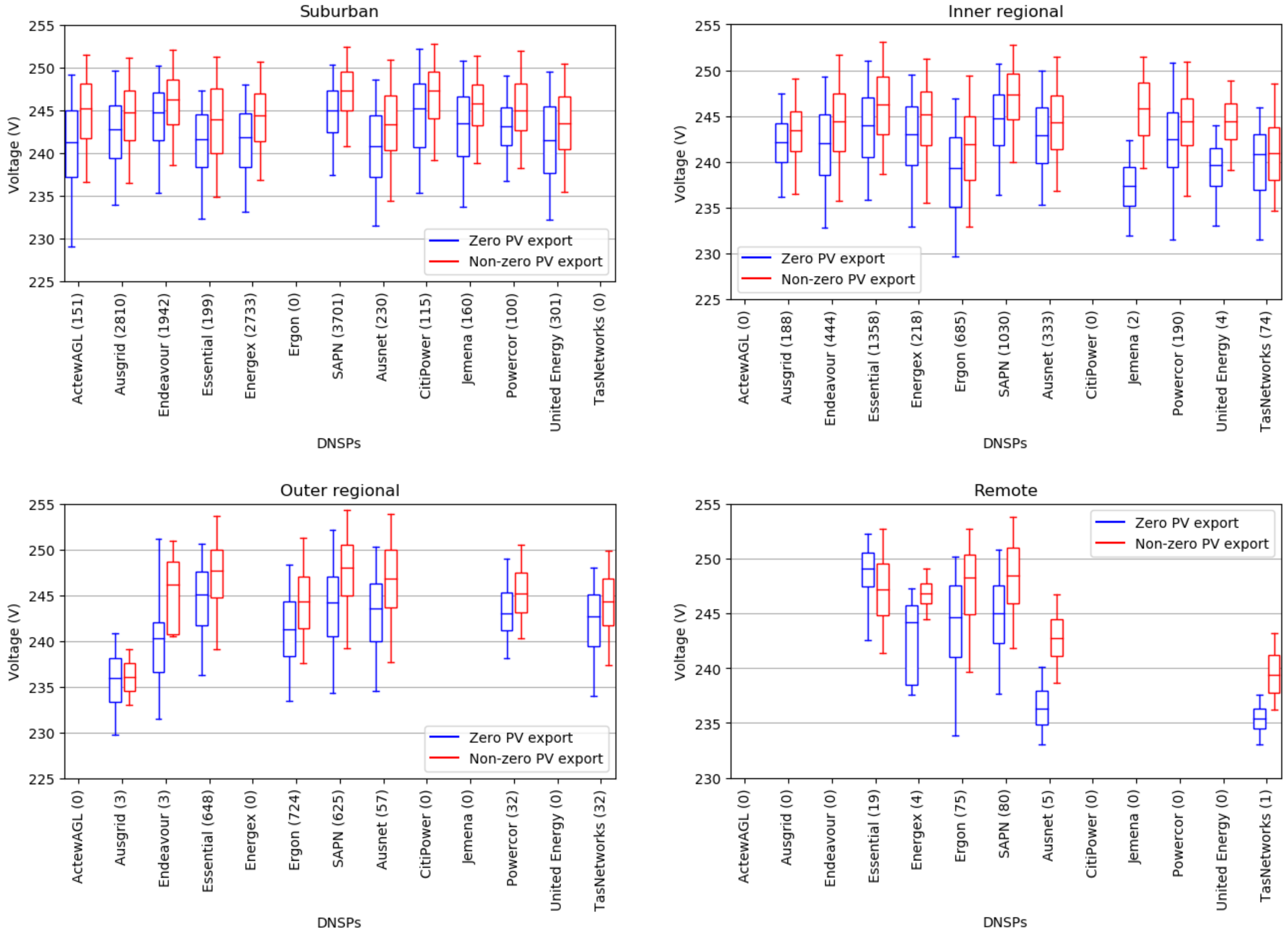


Figure 105 Box and whisker plot showing Voltage distribution difference between zero and non-zero export during daylight hours 10am – 4pm according to Remoteness category.

ActewAGL. The following group of plots shows the voltage distribution difference between zero and non-zero PV export for DNSP ActewAGL. Key point: Voltage impact is generally greater in higher PV penetrations.

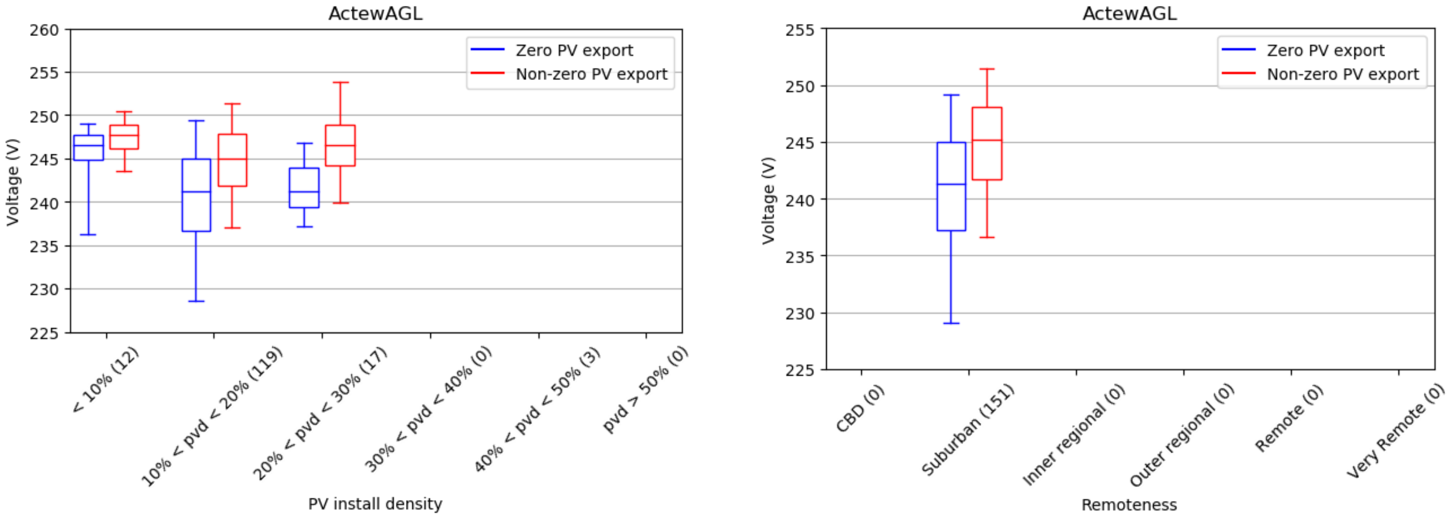


Figure 106 Box and whisker plot showing Voltage distribution difference between zero and non-zero export during daylight hours 10am – 4pm according to PV install density and Remoteness for ActewAGL.

Ausgrid. The following group of plots shows the voltage distribution difference between zero and non-zero PV export for DNSP Ausgrid. Key point: there seems to be only marginal increase in voltage impact at higher PV penetrations, or between suburban and inner regional.

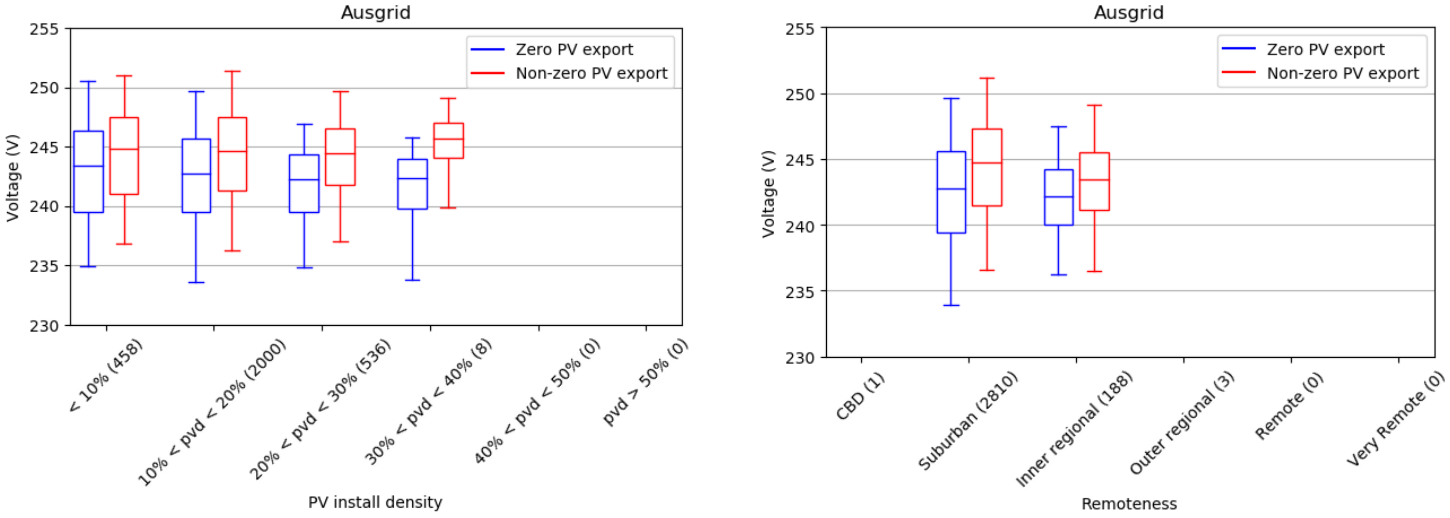


Figure 107 Box and whisker plot showing Voltage distribution difference between zero and non-zero export during daylight hours 10am – 4pm according to PV install density and Remoteness for Ausgrid.

Endeavour. The following group of plots shows the voltage distribution difference between zero and non-zero PV export for DNSP Endeavour. Key point: there may be a slight increase in voltage impact as PV penetration increases to between 20% and 30% but then this decreases going to 30% to 40% then decreases again. Note that these last two values are derived from very low customer numbers. There is a noticeable increase going from Suburban to Regional.

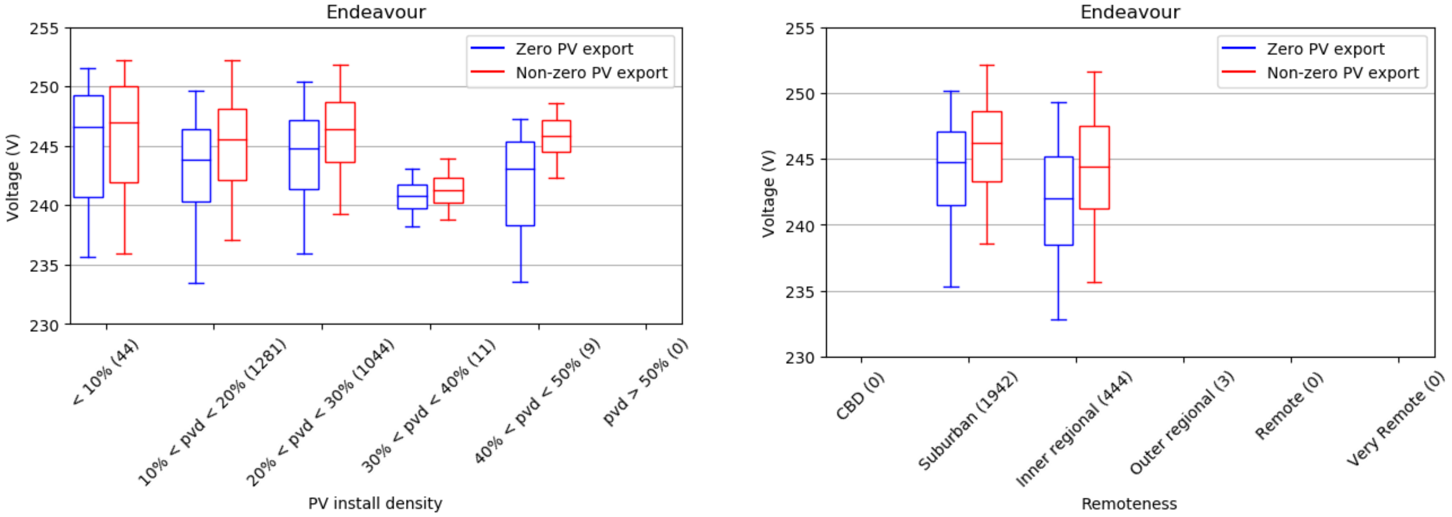


Figure 108 Box and whisker plot showing Voltage distribution difference between zero and non-zero export during daylight hours 10am – 4pm according to PV install density and Remoteness for Endeavour.

Essential. The following group of plots shows the voltage distribution difference between zero and non-zero PV export for DNSP Essential. Key point: there seems to be little increase in voltage impact at higher PV penetrations, or between suburban and inner regional, although note that voltage seems to increase going from suburban to outer regional. The Remote median voltage is actually lower during times of PV export, illustrating the point that other factors can have a significant impact on voltage.

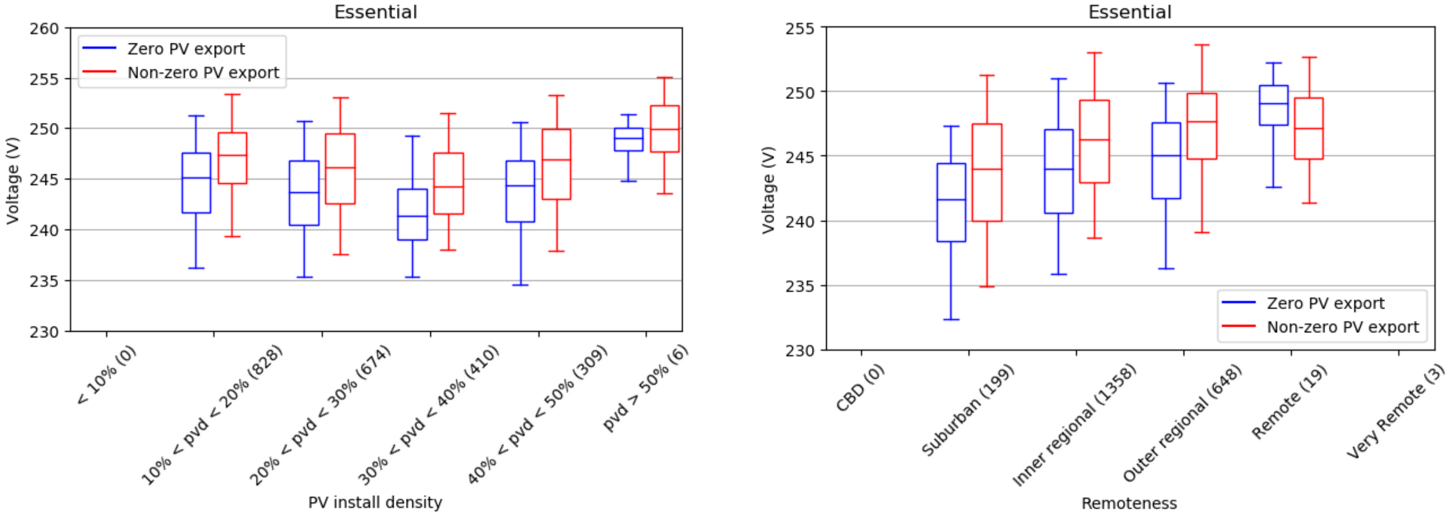


Figure 109 Box and whisker plot showing Voltage distribution difference between zero and non-zero export during daylight hours 10am – 4pm according to PV install density and Remoteness for Essential.

Energex. The following group of plots shows the voltage distribution difference between zero and non-zero PV export for DNSP Energex. Key point: there seems to be little increase in voltage impact at higher PV penetrations, or according to remoteness.

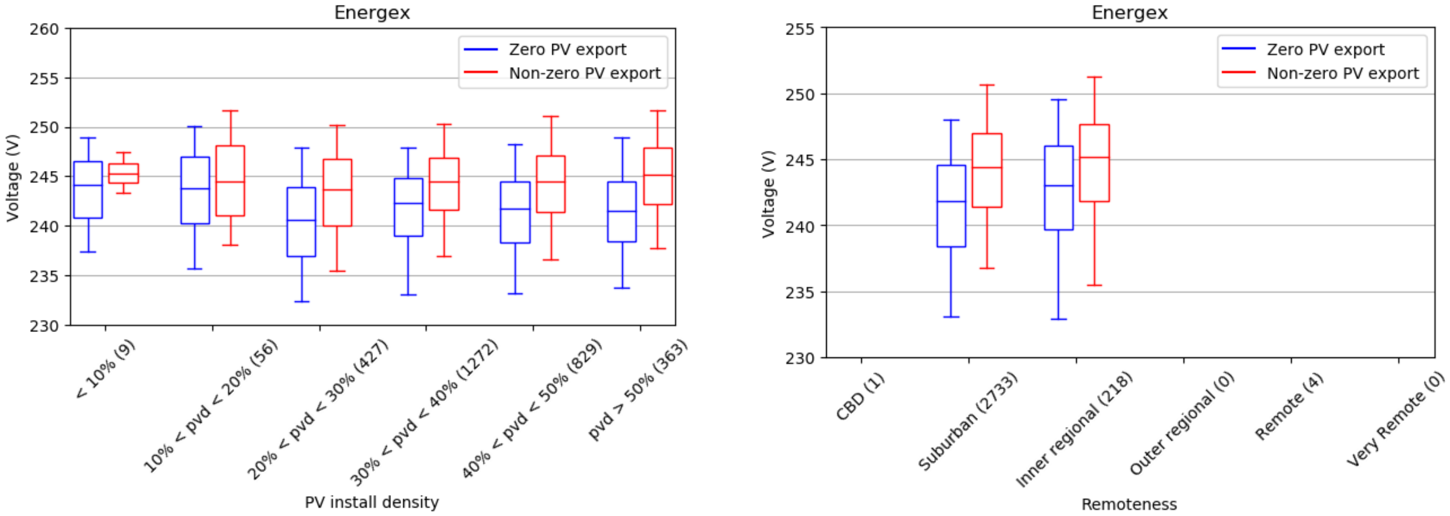


Figure 110 Box and whisker plot showing Voltage distribution difference between zero and non-zero export during daylight hours 10am – 4pm according to PV install density and Remoteness for Energex.

Ergon. The following group of plots shows the voltage distribution difference between zero and non-zero PV export for DNSP Ergon. Key point: there seems to be little increase in voltage impact at higher PV penetrations, with a slight increase for Very Remote.

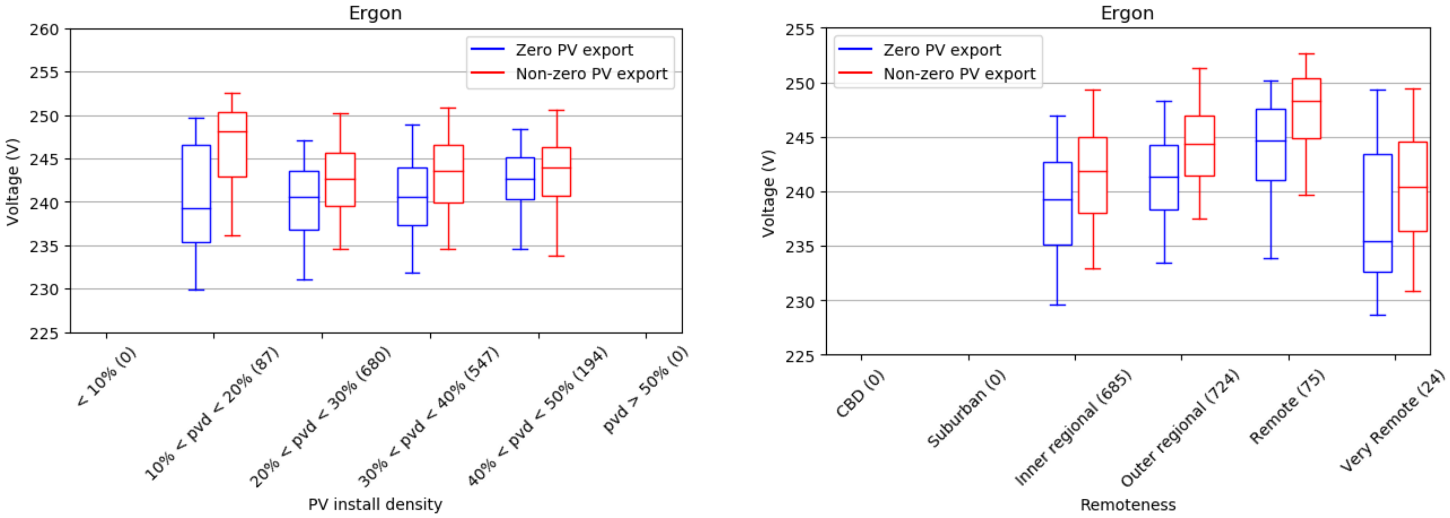


Figure 111 Box and whisker plot showing Voltage distribution difference between zero and non-zero export during daylight hours 10am – 4pm according to PV install density and Remoteness for Ergon.

SAPN. The following group of plots shows the voltage distribution difference between zero and non-zero PV export for DNSP SAPN. Key point: There is a slight increase in voltage impact at higher PV penetrations, as well as a slight increase as the level of remoteness increases.

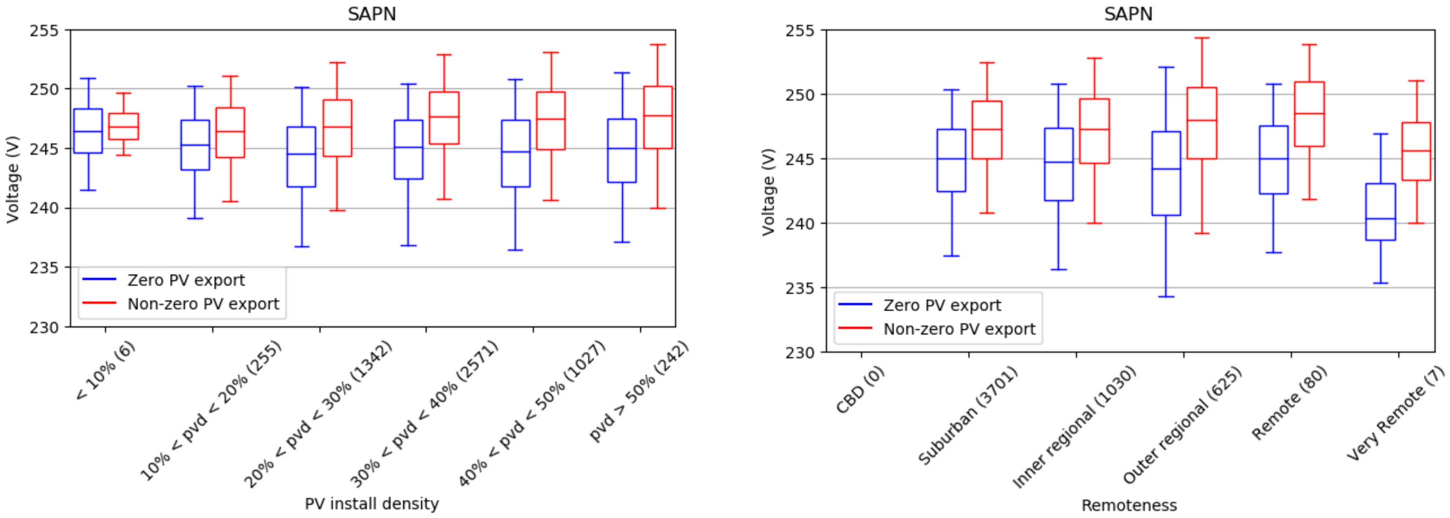


Figure 112 Box and whisker plot showing Voltage distribution difference between zero and non-zero export during daylight hours 10am – 4pm according to PV install density and Remoteness for SAPN.

Ausnet. The following group of plots shows the voltage distribution difference between zero and non-zero PV export for DNSP Ausnet. Key point: there seems to be a slight increase in voltage impact at higher PV penetrations (noting that the 40%<pvd<50% value is for only 8 sites), with little difference between remoteness categories (greater for Remote, but with only 5 sites).

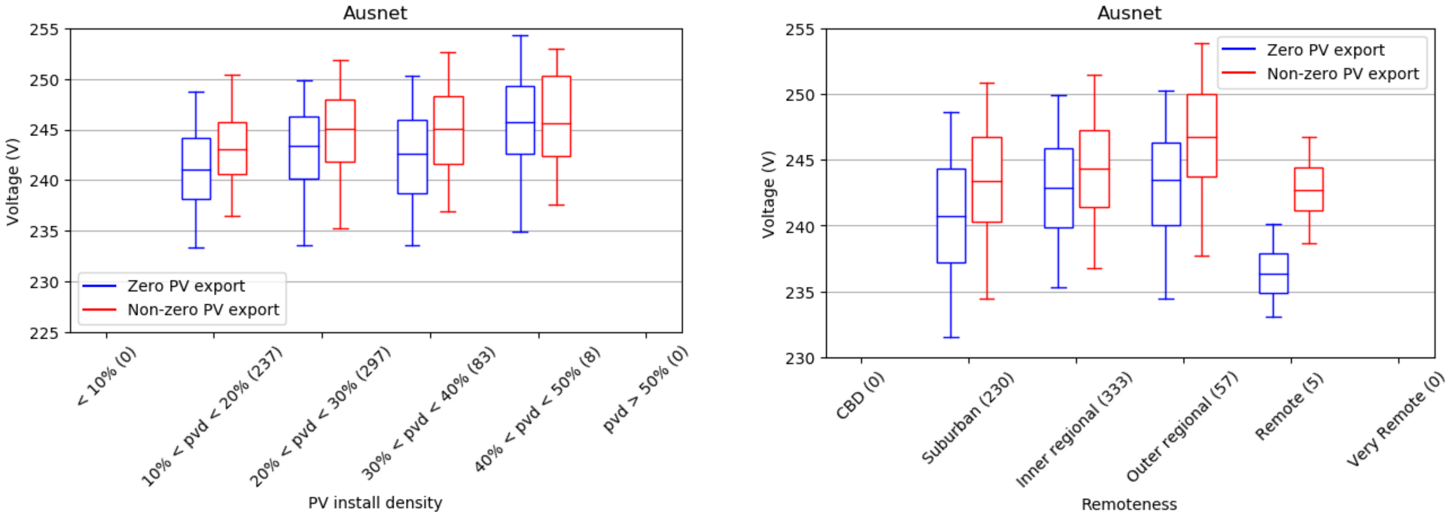


Figure 113 Box and whisker plot showing Voltage distribution difference between zero and non-zero export during daylight hours 10am – 4pm according to PV install density and Remoteness for Ausnet.

Citipower. The following group of plots shows the voltage distribution difference between zero and non-zero PV export for DNSP Citipower. Key point: there seems to be some increase in voltage impact at higher PV penetrations. The CBD median voltage is actually lower during times of PV export (although note the small number of sites), illustrating the point that other factors can have a significant impact on voltage.

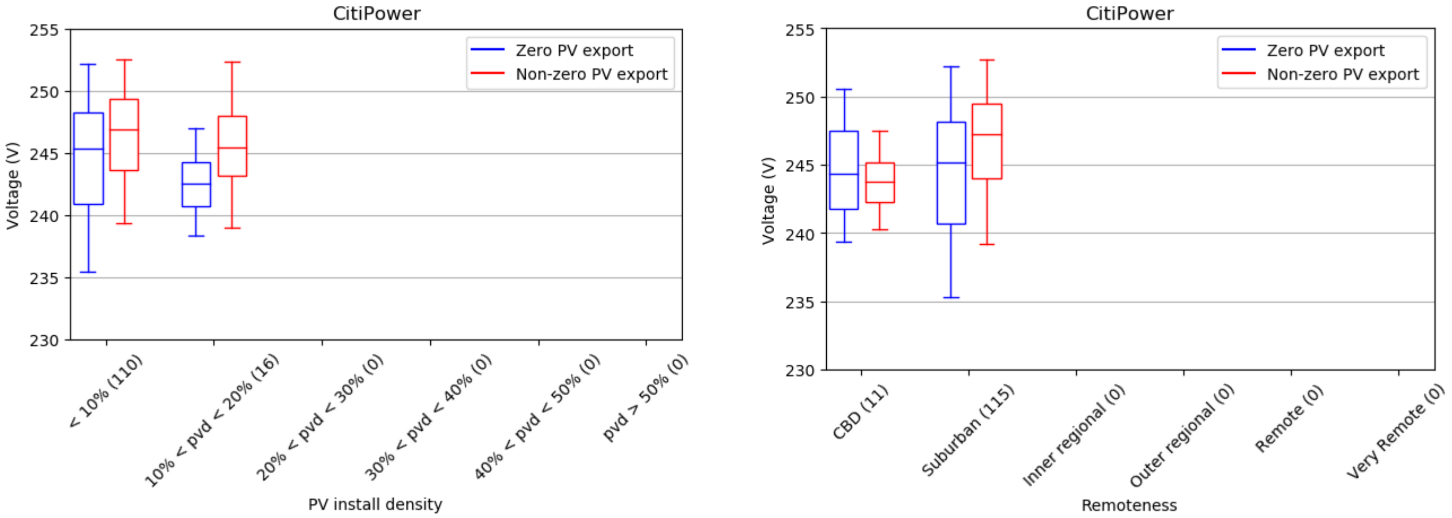


Figure 114 Box and whisker plot showing Voltage distribution difference between zero and non-zero export during daylight hours 10am – 4pm according to PV install density and Remoteness for Citipower.

Jemena. The following group of plots shows the voltage distribution difference between zero and non-zero PV export for DNSP Jemena. Key points: The voltage impact is greater at lower PV penetrations, possibly because of the small number of sites, but also because of other influences on voltage.

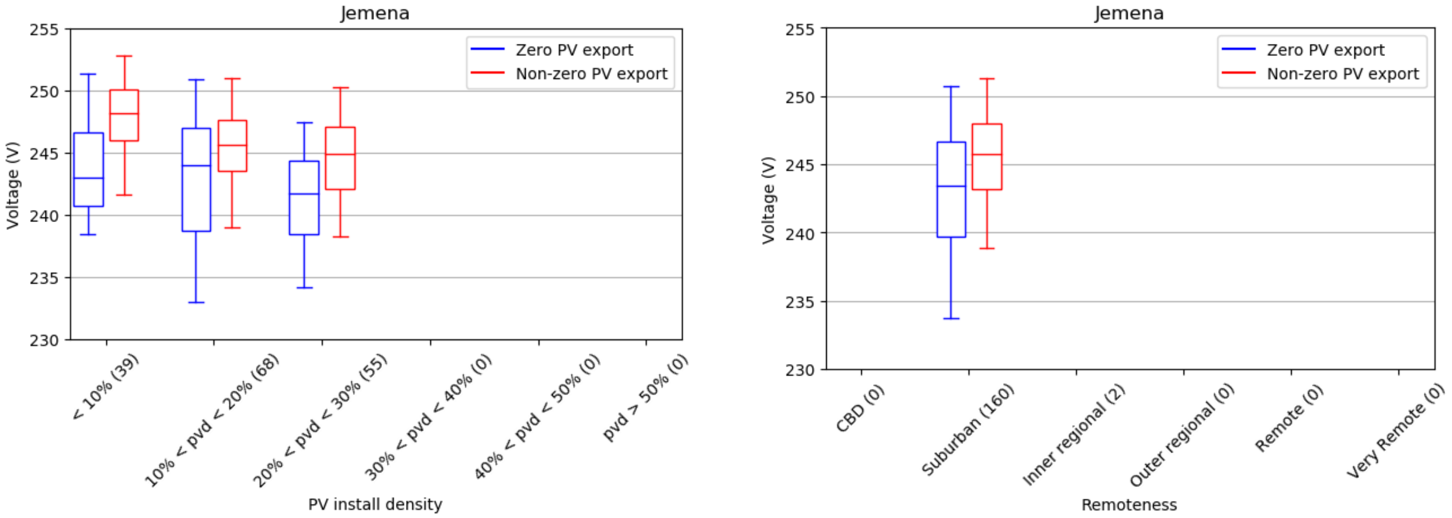


Figure 115 Box and whisker plot showing Voltage distribution difference between zero and non-zero export during daylight hours 10am – 4pm according to PV install density and Remoteness for Jemena.

Powercor. The following group of plots shows the voltage distribution difference between zero and non-zero PV export for DNSP Powercor. Key point: there seems to be little increase in voltage impact at higher PV penetrations, or between remoteness categories.

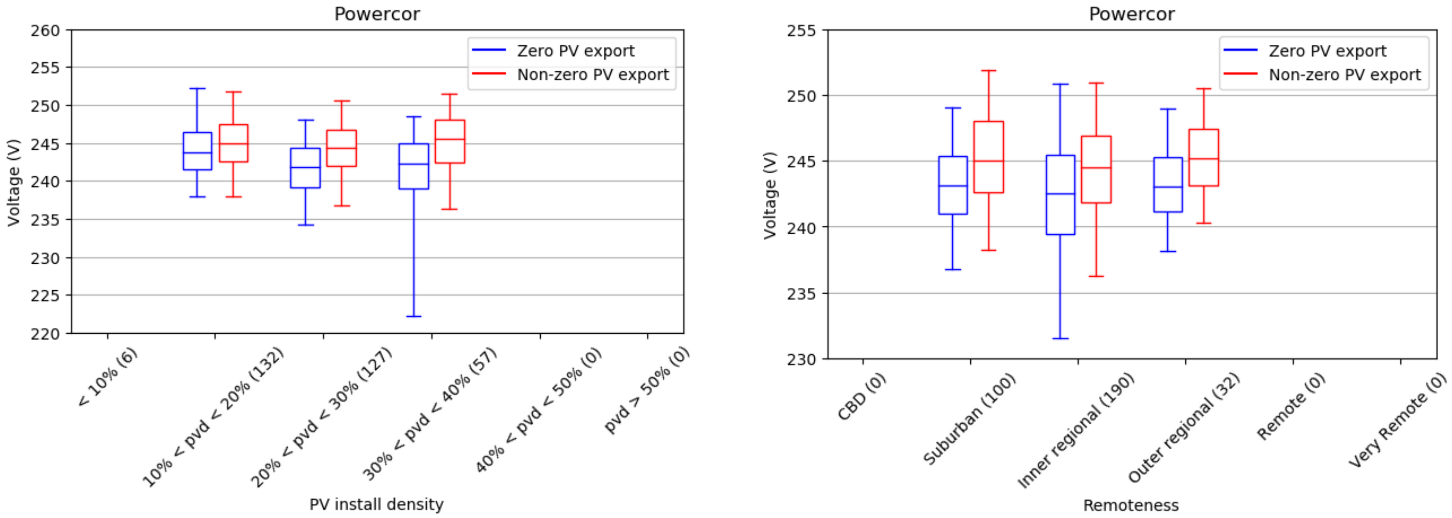


Figure 116 Box and whisker plot showing Voltage distribution difference between zero and non-zero export during daylight hours 10am – 4pm according to PV install density and Remoteness for Powercor.

United Energy. The following group of plots shows the voltage distribution difference between zero and non-zero PV export for DNSP United Energy. Key point: there is a significant increase in voltage impact at higher PV penetrations (although also greater variability), and a clear impact between remoteness categories (noting the small number of sites for Inner Regional).

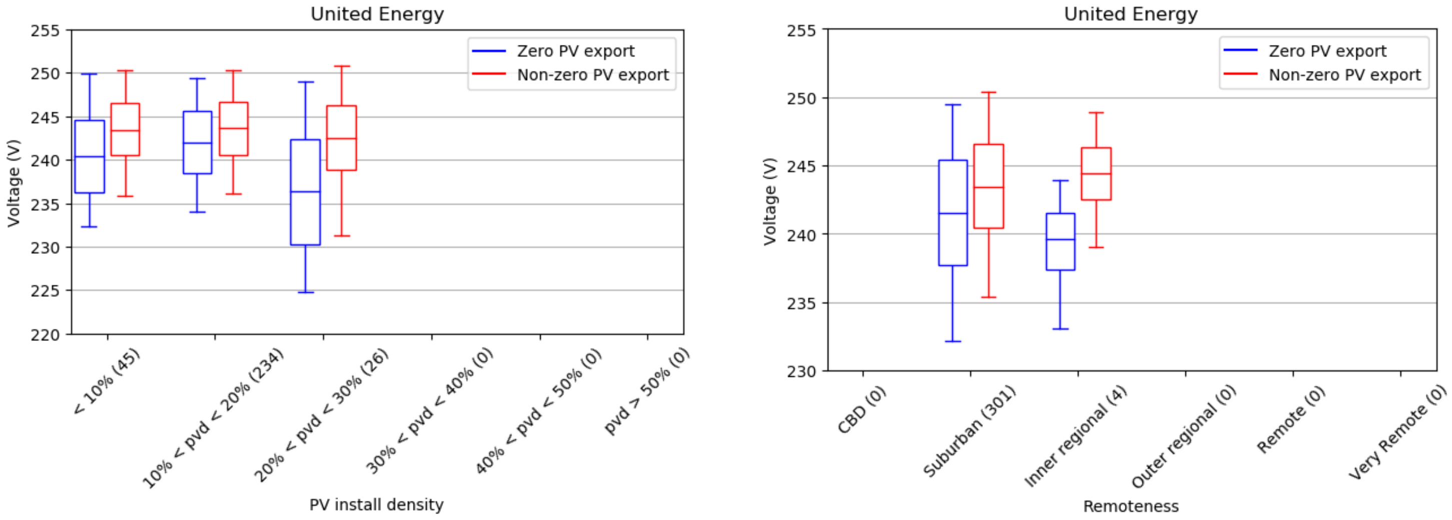


Figure 117 Box and whisker plot showing Voltage distribution difference between zero and non-zero export during daylight hours 10am – 4pm according to PV install density and Remoteness for United Energy.

TasNetworks. The following group of plots shows the voltage distribution difference between zero and non-zero PV export for DNSP TasNetworks. Key point: there is a noticeable increase in voltage impact as the PV density increases (although note the small number of customers in the 20%<pvd<30% sample). The voltage impact in remote areas appears to be more significant.

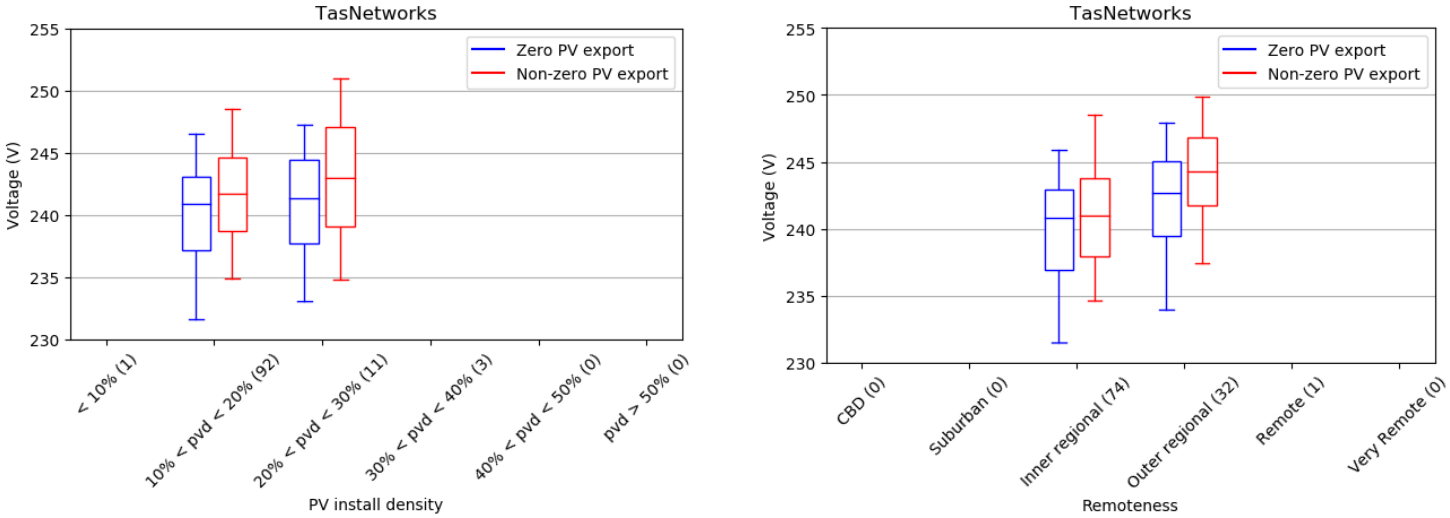


Figure 118 Box and whisker plot showing Voltage distribution difference between zero and non-zero export during daylight hours 10am – 4pm according to PV install density and Remoteness for TasNetworks.

7 Potential for Distributed PV Curtailment

7.1 Method

In this section we present voltage analysis for the DNSPs in South Australia, Queensland, New South Wales, the ACT, Victoria and Tasmania. The analysis focuses primarily on voltage conditions outside the present voltage Standard, and particularly high voltages at which PV inverters may see curtailment. The specifics of these various voltage standards for both the network and PV inverters are summarised in Table XIV.

Table XIV Voltage Standards for the Network and PV Inverters

Voltage	Description	Source
216V	Lower bound of nominal steady state voltage range (230V +10%/-6%) Voltage should not fall lower than 216V for more than 1% of the time for most DNSPs in most regions.	AS 61000.3.100-2011
253V	Upper bound of nominal stead state voltage range (230V +10%/-6%) Voltage should not rise greater than 253V for more than 1% of the time for most DNSPs in most regions.	AS 61000.3.100-2011
255V	Default set point for inverter limit for sustained operation. When the average voltage is greater than this value for 10min then an inverter should disconnect.	AS4777.2-2015
258V	Maximum set point for inverter limit for sustained operation.	AS4777.2-2015
260V	Over voltage set point 1 (disconnection within 2 seconds)	AS4777.2-2015
265V	Over voltage set point 2 (disconnection within 0.2 seconds)	AS4777.2-2015

It is important to note that the specifics of how voltages should be measured in the standard, how they are actually measured by PV inverters, and the limitations of the voltage monitoring of the SolA equipment (5 second sampling with only the maximum and minimum voltages over each 5 minute period recorded) all mean that it is not possible to precisely ascertain how often PV inverters should be curtailing. Furthermore, actual curtailment may or may not occur depending on the year of installation (hence version of AS4777 with older systems having a greater allowed voltage range) and potentially installation settings or other compliance issues.

Nevertheless, it is possible to present probability distributions of what proportion of sites experience maximum and minimum voltages exceeding 253, 255, 258, 260 and 265V for what period of time over the year of data monitoring. These plots provide an indicative estimate of the extent of potential curtailment issues in terms of both the proportion of sites potentially impacted, and the proportion of the year this occurs.

More detailed curtailment analysis, albeit with a smaller dataset, that actually seeks to identify and estimate actual curtailment from PV generation data is presented in Section 7.5.

7.2 South Australia

Table XV shows the number of households analysed per DNSP in NSW based on their location's PV installation density.

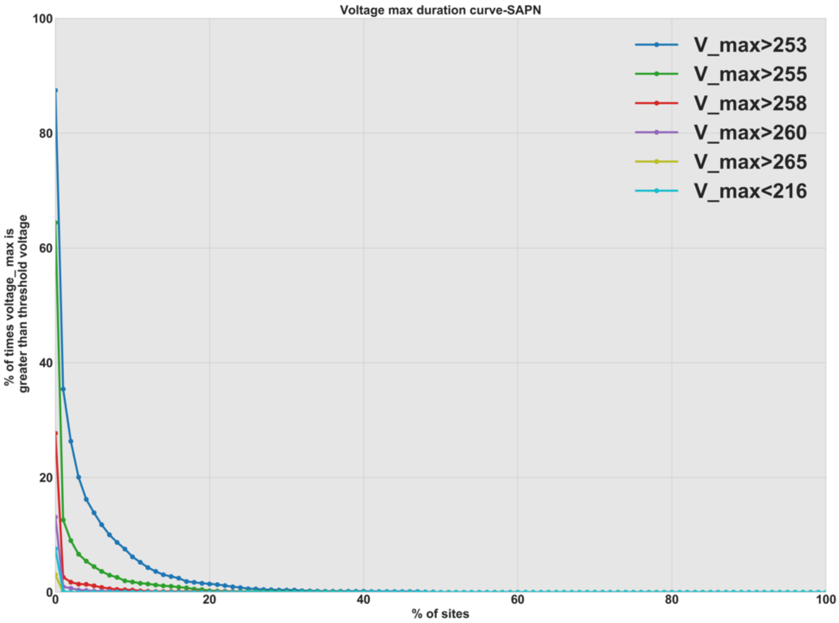
Table XV PV density regions vs number of analysed households per DNSP

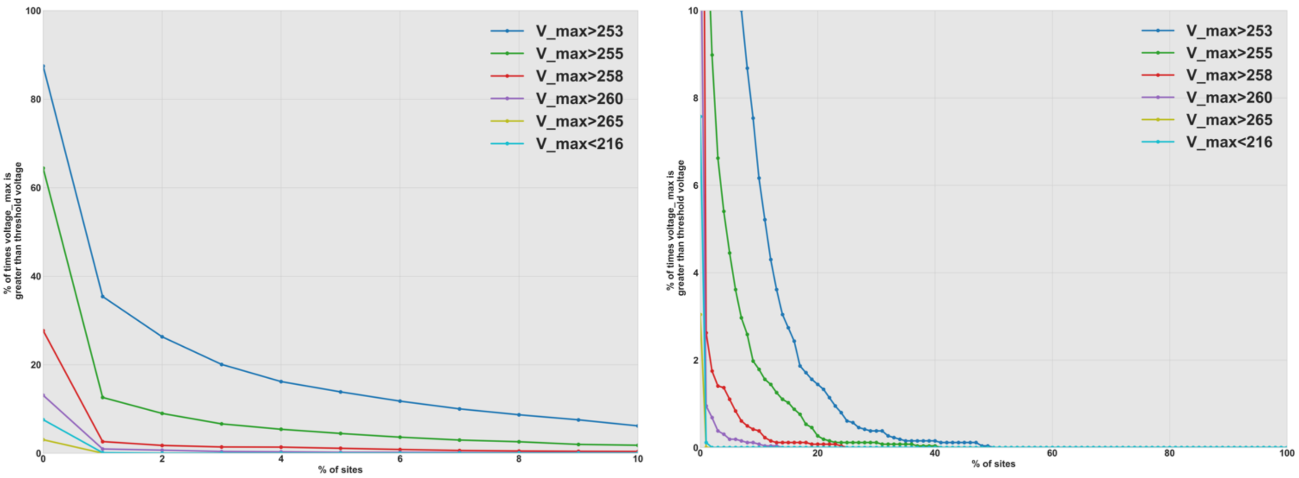
PV Density	Number of Households
PV density 0: 0%-10%	0
PV density 1: 10%-20%	181
PV density 2: 20%-30%	883
PV density 3: 30%-40%	1831
PV density 4: 40%-50%	678
PV density 5: 50%-60%	143

Figure 119 a) shows the percentage of the sites with a full year of data vs the percentage of over and under voltage events within the analysed year. The analysed voltage thresholds include 253, 255, 258, 260, 265 for over voltages with respect to Australian Standards and 216 V for the under-voltage events. Figure 119 b) and c) zoom into the x and y axes respectively.

It can be seen that around 17% of the sites experience over voltage (>253) at least 2% of the time and around 40% of the sites experience voltage >255. Moreover, around 2% of the sites were experiencing regular over voltage events with voltages being over 253, 255 and 258 levels for 27%, 8% and 2% of the time respectively. It is important to note that the standard for upper voltage and for inverter curtailment around 255-258V is based on average voltages over 10 minutes and PV inverter connection standards have changed over time. Still, it does suggest that if these high voltages are being sustained over such time periods, it is likely that some curtailment is occurring. Use of minimum voltages provides a more conservative estimate of the severity of high voltage excursions as shown in Figure 120. It is evident that even according to minimum voltage, there are still significant number of households which regularly experience over voltage events. It is also worth noting that the under-voltage events are much less severe than the over voltage events in terms of the frequency of their occurrence.

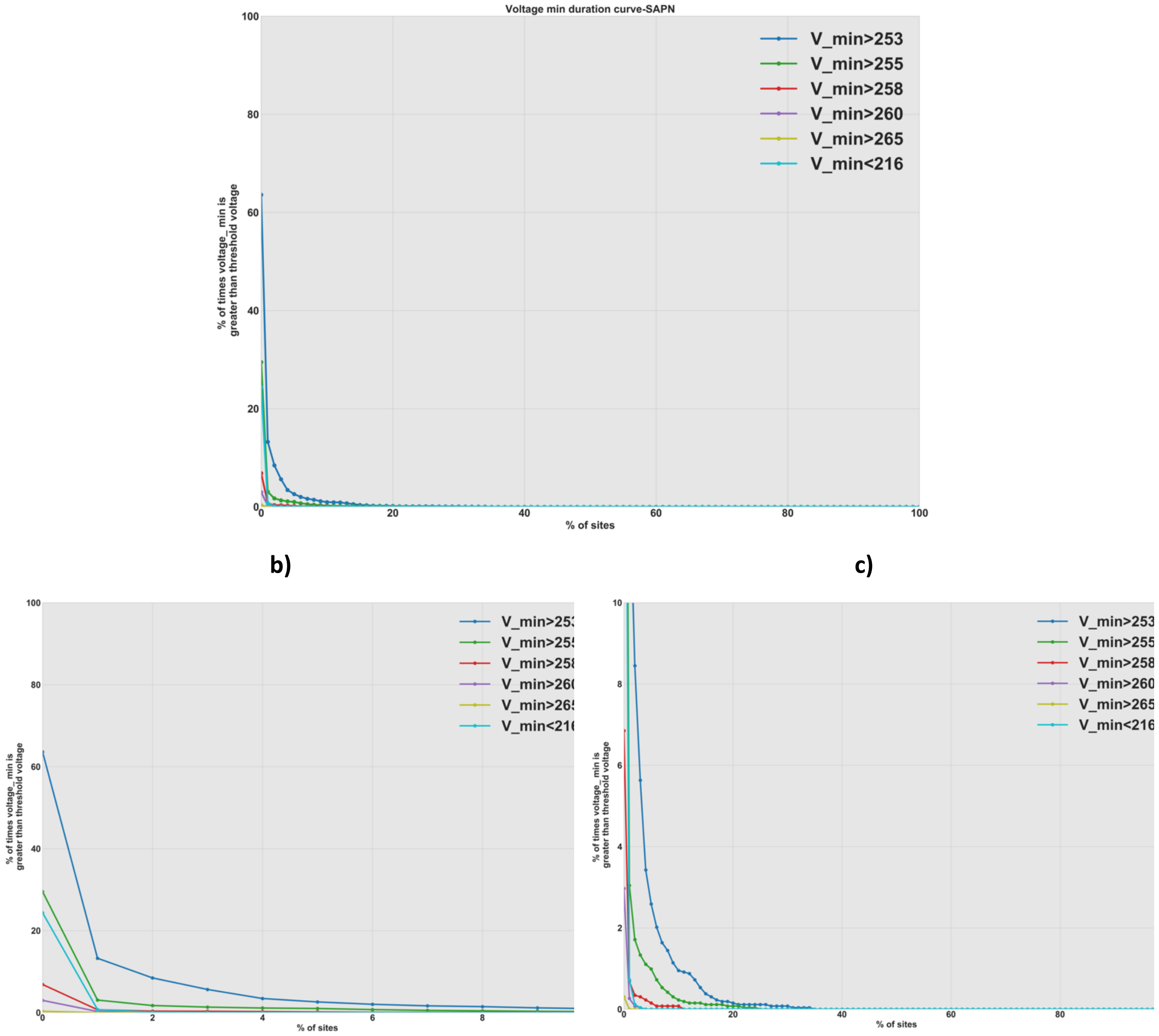
a)





b) c)

Figure 119 Percentage of sites vs. percentage of times of under and over voltage events based on voltage maximum



a)

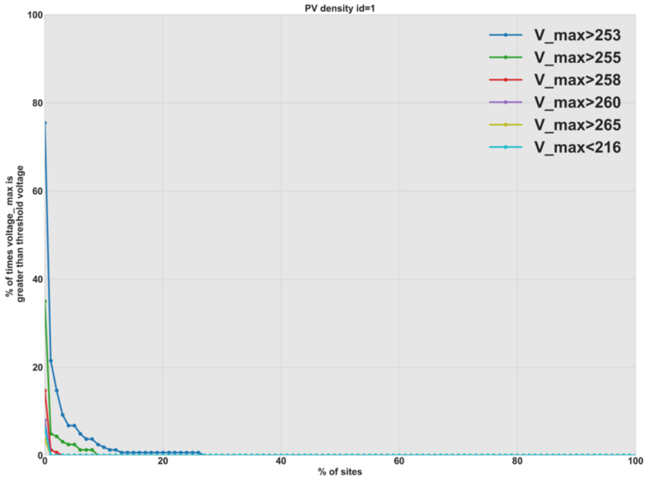
b) c)

Figure 120 Percentage of sites vs. percentage of times of under and over voltage events based on voltage minimum

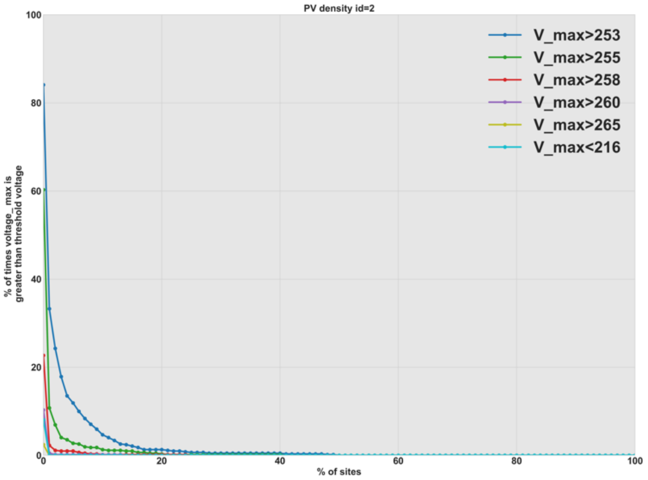
7.2.1 Impact of PV Density

To understand whether the over and under voltage events are affected by the distributed PV penetration levels, Figure 121 shows the equivalent charts broken down into different PV density regions, based on postcode data. Figure 121 a) to e) represents voltage maximum analysis and f) to k) represents voltage minimum analysis. The results show that over voltage events generally become more prevalent for the regions with higher PV penetration levels, especially at the highest level. The results are valid both for voltage maximum and minimum analysis, with the prior showing a stronger relationship.

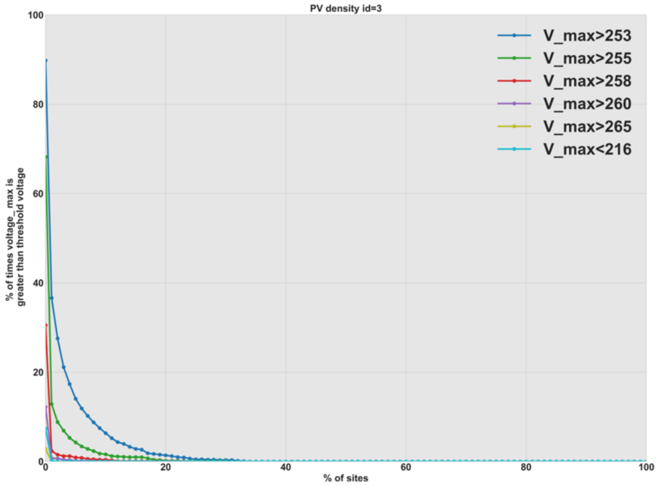
a)



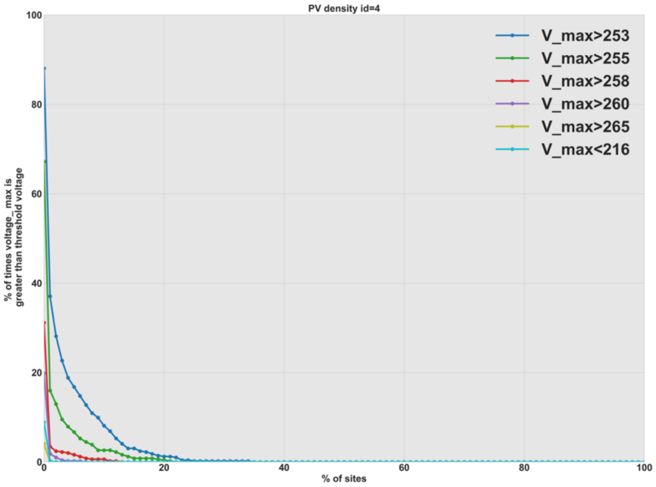
b)



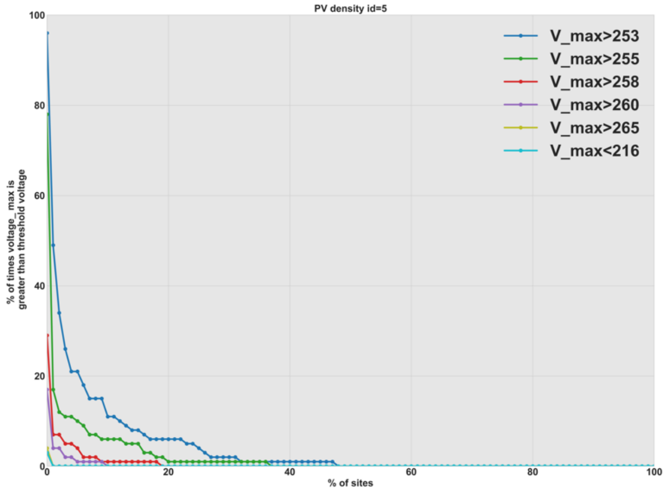
c)



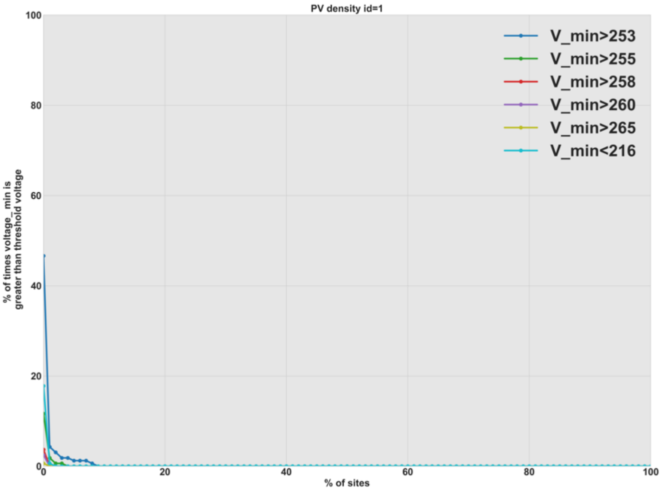
d)



e)



f)



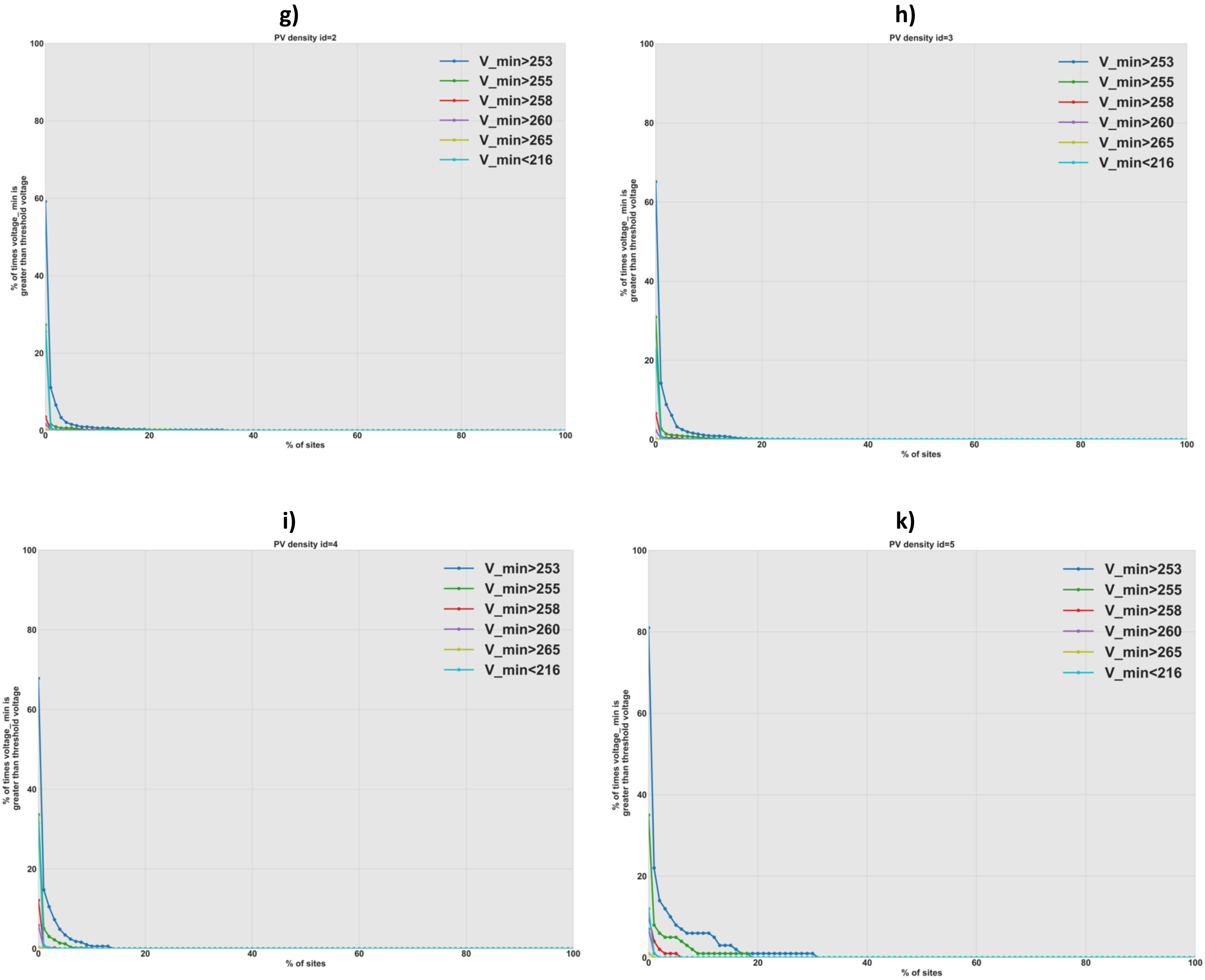


Figure 121 Percentage of sites vs. percentage of times of under and over voltage events based on household region's PV density (id=1 10-20%, id=2 20-30%, id=3 30-40%, id=4 40-50%, id=5 50-60% PV install density)

7.3 Queensland (Energex & Ergon)

Table XVI shows the number of analysed per DNSP in Qld based on their location’s PV installation density.

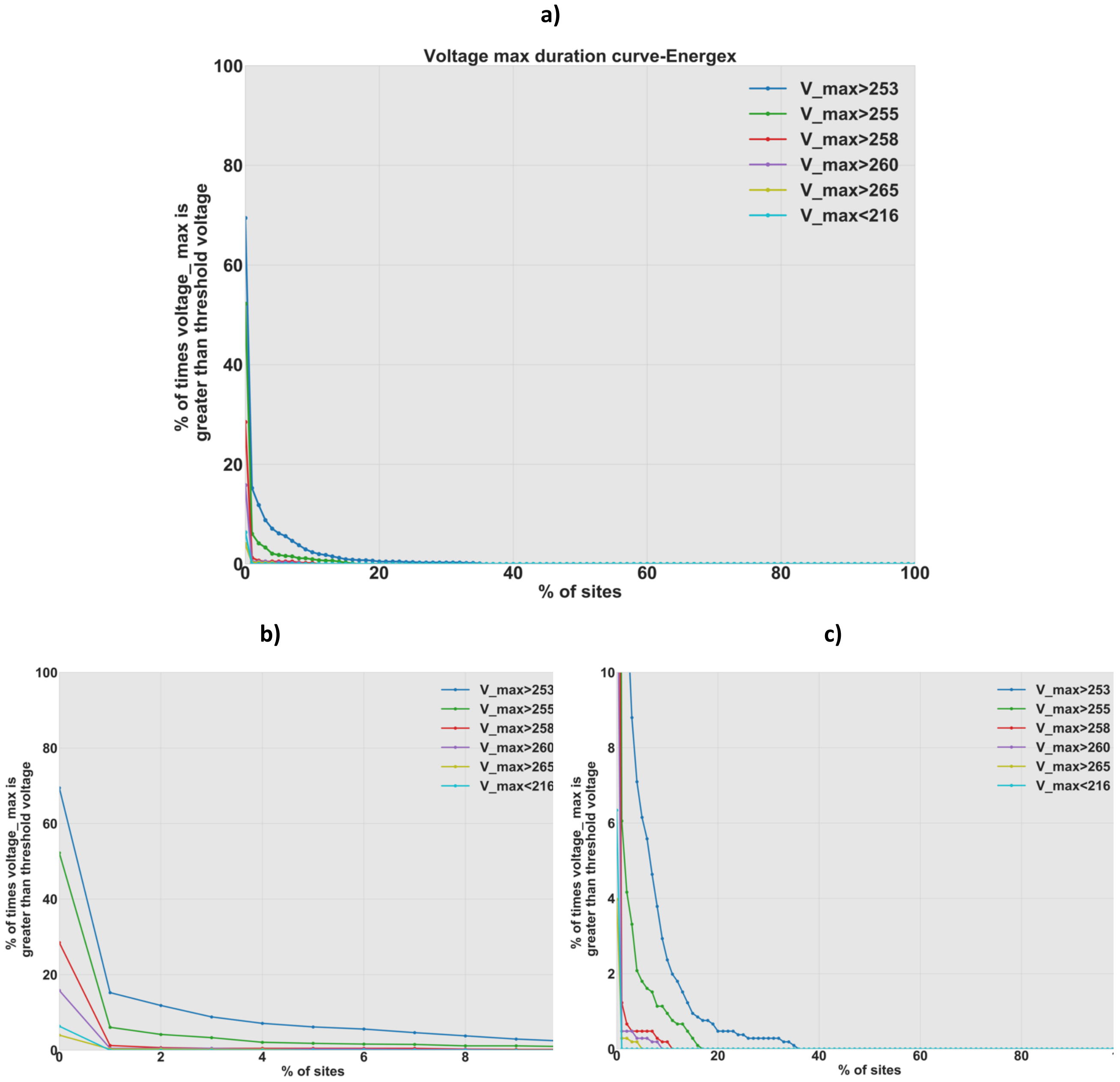
Table XVI PV density regions vs number of analysed household per DNSP

	Number of Households	
PV Density	**Ergon**	**Energex**
PV density 0: 0%-10%	1	1
PV density 1: 10%-20%	37	36
PV density 2: 20%-30%	498	321
PV density 3: 30%-40%	410	964
PV density 4: 40%-50%	153	676
PV density 5: 50%-60%	0	296

7.3.1 Energex

Figure 122 a) shows the percentage of the sites with full year of data vs the percentage of over and under voltage events within the analysed year for the Energex network. The analysed voltage thresholds include 253, 255, 258, 260, 265 for over voltages with respect to Australian Standards and 216 V for the under-voltage events. Figure 122 b) and c) zoom into the x and y axes respectively.

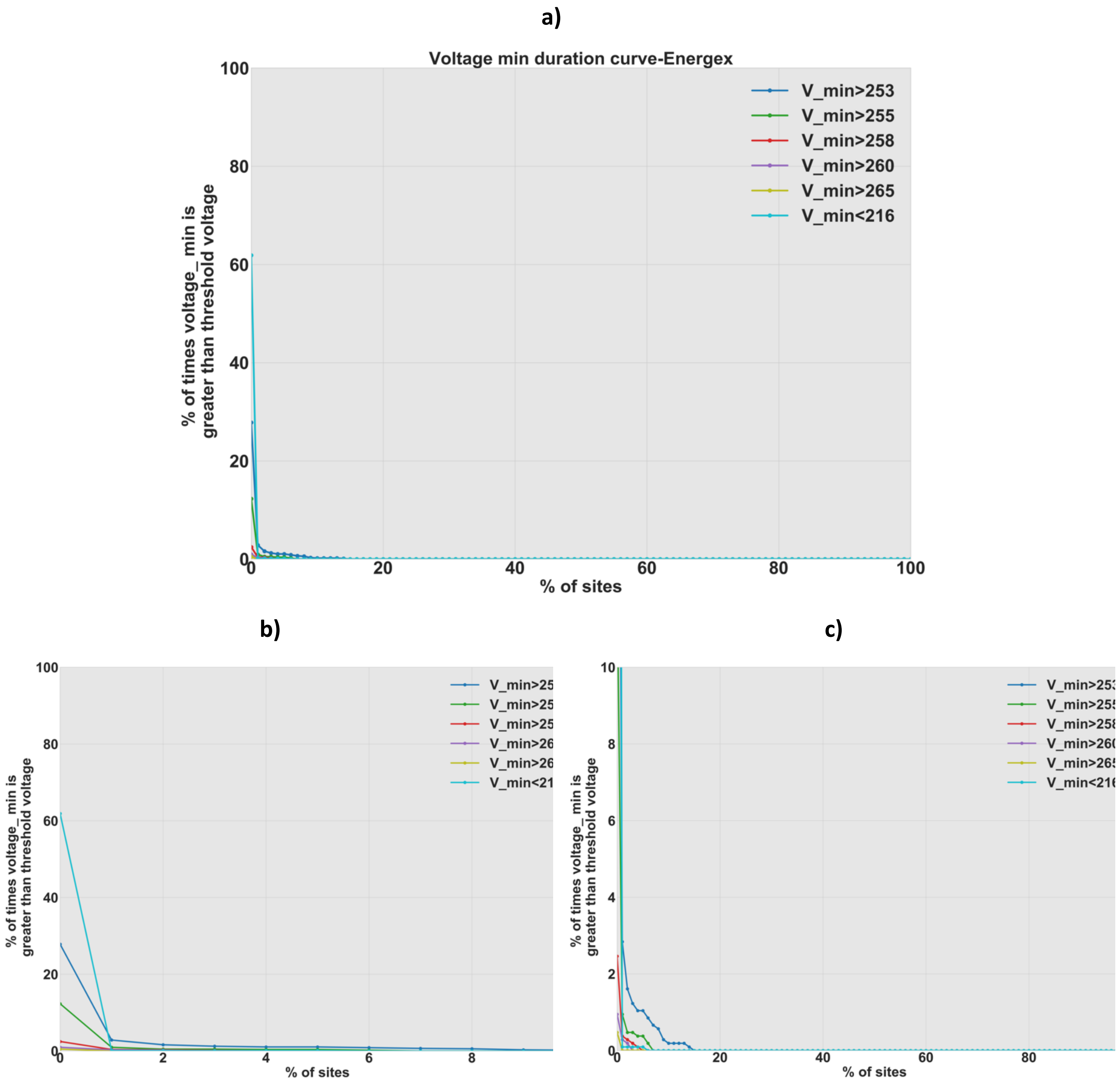
It can be seen that around 11% of the Energex sites experience over voltage (>253) at least 2% of the time and around 16% of the sites experience voltage >255. Moreover, around 2% of the sites are experiencing over voltage events with voltages being over 253, 255 and 258 levels for 12%, 4% and 1% of the time respectively. It is important to note that the standard for upper voltage and for inverter curtailment around 255-258V is based on average voltages over 10 minutes and PV inverter connection standards have changed over time. Still, it does suggest that if these high voltages are being sustained over such time periods, it is likely that some curtailment is occurring. Use of minimum voltages provides a more conservative estimate of the severity of high voltage excursions as shown in Figure 123. It is evident that even according to minimum voltage, there are still significant number of households which regularly experience over voltage events. It is worth noting again that the under-voltage events are much less severe than the over voltage events in terms of frequency of occurrence.


a)

b)

c)

Figure 122 Percentage of sites vs. percentage of times of under and over voltage events based on voltage maximum for Energex


a)

b)

c)

Figure 123 Percentage of sites vs. percentage of times of under and over voltage events based on voltage minimum for Energex

7.3.2 Ergon

Figure 124 presents similar results for the Ergon network. Over voltage is a greater problem for the Ergon network compared to Energex. Around 37% of the sites experience over voltage (>253) at least 2% of the time and around 39% of the sites experience an over voltage event (>255). Around 2% of the sites are experiencing over voltage events with voltages being over 253, 255 and 258 levels for 13%, 4% and 1% of the time respectively, and almost all sites experience at least one over voltage event. Even when using voltage minima as shown in Figure 125, there are significant over voltage events observed for a great number of households. It is worth noting that like Energex and SAPN, the under-voltage events are much less severe than the over voltage events.

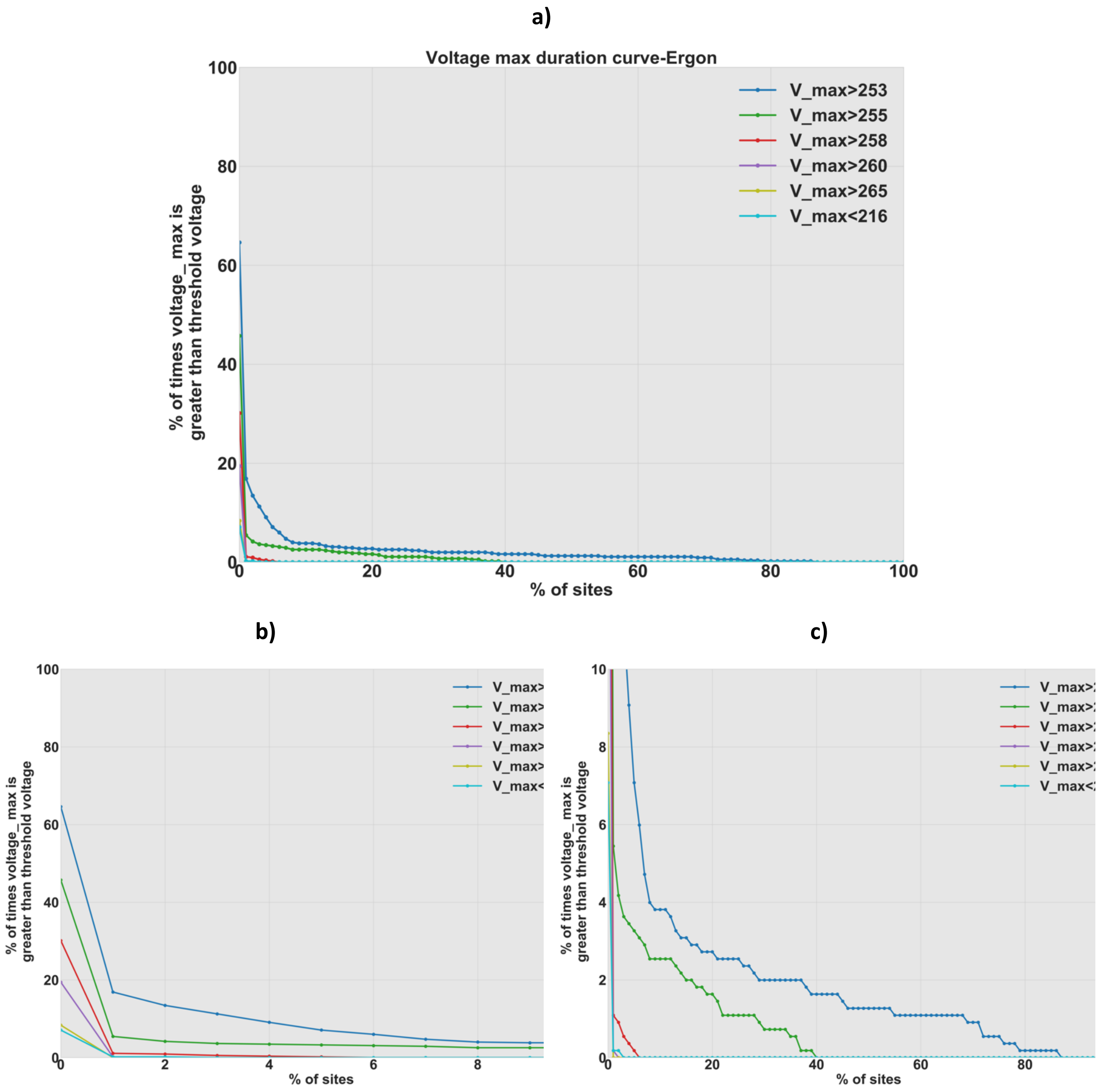


Figure 124 Percentage of sites vs. percentage of times of under and over voltage events based on voltage maximum for Ergon

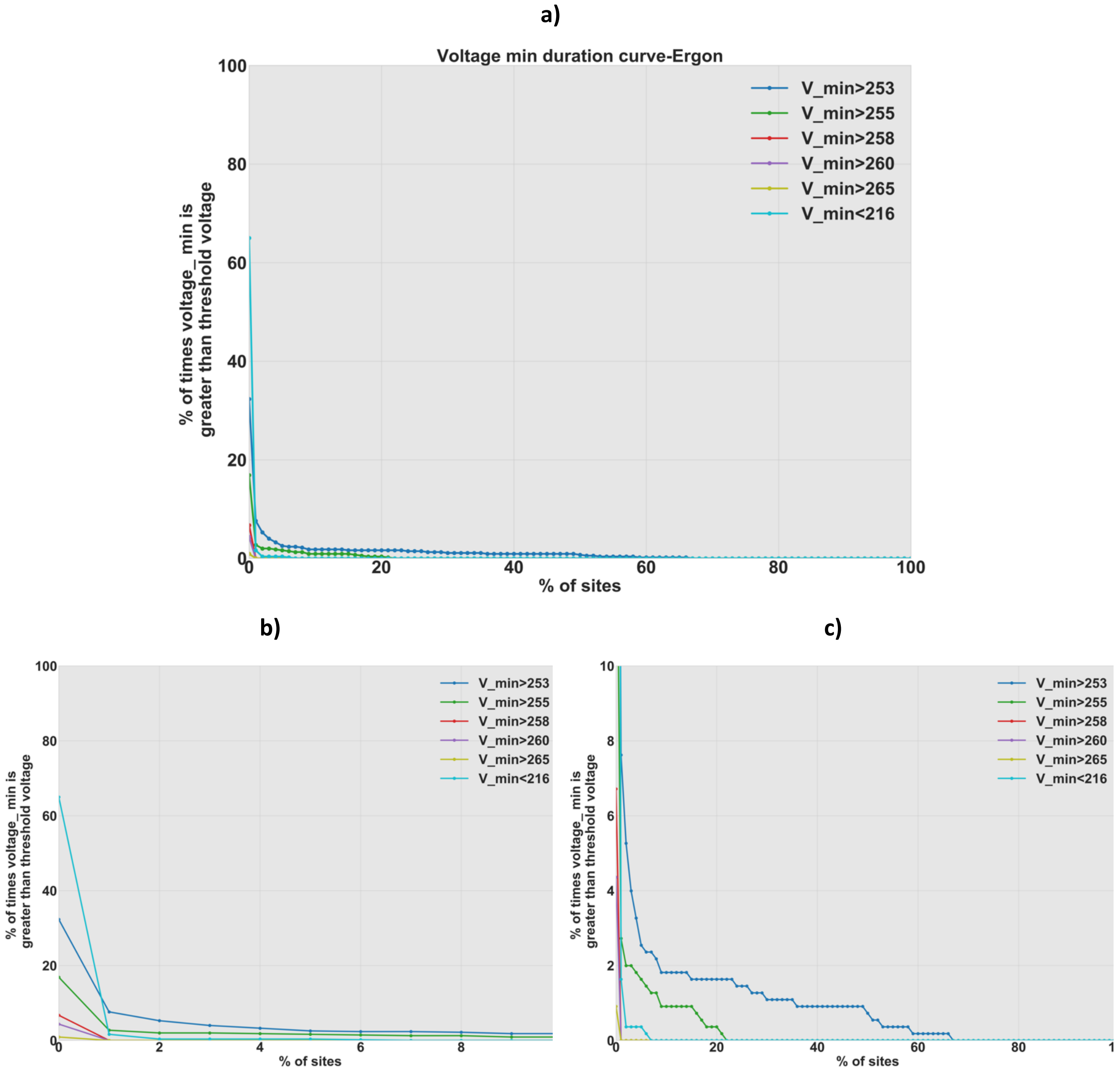


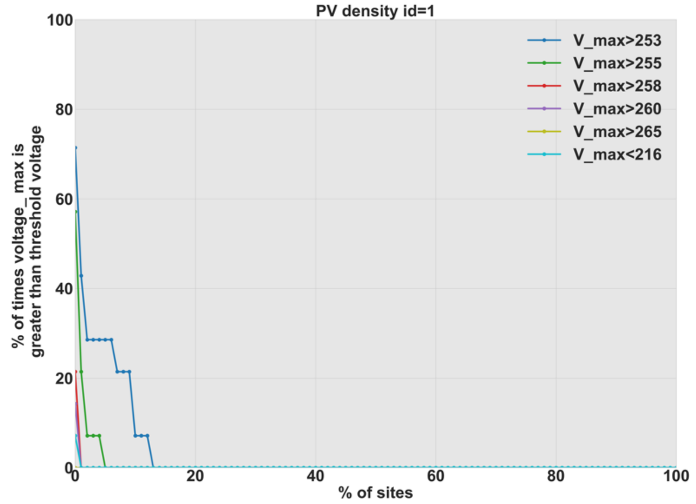
Figure 125 Percentage of sites vs. percentage of times of under and over voltage events based on voltage minimum for Ergon

7.3.3 Impact of PV Density

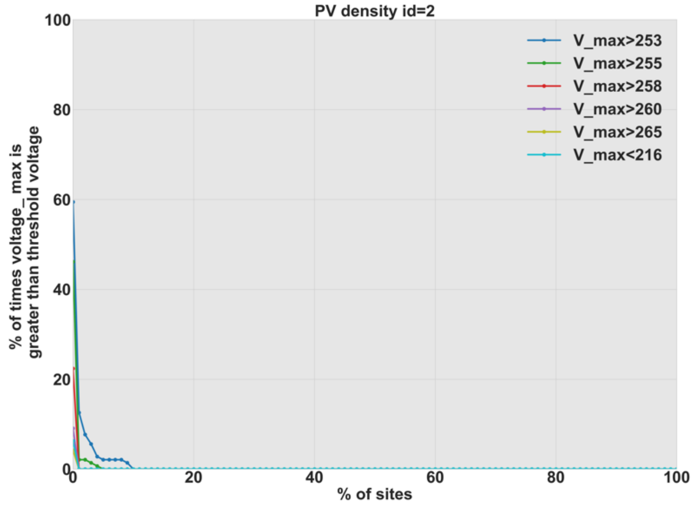
To understand whether the over and under voltage events are affected by the distributed PV penetration levels, Figure 126 and Figure 127 show the equivalent charts (both max and min) broken down into different PV density regions for Energex and Ergon networks respectively, based on postcode data as shown in Table XVI above:

The results show that, for both Energex and Ergon, over voltage events generally become more prevalent for the regions with higher PV penetration levels. The results are valid for both voltage maximum and minimum analysis, with the former showing a stronger relationship. For both Energex and Ergon, at very low penetrations, over voltage events are observed, how this is most likely because of the smaller number of sites in the sample.

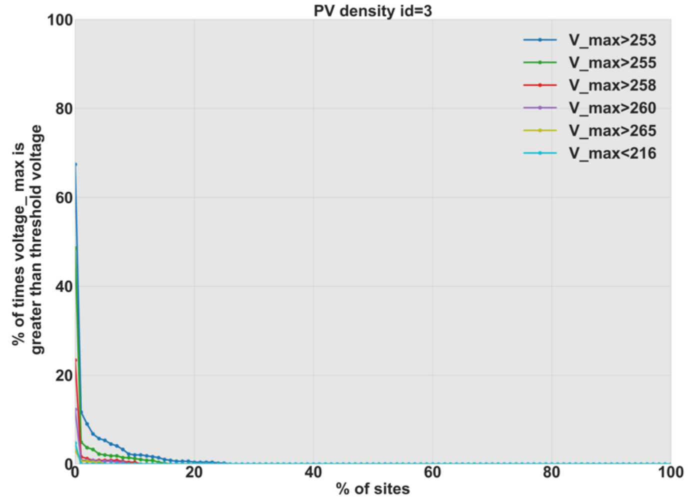
a)


PV density id=1

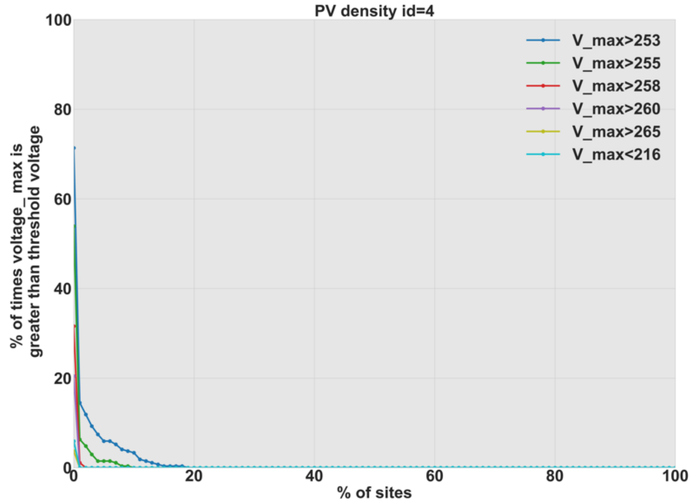
b)


PV density id=2

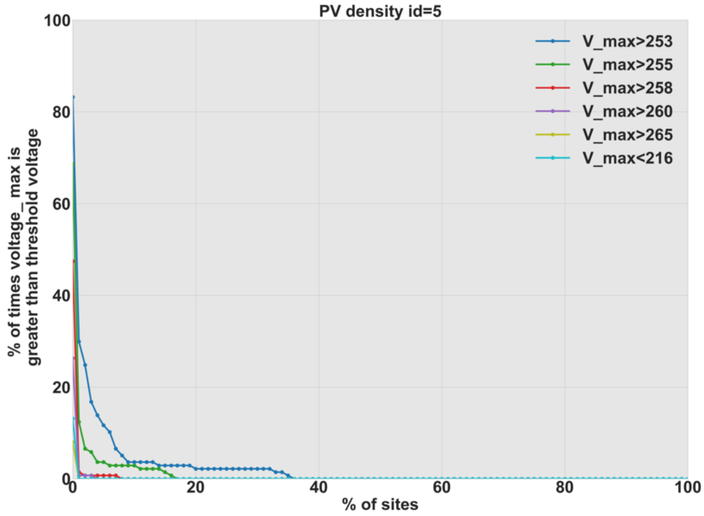
c)


PV density id=3

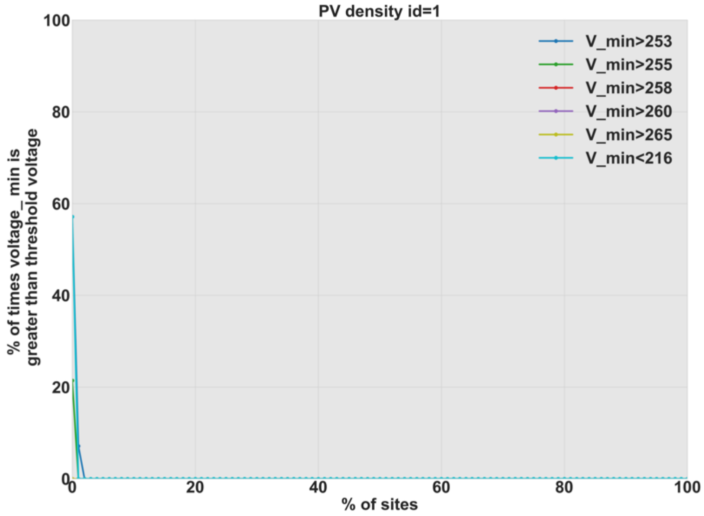
d)

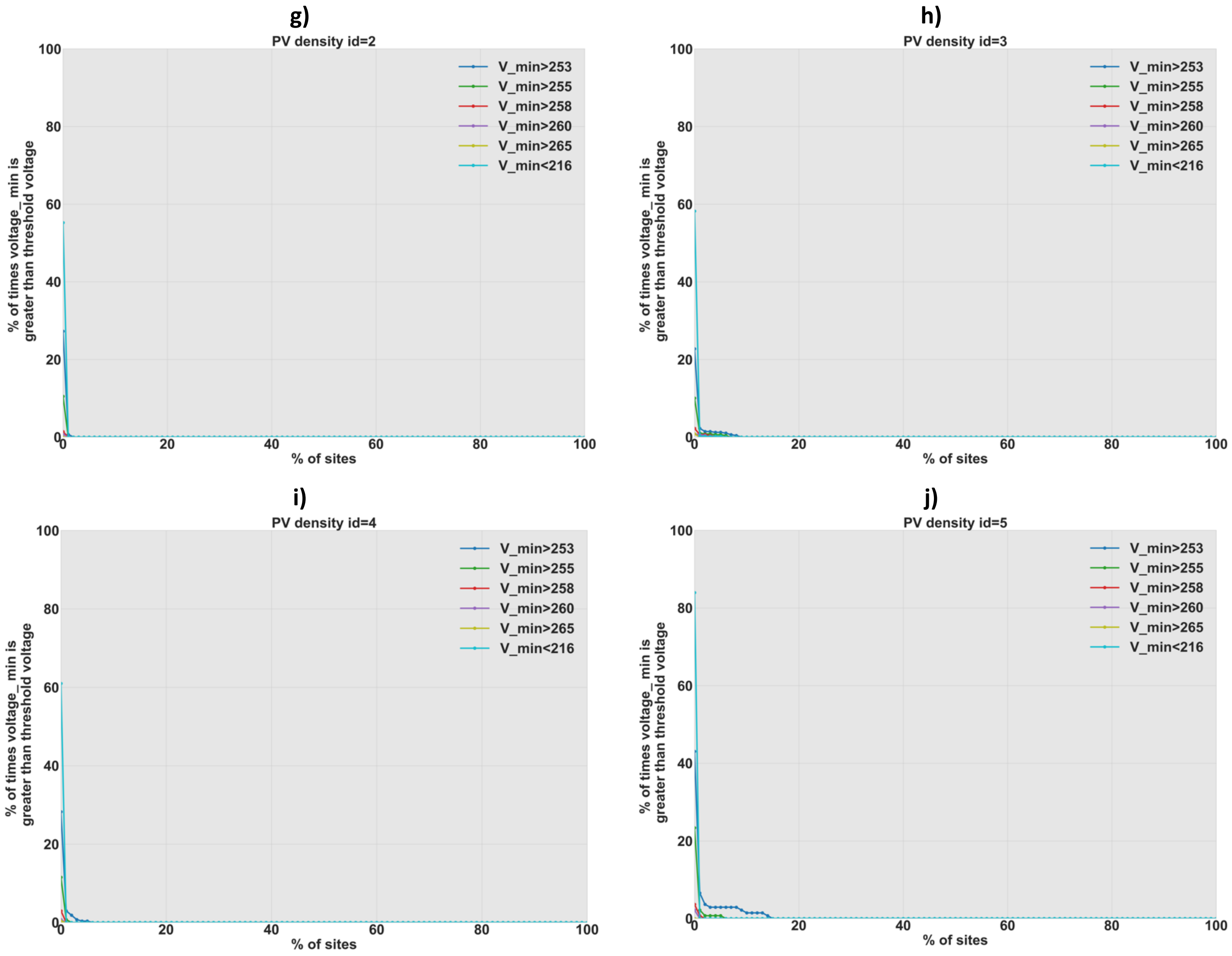

PV density id=4

e)


PV density id=5

f)


PV density id=1

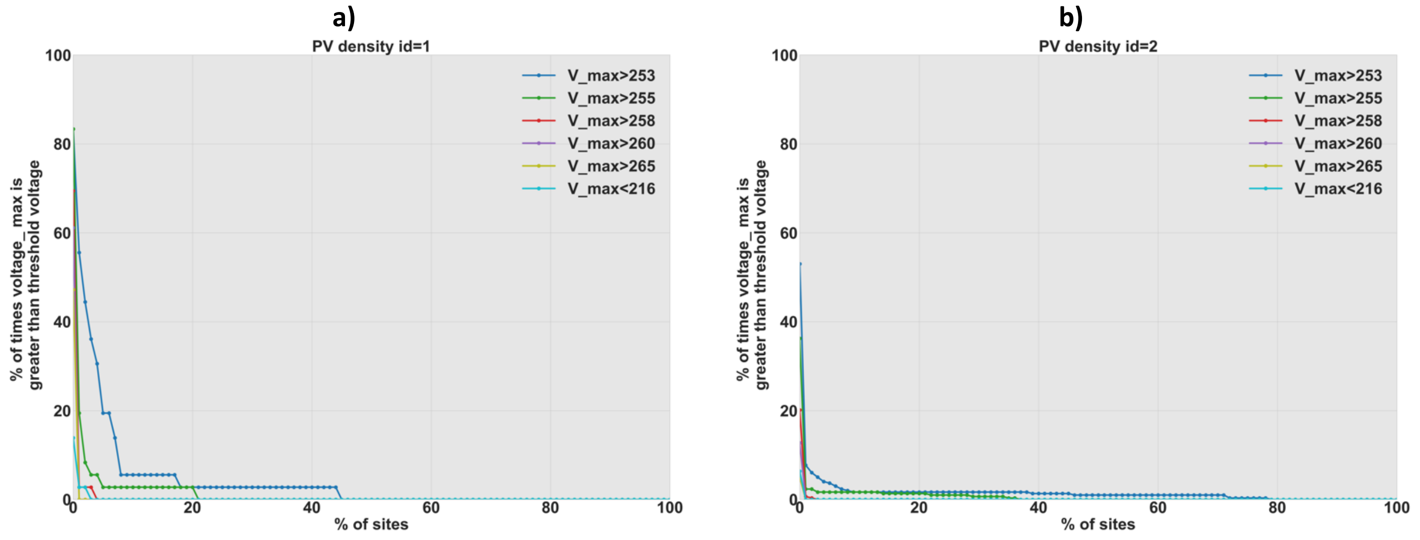

g)

h)

i)

j)

Figure 126 Percentage of sites vs. percentage of times of under and over voltage events based on household region's PV density for Energex network


a)

b)

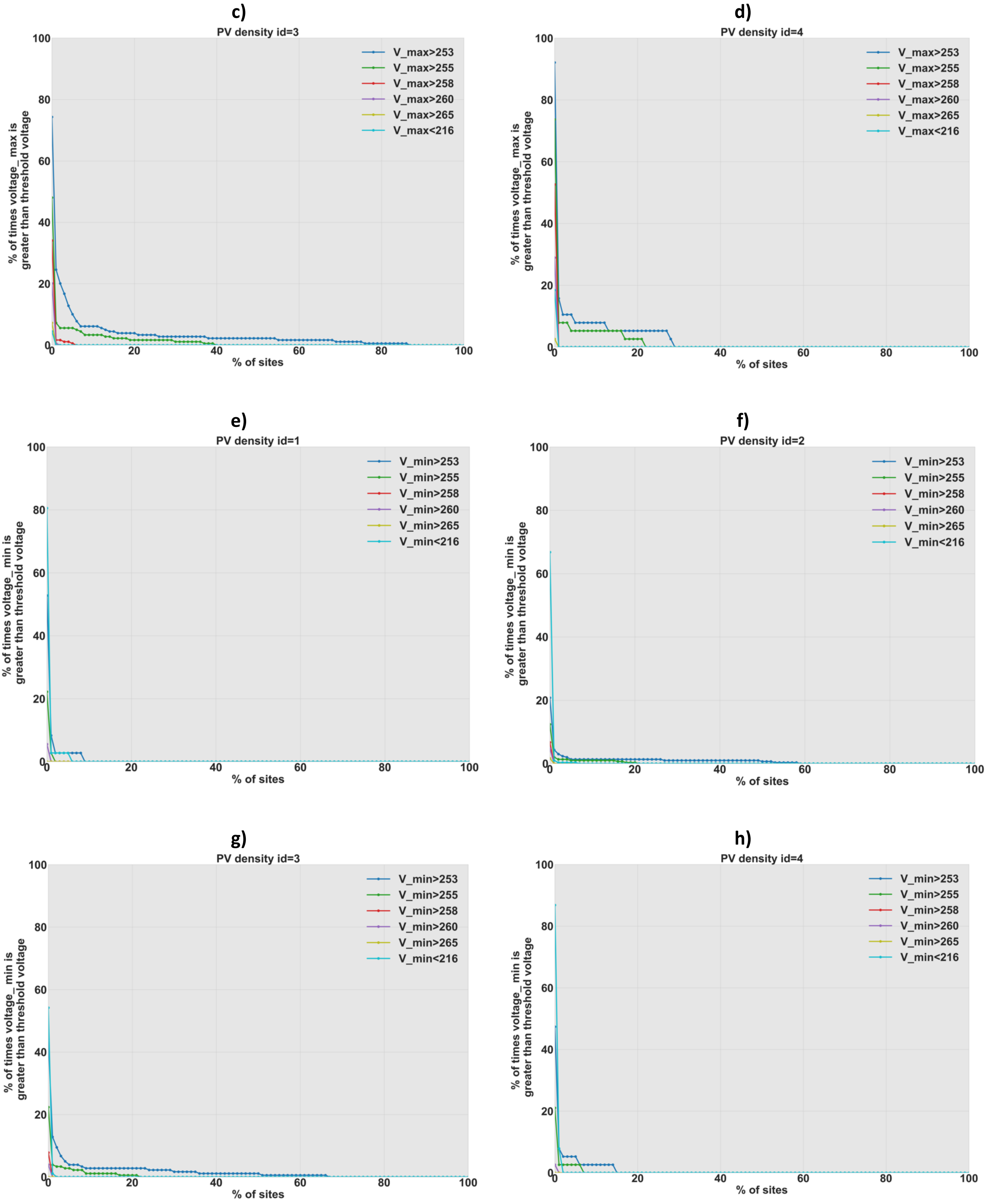


Figure 127 Percentage of sites vs. percentage of times of under and over voltage events based on household region's PV density for Ergon network (id=1 10-20%, id=2 20-30%, id=3 30-40%, id=4 40-50%, id=5 50-60% PV install density)

7.4 NSW (Ausgrid & Endeavour & Essential)

Although the data provided were not sufficient to determine whether individual PV systems had been curtailed because of over voltage constraints, the following analysis serves as a proxy by identifying how often the grid voltage exceeded thresholds. Table XVII shows the number of households analysed per DNSP in NSW based on their location’s PV installation density.

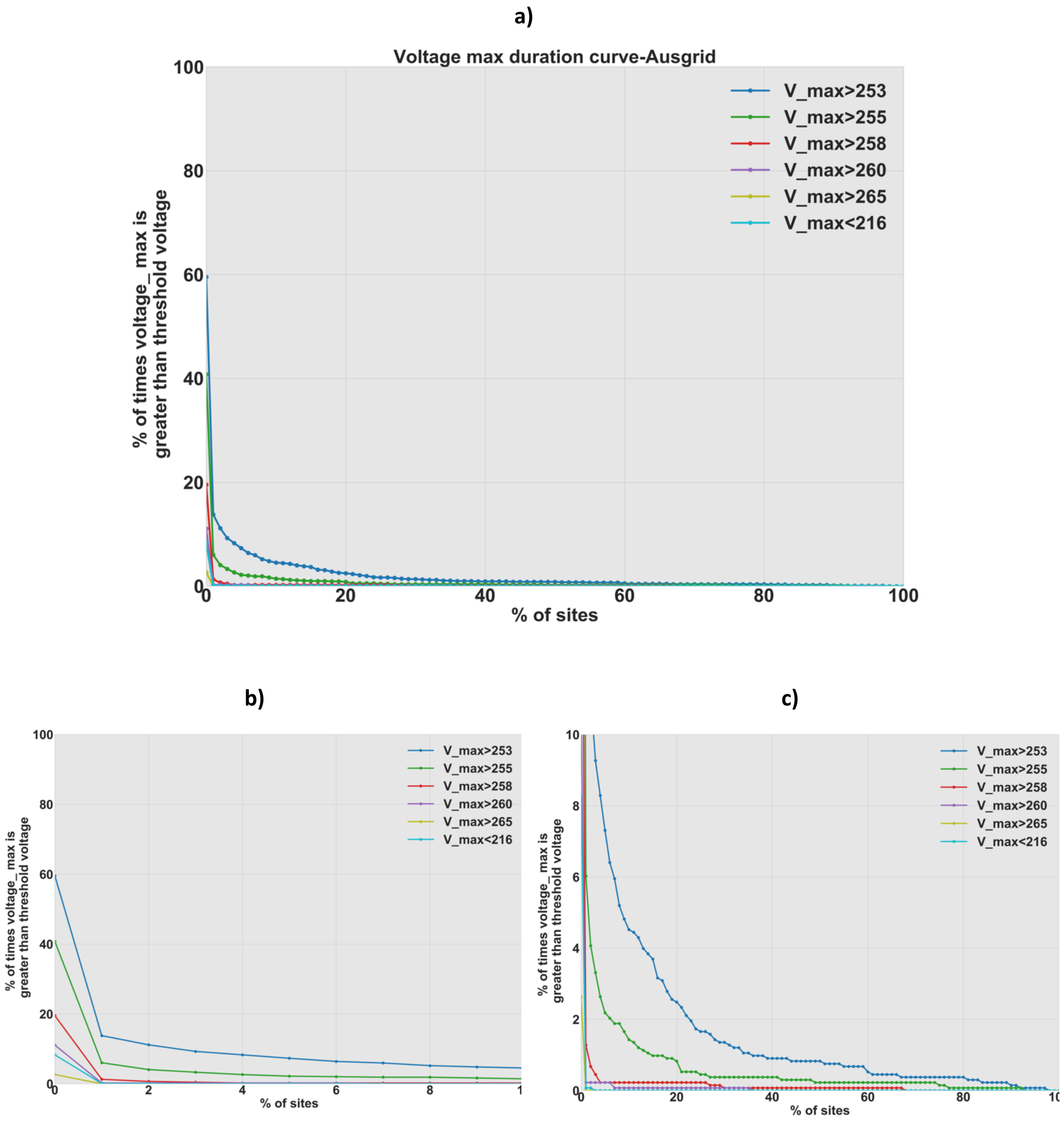
Table XVII PV density regions vs number of analysed household per DNSP

Number of households			
PV Density	**Ausgrid**	**Endeavour**	**Essential**
PV density 0: 0%-10%	280	19	0
PV density 1: 10%-20%	1154	665	405
PV density 2: 20%-30%	318	537	437
PV density 3: 30%-40%	13	11	321
PV density 4: 40%-50%	0	4	209
PV density 5: 50%-60%	1	0	7

7.4.1 Ausgrid

Figure 128 a) shows the percentage of the sites with full year of data vs the percentage of over and under voltage events within the analysed year for the Ausgrid network. The analysed voltage thresholds include 253, 255, 258, 260, 265 for over voltages with respect to Australian Standards and 216 V for the under-voltage events. Figure 128 b) and c) zoom into the x and y axes respectively.

It can be seen that around 23% of the sites experience over voltage (>253) at least 2% of the time and around 92% of the sites experience voltage >255. Moreover, around 2% of the sites are experiencing over voltage events with voltages being over 253, 255 and 258 levels for 12%, 4% and 1% of the time respectively. It is important to note that the standard for upper voltage and for inverter curtailment around 255-258V is based on average voltages over 10 minutes and PV inverter connection standards have changed over time. Still, it does suggest that if these high voltages are being sustained over such time periods, it is likely that some curtailment is occurring. Use of minimum voltages provides a more conservative estimate of the severity of high voltage excursions as shown in Figure 129. It is evident that even according to minimum voltage, there are still significant number of households which regularly experience over voltage events. It is worth noting that the under-voltage events are much less severe than the over voltage events.


a)

b)

c)

Figure 128 Percentage of sites vs. percentage of times of under and over voltage events based on voltage maximum for Ausgrid

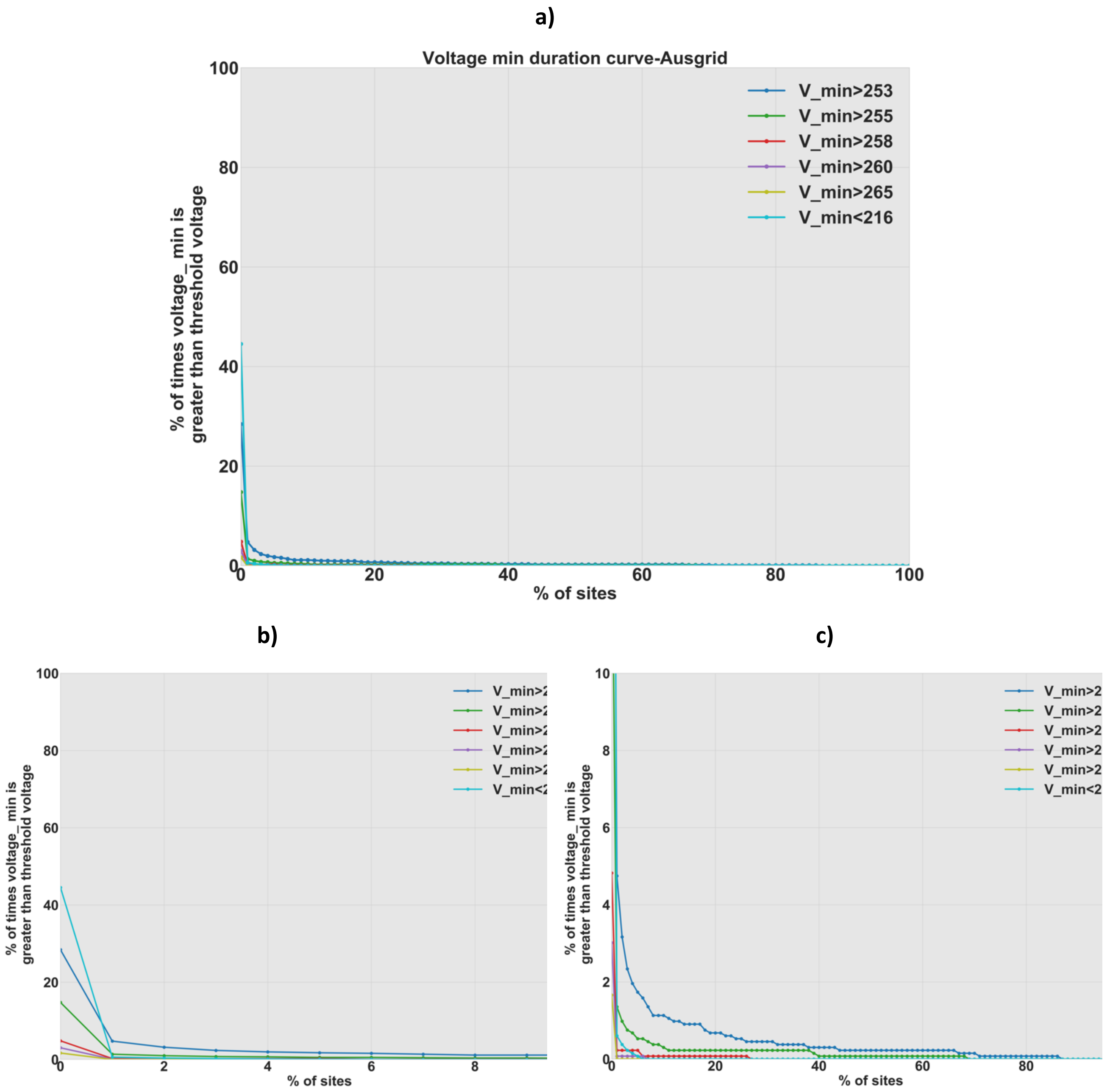


Figure 129 Percentage of sites vs. percentage of times of under and over voltage events based on voltage minimum for Ausgrid

7.4.2 Endeavour

Figure 130 presents similar results for the Endeavour network. Around 35% of the sites experience over voltage (>253) at least 2% of the time and around 44% of the sites experience voltage >255. Around 2% of the sites are experiencing over voltage events with voltages being over 253, 255 and 258 levels for 19%, 7% and 2% of the time respectively. Even when using voltage minima as shown in Figure 131, there are significant over voltage events observed for a great number of households. It is worth noting that the under-voltage events are much less severe than the over voltage events.

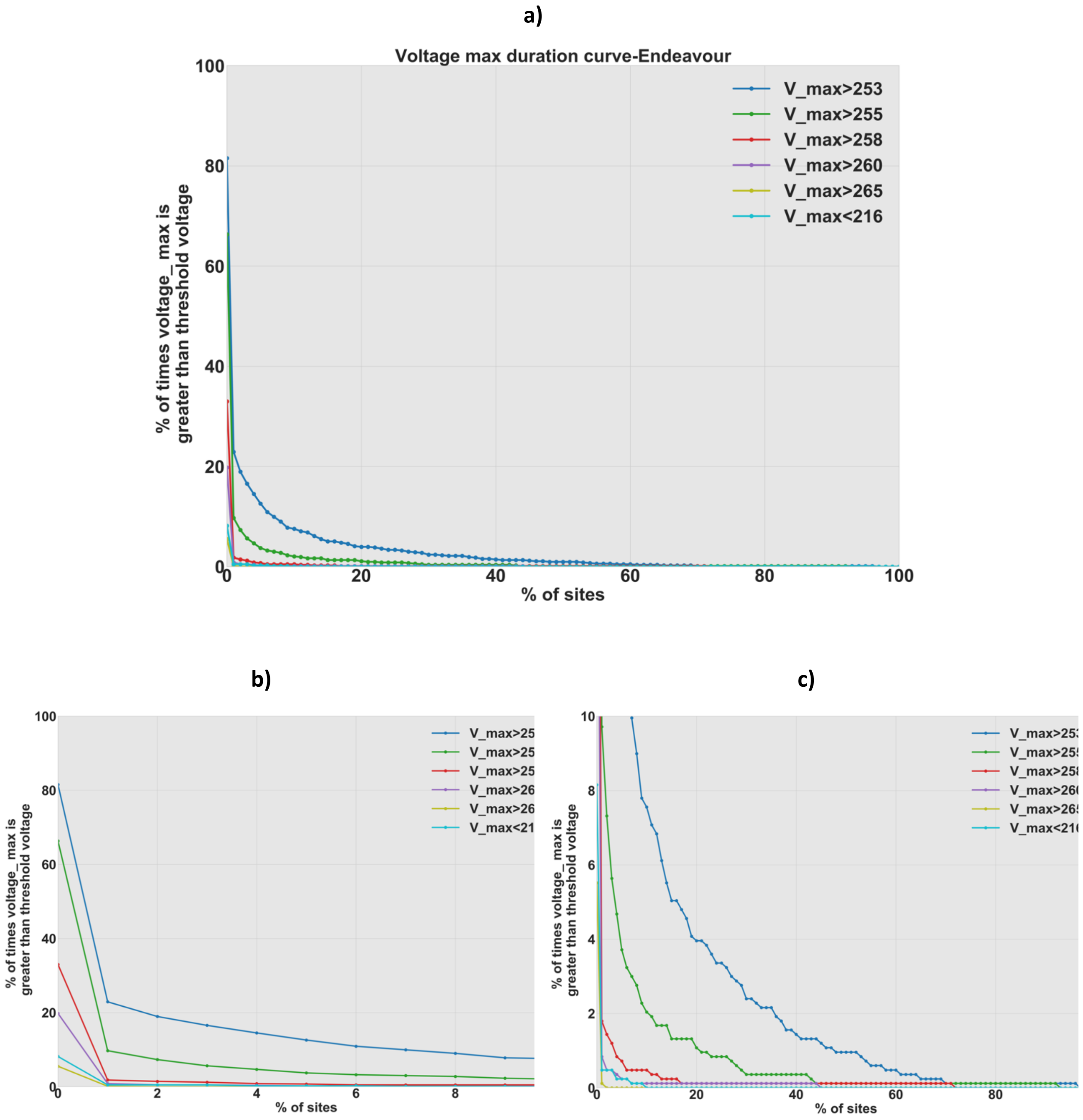


Figure 130 Percentage of sites vs. percentage of times of under and over voltage events based on voltage maximum for Endeavour

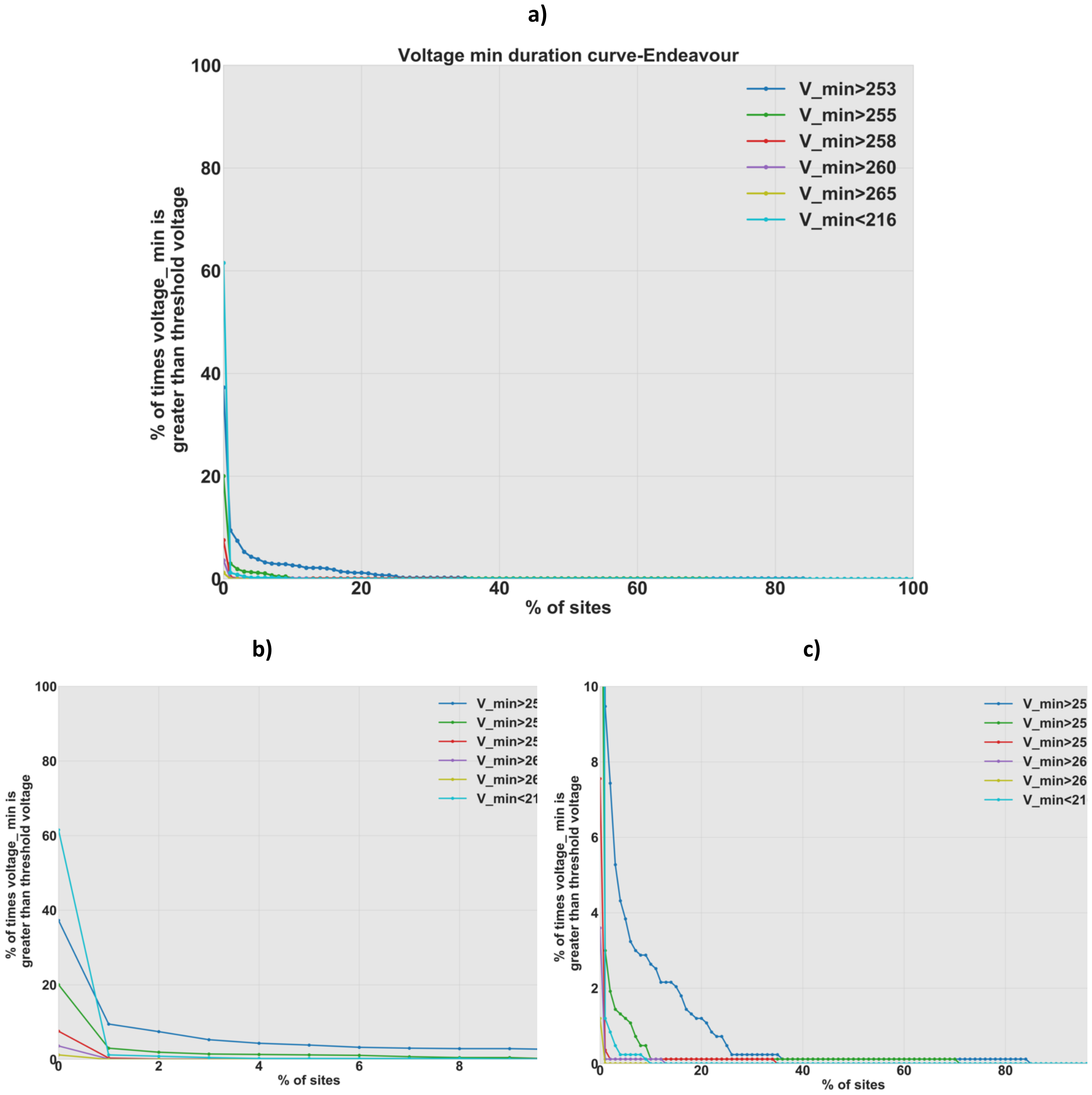


Figure 131 Percentage of sites vs. percentage of times of under and over voltage events based on voltage minimum for Endeavour

7.4.3 Essential

Figure 132 presents similar results for the Essential network. Around 43% of the sites experience over voltage (>253) at least 2% of the time and around 48% of the sites experience an over voltage event (>255). Around 2% of the sites are experiencing over voltage events with voltages being over 253, 255 and 258 levels for 24%, 12% and 3% of the time respectively, and almost all sites experience at least one over voltage event. Even when using voltage minima as shown in Figure 133, there are significant over voltage events observed for a great number of households. It is worth noting that the under-voltage events are much less severe than the over voltage events.

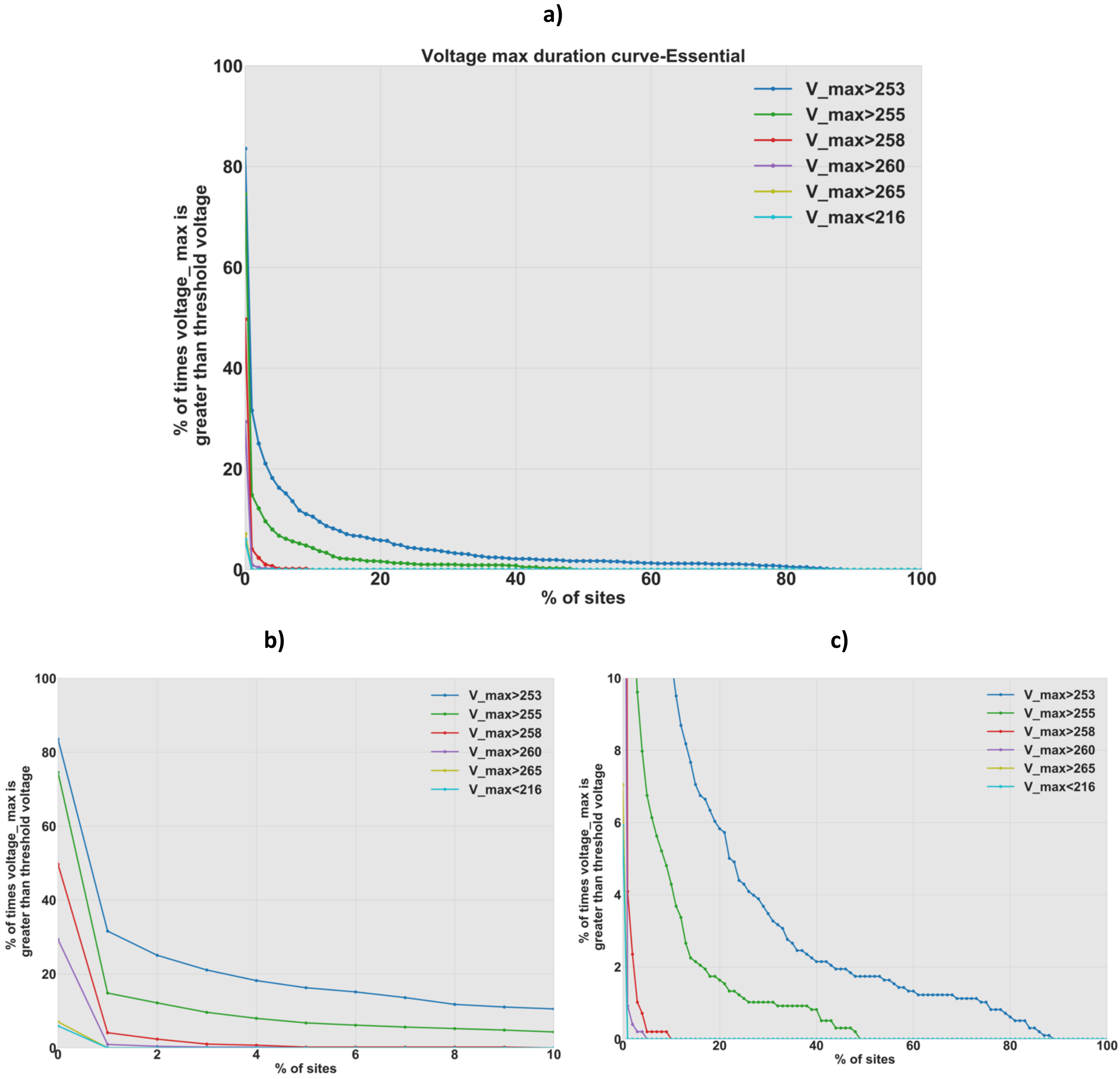


Figure 132 Percentage of sites vs. percentage of times of under and over voltage events based on voltage maximum for Essential

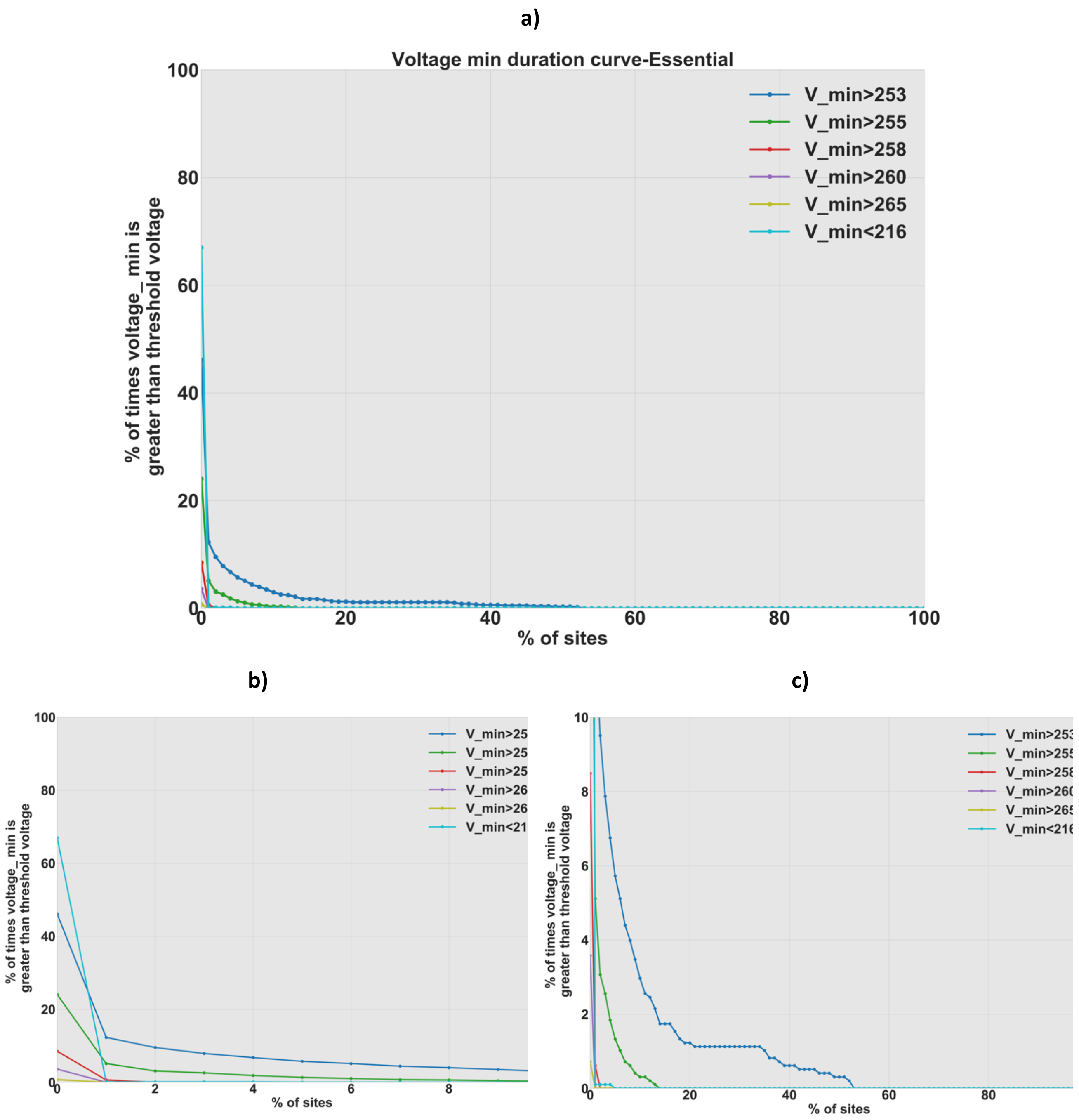


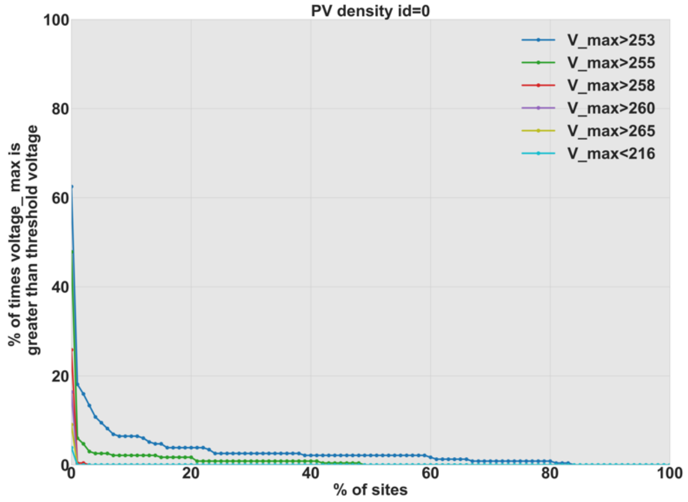
Figure 133 Percentage of sites vs. percentage of times of under and over voltage events based on voltage minimum for Essential

7.4.4 Impact of PV Density

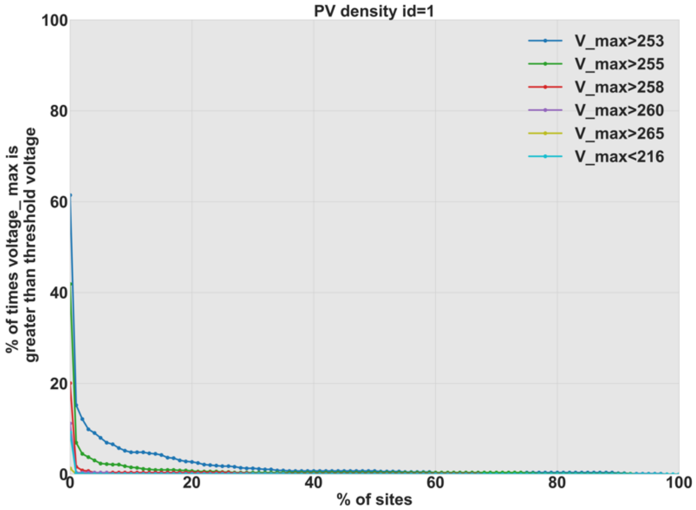
To understand whether the over and under voltage events are affected by the distributed PV penetration levels, Figure 134, Figure 135 and Figure 136 show the equivalent charts (both max and min) broken down into different PV density regions for Ausgrid, Endeavour and Essential networks respectively, based on postcode data as shown in Table XVII above.

Interestingly, none of Ausgrid, Endeavour or Energex show any particular correlation between installation density and voltage, often being lower at higher penetrations. Even excluding the very low and high penetrations, which have a small number of customers, there is still little correlation, presumably reflecting the various other influences on voltage.

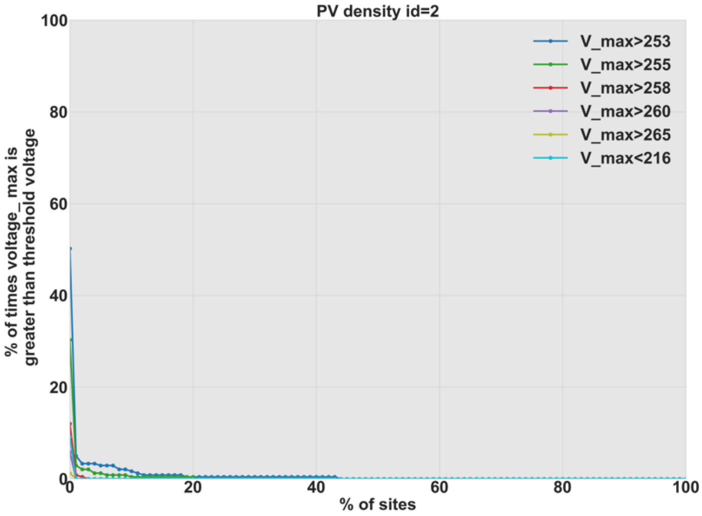
a)


PV density id=0
V_max>253
V_max>255
V_max>258
V_max>260
V_max>265
V_max<216
% of times voltage_ max is greater than threshold voltage
% of sites
0
20
40
60
80
100

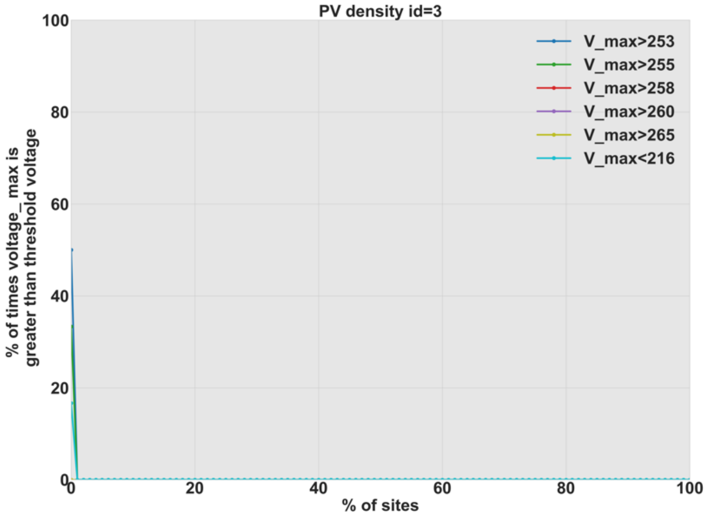
b)


PV density id=1
V_max>253
V_max>255
V_max>258
V_max>260
V_max>265
V_max<216
% of times voltage_ max is greater than threshold voltage
% of sites
0
20
40
60
80
100

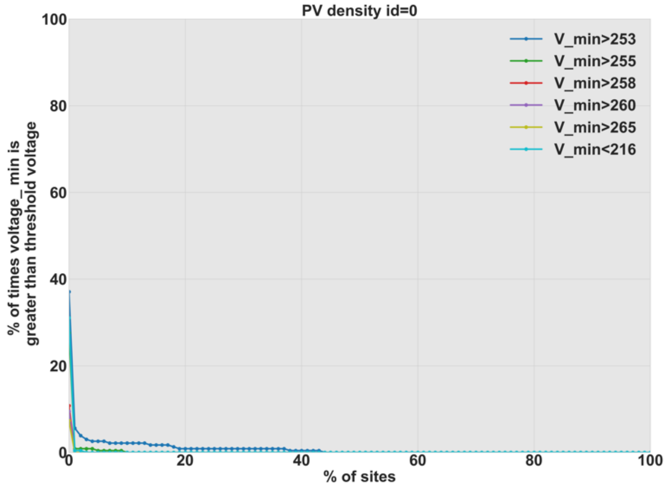
c)


PV density id=2
V_max>253
V_max>255
V_max>258
V_max>260
V_max>265
V_max<216
% of times voltage_ max is greater than threshold voltage
% of sites
0
20
40
60
80
100

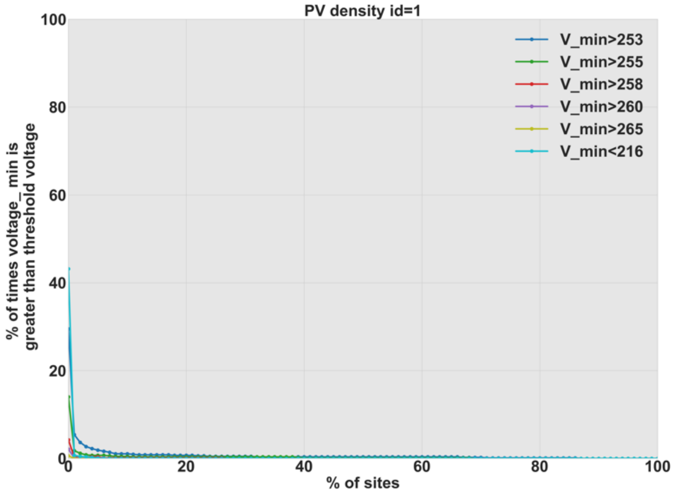
d)


PV density id=3
V_max>253
V_max>255
V_max>258
V_max>260
V_max>265
V_max<216
% of times voltage_ max is greater than threshold voltage
% of sites
0
20
40
60
80
100

e)


PV density id=0
V_min>253
V_min>255
V_min>258
V_min>260
V_min>265
V_min<216
% of times voltage_ min is greater than threshold voltage
% of sites
0
20
40
60
80
100

f)


PV density id=1
V_min>253
V_min>255
V_min>258
V_min>260
V_min>265
V_min<216
% of times voltage_ min is greater than threshold voltage
% of sites
0
20
40
60
80
100

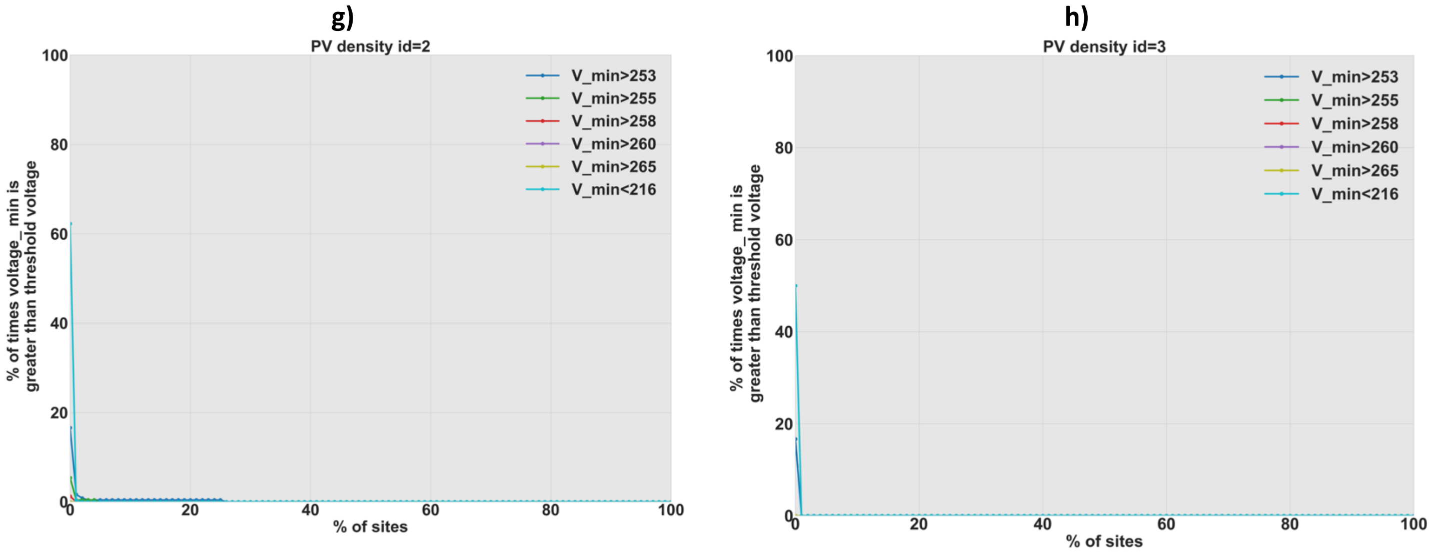
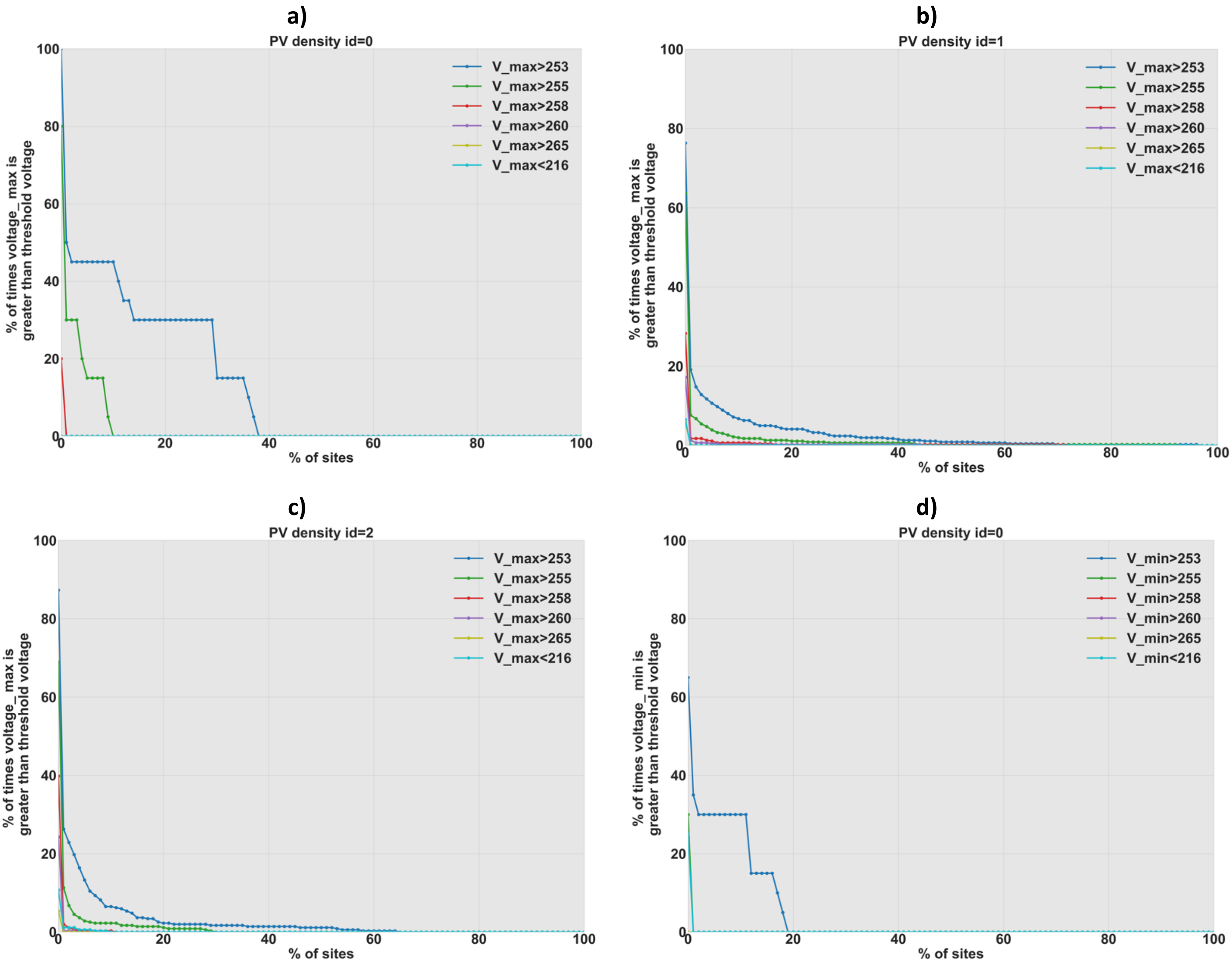

g) h)

Figure 134 Percentage of sites vs. percentage of times of under and over voltage events based on household region’s PV density for Ausgrid network (id=0 <10%, id=1 10-20%, id=2 20-30%, id=3 30-40%, id=4 40-50%, id=5 50-60% PV install density)


a) b) c) d)

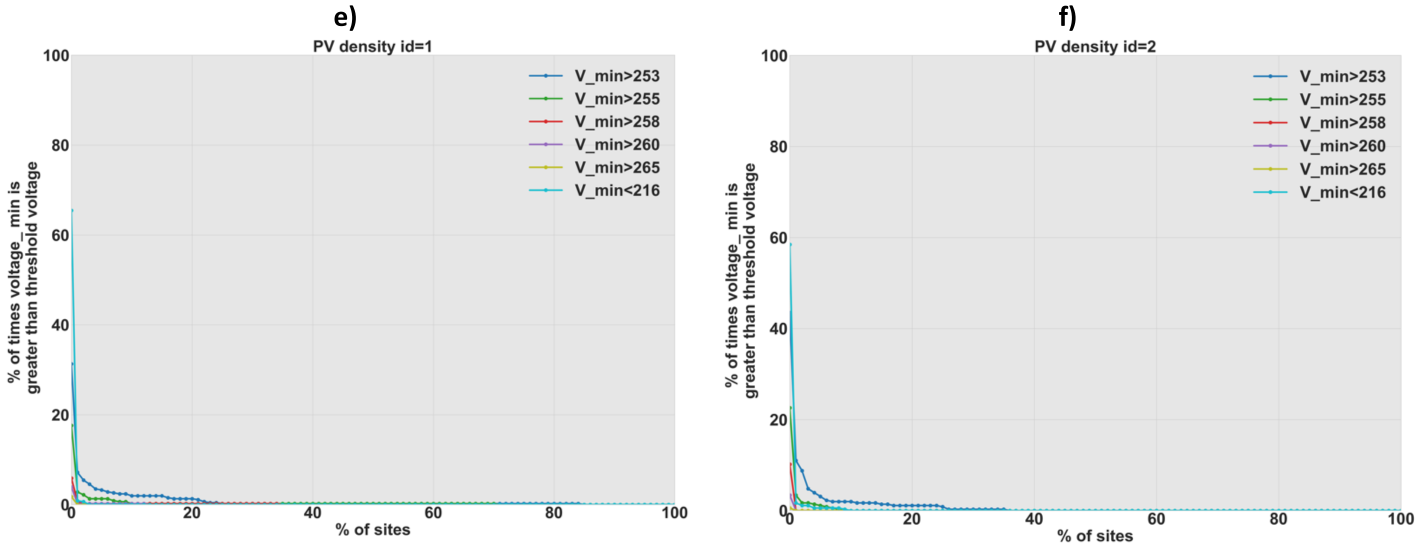
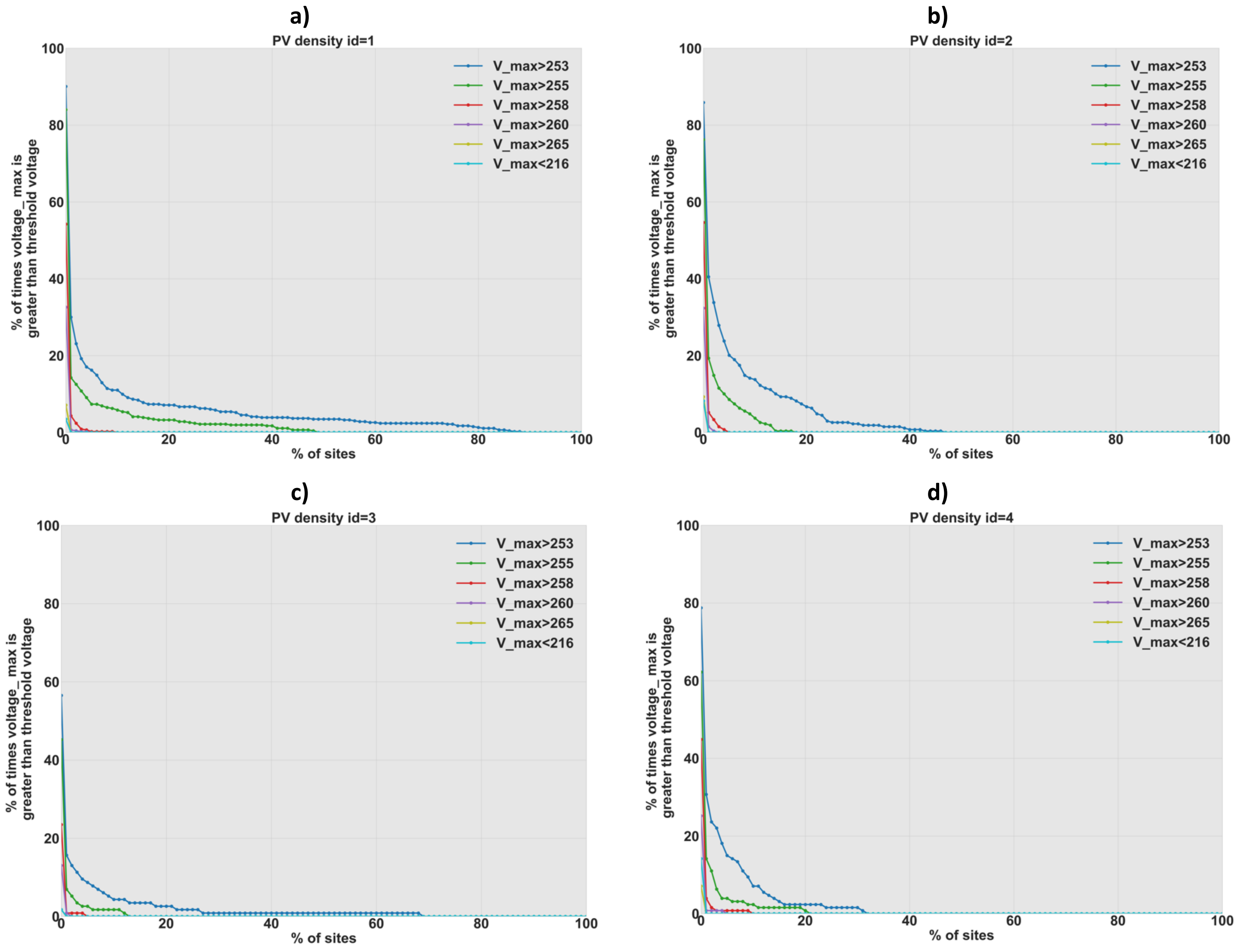


Figure 135 Percentage of sites vs. percentage of times of under and over voltage events based on household region's PV density for Endeavour network



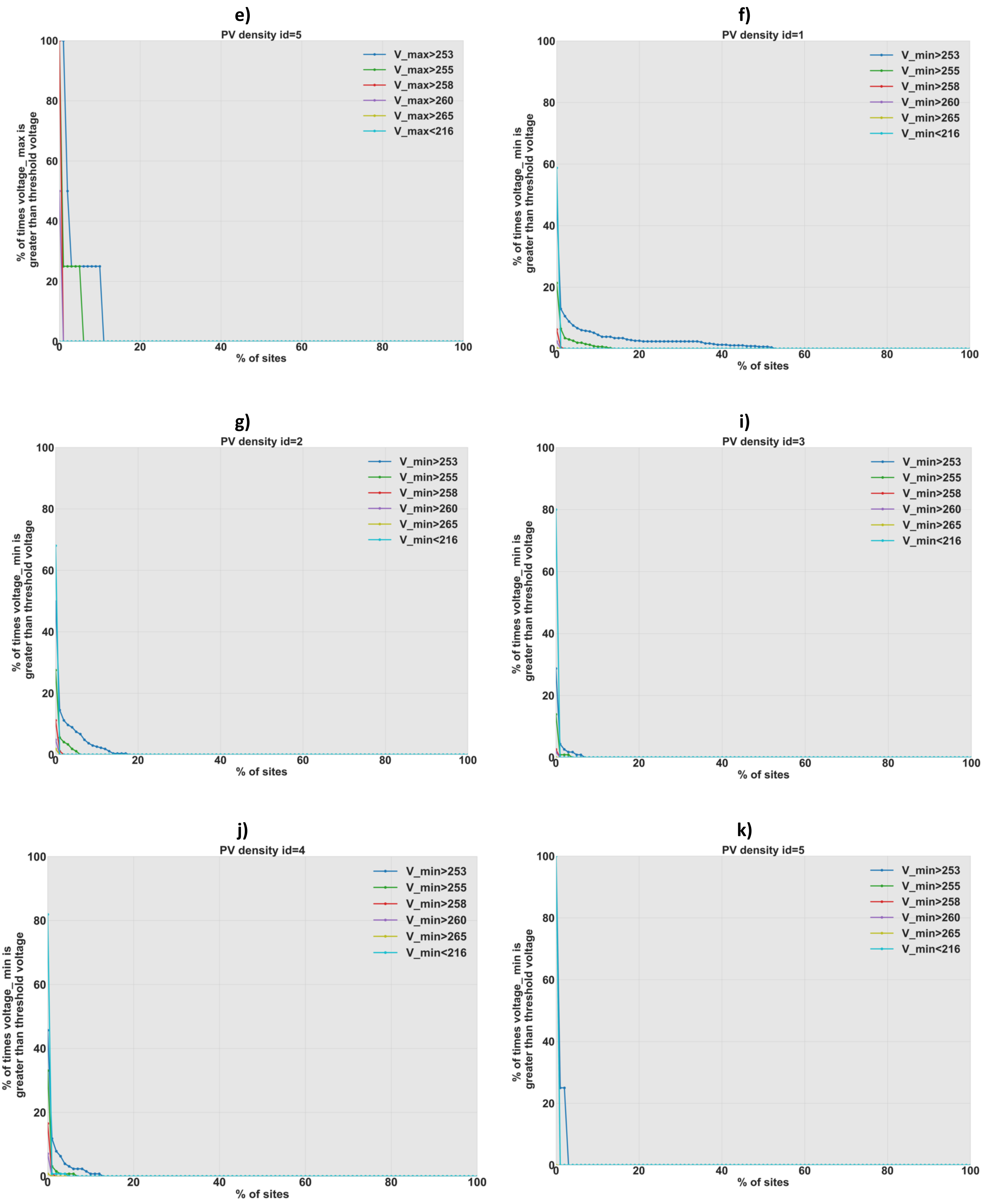


Figure 136 Percentage of sites vs. percentage of times of under and over voltage events based on household region's PV density for Essential network

7.5 Victoria (Powercor, United Energy, Jemena, Citipower & Ausnet)

Although the data provided were not sufficient to determine whether individual PV systems had been curtailed because of over voltage constraints, the following analysis serves as a proxy by identifying how often the grid voltage exceeded thresholds. Table XVII shows the number of households analysed per DNSP in Vic based on their location's PV installation density.

Table XVIII PV density regions vs number of analysed households per DNSP

Number of households					
PV Density	**Powercor**	**United Energy**	**Jemena**	**Citipower**	**Ausnet**
PV density 0: 0%-10%	2	20	22	48	0
PV density 1: 10%-20%	112	138	41	13	145
PV density 2: 20%-30%	93	13	60	0	188
PV density 3: 30%-40%	30	0	0	0	46
PV density 4: 40%-50%	0	0	0	0	6
PV density 5: 50%-60%	3	0	0	0	0

7.5.1 Powercor

Figure 137 a) shows the percentage of the sites with full year of data vs the percentage of over and under voltage events within the analysed year for the Powercor network. The analysed voltage thresholds include 253, 255, 258, 260, 265 for over voltages with respect to Australian Standards and 216 V for the under-voltage events. Figure 137 b) and c) zoom into the x and y axes respectively.

It can be seen that around 24% of the sites experience over voltage (>253) at least 2% of the time and around 11% of the sites experience voltage >255. Moreover, around 2% of the sites are experiencing over voltage events with voltages being over 253 and 255 levels for 19% and 7% of the time respectively. It is important to note that the standard for upper voltage and for inverter curtailment around 255-258V is based on average voltages over 10 minutes and PV inverter connection standards have changed over time. Still, it does suggest that if these high voltages are being sustained over such time periods, it is likely that some curtailment is occurring. Use of minimum voltages provides a more conservative estimate of the severity of high voltage excursions as shown in Figure 138. It is evident that even according to minimum voltage, there are still significant number of households which regularly experience over voltage events. It is worth noting that the under-voltage events are much less severe than the over voltage events.

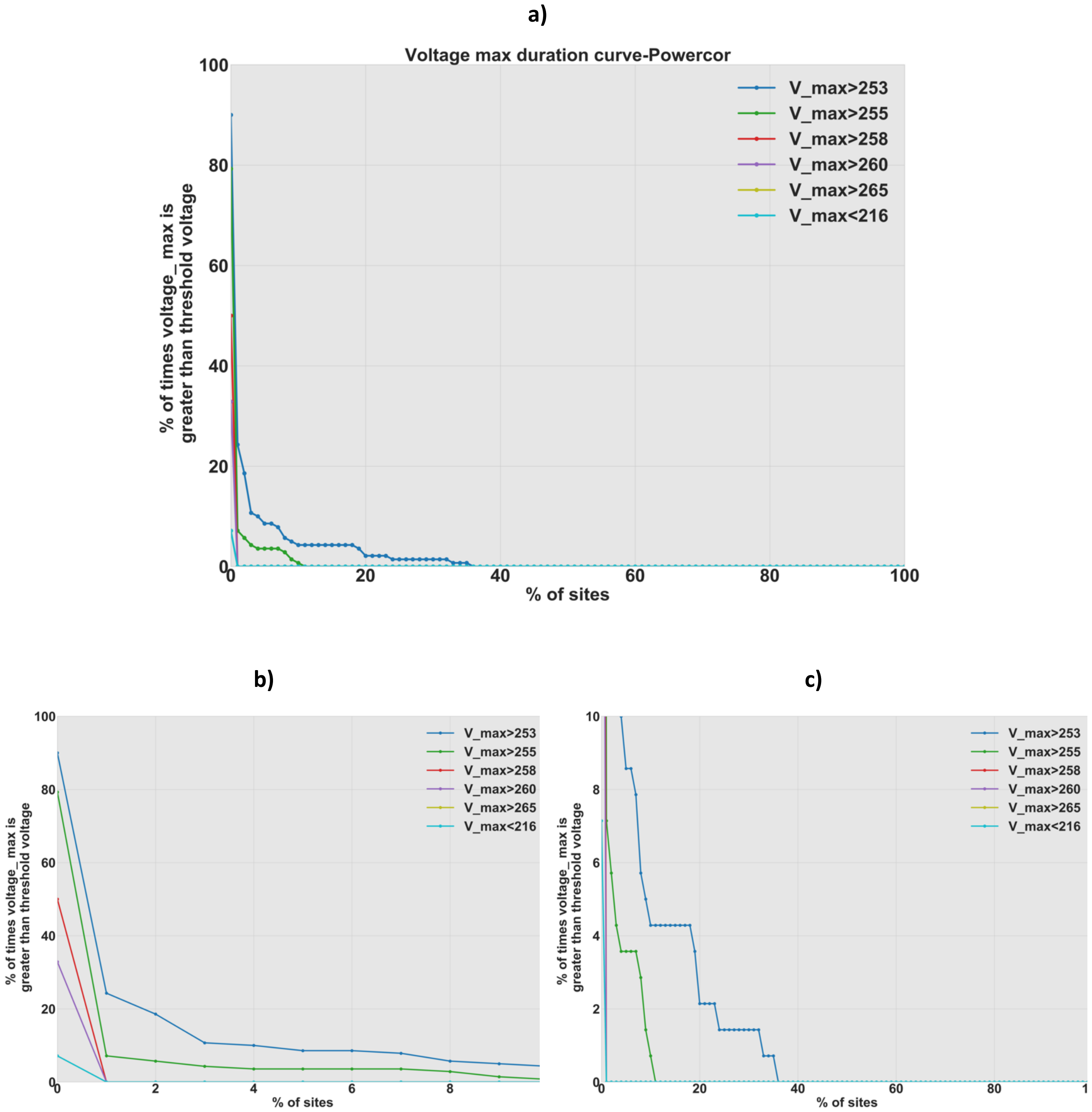


Figure 137 Percentage of sites vs. percentage of times of under and over voltage events based on voltage maximum for Powercor

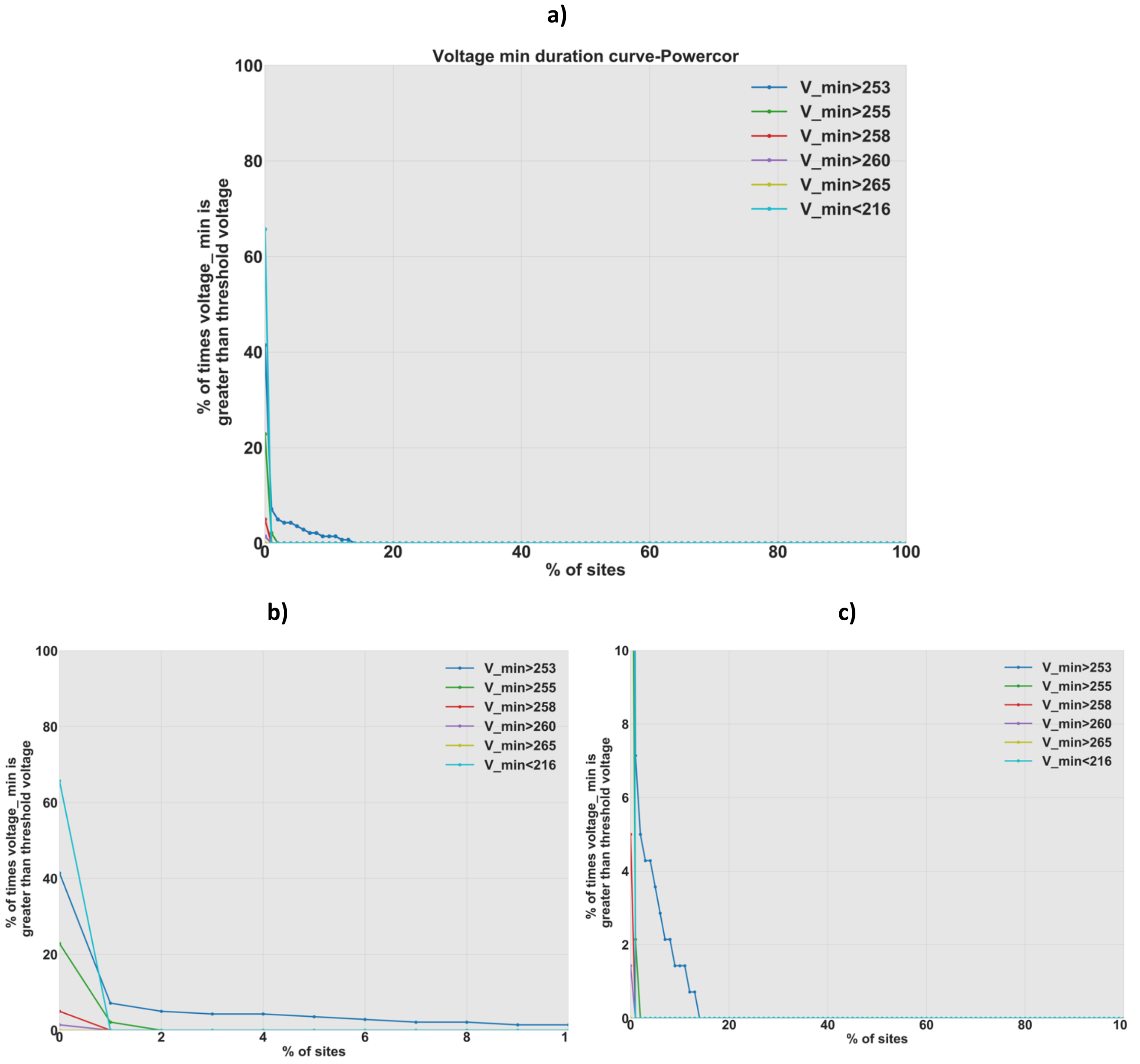
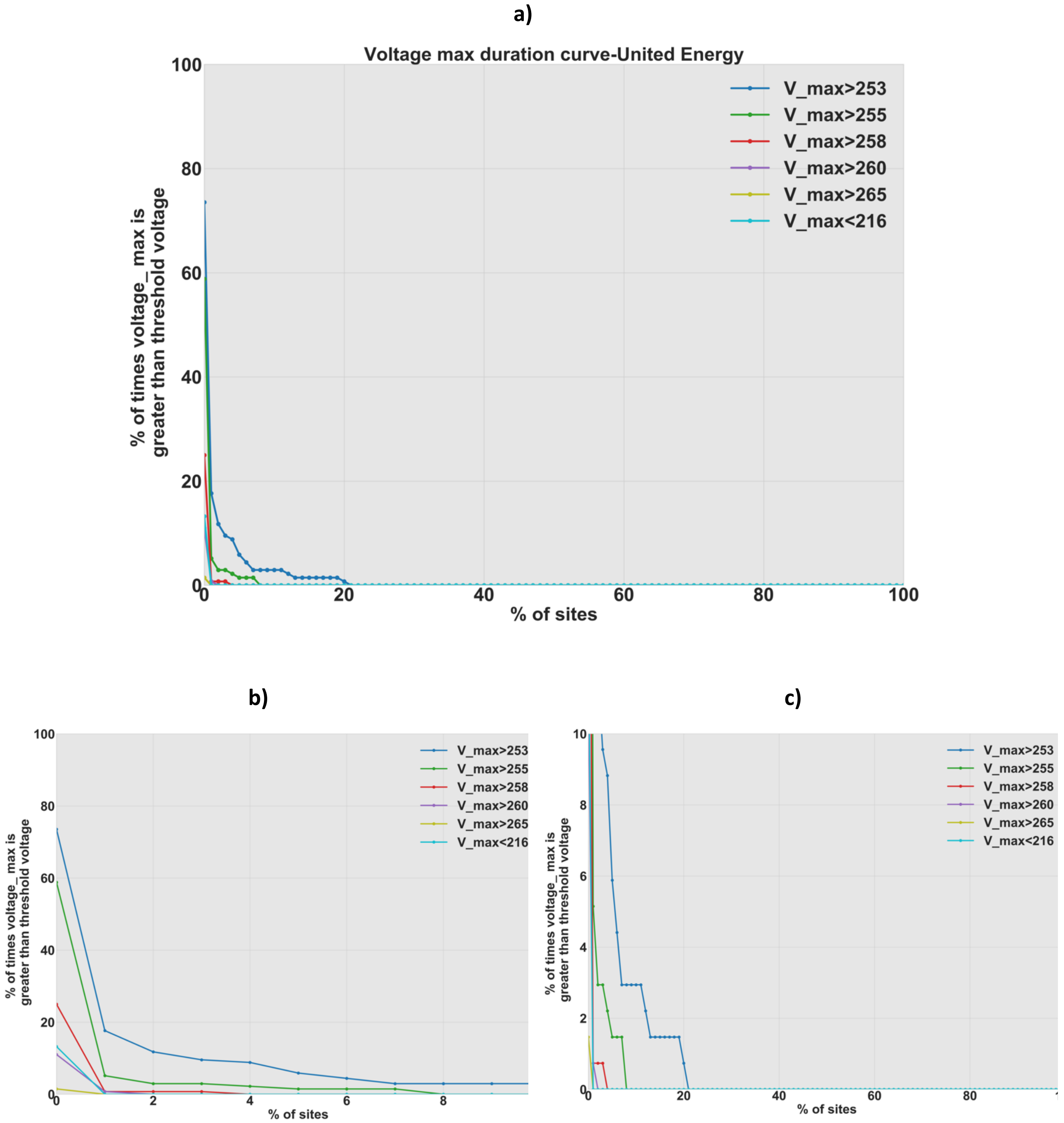


Figure 138 Percentage of sites vs. percentage of times of under and over voltage events based on voltage minimum for Powercor

7.5.2 United Energy

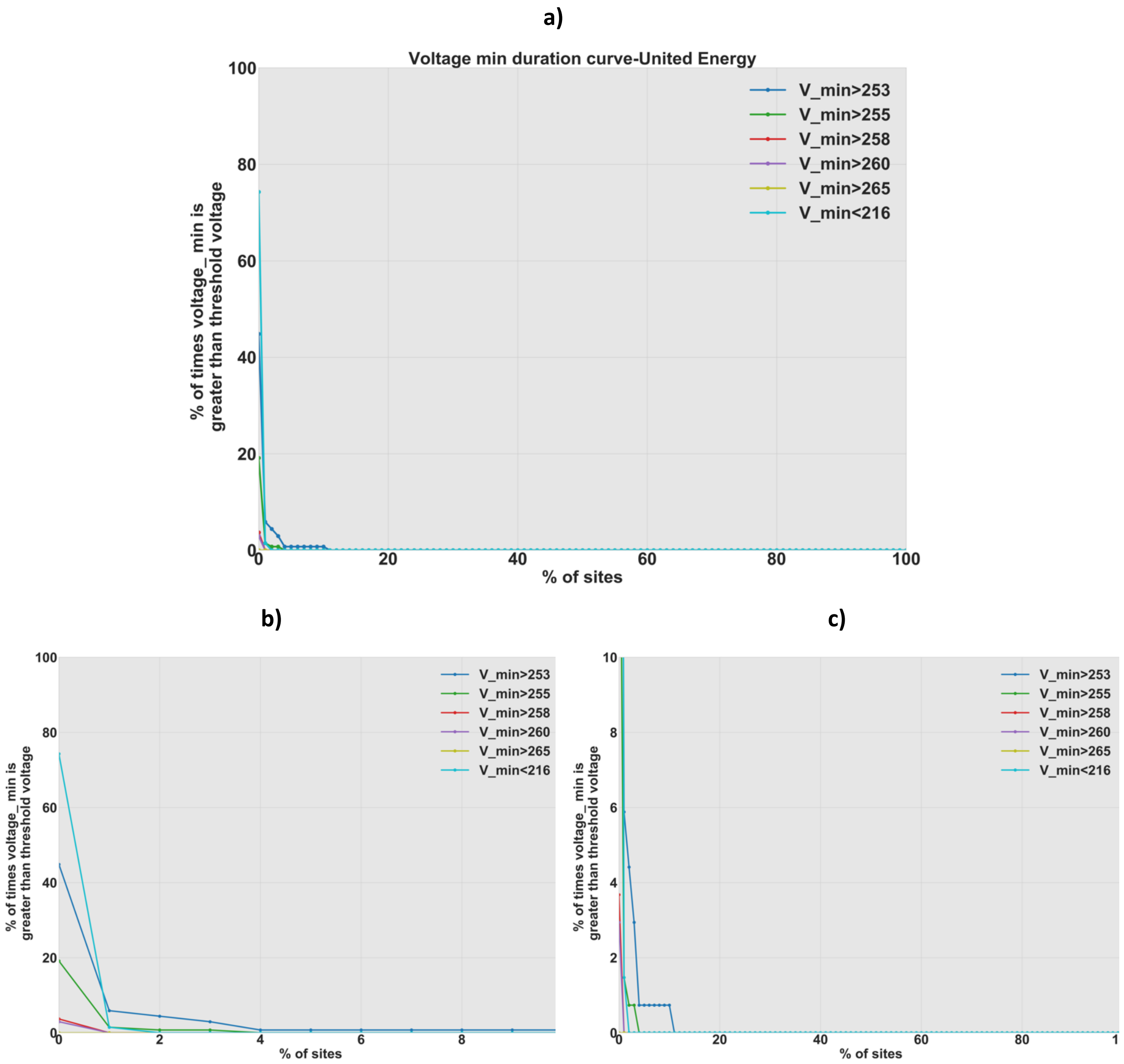
Figure 139 presents similar results for the United Energy network. Around 12% of the sites experience over voltage (>253) at least 2% of the time and around 7% of the sites experience voltage >255. Around 2% of the sites are experiencing over voltage events with voltages being over 253 and 255 levels for 13% and 3% of the time respectively. Even when using voltage minima as shown in Figure 140, there are significant over voltage events observed for a great number of households. It is worth noting that the under-voltage events are much less severe than the over voltage events.


a)

b)

c)

Figure 139 Percentage of sites vs. percentage of times of under and over voltage events based on voltage maximum for United Energy


a)

b)

c)

Figure 140 Percentage of sites vs. percentage of times of under and over voltage events based on voltage minimum for United Energy

7.5.3 Jemena

Figure 141 presents similar results for the Jemena network. Around 21% of the sites experience over voltage (>253) at least 2% of the time and around 14% of the sites experience an over voltage event (>255). Around 2% of the sites are experiencing over voltage events with voltages being over 253, 255 and 258 levels for 19%, 6% and 4% of the time respectively, and almost all sites experience at least one over voltage event. Even when using voltage minima as shown in Figure 142, there are significant over voltage events observed for a great number of households. It is worth noting that the under-voltage events are much less severe than the over voltage events.

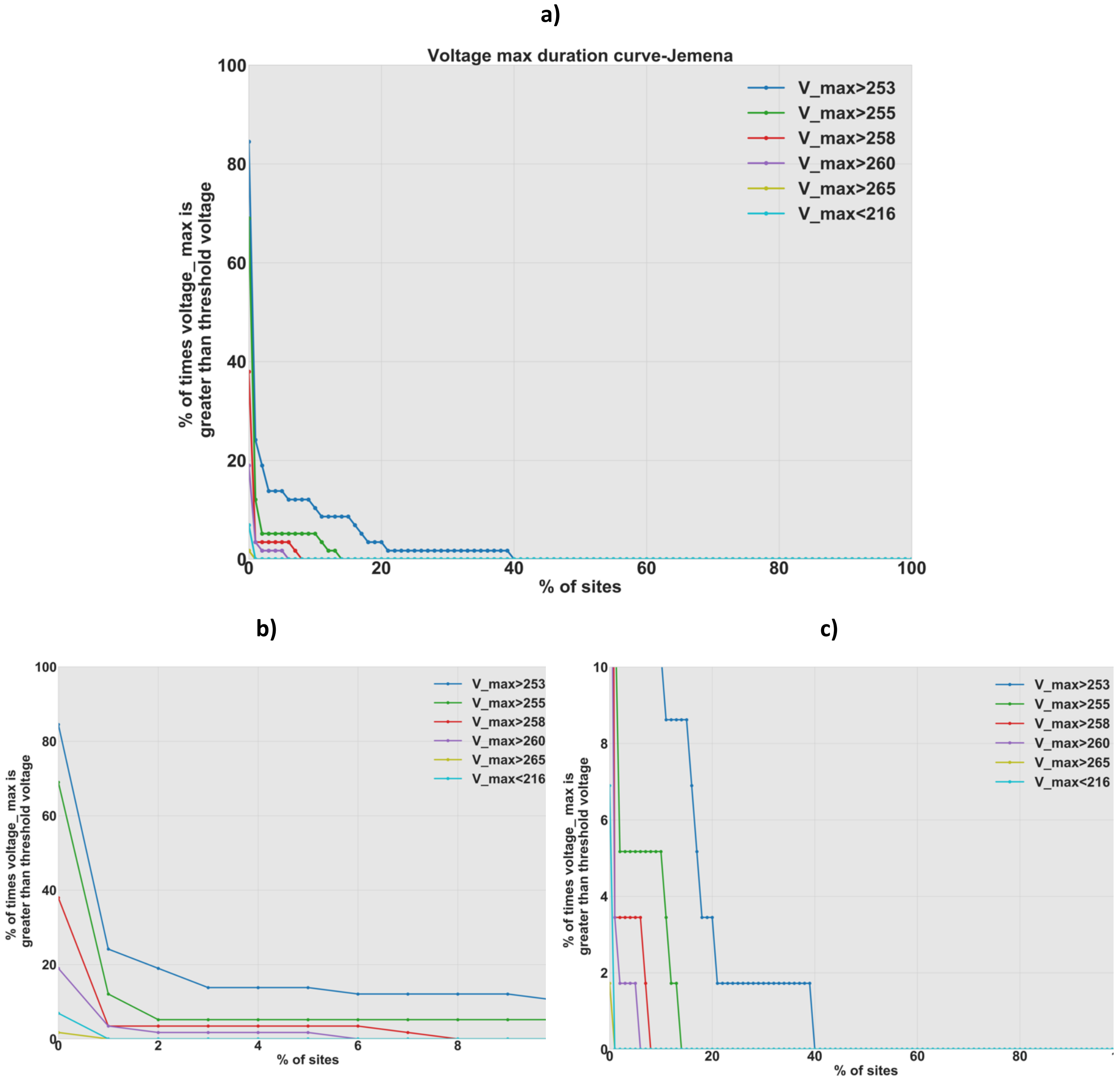


Figure 141 Percentage of sites vs. percentage of times of under and over voltage events based on voltage maximum for Jemena

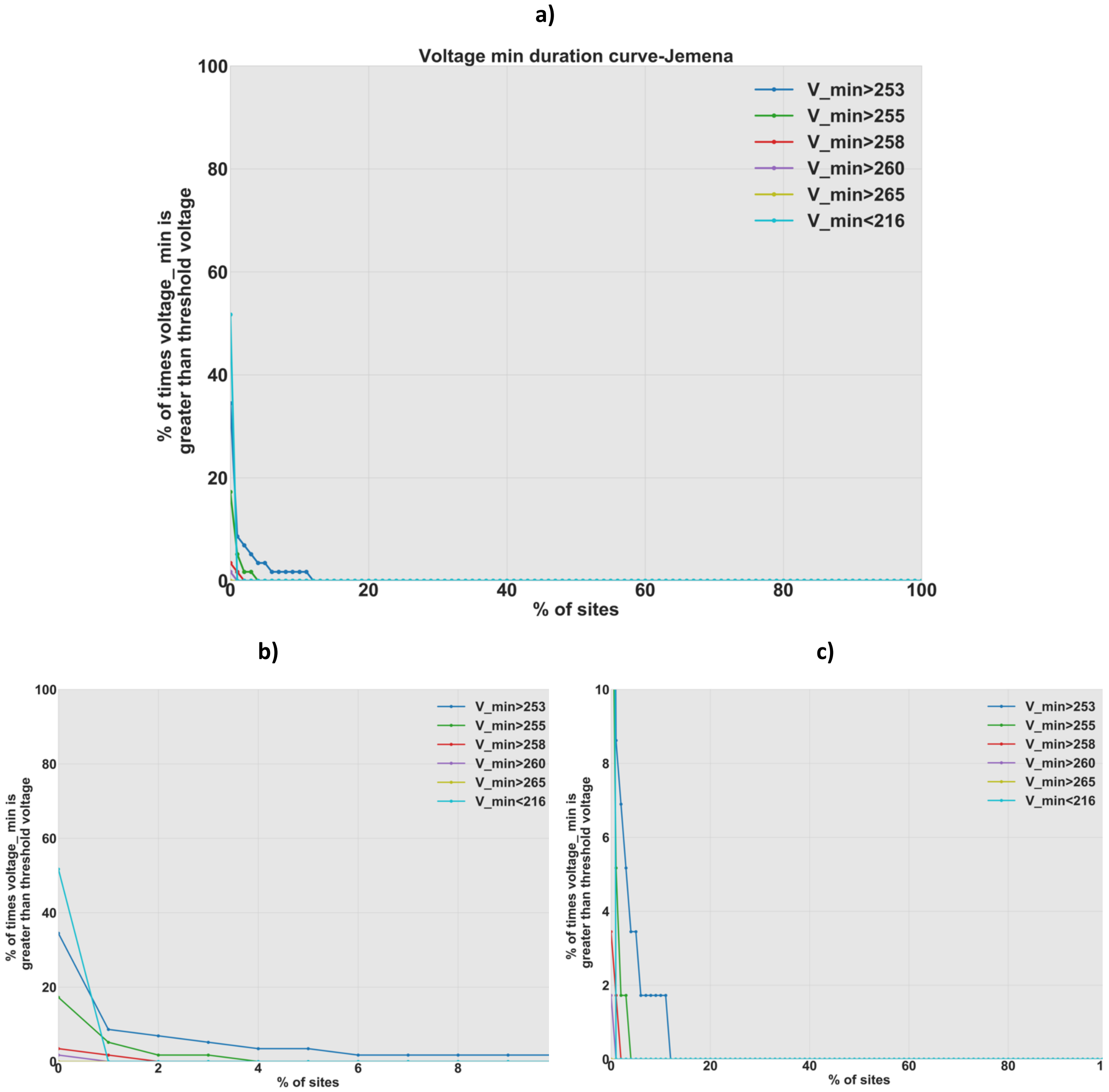


Figure 142 Percentage of sites vs. percentage of times of under and over voltage events based on voltage minimum for Jemena

7.5.4 Citipower

Figure 143 presents similar results for the Citipower network. Around 71% of the sites experience over voltage (>253) at least 2% of the time and around 30% of the sites experience an over voltage event (>255). Around 2% of the sites are experiencing over voltage events with voltages being over 253, 255 and 258 levels for 26%, 16% and 2% of the time respectively, and almost all sites experience at least one over voltage event. Even when using voltage minima as shown in Figure 144, there are significant over voltage events observed for a great number of households. It is worth noting that the under-voltage events are much less severe than the over voltage events.

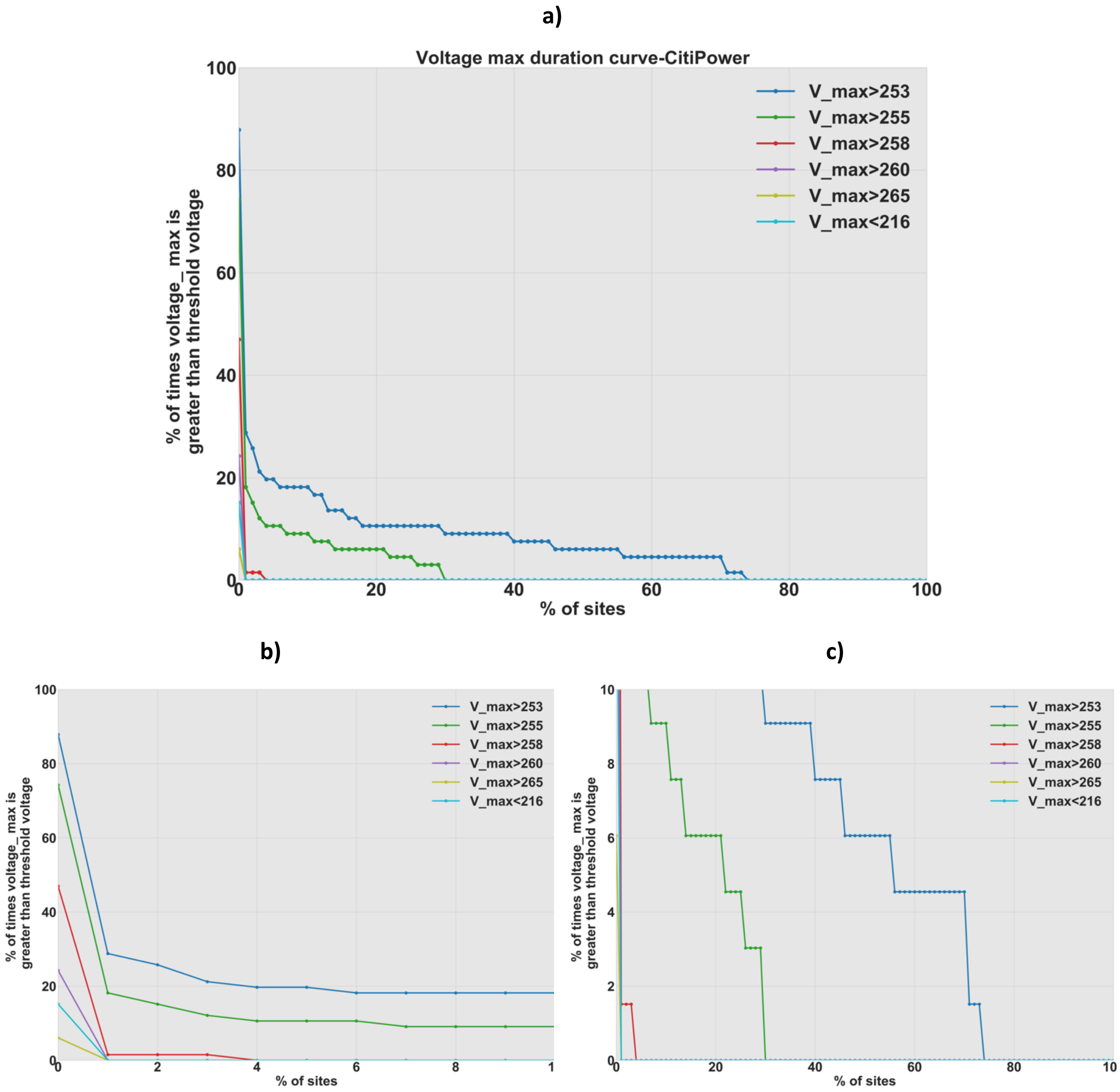
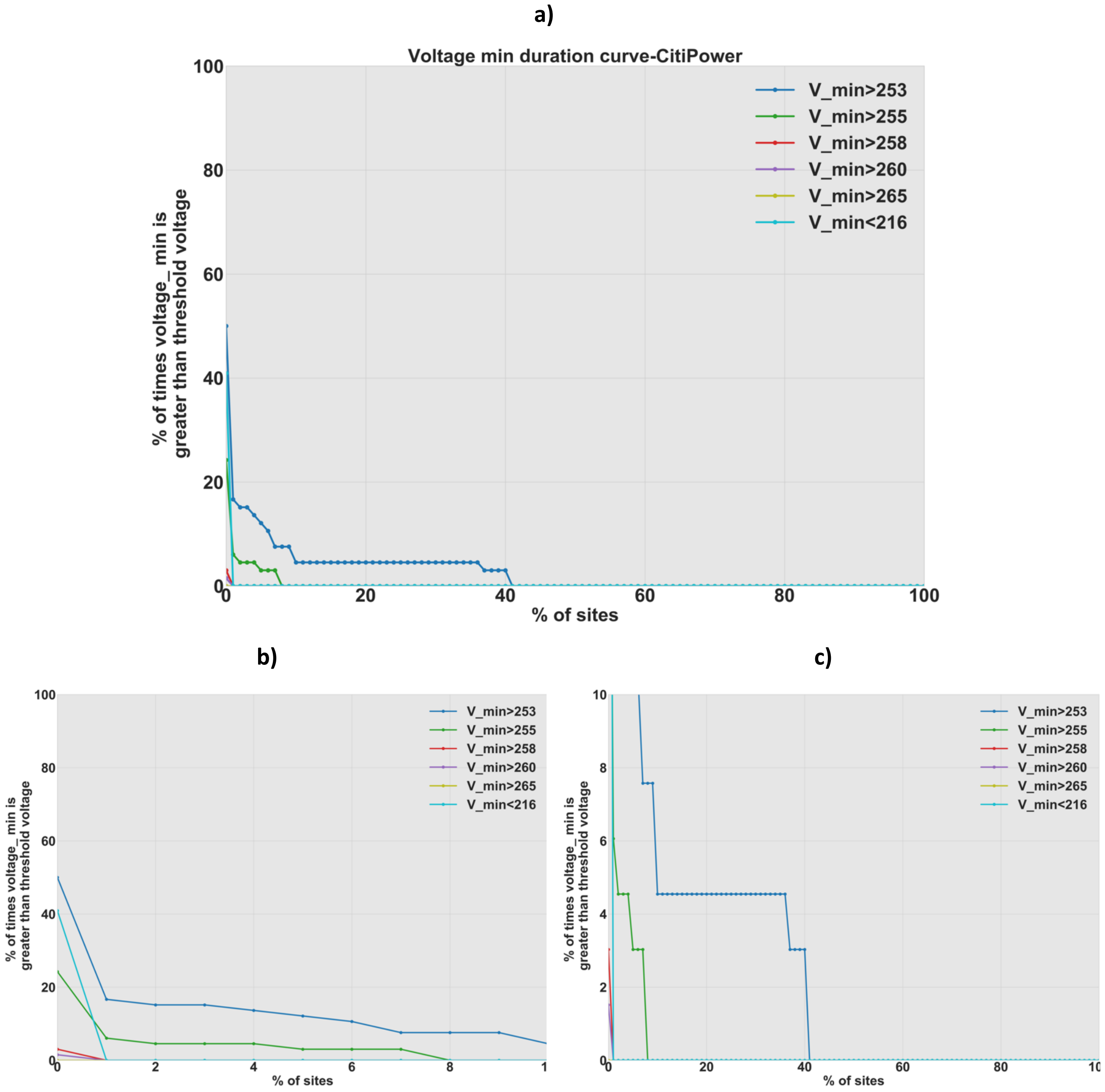


Figure 143 Percentage of sites vs. percentage of times of under and over voltage events based on voltage maximum for Citipower


a)

b)

c)

Figure 144 Percentage of sites vs. percentage of times of under and over voltage events based on voltage minimum for Citipower

7.5.5 Ausnet

Figure 145 presents similar results for the Ausnet network. Around 16% of the sites experience over voltage (>253) at least 2% of the time and around 37% of the sites experience an over voltage event (>255). Around 2% of the sites are experiencing over voltage events with voltages being over 253, 255 and 258 levels for 17%, 4% and 2% of the time respectively, and almost all sites experience at least one over voltage event. Even when using voltage minima as shown in Figure 146, there are significant over voltage events observed for a great number of households. It is worth noting that the under-voltage events are much less severe than the over voltage events.

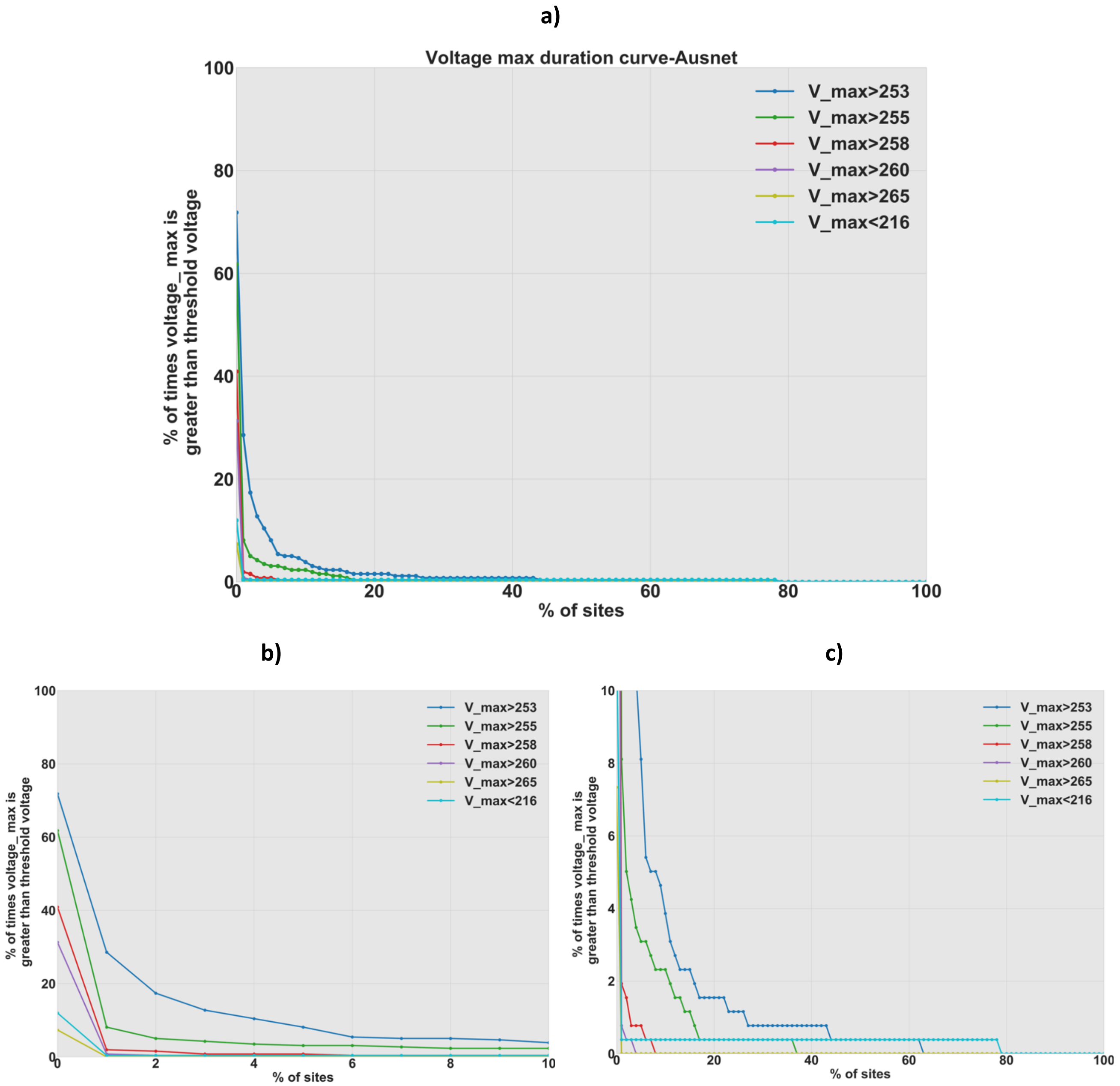


Figure 145 Percentage of sites vs. percentage of times of under and over voltage events based on voltage maximum for Ausnet

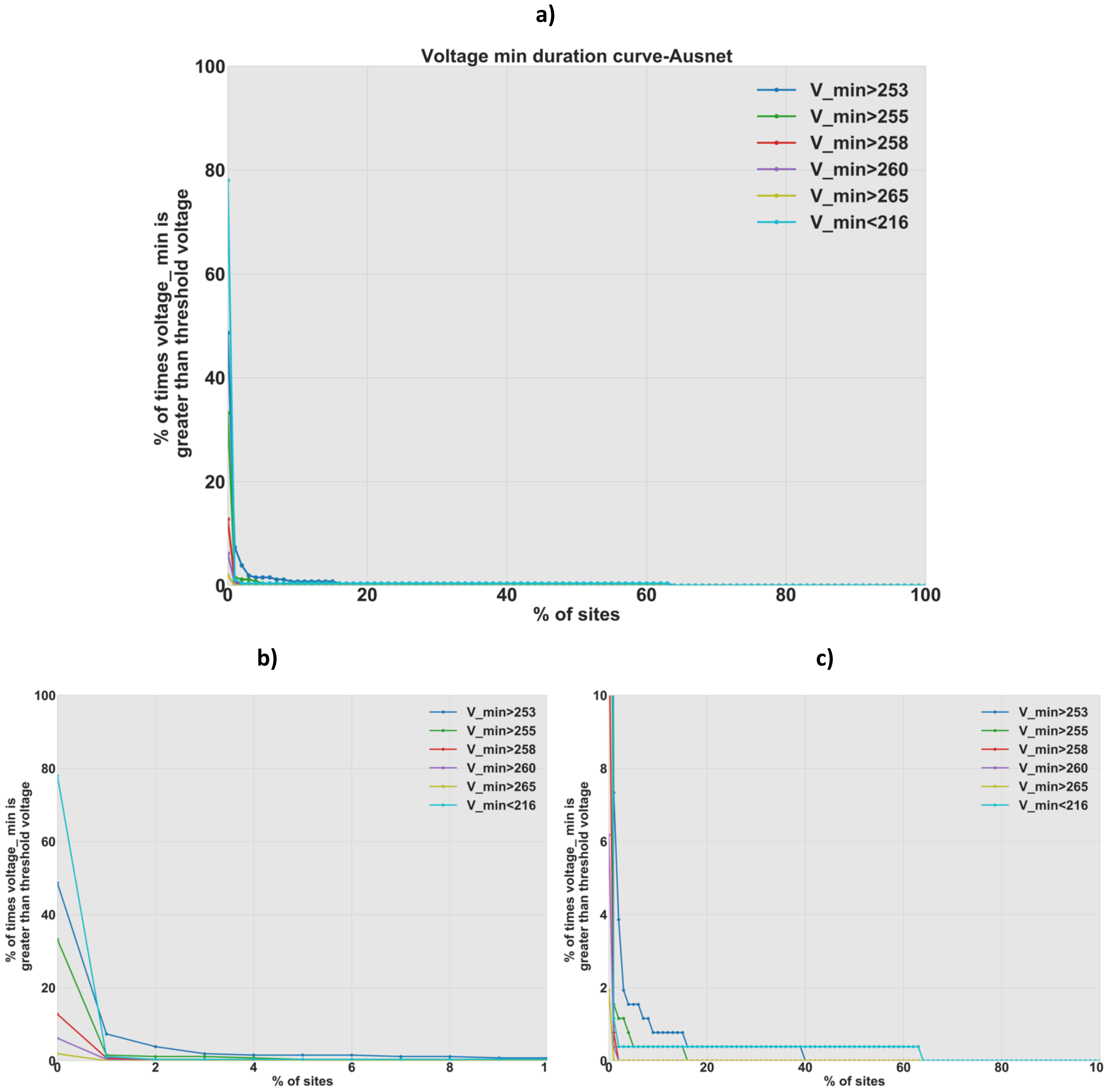


Figure 146 Percentage of sites vs. percentage of times of under and over voltage events based on voltage minimum for Ausnet

7.5.6 Impact of PV Density

To understand whether the over and under voltage events are affected by the distributed PV penetration levels, Figure 147, Figure 148, Figure 149, Figure 150 and Figure 151 show the equivalent charts (both max and min) broken down into different PV density regions for the Powercor, United Energy, Jemena, Citipower and Ausnet networks respectively, based on postcode data as shown in Table XVIII above.

Interestingly, none of Vic DNSPs show a particular correlation between installation density and voltage, often being lower at higher penetrations. Even excluding the very low and high penetrations, which have a small number of customers, there is still little correlation, presumably reflecting the various other influences on voltage.

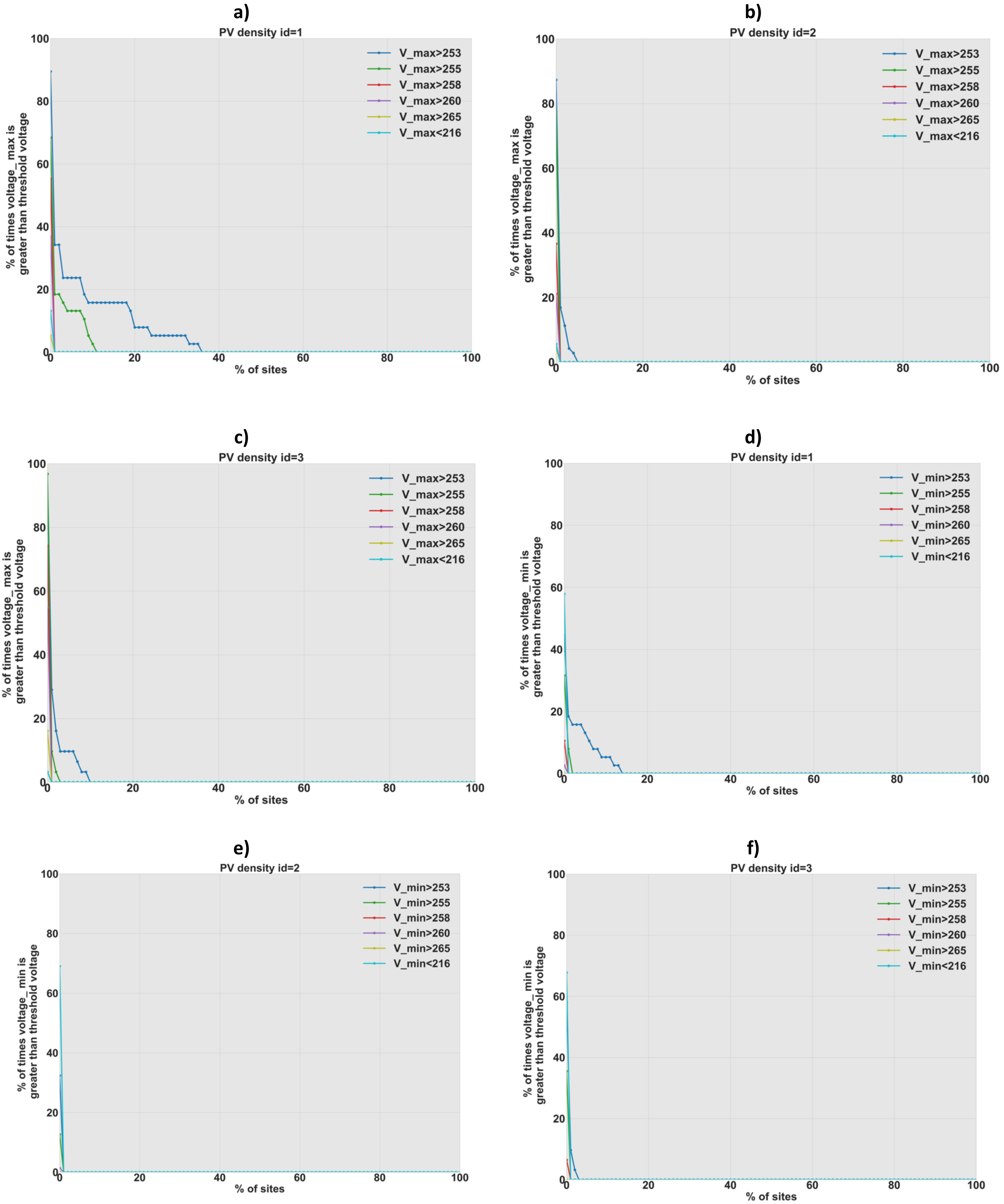


Figure 147 Percentage of sites vs. percentage of times of under and over voltage events based on household region's PV density for the Powercor network (id=0 <10%, id=1 10-20%, id=2 20-30%, id=3 30-40%, id=4 40-50%, id=5 50-60% PV install density)

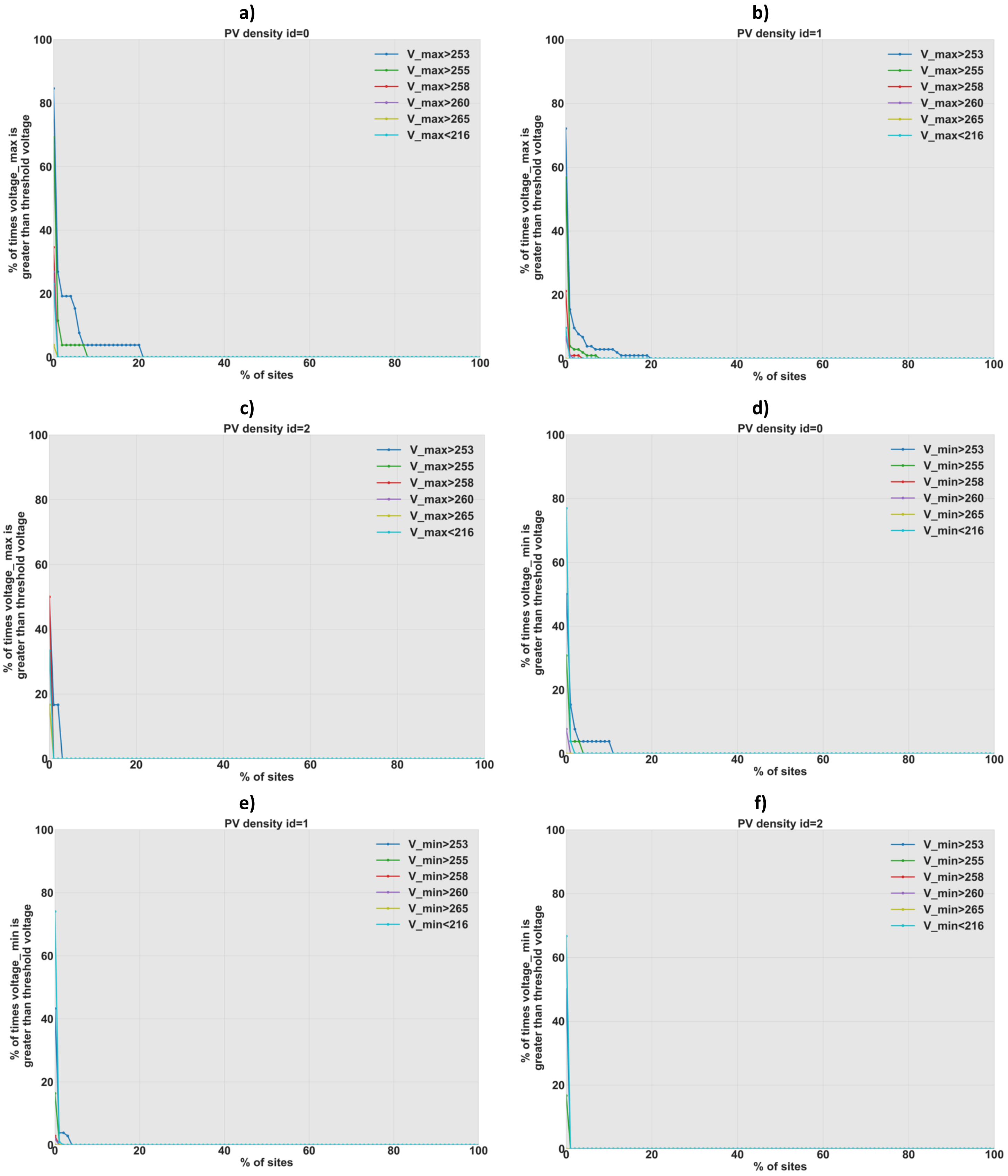


Figure 148 Percentage of sites vs. percentage of times of under and over voltage events based on household region's PV density for the United Energy network

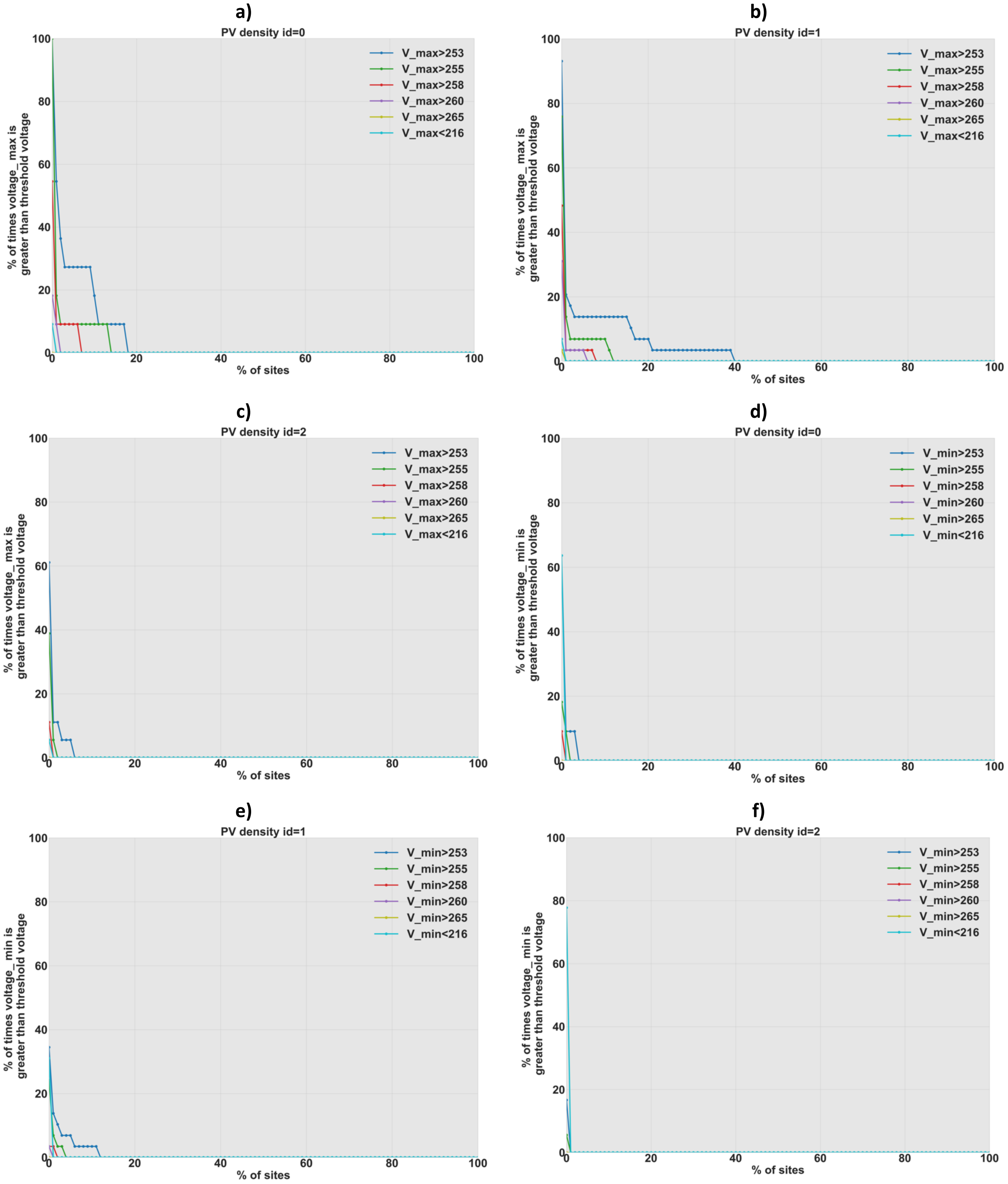


Figure 149 Percentage of sites vs. percentage of times of under and over voltage events based on household region's PV density for the Jemena network

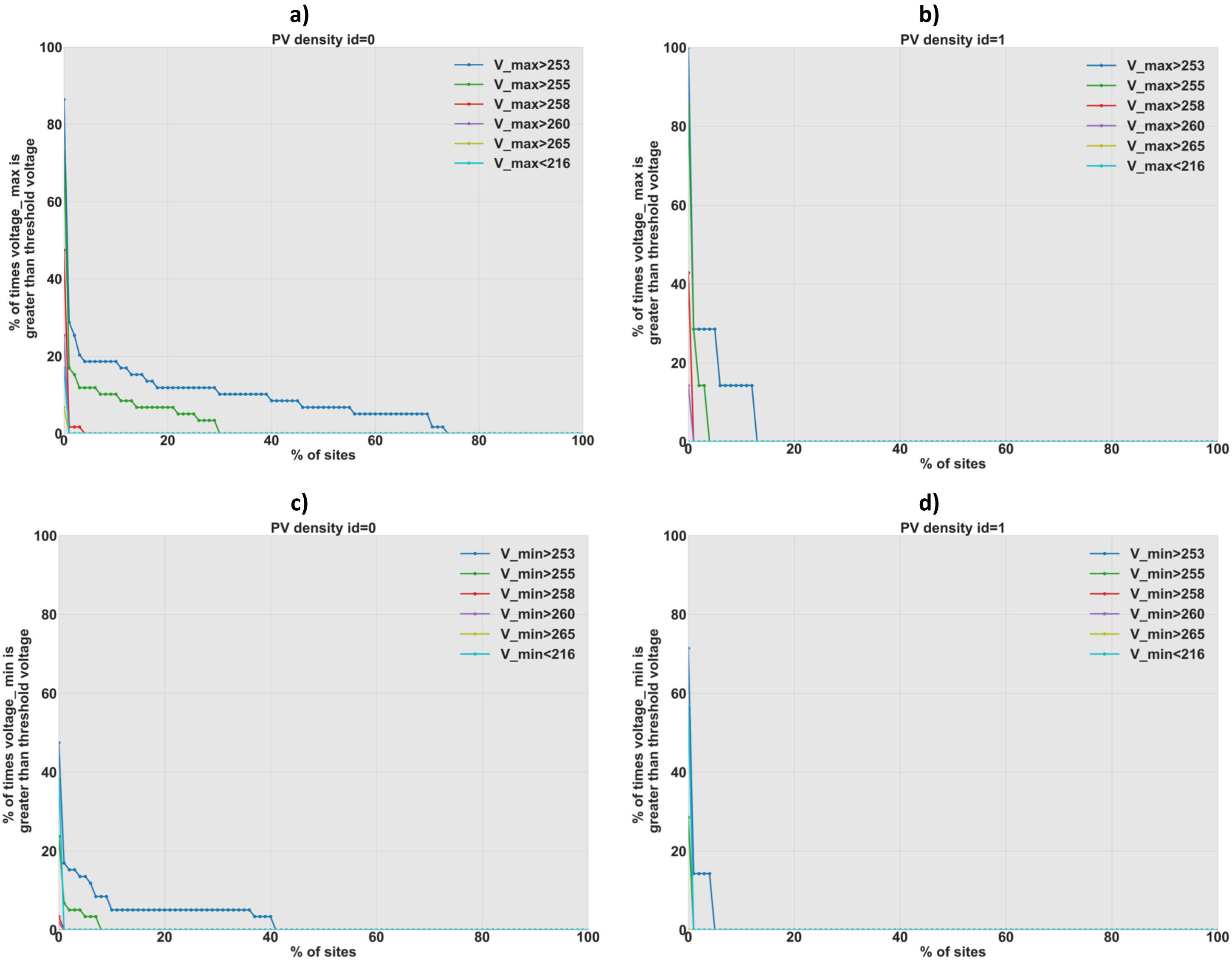
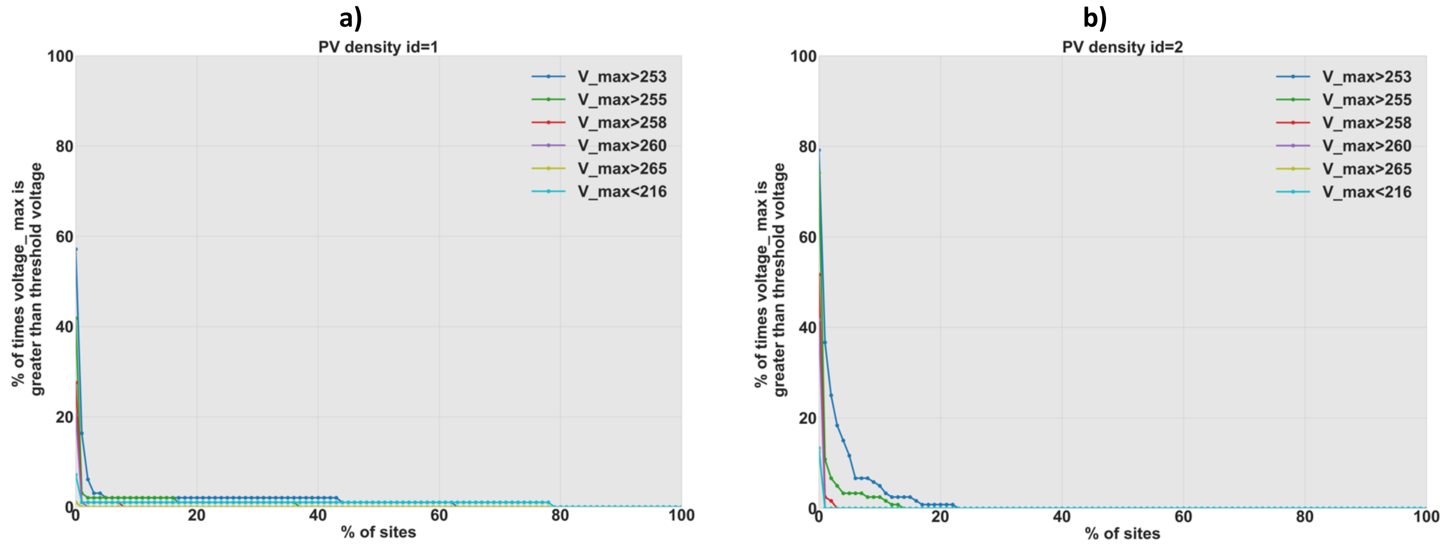


Figure 150 Percentage of sites vs. percentage of times of under and over voltage events based on household region's PV density for the Citipower network



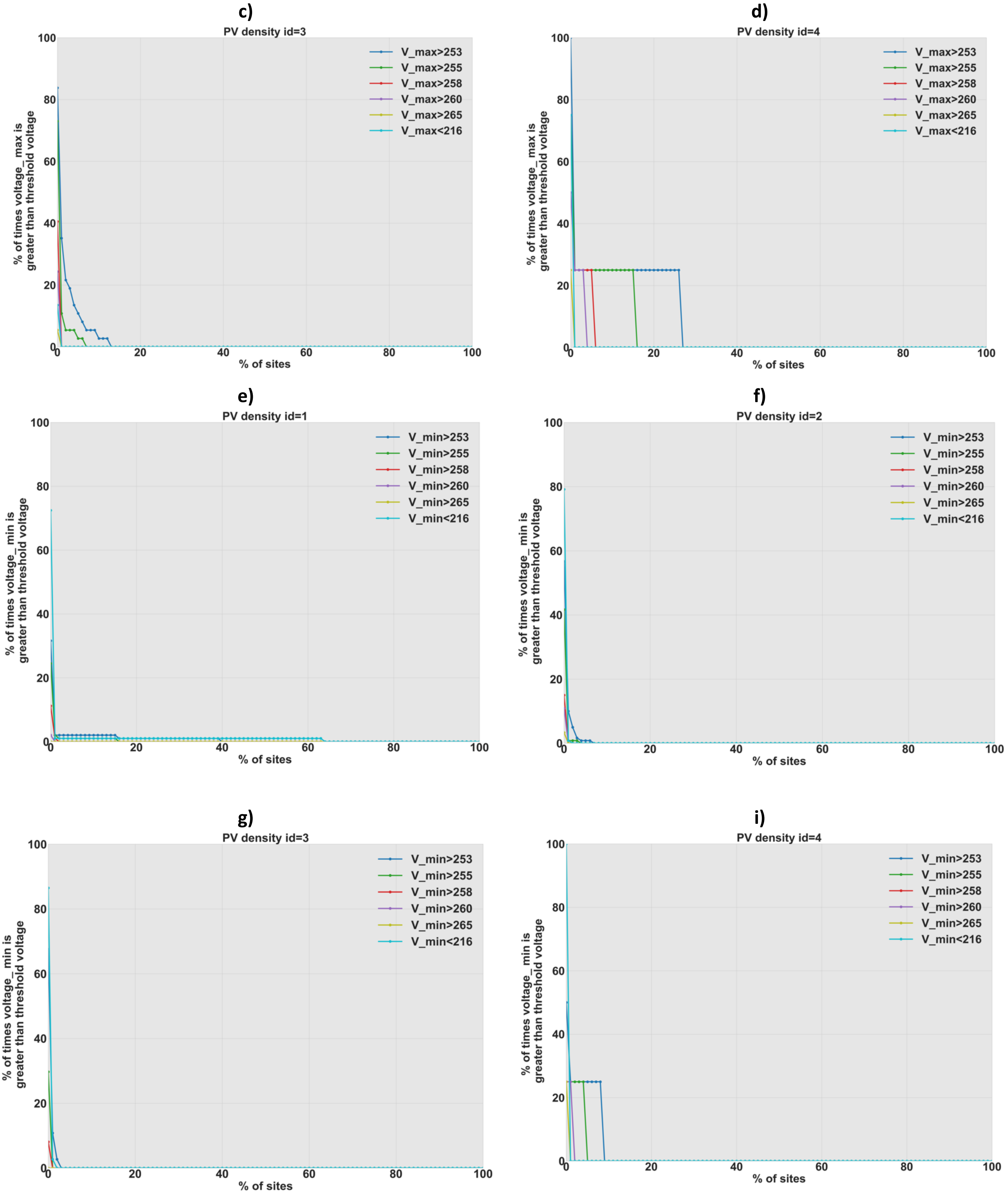


Figure 151 Percentage of sites vs. percentage of times of under and over voltage events based on household region's PV density for the Ausnet network

7.6 Tasmania

Table XIX shows the number of analysed per DNSP in Tas based on their location's PV installation density.

Table XIX PV density regions vs number of analysed household per DNSP

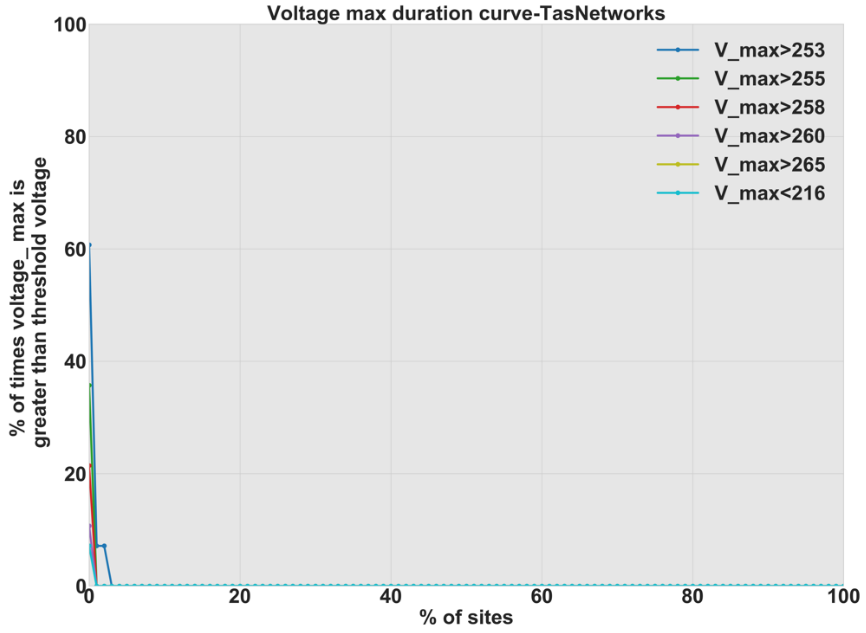
PV Density	Number of Households
PV density 0: 0%-10%	2
PV density 1: 10%-20%	53
PV density 2: 20%-30%	7
PV density 3: 30%-40%	1
PV density 4: 40%-50%	0
PV density 5: 50%-60%	0

Figure 152 a) shows the percentage of the sites with a full year of data vs the percentage of over and under voltage events within the analysed year. The analysed voltage thresholds include 253, 255, 258, 260, 265 for over voltages with respect to Australian Standards and 216 V for the under-voltage events. Figure 152 b) and c) zoom into the x and y axes respectively.

There were only 63 sites for Tasmania and so the results should be treated with some caution.

According to this limited dataset, less than 3% of the sites experience over voltage (>253) at least 2% of the time and less than 1% of the sites experience voltage >255. Moreover, around 2% of the sites were experiencing over voltage events with voltages being over 253 for 7% of the time. It is important to note that the standard for upper voltage and for inverter curtailment around 255-258V is based on average voltages over 10 minutes and PV inverter connection standards have changed over time. Still, it does suggest that if these high voltages are being sustained over such time periods, it is likely that some curtailment is occurring. Use of minimum voltages provides a more conservative estimate of the severity of high voltage excursions as shown in Figure 153. It is also worth noting that the under-voltage events are much less severe than the over voltage events in terms of the frequency of their occurrence.

a)



b) c)

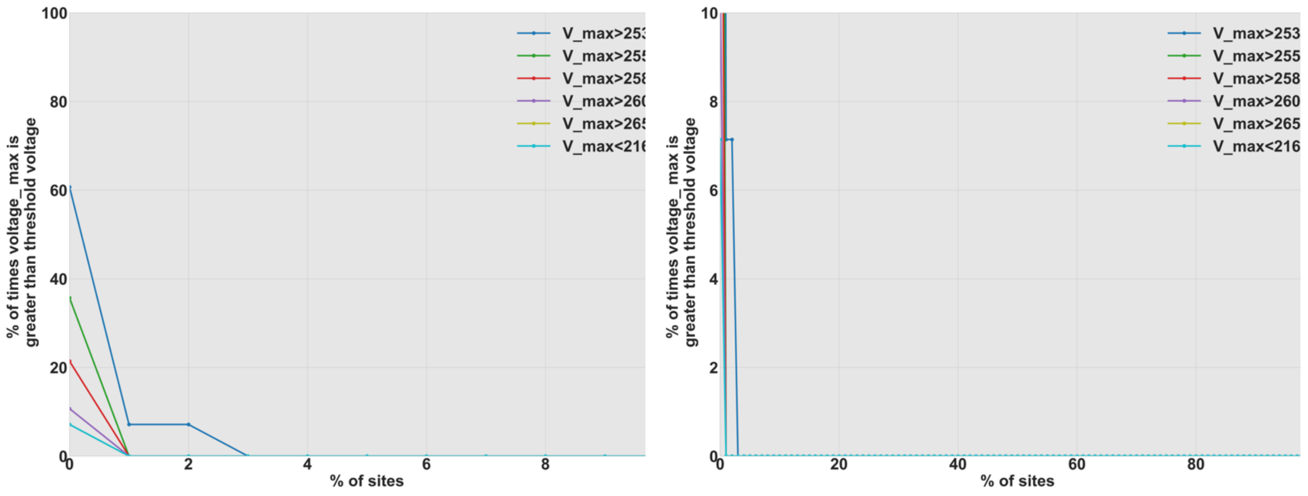


Figure 152 Percentage of sites vs. percentage of times of under and over voltage events based on voltage maximum

a)

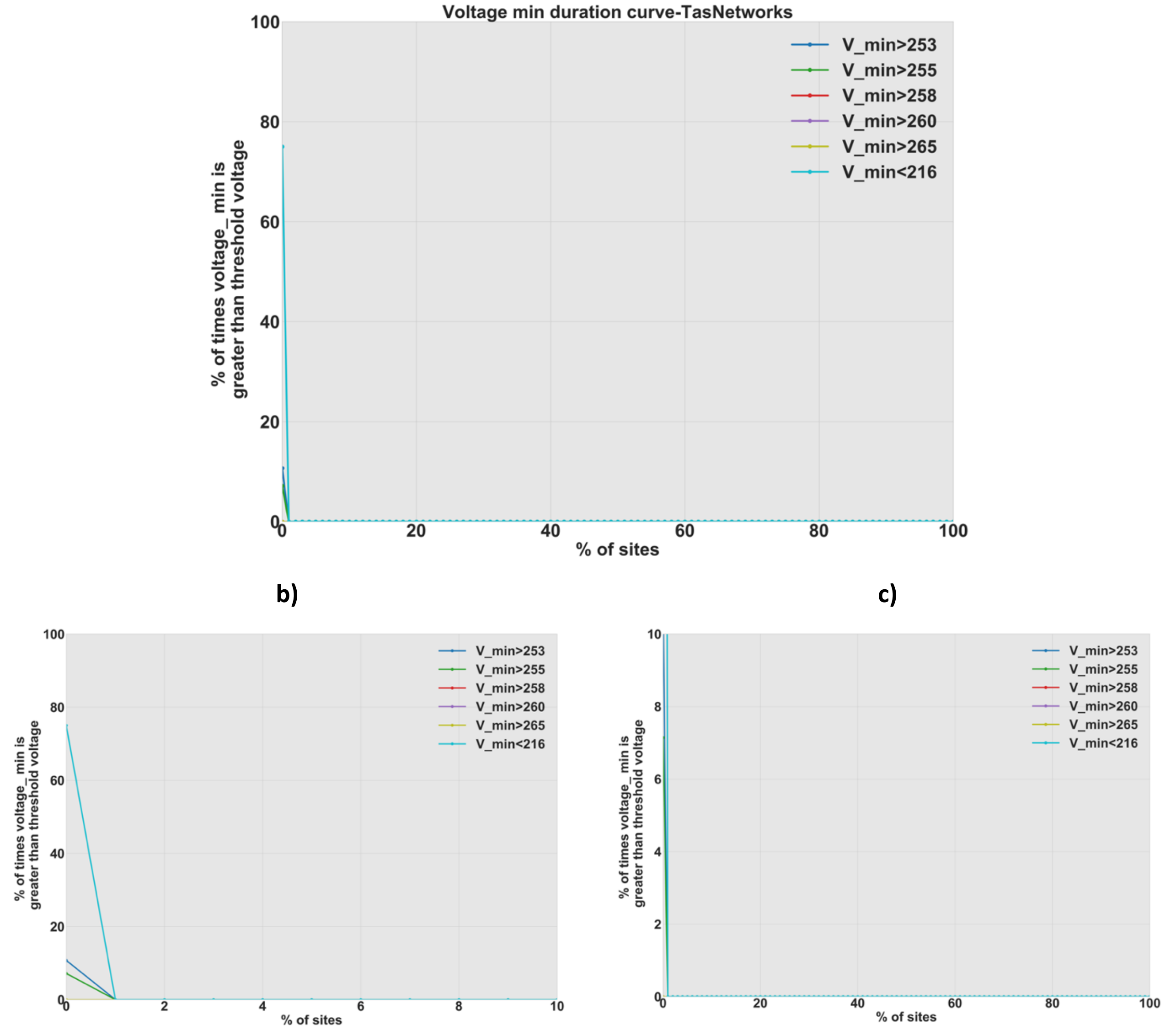


Figure 153 Percentage of sites vs. percentage of times of under and over voltage events based on voltage minimum

7.6.1 Impact of PV Density

To understand whether the over and under voltage events are affected by the distributed PV penetration levels, Figure 154 shows the equivalent charts broken down into different PV density regions, based on postcode data. Figure 154 a) to b) represents voltage maximum analysis and c) to d) represents voltage minimum analysis. There are insufficient sites to form a valid conclusion. The results are valid both for voltage maximum and minimum analysis, with the prior showing a stronger relationship.

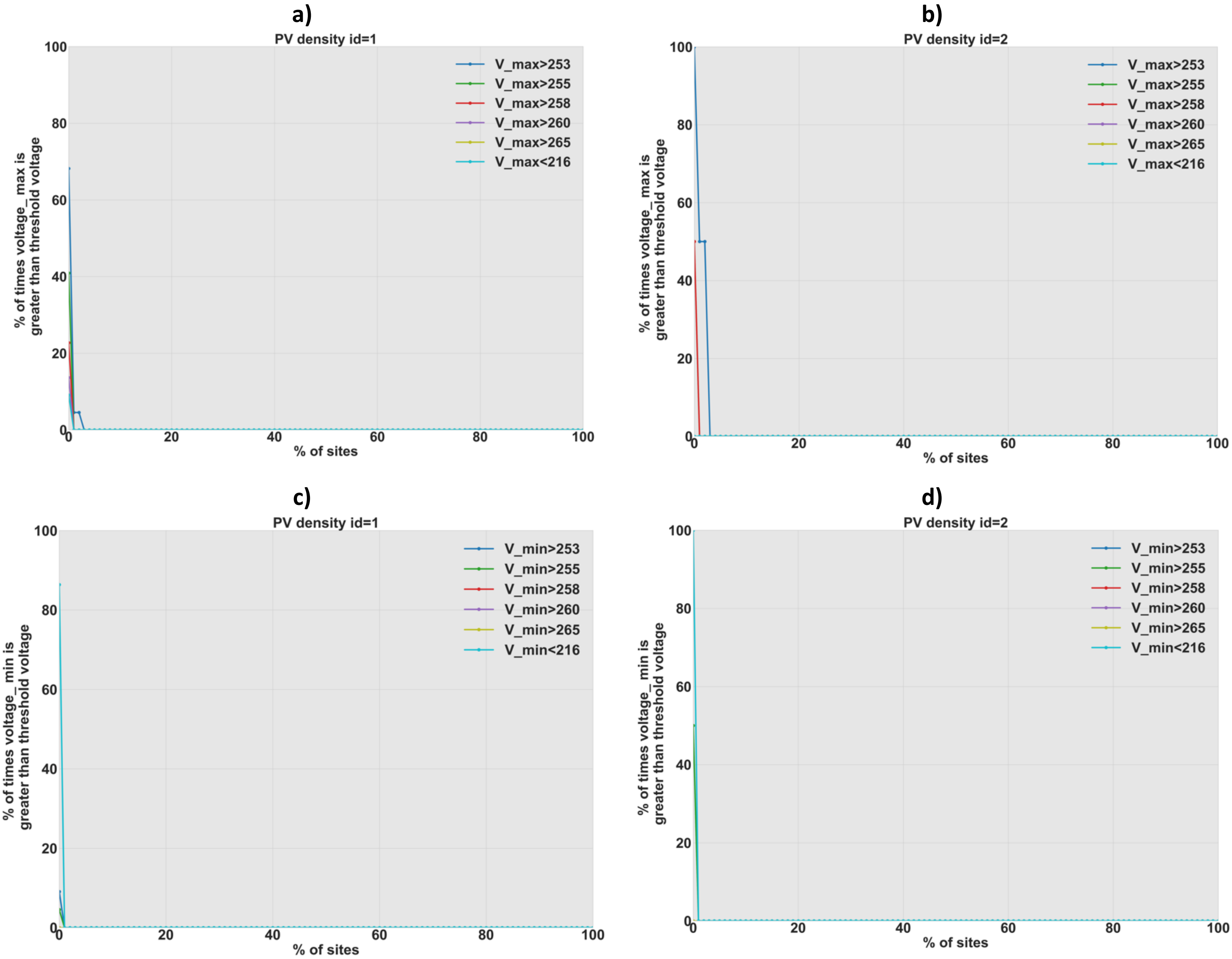


Figure 154 Percentage of sites vs. percentage of times of under and over voltage events based on household region's PV density (id=1 10-20%, id=2 20-30%, id=3 30-40%, id=4 40-50%, id=5 50-60% PV install density)

8 Separate work undertaken on Distributed PV curtailment

UNSW has previously undertaken analysis of PV curtailment using a data set of over 600 sites (over 1,300 sites on some dates) provided by Solar Analytics from **South Australia over 24 clear sky days in 2018**. The analysis led by Naomi Stringer during late 2019 and preliminary findings were presented at the Asia Pacific Sola Research Conference, Canberra in December 2019.

A summary of key findings, limitations and proposed next steps is set out here. The full draft paper can be found in Appendix A please note that this has not yet undergone peer review and it is our intention to submit it to a journal in the first half of 2020.

8.1.1 Key findings

Please note that the study has significant limitations and that key findings should be read in context of these limitations (section 8.1.2).

1. Significance: How significant is PV curtailment in South Australia?

- Findings indicate that on average one per cent of generation is being curtailed over all systems on all days studied.
- PV curtailment overall is not currently significant, however it can be extremely significant for specific customers with maximum losses throughout the year of 27% – 94% over a single day (noting only clear sky days were studied).
- A significant proportion of sites (53 per cent) were impacted at least once during the 24 days examined however the majority of these experienced a very small amount of curtailment.
- On the ‘worst’ day in this study (4 September) the 5% most impacted consumers (of all consumers in the data set on this date) experienced at least 16% curtailment.
- Upscaling the observed degree of curtailment to all of South Australia shows ~10GWh per annum of lost PV generation. It is important to note that only clear sky days were studied and therefore upscaling these days to a full year is likely to provide an over estimation of PV curtailment, refer to the limitations section. This curtailed generation has a value of approximately $0.8 – $2.6 million per annum to consumers.

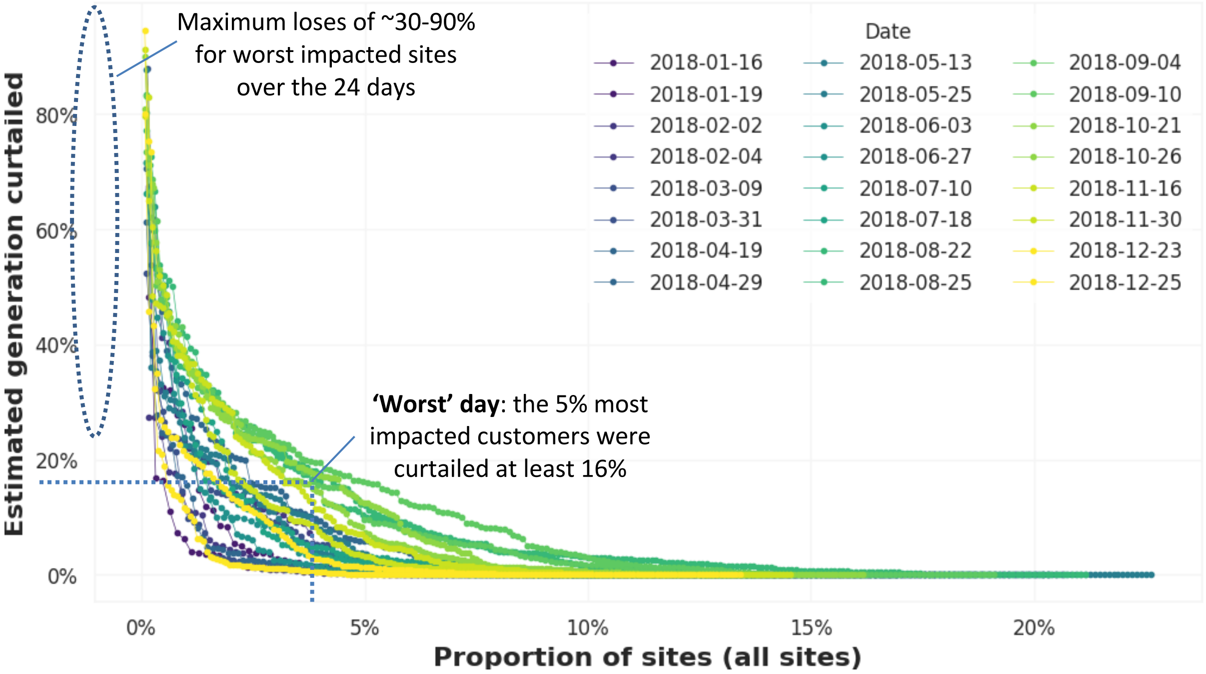


Figure 155 – Distribution of PV curtailment, where each data point indicates an individual site

2. Consumer financial impacts: What is the distribution of impacts on consumers with PV?

- The majority of consumers in the sample do not suffer significant PV curtailment, with approximately $3 - $12 per year per site on average in lost generation value (assuming a typical 5kW system. It is important to note that this also assumes the 24 clear sky days are representative of the entire year along with other key limitations, please see below for details).
- However, the consumers which are significantly impacted can experience considerable financial penalty. The most impacted consumer is estimated to lose approximately $225 - $900 per year (assuming a typical 5kW system. As above, this also assumes the 24 clear sky days are representative of the entire year and is therefore indicative only).

3. Seasonal variation: When does PV curtailment occur most?

- The highest levels of curtailment occur in late winter and spring.
- This is consistent with the higher levels of solar resource and generally lower loads that occur during these periods, likely leading to higher local network voltage.

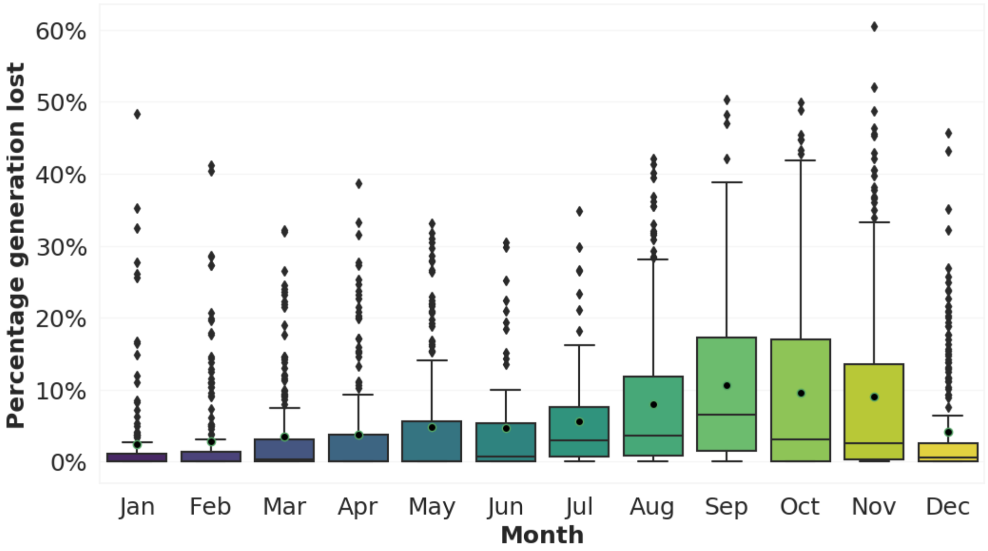


Figure 156 – Spread of curtailment over the year (impacted consumers only), black dot indicates average percentage generation lost, black diamonds indicate outliers

4. Future impacts: Is curtailment increasing as PV penetrations rise? *[inconclusive]*

- As PV penetration increases it is expected that voltage will also increase and therefore curtailment will occur to a greater degree. However the sample of days and sites examined in this data set did not exhibit a correlation between:
  - PV penetration and average voltage,
  - Average voltage and curtailment, or
  - PV penetration and curtailment.
- This lack of correlation is likely driven by a number of factors, including that the postcode PV penetration may not be representative of the feeder PV penetration. In addition, the voltage conditions experienced at an individual site are heavily influenced by factors other than PV penetration (see paper for further details)

A note on consumer choice…

- Currently PV curtailment can occur at times when a consumer is using power. That is, consumer may be prevented both from exporting PV generation to the grid, and also from consuming their own PV generation behind the meter. Figure 157 provides an example.
- This effectively prevents a consumer from reducing their electricity consumption, using their own PV generation.
- It is important to note that other inverter connected devices, such as battery energy storage systems, will also be prevented from operating in high voltage conditions. Including at times when batteries are attempting to charge and if able to operate, would aid in alleviating the over voltage condition.

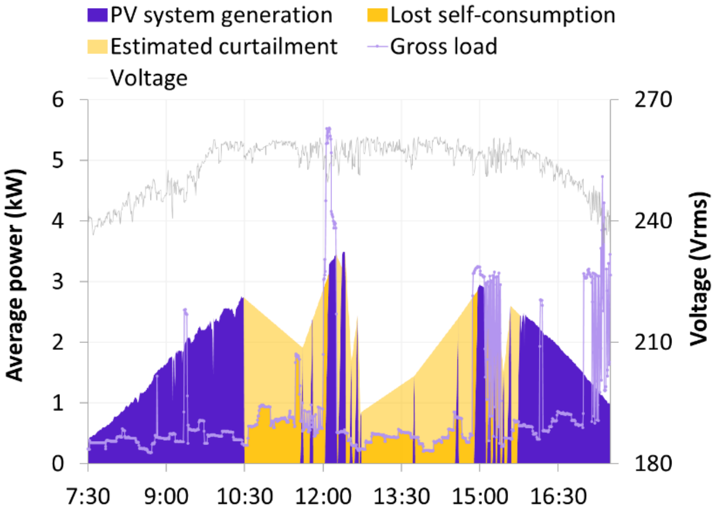


Figure 157 – Example of prevented self-consumption

8.1.2 Key limitations

These results must be considered in light of several key limitations. There are opportunities to improve the analysis and manage some of these limitations as set out in *Next steps* below.

- **This study does not attempt to prove that the curtailment identified is due to over voltage.** We assumed where PV reduced power output to 'near zero', it suggests PV curtailment due to high local network voltage conditions (see Figure 158). This assumption is challenging to prove mathematically. In part, this is because the data being examined has been recorded by a device separate to the PV inverter and therefore the exact conditions as seen by the inverter are unknown

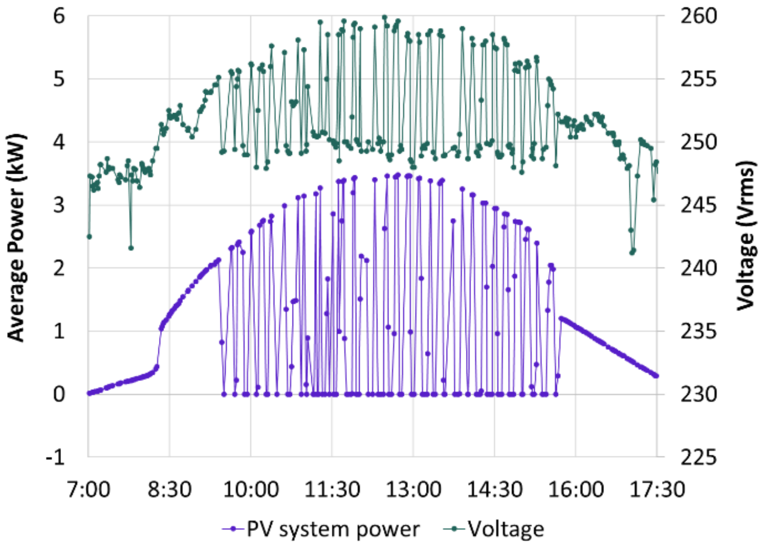


Figure 158 – Example site indicating link between PV curtail and voltage

- The method adopted likely results in an **over estimation of PV curtailment over the course of the year** due to the focus on clear sky days, on which it is likely that high PV curtailment may occur (noting that load behaviour is also critical). However, this is offset to some degree by the method for estimating the volume of PV generation being lost.
- The data set is **unlikely to be representative of the broader fleet**, for example there is likely to be a smaller number of legacy systems in the Solar Analytics data set compared with the broader Australian fleet. In addition, these sites are being actively monitored and therefore it is more likely that any over voltage conditions will have already been identified and addressed by the local DNSP
- **Volt-Watt and Volt-VAR** response modes are outside the scope of the analysis.

8.1.3 Next steps

The key questions that should be answered next are as follows, with the suggested high level methodology set out in Table XX.

1. *Is curtailment increasing over time?*
2. *How much PV is being curtailed due to Volt-Watt and Volt-VAR response modes?*
3. *Are curtailment levels similar in other regions?*
4. *How does the economic value of PV curtailment (currently and into the future) compare with the cost of proposed network options for managing voltage?*

Table XX – Key questions and suggested high level method

Key question	High level method	Impact	Achievability
1. Is curtailment increasing over time?	Conduct data analysis in collaboration with Solar Analytics and DNSPs to establish the relationship between PV penetration and PV curtailment. The initial study presented here proved inconclusive, a key factor was likely the assumption that PV penetration within a postcode is a reasonable estimate for PV penetration on a feeder. To counter this, a study could: - Match consumer home address or NMI to specific feeders in order to estimate the PV penetration by feeder.	● High Currently there is limited understanding of the impact of increased PV penetration on curtailment levels. An improved evidence base could enable better network investment and operational outcomes for consumers.	● Low Key concerns regarding consumer privacy may prevent any analysis using consumer addresses. Also requires GIS feeder data from DNSPs (publicly available for Ergon however most other DNSPs do not publish this information)

Key question	High level method	Impact	Achievability
	- Use GIS analysis techniques to identify PV systems via google earth. - Estimate PV penetration by feeder. - Compare PV curtailment with penetration at the feeder level. - Estimate likely future curtailment based on projected PV uptake.		Would need to estimate the volume of legacy PV systems using postcode level information still, which may reduce efficacy of results.
2. How much PV is being curtailed due to Volt-Watt and Volt-VAR response modes?	Conduct data analysis in collaboration with Solar Analytics to estimate the volume of PV curtailment occurring due to Volt-Watt and Volt-VAR response modes (could also include battery energy storage systems if data is available, or potentially collaborate with entities such as Tesla and AGL) There is very limited information available regarding the impacts of Volt-Watt and Volt-VAR response mode on DER operation. Given the adoption of increasingly aggressive Volt-VAR requirements by many DNSPs it is important to quantify the impact on consumers. - Develop data analysis techniques for identifying Volt-Watt and Volt-VAR operation - Estimate the volume of curtailed generation. - Develop methods to upscale these estimates across the broader fleet.	● High Currently there is a limited evidence base that utilises real world operating data to demonstrate the impact of Volt-VAR and Volt-Watt on PV generation (and also on network voltages). However Volt-VAR settings are being required by a large number of DNSPs and are included in the current review of AS4777.	● Medium Data analysis methods may prove challenging to develop.
3. Are curtailment levels similar in other regions?	Repeat the analysis conducted in this initial study for: - All NEM regions - A greater sample of days	● Medium It is unclear whether curtailment levels may be similar across all NEM regions. However analysing a greater sample of days will improve the significance of results.	● High The data analysis methods have already been developed. Data access is the key barrier.
4. How does the economic value of PV curtailment (currently and into the future) compare with the cost of proposed network options for managing voltage?	In collaboration with Solar Analytics and DNSPs and leveraging findings from 1. (curtailment increases over time), estimate the total value of curtailed PV generation. - Estimate future PV curtailment - Develop a method for translating curtailed energy into economic benefit (note the DEIP DER valuation package of work will have a similar focus – leverage findings) - Develop techniques to compare the benefit of avoided curtailment with proposed network solutions Note: network solutions will likely provide benefits beyond avoided curtailment. This should be reflected in the comparative methods developed.	● High As data availability grows, DER uptake continues and voltage constraints (likely) become more critical it is important to have agreed, rigorous methods to undertake CBA of proposed network solutions.	● Low Relies on being able to estimate future curtailment as well as current curtailment. Therefore necessitates project 1 set out above.

The method applied in this initial study could also be improved through addressing the key limitations noted above, with suggested next steps summarised in Table XXI.

Table XXI – Summary of limitations and suggested next steps to address limitations

Limitation	Next steps to address limitation
Proof of curtailment due to over voltage	Develop mathematical tests to establish the relationship between voltage and curtailment
Underestimate of curtailment	Include use of irradiance data for clear sky days to develop an upper bound on possible curtailment
Overestimate of curtailment	Repeat the analysis using data for an entire year (including cloudy days) rather than 24 days
Unrepresentative data set	Characterise difference in curtailment behaviours based on key factors (e.g. AS4777 version) and develop methods to scale PV curtailment estimates accordingly
Volt-Watt and Volt-VAR modes	Develop methods to estimate the impact of Volt-Watt and Volt-VAR on PV curtailment (also noted above)

9 High level findings and Recommendations

9.1 Findings

This study used what is almost certainly the largest dataset of PV owner voltage conditions analysed to date in Australia in terms of monitored sites, the duration of the data and the spread of locations across the 6 State and Territory regions. Nevertheless, it cannot be assumed that the SolA monitored sites are fully representative of the total 2.2 million rooftop PV systems now installed across Australia, while some of the regions analysed have only a limited number of sites. Caution is required. Nevertheless, the findings are significant.

Efforts to date to assess LV network voltages, the potential impacts of PV and opportunities to better manage adverse voltage outcomes in the NEM provide useful insights, and these efforts are growing rapidly

- Our preliminary literature review has identified a wide range of work from equipment vendors, customer monitoring service providers, the DNSPs, academia, consultants and NGOs seeking to better understand voltage management challenges and options in the NEM.
- Present Australian standards for LV voltage specify a preferred range of voltages around 230V nominal (+6%/-2% or around 225-244V) and acceptable upper and lower limits of +10%/-6% or 216-253V. The offset reflects in part the transition from 240V (the same range applies in the UK). The Standard does acknowledge that the challenges of voltage management in the NEM for some consumers at some locations and at some times may well see occasional excursions outside this acceptable range.
- A challenge for all this work has been the poor visibility DNSPs, and other stakeholders, have regarding voltages in the LV network. Much of the recent work to date, therefore, has used new sources of network data from monitoring and metering service providers.
- This work has highlighted the very high voltages currently being experienced by consumers connected to the LV network in the NEM.
- A number of DNSPs have sought to improve voltage compliance around excessively high voltages through a variety of methods.
- A key insight is that it is the voltage range experienced by consumers, rather than just the maximum voltage, that needs to be addressed given that there are relatively straightforward options to bring the voltage range down using distribution tap changer transformers in many cases.
- The Standards for grid connection of PV inverters in Australia have strengthened the requirements placed upon PV installations over time, in particular to reduce any contribution to excessive voltages, with the most recent Standard specifying Volt-VAR, Volt-Watt as well as disconnection requirements in response to excessive voltages for sustained periods of time, regardless of the cause.
- Much of the evidence for PV system curtailment to date is case-specific, and often associated with consumer power quality complaints to their DNSP in response to what they see as adverse impacts on their PV system operation.
- DNSPs are now developing more systemic frameworks for addressing voltage challenges with some innovative approaches being proposed in their future expenditure plans.
- Approaches to address over voltage associated with PV generation include allowing greater PV curtailment to occur, fairly conventional changes to DNSP operations (reducing distribution transformer tap settings, better phase balancing) as well as capital expenditure to reduce line losses and hence voltage variation. A growing range of technology options to actively manage changing voltage conditions in the distribution network are also available and being deployed in particular cases. New approaches based on dynamic PV export ratings, voltage regulating transformers, dynamic power compensation and the use of battery energy storage or controllable loads, potentially coordinated through Virtual Power Plants (VPP) to effectively increase consumption (hence reduce voltages) at times of high PV generation, all show great promise.
- Regulatory and market frameworks are required that assist DNSPs and other stakeholders in best matching these options to the particular context being experienced in different parts of the network, provide appropriate returns for those investing in such options, and ensure that incentives for DER owners as well as the DNSPs and other key stakeholders are appropriately aligned.

The literature review highlighted some key gaps in the coverage of PV and voltage issues to date, particularly in terms of the number of monitored sites available for analyses, the sampling rate of these sites, the duration over which data were made available, and the extent of spread of sites over all NEM regions. It is this which we sought to address with our work. Solar Analytics was able to provide 5 minute maximum and minimum voltage data for 6,863 sites across the 13 DNSPs and 6 States and Territories of the NEM. Sites could also be categorised by region from suburban through to remote, and according to the extent of PV penetration by postcode (proportion of households in that postcode with a PV system.

We undertook three sets of analyses:

- The distribution of maximum and minimum voltages across the sites over the year, categorised by State, DNSP and location (remoteness), the seasonality and daily profiles of these voltages, and the voltage spread experienced across the sites
- The extent of correlation between site voltages and any net PV exports from those sites during high PV hours of 10am-4pm
- The proportion of sites seeing voltages above or below the acceptable Standard, and potentially experiencing inverter curtailment

Our work highlights some significant issues with LV network voltages across the NEM

- Our preliminary analysis highlights the diversity of the LV voltage ranges seen at the monitored sites, and illustrates the broad drivers of voltage outcomes, including regional network arrangements, and particularly changing local as well as system level demand. These voltages exhibit a modest seasonal pattern, while lower voltages are clearly associated with periods of peak State demand, particularly in South Australia.
- Maximum voltages recorded at the monitored sites are generally towards the upper bound of acceptable voltage in all States and DNSPs, in all seasons for all daily hours. Maximum voltages mostly fall outside the Standard's preferred operating range of +6%/-2% (244V / 225V) in South Australia, while falling within this range for less than half the time in Queensland and NSW.
- Voltage at many of the monitored sites would seem to occasionally exceed the upper 253V limit as well as falling, far more infrequently, below the lower 216V limit set by Australian Standards.
- Voltage excursions above 253V are present for at least some sites over all seasons and hours of the day. In some regions, such as South Australia, a significant proportion of consumers (5% or more) are seeing maximum voltages near or beyond the upper 253V limit for much of the day and night, in all seasons.
- Maximum voltages would seem to be less extreme in Queensland, and 95% or more of the sites see average voltages below the 253V limit at all times of the day and all seasons. In NSW, the highest average maximum voltages are seen by Essential Energy which serves regional and rural consumers in the State. Maximum voltages seen in the State generally fall between Queensland and South Australian voltages.
- While mean maximum voltages across the sites don't generally exhibit a particularly marked pattern, periods of higher maximum voltage of the most impacted consumers are associated with daylight hours, and particularly peak PV hours (generally around 10am-4pm).
- Mean minimum voltages experienced by the majority of sites in most regions, seasons and times of day are above the 230V nominal standard, in some cases well above, and even above the preferred higher voltage range of 244V.
- However, there are still infrequent periods of voltages below the acceptable range at some sites during particular periods. Generally, these seem to be particularly associated with summer evenings when PV generation has fallen away while air-conditioning load remains high. The voltage range experienced at sites is very large, highlighting the management challenge of staying within both upper and lower bounds. However, upper bound excursions appear far more frequent than lower bound excursions which are generally extremely infrequent.
- It is also notable that the voltage range experienced at sites generally increases from suburban to regional and then to remote locations within the distribution network reflecting factors including the generally weaker network configurations in remote areas that see more losses from changes to load and PV generation.

These voltage issues are due to a wide range of factors, but distributed PV generation is clearly contributing to the existing issues, and some level of PV curtailment is now present.

- Voltage outcomes experienced by consumers vary enormously, influenced by a wide range of factors from local network configuration, network settings (particularly distribution transformer tap settings) and especially local to system wide network demand. PV generation adds to an already complex existing mix of drivers and establishing clear causation across the different factors is a challenging task. Currently available data sets and limited time available for this analysis mean that we have not attempted to establish strict correlations and causation between PV generation and voltage, or any of the other factors mentioned. Still, it seems clear that changes in aggregate loads in the distribution network, driven by seasonal, daily and other factors such as weather, remain the key driver of voltage variation (certainly for low voltage excursions), although the impact of PV generation is rising as deployment continues to grow.
- Considering the generally high voltages experienced during all hours, including non-daylight hours, in all regions and DNSPs of the NEM, it is clearly an outcome of network management to set voltages near the upper bound of the Standard. This approach seems reasonable given the DNSP’s primary obligation is the reliable delivery of electricity to consumers and managing the risks that low voltage excursions pose for this; and noting their existing voltage management options. However, it does have implications in terms of PV headroom. Notably, different DNSPs would seem to be pursuing somewhat different voltage management regimes, which is unsurprising given the very different as well as shared voltage management challenges they face.
- It is evident that PV exports, which occur when PV generation is greater than local load, do have an impact on voltage, and particularly the distribution of higher voltages. This is evident both from the daily profile analysis as well as specific correlation analysis comparing voltages against PV exports during daylight hours.
- Maximum voltages at some sites, locations and times exceed the various limits at which PV system inverters are required to curtail their generation, although the complexities of how voltage is measured means caution is required in assessing how much curtailment might be occurring, and its role in managing what would otherwise be even higher voltage excursions.
- Associated preliminary curtailment analysis with a limited data set, also included in our report, suggests that the actual levels of PV system curtailment seen to date in South Australia are relatively modest overall. However, there are particularly significant curtailment impacts on some consumer sites, and these therefore involve adverse financial outcomes for the owners of these systems. The associated equity implications of this will need to be addressed. Maximum voltages appear to be higher in South Australia than in the other NEM regions, not only during times of PV generation, but throughout the day.
- Interestingly, PV generation is associated with increasing both minimum as well as maximum voltages. Periods of high summer peak demand due to air-conditioning is associated with generally high PV generation prior to evening hours. It seems likely that PV generation is reducing the frequency of periods when voltage is below acceptable levels during those periods, although this is difficult to ascertain the overall impact on the extent, number and voltage minimums, without more detailed data on load.
- PV system curtailment is almost certainly already assisting in managing what might otherwise be even higher voltage excursions. PV inverters are, indeed, the only household equipment that is actively responding to assist in managing voltage excursions (although strictly resistive loads do show a passive voltage response that can also assist in managing low voltage excursions). Some curtailment may be a reasonably economic outcome in some circumstances, but there are equity issues for the owners of adversely impacted PV systems that need to be considered. Other equipment such as inverter-based residential air-conditioners do increasingly measure voltage continuously during operation, and there are opportunities to take advantage of this by requiring active voltage management in a similar manner to PV inverters, but now by requiring these systems to reduce consumption during extreme low voltage periods.

9.2 Recommendations:

Further analysis

There are excellent opportunities to extend this analysis to provide more insights into the challenges and opportunities of PV in relation to voltage management in the NEM.

- In further work, we could use the existing data set to provide more disaggregated impacts to postcode level, and particularly strengthen our findings on correlations between PV generation and voltage.
- More sites over greater time periods will assist in the analysis. So would higher resolution (e.g. 1 minute) data, particularly for the estimation of PV generation curtailment.
- Additional data points from three phase PV system sites will provide more clarity in the results and therefore more insights, but also support preliminary analysis of factors such as phase imbalance which would seem to offer low cost opportunities to improve head room for PV generation to be exported into the network.
- Additions to the available data sets including gross PV system generation and ideally net site loads would allow more detailed assessment of correlation and causation between PV and voltage, as well as other factors including air-conditioner operation.
- We have developed particularly detailed recommendations for improved curtailment analysis, as noted at the end of the previous section. More detailed curtailment analysis is a clear priority area for future work given its importance.
- Finally, this sort of analysis will need to be continued as distributed PV penetrations continue to climb, and hence the issues that this is causing for voltage management also increase. Ongoing analysis will also support assessments of the usefulness of different voltage management approaches implemented by DNSPs.

Wider recommendations – voltage visibility

- Our analysis, and that of others, highlights both the need and opportunity for greater voltage visibility in the LV network. Distributed PV is one, but not the only factor, driving this need. Other distributed resources including battery energy storage systems and EVs may well also become significant factors while air-conditioning is already a major contributor to our voltage management challenges.
- As evident with our use of Solar Analytics data, our options for improving voltage visibility in the LV network are, fortunately, also improving. Beyond monitoring service providers, smart meters have voltage measurement capabilities that would currently appear to be underutilised while PV inverters measure voltage continuously as part of their operation and are increasingly communications-enabled. There are also other consumer and network equipment that monitor voltage and might also be useful sources of real-time and historical data - including Building Energy Management Systems in the Commercial sector, Uninterruptible Power Supplies used to protect critical loads for commercial and industrial as well as sites of telecoms and other infrastructure providers. Even modern residential air-conditioners undertake real-time voltage monitoring as part of their power electronics (inverter) control systems.
- Greater coordination across key electricity sector stakeholders regarding these opportunities offers relatively low cost and highly valuable improvements in voltage visibility. Arrangements for the collection and availability of smart meter power quality measurements can certainly be improved, while innovative new data provision opportunities are further explored and developed.
- These opportunities will need to be appropriately integrated into the energy sector-specific as well as wider consumer data rights provisions that are currently under development. It is important to note that voltage is a system rather than consumer specific data stream; voltage monitoring at one location generally provides reasonably detailed information on network voltages nearby. Voltage data also has major public good aspects that need to be considered in discussions regarding data availability to a wide set of stakeholders.
- More detailed descriptions, and ideally standards, for LV voltage and associated data collection would assist in sharing and comparing analysis by different stakeholders. Again, this is primarily a coordination challenge.

Wider recommendations – voltage management.

- As noted in the literature review, there is a growing body of work exploring both voltage characterisation as well as management across the NEM. There would be great value in better sharing the learnings from these efforts, as well as development of a coordination strategy to drive new work that fills existing gaps.
- A particular opportunity is to ensure better data sharing from the growing range of trials and modelling being undertaken so that a wide range of researchers, industry and other stakeholders can contribute to deriving insights from the data.
- Our range of options for cost-effective voltage management extends across PV and other DER operation, network planning and operation yet also load management. These options continue to improve, particularly those based around power electronics (from inverters to load control to network equipment) given progress in these technologies.
- The key voltage management challenge is the present wide spread of voltages, an issue of both high and low voltage excursions. Narrowing the range of low voltage excursions would allow distribution transformer tap settings that provide more headroom for PV generation. There may be many cases where these tap settings can be reduced without unacceptable impacts on low voltage extremes.
- Conservation voltage reduction trials in Victoria have highlighted opportunities to not only reduce LV voltages as a means to reduce demand during extreme demand periods; but also extend the times over which such reductions are undertaken in a more dynamic manner.
- Legacy inverters installed under earlier AS4777 versions have less strict requirements around curtailment due to high voltages. This may raise some challenges, such as more recent installations curtailing to reduce the impacts of older installations that don't. Note that BESS inverters also fall under AS4777 and there are potentially adverse situations where BESS units that could be charging and hence assisting to reduce voltages are forced to disconnect while the household's older PV system continues to generate. This highlights the importance of rapid updating of relevant Standards as PV and other DER deployment grows. Consideration should also be given to requiring inverters to be capable of having their voltage behaviour characteristics dynamically updated – a capability some models already have.
- At present, PV systems are required to curtail in response to high voltages even if they are not exporting, which prevents self-consumption of PV behind the meter. This issue deserves attention, given that the consumer might be being penalised for a voltage management issue they are not causing. Similarly, BESS disconnection during periods of high voltage will prevent consumers (or aggregators) from accessing the value available through charging or discharging during that period.
- Work to better understand the strengths, weaknesses and most appropriate contexts for deploying different possible voltage management options is essential. While economics will and should be a key factor in decisions regarding which methods are deployed, it is important to factor longer-term considerations into these choices as well. It seems very likely that a growing range of DER options will be deployed in our distribution networks over the medium to longer term.
- Existing frameworks for voltage management will continue to need to evolve with improvements in these options. Taking advantage of DER and load options will particularly require improved coordination and collaboration with energy consumers. Wider stakeholder consultation and engagement is therefore a key requirement for deploying the most cost-effective voltage management options.
- Some options for voltage management seem likely to require revisiting regulatory arrangements for DNSPs in terms of their obligations and allowable expenditure for cost recovery. Safe, reliable and secure provision of electricity to meet consumer demand is clearly the priority. However, a growing proportion of consumers also have the reasonable expectation that they should be able to export excess PV generation to the grid.
- PV inverter standards for Australia are currently being revisited given growing security concerns associated with the operation of distributed PV under major power system voltage and frequency disturbances. There are opportunities to improve present curtailment and broader voltage responses of inverters for LV network management as part of this process. Other work by UNSW has highlighted some potential compliance issues that also need attention. Incorporation of remote dynamic inverter control capabilities could also be of great value, as noted in a number of DNSP proposals.

- Load management options are likely the most neglected at present, but present key opportunities. Moving controllable loads to periods of higher PV generation (lower net loads) is a key opportunity. There are also growing opportunities to use local or remote air-conditioning load control to reduce those very infrequent low voltage excursions seen at some sites that currently drive the high voltage settings currently seen in the network. These efforts could involve development of more sophisticated standards for installation of such appliances – they could, as seen with PV, adjust their operation under certain voltage conditions, in this case low voltage conditions. They could also build upon existing programs for remote air-conditioning control as seen in Queensland, and some other NEM regions.
- A clear opportunity for early attention would seem to be Demand Response Enabled Devices on A/C units under the control of the DNSP (as already occurs for over 100,000 customers in Energy Queensland) and batteries (both owned by the DNSPs and by customers behind the meter). As well as reducing the size of network assets required to meet these peaks, this would allow the voltage to be reduced across all networks, thereby enabling greater penetration of PV, and associated benefits in terms of financial outcomes for owners of PV systems, but also benefits for non-owners through reduced wholesale spot prices through the merit order effect, reduced network costs and reduced greenhouse gas emissions.
- The growing number of residential and commercial BESS units also offer new options for reducing PV exports to the grid and the voltage challenges they pose. At present, BESS owners are generally incentivised to store their other exported PV generation in daylight hours and then discharge in the evening – operation that would seem relatively well suited to assisting in voltage management as well as reducing demand during network peaks. However, there are opportunities to better coordinate such operation for greater benefit, and VPP and other coordination frameworks provide one such avenue.

To conclude, the challenges yet opportunities of improved voltage management in the NEM both seem likely to grow as DER uptake continues and broadens beyond distributed PV. While there are pressing needs for early action in some cases, such actions need to support development of a longer-term, more strategic framework for distribution network management more generally. Looking beyond voltage management, there are growing concerns about peak reverse flows and security risks with DER operation. At the same time, looking beyond current voltage management frameworks toward more holistic distribution network arrangements will help us take advantage of the growing capabilities of both network as well as DER assets to assist in maximising the value of the LV network into the future.

10 References

[1] Australian Standards, *AS 61000.3.100-2011 Electromagnetic compatibility (EMC),* 2011.

[2] E. Demirok, "Clustered PV Inverters in LV Networks: An Overview of Impacts and Comparison of Voltage Control Strategies," in *IEEE Electrical Power and Energy Conference*, Montreal, 2009.

[3] AEMO, "Integrated System Plan," 2020.

[4] J. DESCHEEMAEKER, M. V. LUMIG and J. DESMET, "Influence of the supply voltage on the performance of household appliances," in *CIRED 23rd International Conference on Electricity Distribution*, Lyon, France, 2015.

[5] *AS4777, Grid connection of energy systems via inverters,* Standards Australia, 2016.

[6] AEMO, "Integrated System Plan," 2018.

[7] AEMC, "Electricity Networks Economic Regulatory Framework Review - Integrating Distributed Energy Resources for the Grid of the Future," 2019.

[8] SA Power Networks, "Maximising customer value from the network in a high DER environment," in *AEMC / ARENA Regulatory DEIP dive, 6th June*, 2019.

[9] AusNet Services, "Distribution Annual Planning Report 2020-2024," 2019.

[10] N. Stringer, A. Bruce and I. MacGill, "Data driven exploration of voltage conditions in the Low Voltage network for sites with distributed solar PV," in *Asia Pacific Solar Research Conference 2017*, Melbourne, 2017.

[11] Queensland Department of Energy and Water Supply, "Decision regulatory impact statement: Queensland's statutory voltage limits," 2017.

[12] J. Dore, Ecogeneration, 2019. [Online]. Available: https://www.ecogeneration.com.au/what-voltage-tells-us-about-the-solar-revolution/.

[13] J. Dore, "Voltage Visibility," in *Solar Analytics Data Symposium*, 2019.

[14] AEMO, "Technical Integration of Distributed Energy Resources," 2019.

[15] Energy Networks Australia, "National Connection Guidelines," 2020. [Online]. Available: https://www.energynetworks.com.au/projects/national-grid-connection-guidelines/.

[16] "Integrating Distributed Energy resources for the grid of the future," AEMC, 2019.

[17] D. Alexander, J. Wyndham, G. James and L. McIntosh, "Networks Renewed," Institute for Sustainable Futures, UTS, 2017.

[18] International Energy Agency, "Do It Locally: Local Voltage Support by Distributed".

[19] SA Power Networks, "LV Management Strategy," 2019c.

[20] P. Kilby, "Voltage management on distribution networks with high PV penetrations," May 2019. [Online]. Available: https://www.qut.edu.au/science-engineering/about/events?id=139776.

[21] P. Kilby, "Managing excessive voltage rise and enabling increasing penetrations of rooftop solar using voltage regulating distribution transformers (VRDT)," in *CIDER 2019 Aisa Pacific Conference on Intergration of Distributed Energy Resources*, 2019.

[22] Jemena, "Solar Friendly Neighbourhoods Project," Not yet publicly available.

[23] "Demonstration of Three Dynamic Grid-Side Technologies," Jemena, [Online]. Available: https://arena.gov.au/projects/demonstration-of-three-dynamic-grid-side-technologies/.

[24] Evoenergy, "Annual Planning Report 2019," 2019.

[25] Essential Energy, "Asset Management Distribution Annual Planning Report 2019," 2019.

[26] Endeavour Energy, "Distribution Annual Planning Report," 2019.

[27] Energex, "Distribution Annual Planning Report 2018-19 to 2022-23," 2018.

[28] Ergon Energy, "Distribution Annual Planning Report 2019-20 to 2023-24," 2019.

[29] SA Power Networks, "Distribution Annual Planning Report 2019/20 to 2023/24," 2019.

[30] TasNetworks, "Annual Planning Report 2019," 2019.

[31] United Energy, "Distribution Annual Planning Report," 2019.

[32] CitiPower, "Distribution Annual Planning Report," 2019.

[33] Jemena, "2019 Distribution Annual Planning Report," 2019.

[34] Essential Services Commission, "Electricity Distribution Code review," [Online]. Available: https://engage.vic.gov.au/electricity-distribution-code-review.

[35] "Smart Hot Water System," Royal Automobile Club of Victoria, [Online]. Available: https://arena.gov.au/projects/smart-hot-water-system/.

[36] "Pooled Energy Demonstration Project," Pooled Energy, [Online]. Available: https://arena.gov.au/projects/pooled-energy-demonstration-project/.

[37] "Net Zero Energy Homes," Mirvac Victoria, [Online]. Available: https://arena.gov.au/projects/net-zero-energy-homes/.

[38] "My Energy Marketplace," Wattwatchers, [Online]. Available: https://arena.gov.au/projects/wattwatchers-my-energy-marketplace/.

[39] "Solar Analytics: Monitoring for Better Outcomes," Solar Analytics, [Online]. Available: https://arena.gov.au/projects/solar-analytics-monitoring-better-energy-outcomes/.

[40] N. Stringer, N. Haghadi, A. Bruce, J. Riesz and I. Macgill, "Observed behavior of distributed photovoltaic systems during major voltage disturbances and implications for power system security," *Applied Energy,* vol. 260, 2020.

[41] "National Low-Voltage Feeder Taxonomy Study," CSIRO, [Online]. Available: https://arena.gov.au/projects/national-low-voltage-feeder-taxonomy-study/.

[42] "Decentralised Energy Exchange (deX) Program," GreenSync, [Online]. Available: https://arena.gov.au/projects/decentralised-energy-exchange/.

[43] "evolve DER Project," Zeppelin Bend, [Online]. Available: https://arena.gov.au/projects/evolve-der-project/.

[44] ARENA, "Demand response," [Online]. Available: https://arena.gov.au/projects/?project-value-start=0&project-value-end=200000000&technology=demand-response.

[45] "Consumption Response Project Performance Report ARENA Knowledge Share Report January 2019," EnergyAustralia, 2019.

[46] "Power Changers Trial Evaluation Report," Jemena, 2019.

[47] Powershop, “Consumption Response Program Project Report (1 of 7),” 2017.

[48] “ARENA/AEMO DR Trial, Project Performance Report, Summer 2017 and Winter 2018,” Zen Ecosystems, 2019.

[49] United Energy, “United Energy Dynamic Voltage Management System,” 2020. [Online]. Available: https://www.unitedenergy.com.au/arena-funded-projects/.

[50] EPRI, “International Review of Residential PV Feed-in Management,” [Online]. Available: https://aemo.com.au/-/media/files/electricity/nem/der/2019/standards-protocols/epri-pv-feed-in-management-report.pdf?la=en&hash=D2DF912B4357D7BCD36CD84109EAE84D.

[51] AER, “Values of customer reliability - Final report,” AER, 2019.

[52] “APVI Solar Mapping Tool,” APVI, [Online]. Available: https://pv-map.apvi.org.au/historical#4/-26.67/134.12.

[53] J. Giraldez, A. Hoke, P. Gotseff, N. Wunder, M. Blonsky, M. Emmanuel, A. Latif, E. Ifuku, M. Asano, T. Aukai and R. Sasaki, “Advanced Inverter Voltage Controls: Simulation and Field Pilot Findings,” NREL, Hawaiian Electric, 2018.

Appendix A

Distributed PV curtailment in Australian distribution networks and costs to consumers

Naomi Stringer[1,2], Navid Haghdadi[1,2,3,4], Anna Bruce[1,2,3] and Iain MacGill[2,4]

[1]*School of Photovoltaic and Renewable Energy Engineering, UNSW Sydney, Australia*
[2]*Centre for Energy and Environmental Markets, UNSW Sydney, Australia*
[3]*Australian Photovoltaic Institute (APVI), Sydney, Australia*
[4]*School of Electrical Engineering and Telecommunications, UNSW Sydney, Australia*
E-mail: n.stringer@unsw.edu.au

Abstract

Distributed solar PV presents a number of technical and regulatory challenges and opportunities, with an early focus on management of voltage in the distribution network. As PV penetration increases there are ongoing efforts to ensure appropriate inverter connection standards, network operational and investment practises as well as network hosting capacity algorithms and supporting regulation. Despite this, there remains limited evidence for decision making due to the lack of visibility in the distribution network. As visibility improves tools and techniques for analysing large volumes of data originating in the distribution system are required.

This study proposes and demonstrates novel techniques for analysing operational distributed PV data in order to estimate the volume of PV generation being ‘curtailed’, likely due to over voltage conditions. We assess a data set from over 1,300 distributed PV systems in South Australia provided by solar monitoring company Solar Analytics for twenty-four days throughout 2018. Results are then examined in terms of aggregate impacts and the distribution of impacts on individual consumers.

Key findings indicate that PV curtailment can significantly impact some sites with maximum daily generation loss of up to 27%-94%. However the analysis indicates that overall curtailment is low with an average of 1.0% generation loss over the study period for all sites (including those which experienced zero curtailment losses). Upscaling the estimated generation loss to all of South Australia finds a total value of $0.8m - $2.6m per year. The most significant curtailment is found to occur in spring corresponding to low load and high solar resource conditions. Investigation of whether curtailment is increasing is inconclusive.

Implications for policy makers, regulators, distribution network operators and researchers are discussed in the context of strong projected PV uptake. A particular focus is placed on considerations for inverter connection standards review, and implications for consumer expectations and choice, as well as possible implications for future decentralised power system architectures such as Virtual Power Plants.

1. Introduction

A high penetration of solar photovoltaics (PV) in distribution networks presents a number of technical and regulatory challenges, yet also opportunities, for grid operators, regulators and policy makers. Distributed PV uptake continues to grow in many parts of the world, and Australia presents a useful case study for examining the potential impacts of high penetration, given its world leading uptake of rooftop PV, with around one in five dwellings now having installed a PV system (1).

Voltage management is the primary technical challenge for high penetration PV integration in distribution networks (2, 3). The injection of power at the consumer point of connection can cause local voltages to increase outside network statutory limits, with potential to damage nearby consumer or network equipment, increase wear on distribution network assets and cause curtailment of generation from PV systems due to PV inverter disconnection requirements (4-6). As the power system becomes increasingly decentralised power quality in the distribution network and inverter connection standards are attracting warranted attention (7-11).

Network voltages have historically been 'run high' in Australia (close to the upper bound of statutory voltage limits) in order to accommodate peak load, which has been increasing predominantly due to air conditioner use during high temperature conditions. However, there are clear opportunities to revisit standard operational and investment network practices as PV penetrations climb. Indeed, previous work by the authors and others has confirmed that the low voltage networks in Australia are typically maintained near the upper bound of allowable operation (12). While high average voltages reduce the available headroom for PV systems to inject power, the extent to which this results in the curtailment of PV generation is currently unclear. There has been considerable effort to model solutions for managing high voltages due to PV, for instance through the application of volt-var or volt-watt modes at the PV inverter power electronic interface (11, 13, 14). However there remains limited if any published analysis and poor operational visibility of distributed PV and broader power quality conditions in the low voltage network.

The Australian Energy Market Operator's (AEMO) 2018 Integrated System Plan found that effective integration of DER could offer $4b in value (15), illustrating the importance of effective decision making in this space. There is considerable ongoing work across the industry including the review of inverter connection standard AS4777 (9), the Open Energy Networks project (16), Electricity Networks Economic Regulatory Frameworks review (17) as well as numerous trials and research efforts (10, 11, 18). However, limited visibility in the distribution system persists and there is a limited evidence base for decision making, forming the motivation for this work.

This study builds on our preliminary work (19) and contributes new illustrative evidence indicating the volume of PV curtailment currently occurring in South Australia, using a data set of PV generation from over 1,300 rooftop systems taken at 30sec and 60sec intervals, provided by solar monitoring company, Solar Analytics (20). Custom scripts implemented in R and Python are used to quantify an estimated volume of curtailed PV generation, focussing on 24 clear sky days during 2018.

The volume of curtailed PV is translated into financial impacts and upscaled across South Australia. This estimated curtailment value is then compared with the proposed South Australian Power Network (SAPN) integration project which includes efforts to manage voltage. In addition to the South Australia wide comparison, the distribution of impacts is presented in terms of the financial penalty and percentage of curtailed PV generation for all sites analysed. We aim to respond to the following research questions:

Box 1. Research Questions

1. **Significance:** How significant is PV curtailment in South Australia?
2. **Consumer financial impacts:** What is the distribution of impacts on consumers with PV?
3. **Seasonal variation**: When does PV curtailment occur most?
4. **Future impacts:** Is curtailment increasing as PV penetrations rise?[1] *[inconclusive]*

The remainder of this paper is structured as follows: section 2 provides an overview of data sources used throughout, section 3 sets out the method and section 4 presents findings. Section 5 provides discussion of results and concludes this study.

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[1] Penetration is defined here to be the number of PV systems installed within a postcode divided by the number of suitable dwellings in that postcode.

2. Data

2.1. PV generation data

Generation data from individual sites in South Australia was kindly provided by solar monitoring company, Solar Analytics (20). The data set includes data from 627 – 1,365 sites (after cleaning) on 'clear sky days' during 2018. That is, the minimum number of sites in any given day is 627 whilst the maximum is 1,365. Data from twenty-four days was examined, with two dates selected per month (see Appendix A for further details). Clear sky days were identified using irradiance data (section 2.2).

Data is reported on a 30s or 60s basis with measures including energy, average real power, average reactive power, voltage and frequency. Voltage and frequency are captured over 100ms each measurement interval and therefore present a 'snapshot' rather than average value over the entire period. Meta data for each site includes location by postcode, installed ac and dc capacity, installation date, inverter manufacturer and model.

2.2. Irradiance data

The clear sky days were selected using publicly available Bureau of Meteorology (BoM) solar irradiance data from Adelaide Airport (station 023034), reported on a 1 minute basis for all days throughout 2018 (21). The average daily irradiance over the year was also retrieved from BoM (22) in order to show the conditions on the twenty-four days and provide context to results.

2.3. South Australian load data

Publicly available half hourly load data for South Australia was sourced from AEMO's data portal (23). This data was used during the date selection process.

2.4. PV fleet data

Information on the capacity of PV generation present in South Australia over the period of the study was retrieved from the Clean Energy Regulator database (24). Information regarding the number of suitable dwelling was retrieved form the APVI map (1) and used as the basis for calculating PV penetration by postcode.

3. Method

The study consists of four stages of analysis: 1) date selection, 2) data cleaning, 3) identifying curtailment and estimating lost energy for individual sites, and 4) using results to respond to the research questions. Each of these stages is addressed in section 3.1, 3.2, 3.3 and 3.4 respectively, with key limitations discussed in section 3.5.

3.1. Data date selection

The twenty-four dates examined in this study were selected through first identifying clear sky days, then selecting two of these clear sky days within each month with varied load conditions (i.e. one 'high' and one 'low' load day). Finally, PV generation on the selected dates was checked using the APVI historical PV performance tool in order to avoid dates on which major cloud cover appears to have occurred.

3.1.1. Criteria 1: clear sky days

Clear sky days were identified through visual inspection of 1min solar irradiance data collected at Adelaide Airport (21). The minimum 1sec global irradiance (over 1min intervals) was graphed and dates with no obvious cloud cover were flagged. The daily global irradiance on dates selected is shown in Fig. 1 (left), with the spread (min-max daily global solar irradiance) and average over each month also indicated for context.

It is worth noting that the clear sky days do not always correspond to highest daily solar irradiance in a given month. This is particularly noticeable in April and September where the daily irradiance changes significantly over the course of the month. Fig. 1 (right) provides an example of this effect where the maximum daily irradiance date (2nd April) is clearly not a clear sky day, whereas the lower irradiance day (29th April) has been flagged as clear sky.

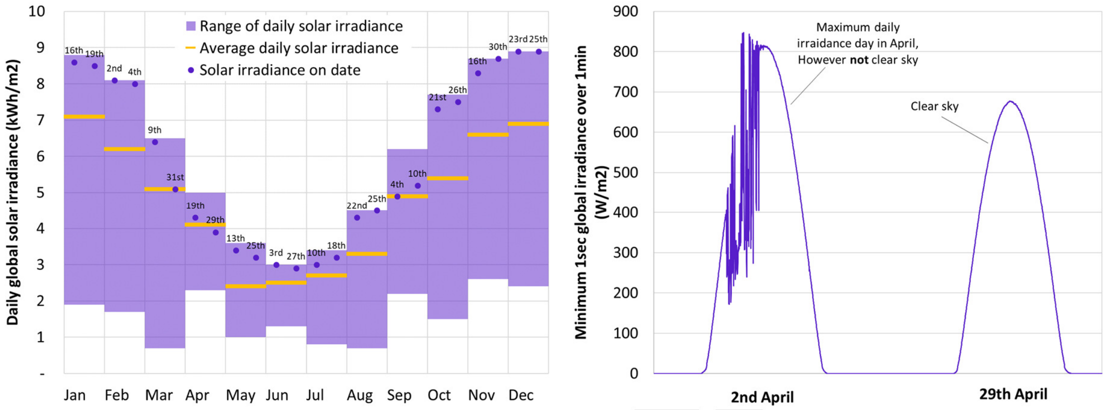

Fig. 1. Seasonal variation of daily global solar irradiance compared with study data dates (left), example of cloudy and clear sky days (right)

Examining a Typical Meteorological Year of solar irradiance data in Adelaide (25, 26), approximately 28 clear sky days occur within one given year (see Appendix A for further details).

3.1.2. *Criteria 2: spread of 'high' and 'low' load conditions*

For all clear sky days flagged the total daily South Australian load was retrieved. For each month two dates were then selected based on the maximum and minimum daily load days. The objective was to capture a more representative sample of dates. Fig. 2 provides an overview of the half-hourly and daily demand in South Australia over 2018, as well as the demand occurring on the twenty-four days examined in this study.

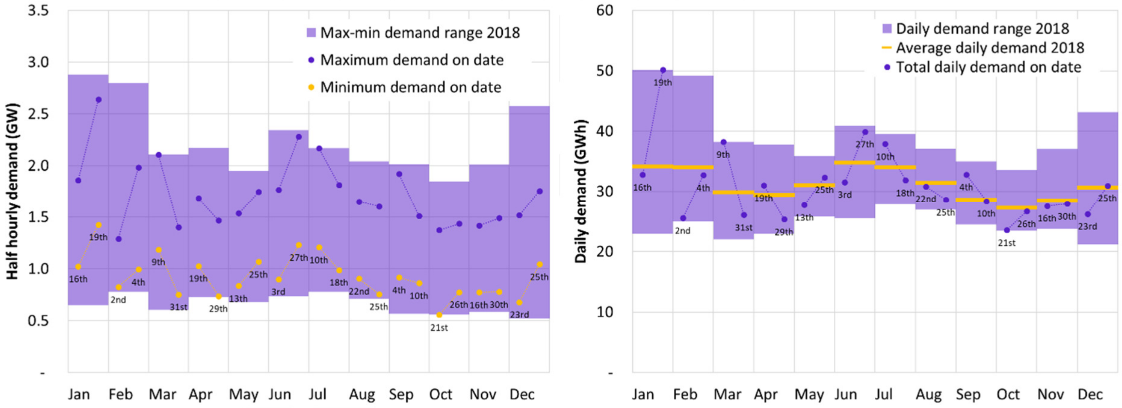

Fig. 2. Historical demand trends South Australia 2018: min-max half hourly demand range (left) and daily total demand range (right) with demand from the sample 24 dates indicated

3.1.3. *Check using APVI map*

Finally, PV performance on the twenty-four dates identified through this process was checked through visual examination of the APVI historical PV production in South Australia. Dates where clear shading was identified were revisited. Actual performance of PV systems

3.2. Data cleaning

Data cleaning is undertaken using customised scripts implemented in R [add reference].

Additional data cleaning scripts are implemented in Python including a missing data check (5% was set as maximum missing data) and identification of sites with very low output over the course of the day (maximum power occurring on a given day is less than 5% of the PV system rated capacity).

3.3. *Identify curtailment and estimate lost energy*

This study is primarily concerned with PV curtailment due to high voltage conditions in the local distribution network. We assumed where PV reduced power output to ‘near zero’, it suggests PV curtailment due to high local network voltage conditions. This assumption is challenging to prove mathematically. In part, this is because the data being examined has been recorded by a device separate to the PV inverter and therefore the exact conditions as seen by the inverter are unknown.

A clear test could be to compare voltages during curtailment periods, with voltage during non-curtailment periods. However, in cases where network voltage is strongly influenced by PV generation the voltage during periods where PV is curtailed may be low compared with periods where PV is not curtailed. An example of this effect is shown in Fig. 3 and emphasised through closer examination in Fig. 4.

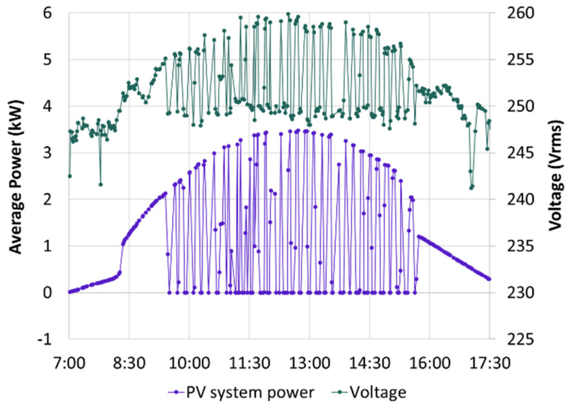

Fig. 3. Example site

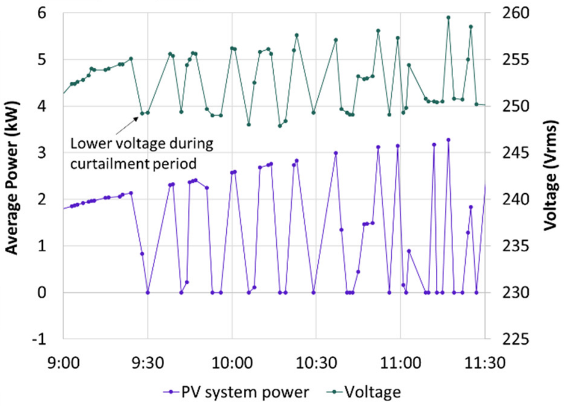

Fig. 4. Example site, 9am-11:30am

The method developed for estimating curtailed PV generation at each individual site consists of four steps which are summarised here and detailed in the remainder of this section: 1) Identify period of near zero generation (≤ 1% performance factor), 2) Identify curtailment 'start points', 3) Identify curtailment 'end points', and 4) Estimate generation lost during curtailment period.

3.3.1. Identify periods of near zero generation

A performance factor profile is calculated using the installed capacity (kW$_{ac}$) as per equation (1):

$$performance\ factor(t)[\%] = \frac{average\ power(t)\ [kW]}{install\ capacity\ [kW_{ac}]} \tag{1}$$

Times at which the performance factor was near zero are then identified, where ‘near zero’ is defined as a performance factor less than or equal to 1%. This step was taken in recognition of the 30s and 60s time increments over which data was recorded.

$$Where\ performance\ factor(t) \leq 1\%, \qquad then\ set\ performance\ factor(t) = 0 \tag{2}$$

Cases where the performance factor increased above 1% for only a single time increment are also set to zero on the basis that inverters can sometimes attempt to start exporting again before immediately switching off. Given the simplified generation estimate method (section 3.3.4) such brief reconnections significantly reduce the accuracy of the generation curtailment estimate method.

$$\begin{aligned} &Where\ performance\ factor(t)\ \neq 0\ and \\ &performance\ factor\ (t-1) = 0\ and \\ &performance\ factor\ (t+1) = 0, \qquad then\ set\ performance\ factor(t) = 0 \end{aligned} \tag{3}$$

3.3.2. *Identify curtailment 'start points'*

The objective of this step is to mathematically identify the PV power immediately prior to curtailment in order to flag the start of the generation curtailment period. The simplest method for identifying when curtailment started is to identify the time period in which the performance factor is greater than 'near zero', and in the next interval is 'near zero':

$$\begin{gathered} When\ performance\ factor(t+1) = 0\ and \\ performance\ factor\ (t)\ \neq\ 0\ then\ start\ flag = 1 \end{gathered} \tag{4}$$

However the ramp down may occur over several time periods. In order to identify the start of the ramp down period, the change in performance factor is calculated:

$$performance\ factor'(t) = performance\ factor(t) - performance\ factor\ (t-1) \tag{5}$$

This change is then used to identify the time intervals prior to the interval flagged in (4) in which ramp down was occurring:

$$\begin{gathered} When\ start\ flag(t+1) = 1\ and \\ performance\ factor'(t) <\ -5\%\ then\ start\ flag = 1 \end{gathered} \tag{6}$$

Equation (6) is applied four times over, and as result the script is expected to accurately identify the start of the curtailment period for sites where power falls over up to five time increments. The first start flag for each event is then used at the start point for the curtailment event.

3.3.3. *Identify curtailment 'end points'*

The method applied to identify curtailment end points is similar to that applied to identify start points. The simplest method for identifying the first ramp up point is initially applied:

$$\begin{gathered} When\ performance\ factor(t-1) = 0\ and \\ performance\ factor\ (t)\ \neq\ 0\ then\ end\ flag = 1 \end{gathered} \tag{7}$$

Again, using the first derivative time intervals after the intervals flagged in (7) in which ramp up is occurring:

$$\begin{gathered} When\ end\ flag(t-1) = 1\ and \\ performance\ factor'(t) >\ 5\%\ then\ end\ flag = 1 \end{gathered} \tag{8}$$

Equation (8) is applied seven times and as result the script is expected to accurately identify the end of curtailment period for sites where power increases over up to eight time increments. The final end flag for each event is then used at the end point for the curtailment event.

3.3.4. *Estimate generation lost during curtailment period*

For each curtailment event the generation which would have occurred if the curtailment did not go ahead is estimated by assuming a straight line between the event start point and end point.

3.4. Data visualisation to address research questions

The research questions and method of investigation is set out in Table I with further detail provided in the remainder of this section.

Table I. Research questions and method of investigation

	Research question	Method of investigation
1	How significant is PV curtailment in South Australia? a) overall and b) for impacted customers	a) Estimate the average percentage curtailment b) Examine the distribution of curtailment
2	Are proposed network solutions proportional? (economically comparable)	Compare the upscaled financial impact on consumers with the DNSP proposed network spend.
3	What is the distribution of impacts on consumers with PV?	Examine the range of financial impact on individual consumers and compare with the proposed network spend.
4	When does PV curtailment occur most?	Examine the spread of PV curtailment over the course of the year

5	Is curtailment increasing as PV penetrations rise?	Examine the relationship between PV penetration, voltage and PV curtailment. Examine the spread of PV curtailment compared with PV penetration.

3.4.1. Key metrics

The first area in which this study aims to provide insight, is the extent and severity of PV curtailment that is currently occurring. In order to do so, several metrics are developed including the percentage of curtailment occurring at each site (9):

$$\mathit{percentage\ curtail}\ (\mathit{site})\ [\%] = \frac{\sum_t^{t=T} \mathit{estimate\ of\ curtailed\ PV\ generation}\ (\mathit{site})\ [kWh]}{\sum_t^{t=T} \mathit{PV\ generation}\ (\mathit{site})[kWh]} \tag{9}$$

The next metric developed is the average curtailment per day per kW of installed capacity or 'normalised daily curtail' (10):

$$\mathit{normalised\ daily\ curtail}\ (\mathit{site})\ [kWh\ \mathit{per\ day\ per}\ kWac] = \frac{\sum_t^{t=T} \mathit{estimate\ of\ curtailed\ PV\ generation}\ (\mathit{site})\ [kWh]}{\mathit{capacity}\ (\mathit{site})\ [kWac]} \tag{10}$$

Both of these metrics are reported for each site, for each day in the data set. The average of all sites and all twenty-four days is then calculated.

3.4.2. Upscaling generation impacts

Either of the metrics defined in (9) and (10) can be used as the basis for estimating the volume of PV generation which is curtailed across South Australia as shown in (11a) and (11b):

$$\mathit{Upscaled\ PV\ generation\ loss\ estimate}\ = (\mathit{average\ normalised\ daily\ curtail}\ )(\mathit{installed\ PV\ capacity})(365d/y) \tag{11a}$$

$$\mathit{Upscaled\ PV\ generation\ loss\ estimate}\ = (\mathit{average\ percentage\ curtail}\ )(\mathit{annual\ PV\ production\ estimate}) \tag{11b}$$

3.4.3. Assessing financial impacts

The financial value of this curtailed generation is then estimated using (12), since curtailment will result in a financial penalty for consumers with effected solar PV. The penalty rate is equal to the retail electricity rate during times where PV is curtailed and generation would otherwise be self-consumed, and is equal to the Feed in Tariff (FiT) rate at times when PV is curtailed and would otherwise be exported to the grid.

$$\begin{gathered}\mathit{Financial\ value\ of\ upscaled\ PV\ generation\ loss\ estimate}\ = (\mathit{Upscaled\ PV\ generation\ loss\ estimate})(\mathit{penalty\ rate}) \\ \mathit{penalty\ rate} = \begin{cases} \mathit{FiT}: 6c/kWh \\ \mathit{Self\ consume}: 25c/kWh \end{cases}\end{gathered} \tag{12}$$

3.5. Limitations

3.5.1. Identifying curtailment due to over voltage conditions

This study does not attempt to prove that the curtailment identified is due to over voltage as discussed in section 3.3. Whilst it is likely that curtailment is due to over voltage conditions the relationship is challenging to mathematically demonstrate due to a number of factors. For instance, that the voltage measurements used in this study were made by a third party device and not the inverter itself.

3.5.2. Conservative or excessive PV generation curtailment estimate?

It is important to note that this method leads to a highly conservative estimate for the volume of PV generation being curtailed and is likely to be underestimating the financial loss due to PV curtailment. This effect will be more extreme for sites with longer curtailment periods. The estimate is conservative because:

- PV generation is typically a function of irradiance which has a parabolic shape, the straight line assumption therefore reduces estimate PV generation at all times. As noted, this is exacerbated when PV generation is curtailed over long time periods.

- Cases where PV returns to service briefly and at a lower performance factor may cause the estimate to be reduced.

The method could be improved through estimating curtailed PV using solar irradiance data.

However conversely, the method may be overestimating PV curtailment given that only clear sky days have been analysed, during which time it is likely that higher PV curtailment occurs. Result accuracy could be improved through analysing a full year of data, including non-clear sky days.

3.5.3. Representativeness of data set

The data set examined may not be representative of the broader PV fleet or of typical PV operation. In particular, the analysis specifically focuses on clear sky days and may therefore over estimate the volume of PV curtailment occurring since there is expected to be less absolute PV curtailment on days when less PV generation occurs.

A second important factor is that the data is sourced from PV systems which are being actively monitored and particularly impactful, recurrent curtailment is likely to have been identified and addressed. For instance through notification of the local network service provider which may reduce distribution transformer tap settings at the local substation. As result, the sample is likely to show less curtailment compared with the broader PV fleet.

3.5.4. Volt-watt and volt-war response modes

This study does not consider volt-watt or volt-var response modes. As result, the estimate of curtailed PV generation is likely to be lower than the actual level of curtailment occurring.

4. Results

4.1. How significant is PV curtailment?

Findings indicate that on average 1.0% of generation is being curtailed over all systems on all days studied. As discussed, this curtailment is likely due to over voltage tripping of PV systems, however mathematical proof of this relationship is outside the scope of this study.

A significant proportion of sites (53%, see Table II) were impacted at least once during the 24 days examined however the majority of these experienced a very small amount of curtailment.

Fig. 5 indicates the spread of most impacted sites over the study period. There is a significant spread between the days, with typically highest levels of curtailment during spring (this is explored further in section 4.3).

The findings indicate that PV curtailment overall is not currently significant, however it can be extremely significant for specific customers with maximum losses throughout the year of 27% – 94%. On the ‘worst’ day in this study (4 September) the 5% most impacted consumers experienced at least 16% curtailment (of all consumers in the data set on this date).

Fig. 6 provides an example of a badly impacted site and also indicates the behind the meter load occurring throughout the day. It indicates that this consumer is effectively being prevented from self-consuming their PV generation at some times.

Table II. Overall PV curtailment findings

Finding	Value
Proportion of sites impacted at least once in the year	53% (982 sites impacted at least once, 1851 sites in the data set. Note most sites are not reporting the entire 24 days.)
Average curtailment (over all sites on all days studied)	1.0%
Average curtailment (impacted sites only)	6.6%
Average kWh lost generation per day / kW_{ac} (all sites)	0.026

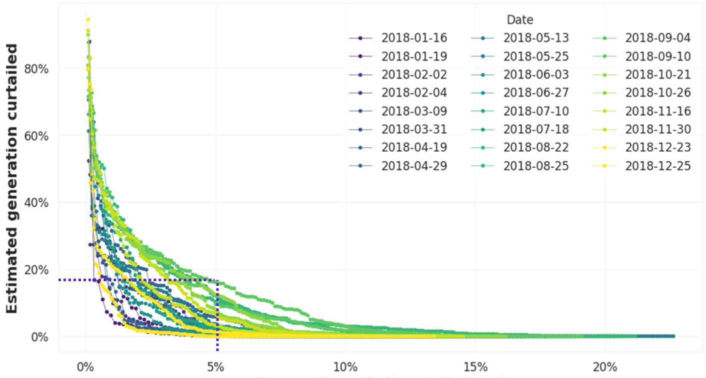

Fig. 5. Distribution of PV curtailment, where each data point indicates an individual site

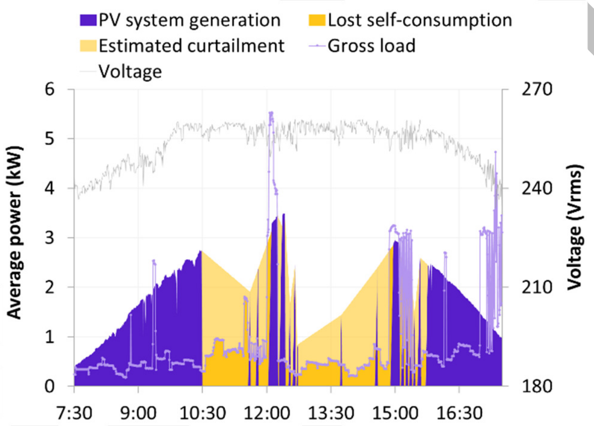

Fig. 6. Example of PV curtailment and loss of self-consumption (19)

4.1.1. Upscaling

Upscaling the observed degree of curtailment to all of South Australia shows ~10.4GWh per annum of lost PV generation. This curtailed generation has a value of \$0.8 – \$2.6 million per annum (Table III).

Table III. Upscaling of financial impacts

Finding	**Value**	**Units**
Average kWh lost generation per day / kW_{ac}	0.025	kWh / day / kW_{ac}
South Australia installed capacity		
<10kW	844	MW
10-100kW	246	MW
Total	*1090*	*MW*
Estimated generation loss	10.4	GWh / year
Financial impact	\$0.8 – 2.6	Million / year

4.2. What is the financial impact on consumers with PV?

Our analysis suggests that the majority of consumers in the sample do not suffer significant PV curtailment, however the consumers which are impacted can experience considerable financial penalty as indicated in Fig. 7. For example, the most impacted consumer is estimated to lose approximately \$45 - \$180 per kWac per year. For a typical 5kW system this is the equivalent of \$225 - \$900 per year.

The approximate annualised cost of a battery is shown in Fig. 7 and indicates that for most PV consumers it is not economically sound to install a battery purely for the purpose of reducing PV curtailment.

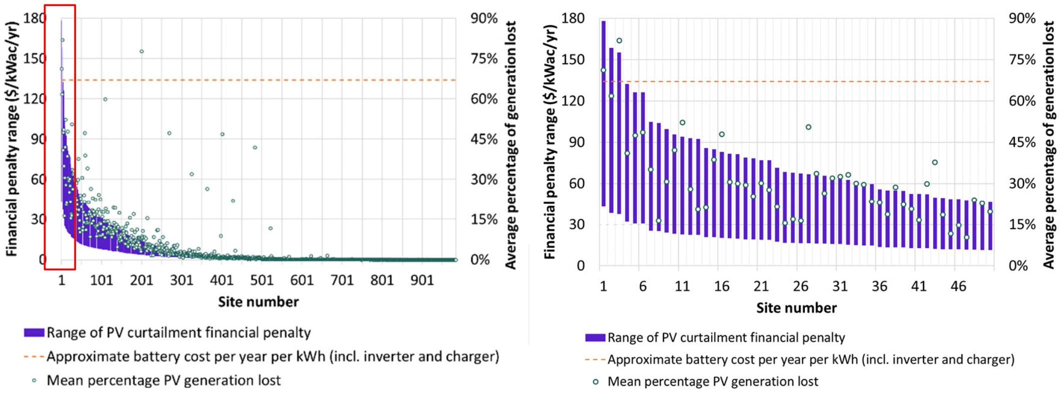

Fig. 7. Financial impact on consumers compared with battery cost: all impacted PV consumers (left) 50 most impacted PV consumers (right). Assumed FiT 6c/kWh and retail rate 25c/kWh.

4.3. When does curtailment occur most?

Fig. 8 indicates that higher levels of curtailment occur in late winter and Spring (August – November) with highest curtailment during September and October. This is consistent with the higher levels of solar resource and generally lower loads that occur during these periods, likely leading to higher local network voltage. This finding suggests that as the ratio of PV generation to load increases, that there will be increased curtailment. It is important to note that this plot only shows the spread of generation lost for impacted consumers.

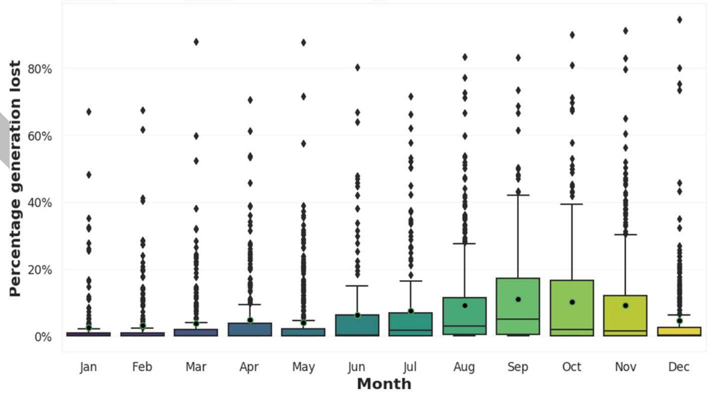

Fig. 8. Spread of curtailment over the year (impacted consumers only), black dot indicates average percentage generation lost, black diamonds indicate outliers

4.4. Is curtailment increasing?

In theory as PV penetration increases, local network voltage is expected to increase and therefore higher instances of PV curtailment due to overvoltage are anticipated. PV penetration is sometimes used by DNSPs as a guide for identifying appropriate voltage management options, although ‘penetration’ is generally defined in this context as a proportion of the local transformer rating (27). Comparing PV penetration with the degree of curtailment may also provide insight into expected future curtailment of PV as installations continue.

Contrary to expectation, findings indicate that there is no clear relationship between PV penetration (by postcode location) and degree of curtailment. It would appear that this is in part due to a lack of relationship between PV penetration and voltage conditions.

The sample of days and sites examined in this data set did not exhibit a strong correlation between PV penetration and average voltage, average voltage and curtailment, or PV penetration and curtailment. A linear regression applied to each of these variable pairs yielded very low Pearson’s sample coefficients (r), indicating week correlation. Fig. 9 shows the spread of voltage and of PV curtailment for increasing PV penetration (the number of sites in each penetration ‘bin’ is also shown, note that each site can contribute up to 24 data points since penetration changes over time).

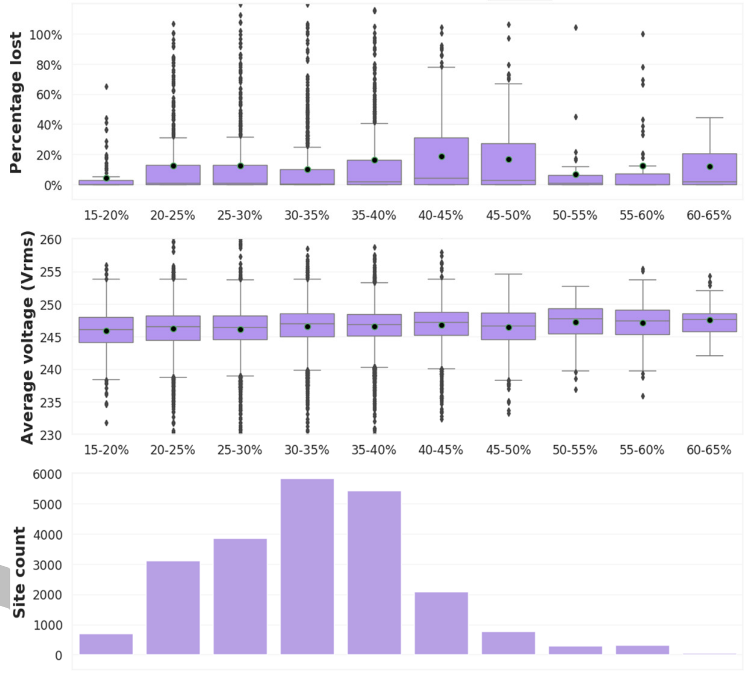

Fig. 9. PV penetration compared with percentage generation lost (top) and average voltage (middle) with count of sites in each penetration bin (bottom).

Note: 1) figure only shows data from impacted sites, 2) the black dot indicates the mean value in each PV penetration bin

This discrepancy between the expected and actual findings is likely driven by a number of factors, including that the postcode PV penetration may not be representative of the feeder PV penetration. In addition, the voltage conditions experienced at an individual site are heavily influenced by factors other than PV penetration, including:

- Load conditions on the feeder and ‘upstream’ of the feeder
- Distribution transformer tap settings
- The capacity of PV systems installed in the local area (the definition of PV penetration adopted in this study reflects the number of PV installations only)
- The inverter connection setpoints of PV systems installed in the local area and whether V-Var or V-W operating modes are enabled (AS4777 version)

It is also worth noting that the sample examined in this study contains a set of actively monitored PV systems (Solar Analytics customers) and therefore major PV losses due to over voltage are likely to be addressed, for instance through re-tapping local distribution transformers. And finally, that regions with high penetration of PV may be flagged as potential trouble spots and addressed by the DNSP.

Given the inconclusive nature of these findings, it is recommended that further analysis is undertaken which examines PV curtailment as a function of local feeder penetration and takes into account the proportion of systems installed under the current and previously version of AS4777.

5. Discussion of results and conclusion

This study indicates that the overall level of PV curtailment is low with 1.0% of generation being lost. However it also finds that some consumers are severely impacted by PV curtailment, losing up to 27% – 94% of generation in a given day. This illustrates the significant penalty that may be imposed on some PV customers due to the current high voltage conditions coupled with inverter connection standards, a challenge which is likely to grow as PV uptake continues. The overall low level of PV curtailment suggests that PV curtailment is not a concern for the majority of consumers, however that monitoring can be highly beneficial given the high levels of curtailment occurring at some sites.

It is important to consider these findings in the context of several key limitations as described above. A central assumption in the analysis is that times at which PV reduces power output to 'near zero' indicates PV curtailment due to high local network voltage conditions. The study does not attempt to prove the relationship between PV reduction and high voltage and also does not consider the impact of V-W or V-Var response modes. This is a key limitation of the analysis and area for further work.

Upscaling the PV curtailment observed to the rest of South Australia we find the estimated current cost of curtailment is \$0.8m - \$2.6m per year. The analysis presented here offers a step towards evidence based decision making regarding appropriate network spend. Future work could consider inter year curtailment to assess the change in PV curtailment over time as well as analysing the impact of inverter standard. The observation that some PV consumers are severely impacted whilst the majority experience minimal impact suggests that the proposed use of representative feeders for network hosting limit analysis (28) may present some limitations.

AEMO's 2018 Integrated System Plan identified \$4b in potential value through effectively integrating DERs, highlighting that cost benefit analyses of network spend with regards to DER integration should extend beyond reducing curtailment.

Asides from the financial penalty, curtailment also has implications for consumer choice through limiting the ability to influence their behind the meter consumption pattern. Fig. 6 (section 4.1) provides an example of curtailment occurring when there is behind the meter load, effectively preventing this consumer from self-consuming their own PV generation. This observation seems to highlight a disconnect between consumer expectations regarding their right to generate, self-consume and export to the network, compared with broader electricity industry expectations regarding generator responsibilities to aid in managing power quality. Generator responsibilities are communicated implicitly through AS4777 and network connection standards. Consumer rights with regards to electricity consumption are enshrined in the National Electricity Objective however consumer expectations and rights with regards to generation are not formally communicated.

The degree of PV loss due to enablement of V-W and V-Var response modes is an area for future work with significant implications for the current review of AS4777. As identified in previous work (12) this study illustrates that network voltages are generally run high, and that tapping down distribution substation transformers where possible to do so could reduce curtailment.

Challenges exist with regards to legacy PV systems installed under the previous version of AS4777 where the anti-islanding over voltage set points were allowed to be set up to 270V (6) compared with 260V in the current standard (second over voltage setpoint in the current standard is set at 265V, and the steady state set point is 255V by default) (5). Given that battery inverters must also comply with the standard these may be unable to operate in regions with high levels of legacy distributed PV, limiting the opportunities for orchestration or response to price signals such as through a VPP. This study does not specifically assess the level of compliance across the PV fleet, or the difference in curtailment amongst PV inverters installed under the previous standard compared with the current standard. This offers a useful area for further investigation.

Findings presented in this study show that the degree of curtailment in South Australia can vary significantly throughout the year, with greater levels in late winter and spring. The finding is reasonable given the high solar resource and low load conditions typically occurring in this period. An evidence based understanding of PV curtailment seasonality, location and extent may prove useful for AEMO, DNSPs and TNSPs in developing PV generation estimates and managing low load conditions.

Finally, we examine whether curtailment is increasing through examination of PV penetration levels by postcode however the analysis is inconclusive. Future work could consider inter year curtailment trends.

This study presents novel analysis techniques and insights through examination of operational data from individual PV systems. Data driven evidence will likely play a key role in effective decision making as the power system transitions to an increasingly decentralised model.

Appendix A

Table IV. Days of data

Month	Data date	Day of the week [A]	Number of sites (post-clean)	Number of clear sky days [B]
January	16	Tuesday	627	0
	19	Friday	630	
February	2	Friday	664	5
	4	Sunday*	662	
March	9	Friday	776	3
	31	Saturday*	840	
April	19	Thursday	879	0
	29	Sunday*	901	
May	13	Sunday*	946	6
	25	Friday	974	
June	3	Sunday*	654	0
	27	Wednesday	844	
July	10	Tuesday	893	0
	18	Wednesday	923	
August	22	Wednesday	999	4
	25	Saturday*	1,050	
September	4	Tuesday	948	0
	10	Monday	884	
October	21	Saturday*	1,226	1
	26	Friday	1,176	
November	16	Friday	1,257	4
	30	Friday	1,280	
December	23	Sunday*	1,179	5
	25	Tuesday* (public holiday)	1,365	

[A] Weekends are indicated in purple with an Asterix

[B] Clear sky days were identified using a Typical Meteorological Year of data for Adelaide, sourced from AREMI (25). 'Clear sky' was taken to mean days in which average absolute percentage change in DNI ≤ 20%, a simplification of the method applied in (26).

References

1. APVI. Australian PV market since April 2001 2019 [Available from: http://pv-map.apvi.org.au/analyses.
2. Passey R, Spooner T, MacGill I, Watt M, Syngellakis K. The potential impacts of grid-connected distributed generation and how to address them: A review of technical and non-technical factors. Energy Policy. 2011;39(10):6280-90.
3. International Energy Agency. Do It Locally: Local Voltage Support by Distributed Generation – A Management Summary. 2017 January. Contract No.: IEA PVPS Task 14, Subtask 2, Activity 2.8, IEA-PVPS T14-08:2017.
4. Queensland Government. Decision regulatory impact statement: Queensland's statutory voltage limit review. In: Department of Energy and Water Supply, editor. 2017.
5. Australian Standards. AS/NZS 4777.2:2015 Grid connection of energy systems via inverters. Part 2: Inverter requirements2015.
6. Standards A. AS/NZS 4777.3-2005 : Grid connection of energy systems via inverters - Grid protection requirements. 2005.
7. AEMC. Electricity Network Economic Regulatory Framework Review. 2019.
8. Energy Networks Australia. Open Energy Networks Interim Report: Required Capabilities and Recommended Actions. 2019 July.
9. AEMO. Technical Integration of Distributed Energy Resources. 2019 April.
10. Miller W, Liu A, Amin Z, Wagner A. Power Quality and Rooftop-Photovoltaic Households: An Examination of Measured Data at Point of Customer Connection. Sustainability. 2018;10(4):1224.
11. Alexander, Wyndham, James, McIntosh. Networks Renewed Technical Analysis. 2017.
12. 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; December; Melbourne2017.
13. Giraldez J, Hoke A, Gotseff P, Wunder N, Blonsky M, Emmanuel M, et al. Advanced Inverter Voltage Controls: Simulation and Field Pilot Findings. NREL; 2018 October.
14. IEEE. 1547-2018 - IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces. 2018.
15. AEMO. Integrated System Plan. 2018.
16. ENA. Open Networks Project 2018 review. 2018.
17. Australian Energy Market Commission. Integrated Distributed Energy Resources for the Grid of the Future. 2019 26 September.
18. ARENA. evolve DER Project 2019 [Available from: https://arena.gov.au/projects/evolve-der-project/.
19. Stringer N, Bruce A, MacGill I, editors. On equity in a distributed electricity system: Voltage management in South Australia. International Association of Energy Economics International Conference: Local Energy, Global Markets; 2019 May 29 - June 1; Montreal, Canada.
20. Solar Analytics. Solar Analytics 2018 [Available from: https://www.solaranalytics.com/au/.
21. Bureau of Meteorology. One Minute Solar Data. 2019.
22. Meteorology Bo. Daily Global Solar Exposure. 2018.
23. AEMO. Aggregated Data Files. 2018.
24. Clean Energy Regulator. Postcode data for small-scale installation - all data. 2018.
25. Data 61. Australian Renewable Energy Mapping Infrastructure - Typical Meteorological Year. 2019-09-13a ed2019.
26. Keeratimahat K, Bruce A, MacGill I. Short term variability of utility-scale PV in the Australian National Electricity Market. Asia Pacific Solar Research Conference; Melbourne2017.
27. Energex. Energex 2017 DAPR 2017/18-2021/22. 2017 27 September.
28. South Australia Power Networks. 2020-2025 Regulatory Proposal - Supporting document 5.18 LV Management Business Case. 2019 25 January.