Enabling a low carbon future

Rooftop solar PV and increasing the voltage standard

Impact on rooftop solar (PV) generation of increasing the maximum allowable voltage on low electricity voltage electricity networks

28 August 2024

Revision 1.1

Dr Allan Miller

Prepared for: Ministry of Business, Innovation & Employment

Disclaimer:

This analysis is based on existing hosting capacity results for a limited number of EDBs and projection of those to a national estimate of PV export. It also uses solar generation previously provided to MBIE that does not represent all major centres in New Zealand. The Results are supplied in good faith and reflect the expertise and experience of the authors. The Models are subject to assumptions and limitations including but not limited to those listed herein. Any reliance on the Results is a matter for the Client's own commercial judgement, taking into account the stated inputs, assumptions and limitations. ANSA Holdings Limited accepts no responsibility for any loss by any person acting, or otherwise, as a result of reliance on the Results.

Acknowledgement:

The author acknowledges the generous provision of hosting capacity results by Aurora Energy, Wellington Electricity, and Orion, which have been instrumental in carrying out this study.

The assistance of Scott Lemon and Auburn Marketing in reviewing this study is also acknowledged.

About ANSA®

Our purpose is to enable a low carbon future. We do this through modelling and insights for the grid connection of electric vehicles, solar power, and other low carbon technologies.

www.ansa.nz

Contact:
Dr Allan Miller
allan@ansa.nz

Contents

Executive Summary 4
1 Introduction 8
2 Methodology 9
  2.1 Introduction and background 9
  2.2 Assessing hosting capacity (kW) differences 10
  2.3 Assessing energy exported (kWh) differences for each EDB’s region 11
  2.4 Assessing energy exported (kWh) differences for all New Zealand regions 14
3 Results and Discussion 17
  3.1 Hosting capacity (kW) differences by EDB 17
  3.2 Additional energy (kWh) exports 22
    3.2.1 High level national results and selection of the base EDB 22
    3.2.2 Sensitivity of the national increase in energy export 24
    3.2.3 Effect of Volt-VAr and increased upper voltage 27
    3.2.4 Increases relative to existing exports 29
    3.2.5 Increases by time of year and region 30
    3.2.6 Increased PV generation from behavioural changes 33
4 Conclusions, Discussion, and Recommendations 35
5 Appendix One – Background on Low Voltage Networks and PV 38
  5.1 Low voltage electricity networks that directly supply consumers 38
  5.2 Voltage on LV networks 40
  5.3 The effect of PV on voltage 41
6 Appendix Two – Process/logic applied to assess additional energy exported for each ICP 44
7 Appendix Three – hosting capacity changes at different hosting capacity percentiles 46

Executive Summary

The Electricity (Safety) Regulations 2010 require that the standard low voltage, nominally 230 Volts AC, must be kept within 6% of that voltage, except for momentary fluctuations. This report gives ANSA's analysis of the impact of raising the upper voltage limit to 230 V + 10% on rooftop solar photovoltaic (PV) generation. This includes both the increase in PV hosting capacity (kW) of low voltage (LV) distribution networks, and the additional energy (kWh) that might be produced and/or exported across PV systems. The values were then extrapolated to provide a national estimate of the potential increase in generated energy.

The analysis is a technical one, based on:

- The increase in LV network hosting capacity assessed using ANSA's tools, which are based on engineering principles and statistical analysis.
- Modelled solar generation by location, also produced from ANSA's models.
- Extrapolation of the local results to a national estimate.

The analysis uses databases of hosting capacities produced for ANSA's clients (with their permission), and benchmarks these against the LV networks for each client. It then selects a preferred set of LV networks, and assumes that all LV networks in New Zealand will, on average, experience similar increases in PV hosting capacity if the upper voltage limit is raised to +10%.

The projection to other centres is based on residential dwelling estimates and estimates of commercial building numbers, average rooftop PV installation capacity, and local solar generation.

Being technical in nature, the analysis does not assess behavioural changes that may occur amongst consumers if they are able to export more PV, such as installing larger PV systems. However, to give an indication of what might happen if consumers do install larger PV systems, an estimate of the additional PV generation and export is briefly made.

Key results and conclusions from this report are:

1. Raising the upper voltage limit from +6% to +10% increases the PV hosting capacity (kW) of LV electricity networks by:

    a. a factor of about three times for residential consumers and

    b. about two times for commercial consumers at 10% PV penetration.

    This increase diminishes as the penetration level increases due to changes in the type of network constraints experienced. This is particularly true for commercial ICPs, while the additional capacity for residential ICPs remains higher for longer. At lower penetration levels PV export is more likely to be limited by conductor voltage constraints, while at higher penetration levels the PV export is increasingly constrained by the thermal limits of the distribution transformers supplying each network.

2. Raising the upper voltage limit from +6% to +10% allows PV exports (kWh) to increase for both residential and commercial consumers. This increase is:

    a. About 24% for commercial ICPs with 20% PV uptake, and 3% for residential ICPs with 30% PV uptake. The combined increase in annual generation is about 507 GWh, lifting rooftop PV's contribution from 11.6% of annual national generation to about 12.8%.

    b. At 50% residential PV uptake and the same 20% commercial PV uptake, the increase is about 8% for residential ICPs. The combined increase in annual generation is about 825 GWh, which lifts rooftop PV's contribution from 16.3 % to about 18.2% of annual national generation.

3. Despite the increase in energy exports being modest at low penetration levels, the additional PV hosting capacity (kW) provides several additional benefits when PV systems are paired with battery storage:
    a. It enables PV systems with batteries to export at higher capacity at times when energy or network capacity is scarce, such as during peak demand. This could help alleviate network voltage and loading constraints, as well as provide further benefit to battery system owners ('value stacking'). However, there is a question over the impact this may have on voltage levels and overvoltage constraints at these times, and how battery exports should best be managed and controlled.
    b. It also enables PV systems with batteries to export at higher capacities to provide more instantaneous reserves. This will again benefit owners of such systems through access to another source of revenue, and will ideally lower the cost of reserves.
4. Raising the upper voltage limit will provide the benefits outlined above, as well as avoid network expenditure to upgrade conductors to relieve voltage constraints. Over the many thousands of LV networks in New Zealand, this could amount to a substantial avoided investment. Such avoided investments can be assessed with ANSA's constraint risk and LV Capex Model, together with other demand changes such as EV uptake and gas-to-electricity transition. Since constraints arising from EV and gas-to-electricity can be driven by winter demand, they may be required ahead of the PV driven investments. This highlights the importance of considering all changes in network use together.
5. For both hosting capacity (kW) and export increase (kWh), there was good agreement between the results of three of ANSA's clients for the LV networks assessed, considering the different ICP types assessed. This supports the selection of a preferred set of LV networks and extrapolating those to a national estimate.
6. Estimated PV export increase varies by time of year, with the greatest increase in exports occurring in the summer. There is some increase in the winter, but this is modest due to higher daytime household demand and lower overall PV generation in the winter.
7. While the PV export increases reported above are relatively small, especially at the lower PV penetration levels:
    a. The increases will benefit those with PV.
    b. There is a further benefit in terms of avoided capital expenditure required by EDBs to release this additional PV energy, which would otherwise be spilled. This will benefit all consumers through more available renewable energy lowering energy prices and avoiding higher electricity prices which would otherwise be required to fund the capital expenditure.
    c. The primary capital expenditure avoided is conductor upgrades to relieve voltage constraints.

   d. Use of reactive power generation equipment such as advanced inverter controls to regulate voltage is questionable at high PV penetration levels as it will give rise to large reactive power flows, higher losses, and potentially overload equipment thermal ratings sooner.

   e. Additional capital expenditure may also be avoided by EDBs using some of the additional voltage range (made available by increasing the upper voltage limit to +10%) to raise distribution transformer tap settings further to accommodate greater voltage fall during times of high load from EV charging. This will have limited benefit because most constraints during high loads are thermal rather than voltage. Such a tap setting change may be avoided by also lowering the lower voltage limit to -10% from -6%. However, as explained, the effectiveness of this in supplying larger loads will be limited due to constraints being dominated by transformer thermal constraints rather than voltage reducing below the -6% limit.

8. If a behavioural change in PV installation was to occur in conjunction with the lifting of the upper voltage limit to +10%, combined with EDBs increasing the allowable PV capacity on residential installations, the additional energy produced by residential PV could be in the order of:

   a. 293 GWh at 10% residential PV penetration (0.7% of New Zealand's current annual electricity generation) and

   b. 1,406 GWh at 40% residential PV penetration (3.2% of New Zealand's current annual electricity generation).

   This assumes that on average residential PV installations increase in capacity by 25%.

   The actual increase in installed PV size that would result from an increase to the upper voltage limit depends on future PV technology and costs, available roof space, and consumer behaviour, and is outside the scope of this study. The key point remains, however, that increasing the upper voltage limit to +10% unlocks additional hosting capacity in many LV networks, thereby allowing consumers to install larger PV systems and to generate more of their own energy.

9. As PV penetration levels increase further, beyond about 60% for residential ICPs (Figure 2) and 50% for commercial ICPs (Figure 3) the increase in the upper voltage limit to +10% diminishes in effectiveness as distribution transformers become the constraining element in LV networks (Table 5). EDBs will then face the decision of whether to upgrade transformers to allow more PV export. Finding local uses for the locally produced PV energy should provide a more cost-effective option for all consumers. For example, load could be managed by shifting storage hot water heating and EV charging demand to coincide with periods of high PV generation.

From this investigation the following recommendations are made:

1. Increasing the upper voltage limit from +6% to +10% allows consumers to continue to install PV without constraining voltages in LV networks.
2. Prior to proceeding with the upper voltage increase, there are other aspects not addressed in this study that should be investigated. One is investigating the impact on other equipment connected to LV networks.

3. If proceeding with increasing the upper voltage limit from +6% to +10%, an analysis of the avoided capital expenditure should be undertaken, as this is likely to be high given how many voltage constraints there are at +6%.

1 Introduction

The Electricity (Safety) Regulations 2010 require that the standard low voltage (nominally 230 Volts AC, calculated or measured at the point of supply) must be kept within 6% of that voltage, except for momentary fluctuations. MBIE has asked ANSA to investigate how much more export from rooftop solar (PV) might be possible if the upper limit is raised to 230 V + 10%, to align it with relevant international standards. MBIE has asked for the estimated national impacts on rooftop photovoltaic solar (PV) generation output for both capacity (kW) and energy (kWh) under a range of assumptions about future penetration of PV.

This report gives the results of ANSA's analysis of the effect on rooftop PV generation from raising the upper voltage limit from 230 V + 6% to 230 V + 10%. The methodology adopted by ANSA was to use data from several hosting capacity studies it has undertaken since including the +10% upper voltage and circuit level local hosting capacity features in those models. The report begins by describing the methodology adopted by ANSA to undertake this investigation. It then presents the results together with a discussion of the results and conclusions made from the results.

The report is supported by several Appendices as follows:

- Appendix One gives a background section that explains low voltage networks, provides relevant definitions for the purpose of this study, and why the upper voltage limit influences PV export.
- Appendix Two gives more detail supporting the methodology.
- Appendix Three gives further results to those in the main report.

2 Methodology

2.1 Introduction and background

ANSA's hosting capacity models assess electric vehicle (EV), and distributed generation (usually photovoltaic solar or PV) network hosting capacity. They are also used to assess other demand transitions such as gas-to-electricity and urban infill, but of interest in this study is PV hosting capacity. These, together with other terms of relevance, are defined below.

PV future hosting capacity	The maximum export to the network (kW) that can be tolerated at one or more ICPs in the network, before it becomes likely that the network will be constrained, at a given PV uptake level and upper voltage level. The term "future" is used to emphasise the fact that the hosting capacity is determined based on future network configurations and PV uptake, rather than simply the present/past network state, as derived from monitoring data. However, "future hosting capacity" may be generalised to "hosting capacity" in this report.
EV future hosting capacity	The maximum power rating of electric vehicle charger (kW) that can be installed at one or more ICPs in the network before it becomes likely that the network will be constrained at a given EV charger uptake level.
Network-level hosting capacity	The hosting capacity, as defined above, for all ICPs in an LV network. Also referred to as global hosting capacity.
Circuit-level hosting capacity	The hosting capacity, as defined above, for all ICPs on a circuit within an LV network. Also referred to as local hosting capacity.
Constraint risk	The probability or "risk" that an element in a low voltage network will become constrained or need to be upgraded to resolve a constraint. Constraint risk is determined by running element-level impact studies, in which the voltage and current is calculated at every point in a network for a range of different demand/export levels and configurations. The constraint risk is then equal to the proportion of cases in which an element becomes constrained due to loading or needs to be upgraded to resolve a downstream voltage constraint.
Constraint risk threshold	A defined level of constraint risk, above which an element is flagged as requiring an upgrade. All elements flagged for upgrade are subsequently used to determine the capex required to prevent unacceptable constraint levels. Setting a high constraint risk threshold flags fewer elements for upgrade, resulting in a lower capex forecast. As constraint risk threshold is lowered, more elements are flagged for upgrade, thereby increasing the capex forecast.
Low voltage (LV)	In New Zealand this refers to the 230 Volt phase-to-neutral / 400 Volt phase-to-phase voltage supplied to most homes and businesses.
LV network	The networks that directly supply most homes and businesses in New Zealand. Appendix One gives more background to LV networks and the impact of PV on them.

Point of supply Consumer main / service main	The point on an LV network at which an ICP takes supply from the LV network, with the consumer main / service main used to carry electricity from the point of supply to the ICP. Appendix One illustrates these. ANSA's models assess the LV network to the point of supply, as well as the consumer main. While only voltage at the point of supply is required, the consumer main is also modelled to implement the Volt-VAr power quality response of inverters.
Installation control point (ICP)	Used generally to refer to the dwelling or building taking supply from the EDB's network. There may be one or more consumers at an ICP.

As indicated in the 'PV future hosting capacity' definition, the hosting capacity is determined for a given upper voltage level. ANSA recently introduced the ability to assess PV future hosting capacity at both the current 6% upper voltage level and a +10% upper voltage level. In addition, ANSA recently introduced circuit-level hosting capacity analysis, also known as local hosting capacity. This determines a unique hosting capacity for each circuit of an LV network and allows for better allocation of capacity across an LV network compared to using a single network-level value.

Since introducing the +10% upper voltage level and circuit-level hosting capacity capabilities, ANSA has completed studies for most LV networks of two EDBs, and a sample of LV networks for a third EDB. These EDBs have given permission for ANSA to use their results for this study, aggregated and anonymised so as not to identify any individual customer. The details of the study for each EDB are given in Table 1.

Table 1: EDB hosting capacity and constraint risk studies used in this study. This represents a subset of LV networks present in each EDB's distribution network, which may not be reflective of all existing LV networks.

EDB	LV networks	Circuits	Residential ICPs	Commercial ICPs	ICPs per LV network / per circuit	Residential ICPs to all ICPs
Aurora Energy	4,035	8,276	77,855	8,586	21.4 / 10.4	90.0%
Wellington Electricity	1,780	4,965	121,534	3,754	70.4 / 25.2	97.0%
Orion	46	111	3,770	313	89.8 / 36.8	92.3%

2.2 Assessing hosting capacity (kW) differences

Any increase in hosting capacity from raising the upper voltage limit was of interest to understand the magnitude of increase possible. It was also of interest to compare the aggregated results between EDBs, since the methodology discussed in Section 2.4 requires scaling from one EDB to the rest of New Zealand.

The assessment of the increase in hosting capacity by penetration level was carried out by a statistical analysis of future hosting capacity results from each EDB. This involved assessing the median values across all ICPs versus penetration level, at three different hosting capacity percentile levels. Each hosting capacity percentile represented a different combination of location of PV and demand in each

LV network, and as discussed in the Appendix One, results from the need to conduct Monte Carlo studies. Hosting capacities at both +6% and +10% upper voltage limit were assessed, with and without inverter Volt-VAr power quality response modes.

The distribution of hosting capacity across all residential ICPs and commercial ICPs was also assessed. The decision of which EDB's data to use when extrapolating the results to a national estimate (see Section 3.1) was based on:

1. The EDB whose results better represent both residential and commercial ICPs;
2. The EDB whose results better represent rural and urban LV networks;
3. The EDB with the larger number of ICPs (samples); and
4. How the distribution of hosting capacities compares between EDBs, with any major deviation excluding that EDB's results from scaling to a national estimate.

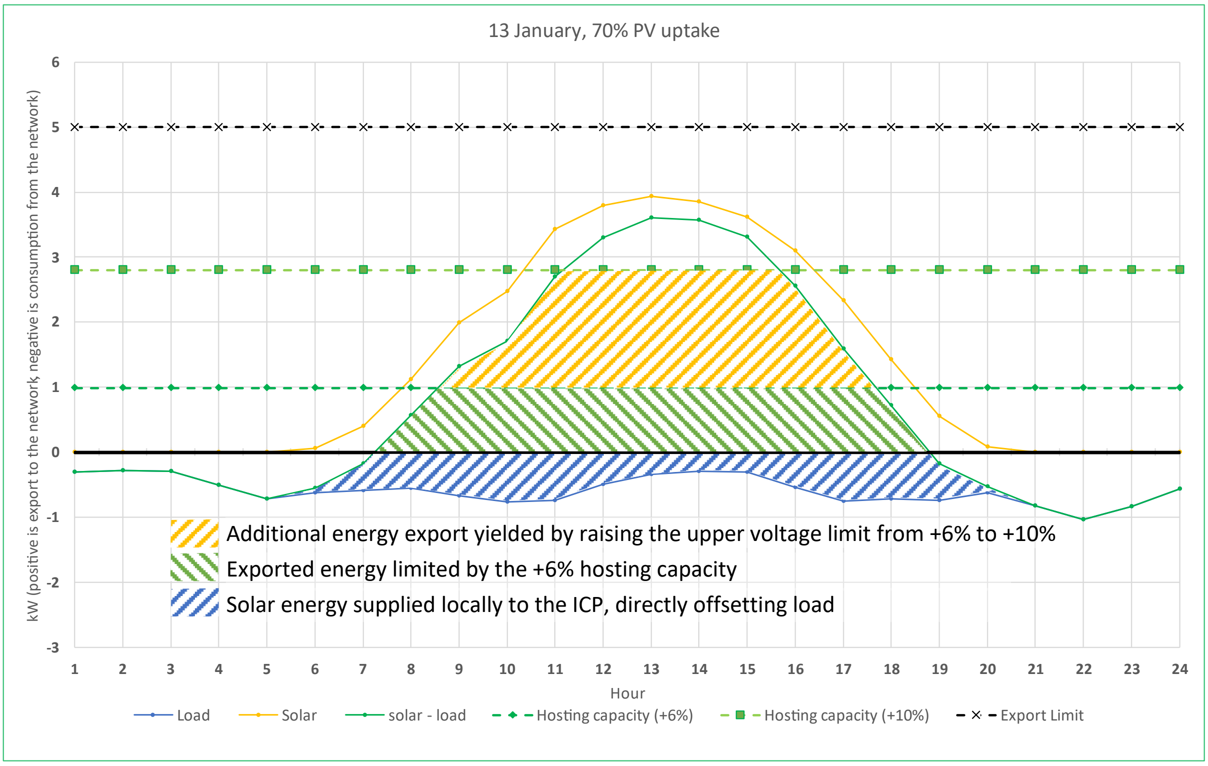
2.3 Assessing energy exported (kWh) differences for each EDB's region

An assessment of additional energy exported to the network was made for each ICP in each EDB's network, with the results scaled by a given PV penetration level. The concept implemented in the study is illustrated in Figure 1, deliberately using a high PV penetration level for the purpose of illustration. The assessment is purely a technical assessment, which assumes that consumers continue to install PV at the recent historical capacity and assesses the additional exports of energy that would otherwise have been spilled. This is in contrast to consumers changing their behaviour and installing larger PV systems because of the increased hosting capacity. Section 3.2.6 does make a brief assessment of the impact of increased exports at the +10% upper voltage level combined with residential consumers installing systems 25% larger than the recent historical capacity.

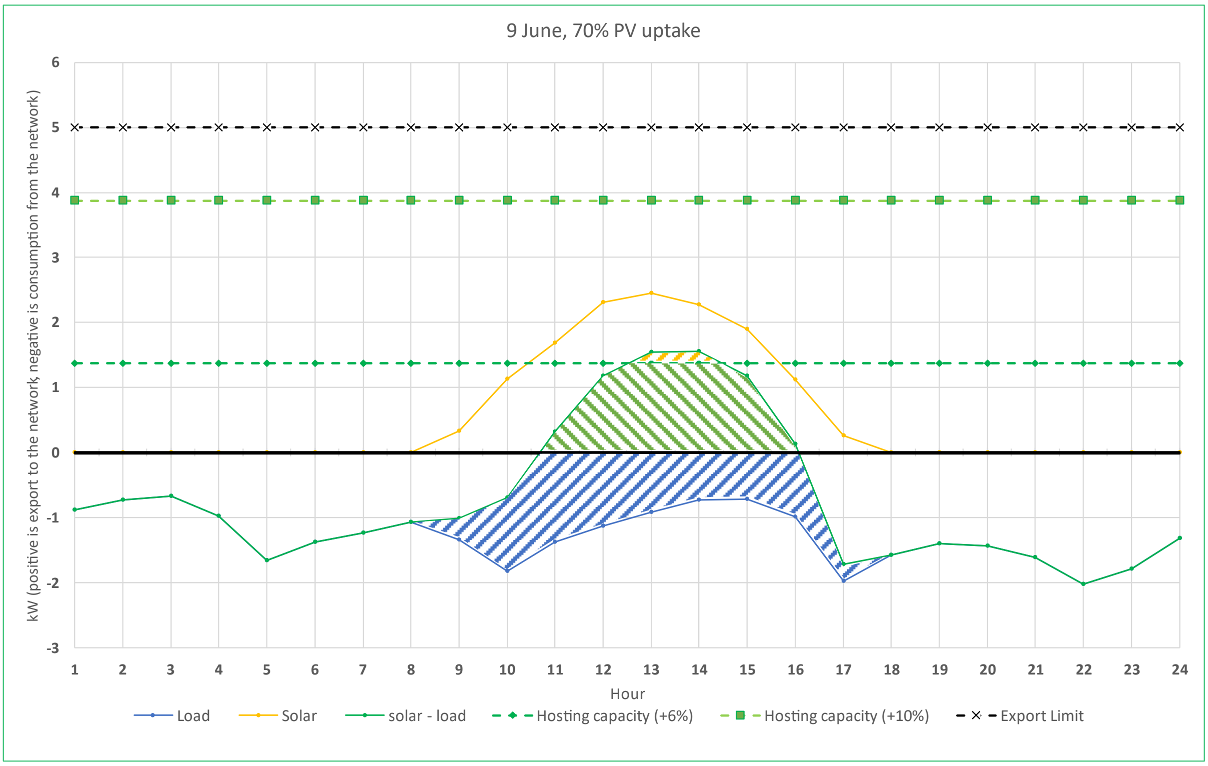
It is assumed that the hosting capacity of an LV network circuit sets a firm limit on PV that can be exported, either through allocation by the EDB together with setting the inverter to limit at the hosting capacity, and/or the implementation of Volt-Watt control in the PV inverter – where the inverter progressively limits active power (kW) production as voltage rises above a limit. The former is more likely to result in a fairer allocation of network capacity, while the latter is more likely to disadvantage those consumers at the end of circuits, especially long circuits, where greater voltage rise can be expected when exporting – see Appendix One for an explanation of voltage rise on LV networks during PV export. Nevertheless, a correctly configured Volt-Watt power quality response mode is an important way of ensuring PV export does not contribute to excessive LV network voltages. For residential ICPs, a backstop export limit is also applied, equal to 5 kW in this example – a value applied by some EDBs. For commercial ICPs with large-scale PV greater than 10 kW, this limit is set to 1 MW.

As discussed in Appendix One, hosting capacity is determined under minimum load conditions, when PV export is likely to be high and therefore have maximum impact on LV network congestion. As shown in Figure 1(b), the combination of higher ICP demand, and lower solar in winter leads to there being less potential for additional export in winter.

The analysis records the additional energy export across all ICPs by month. Monthly increase in export is of interest in terms of the additional contribution of PV solar to winter energy, since energy is usually scarce in winter in New Zealand.



(a) PV export increase in summer.



(b) PV export increase in winter.

Figure 1: the impact on PV solar exports of raising the upper voltage limit. The quantity determined for, and reported in, this report is the yellow cross-hatched area, and as shown in (a) is higher in summer than in winter, shown in (b). This is due to the combination of higher hosting capacity in winter, higher ICP demand in winter, and lower solar generation in winter.

The assessment of additional energy export over all ICPs uses solar data local to the region, as discussed in the following section, and considers the following inputs:

Table 2: Inputs to the assessment of additional PV export

Input	Values used	Comment
Base EDB	Aurora Energy, Wellington Electricity, and Orion	All three EDBs were assessed and scaled to all regions for the purpose of comparison. The results of one EDB were then used in final results. Section 2.2 discusses the selection of the EDBs' results scaled to all regions.
Hosting capacity percentile	25th, 50th, and 75th percentiles	These are the hosting capacity value percentiles, resulting from a Monte Carlo assessment to determine hosting capacity, discussed in Appendix One. They are included for the purpose of sensitivity analysis of the results. To limit the number of combinations, only Aurora Energy's 25th and 75th percentiles are assessed, while all EDBs' assessments are made for the 50th percentile.
Volt-VAr level	0% and 60%	Used to understand the interaction between hosting capacity increase from Volt-VAr and from raising the upper voltage limit.
PV Penetration level (also referred to as PV uptake level)	10, 20, 30, 40, 50, and 60%	To reduce computation time, uptake levels above 60% were not assessed, as they were considered unrealistically high.
ICP type	Residential and commercial	Provided to understand the increase in hosting capacity by consumer type
City	All cities represented in the 16 regional council areas of New Zealand	As discussed in the next section, these were considered separately to enable scaling of results from one EDB's area based on dwelling numbers and estimated commercial building numbers, as well as to apply local solar to the analysis.

The additional energy exported over all ICPs, at the hosting capacity relating to each PV penetration level, was determined for each of the base EDBs. This was then scaled down to the PV penetration level by multiplying the resulting energy value by the PV penetration level. This approach was taken, rather than selecting a sample of ICPs based on the uptake level, to include all ICPs in the analysis since selecting a sample may not represent all ICPs.

2.4 Assessing energy exported (kWh) differences for all New Zealand regions

The resulting change in exports determined from the previous section was then compared between the base EDBs for each customer type, and a choice of base EDB made from this. Section 2.3 discusses this choice.

Following this, the results from that base EDB were extrapolated for the main city of each region:

1. As if that selected EDB's hosting capacity values applied to the LV distribution networks in that region. The analysis in Section 3.1 shows that, as a whole, hosting capacities for residential ICPs between EDBs in both Islands have similar distributions, which supports this assumption. Note however, that this is a high-level view – hosting capacity values for individual LV networks vary substantially based on the network topology and conductor parameters.
2. With available typical meteorological year solar data for that region. Local solar data was found to affect the result by as much as 10%. For example, using Nelson specific solar compared to Christchurch solar led to 10% more export. However, this is still an estimate due to solar data not being available for all centres, and the wide variation in solar within some regions (for example, the Mackenzie District's solar resource is higher than Christchurch's solar resource, yet Christchurch's was used to represent all of Canterbury). Importantly, wherever possible, the solar data used related to the region's main population area.

   The solar generation used in this study had been provided to MBIE some years earlier for another study and was re-used for this study. That did restrict the solar generation that could be used to some extent, most particularly for Otago, the West Coast, and Southland. The main issue was not having data specific to Dunedin, although solar resource varies considerably across the Otago region. Christchurch generation was used as a proxy for Dunedin, since it has a capacity factor somewhere between Dunedin and Central Otago (Cromwell, Wanaka, and Queenstown which all have relatively high solar resource compared to most New Zealand main centres).
3. Using the region's average PV installed capacity for residential and commercial ICPs.
4. In addition to the capacity and location of PV generation data, the characteristics of each rooftop PV system used were north facing arrays with 20-degree roof slopes. Naturally roof orientations and slopes vary considerably, but it was deemed reasonable to use north facing with a low slope (which would generate less energy in the winter). In addition, all solar generation assumes an inverter loading ratio of 1.0. Increasing this by installing more PV panels is an economic way of increasing the capacity of a PV installation, enabling more PV generation in winter especially, in line with the analysis in Section 3.2.6.

The results were then scaled from the base EDB to each region by:

a. the ratio of residential dwellings in the region to the number of residential ICPs in the base EDB's study, and

b. the ratio of estimated commercial buildings to the number of commercial ICPs in the base EDB's study.

Table 3 gives the details used in the above process. Since this report assesses additional PV energy exports by PV penetration level, Table 4 gives the installed PV capacity by customer type at the penetration levels assessed, using the information in Table 3.

Table 3: Details used to scale from the base EDB's results to all regions. As a proxy for residential ICPs, PV installations less than or equal to 10 kW were used to determine the average residential PV capacity by region, while for commercial ICPs, PV installations greater than 10 kW and in the SME (small-medium enterprise) market segment were used to determine the average commercial PV capacity by region (SME was used because they are known to be LV connected). Appendix Two describes the process to determine additional export, and scaling to each region. Dwelling numbers are from Stats NZ "2023 Census population counts", and PV capacity is from the Electricity Authority's electricity market information (EMI) website, "installed distributed generation trends".

Region	City	Dwellings (2023 Census)	Estimated commercial buildings	Nearest solar available	Average residential PV capacity (kW)	Average commercial PV capacity (kW)
Northland	Whakatane	88,092	8,809	Marsden Point	4.6	30.1
Auckland	Auckland	611,895	61,189	Auckland	4.5	44.8
Waikato	Hamilton	216,222	21,622	Hamilton	4.6	37.9
Bay of Plenty	Tauranga	137,349	13,734	Whakatane	4.5	31.7
Gisborne	Gisborne	19,509	1,950	Whakatane	4.1	20.5
Hawke's Bay	Napier	71,364	7,136	Napier	4.7	30.1
Taranaki	New Plymouth	52,992	5,299	Martinborough	4.8	32.5
Manawatu-Wanganui	Whanganui	108,903	10,890	Martinborough	4.4	40.7
Wellington	Wellington	215,991	21,599	Wellington	4.4	48.7
Tasman	Richmond	26,352	2,635	Nelson	4.9	27.5
Nelson	Nelson	22,845	2,284	Nelson	4.6	32.9
Marlborough	Blenheim	24,807	2,480	Blenheim	4.4	23.7
West Coast	Greymouth	18,564	1,856	Christchurch	4.9	16.7
Canterbury	Christchurch	282,039	28,203	Christchurch	4.6	42.1
Otago	Dunedin	112,473	11,247	Christchurch	4.6	33.6
Southland	Invercargill	46,761	4,676	Christchurch	5.0	24.6

Source: [full_results-with_analysis.xlsx]Regions 16/08/2024

Table 4: Estimated installed PV capacity at each PV penetration level.

PV penetration (% of ICPs)	Total installed capacity (GW)		
	Residential	Commercial	Total
10	0.9	0.8	1.7
20	1.9	1.6	3.5
30	2.8	2.4	5.2
40	3.7	3.2	7.0
50	4.7	4.1	8.7
60	5.6	4.9	10.5

Source: [full_results-with_analysis.xlsx]tables 16/08/2024 (1)

3 Results and Discussion

3.1 Hosting capacity (kW) differences by EDB

Figure 2 and Figure 3 give the median hosting capacity values of all ICPs for each EDB at each upper voltage limit. The following are clear from these:

1. The median residential values in Figure 2 are similar for each EDB, with Aurora Energy's being slightly higher at the +10% upper voltage limit. Aurora Energy's median hosting capacity is slightly higher because the LV networks assessed include more rural networks, with fewer ICPs per transformer – the average number of ICPs per LV network is lower than that of Wellington Electricity's and Orion's samples from Table 1. This difference is even higher with Volt-VAr responses, also attributable to fewer ICPs per LV network, allowing more current flow resulting from the higher reactive power flow with the Volt-VAr response.

2. There is also agreement between Aurora Energy's and Orion's commercial ICP median hosting capacity results in Figure 3. However, Wellington Electricity commercial ICP hosting capacity results show a large difference. This is because Wellington Electricity's LV networks were selected to be predominantly residential in the original study, as shown by the higher ratio of residential to all ICPs in Table 1, and comprise mainly dense urban and suburban networks. Consequently, the results do not reflect the same range and size of commercial ICPs as found in Aurora Energy's and Orion's results.

3. The median hosting capacity (kW) values with the +10% upper voltage limit are higher than the values with the +6% upper voltage limit by a factor of about three times (residential) and about two times (commercial) at 10% PV penetration (without Volt-VAr). This difference diminishes as PV penetration level increases due to conductor and/or transformer thermal ratings setting the hosting capacity in more LV networks due to higher reverse current flow. The same effect can be seen with the Volt-VAr response on, with greater convergence as penetration level increases in the residential case due to higher current flow from the higher reactive power flows. The gradual increase in constraints due to transformer loading can be seen in Table 5 for residential ICPs. This shows that more LV transformer constraints occur at the upper voltage level, which has a higher hosting capacity.

For completeness the median of all residential and commercial 25th percentile and 75% percentile hosting capacity values are shown in Appendix Three for residential ICPs (Figure 14 and Figure 15 respectively) and commercial ICPs (Figure 16 and Figure 17 respectively). These show a decrease in hosting capacity of approximately 25% at the 25th percentile, and an increase of approximately 25% at the 75th percentile.

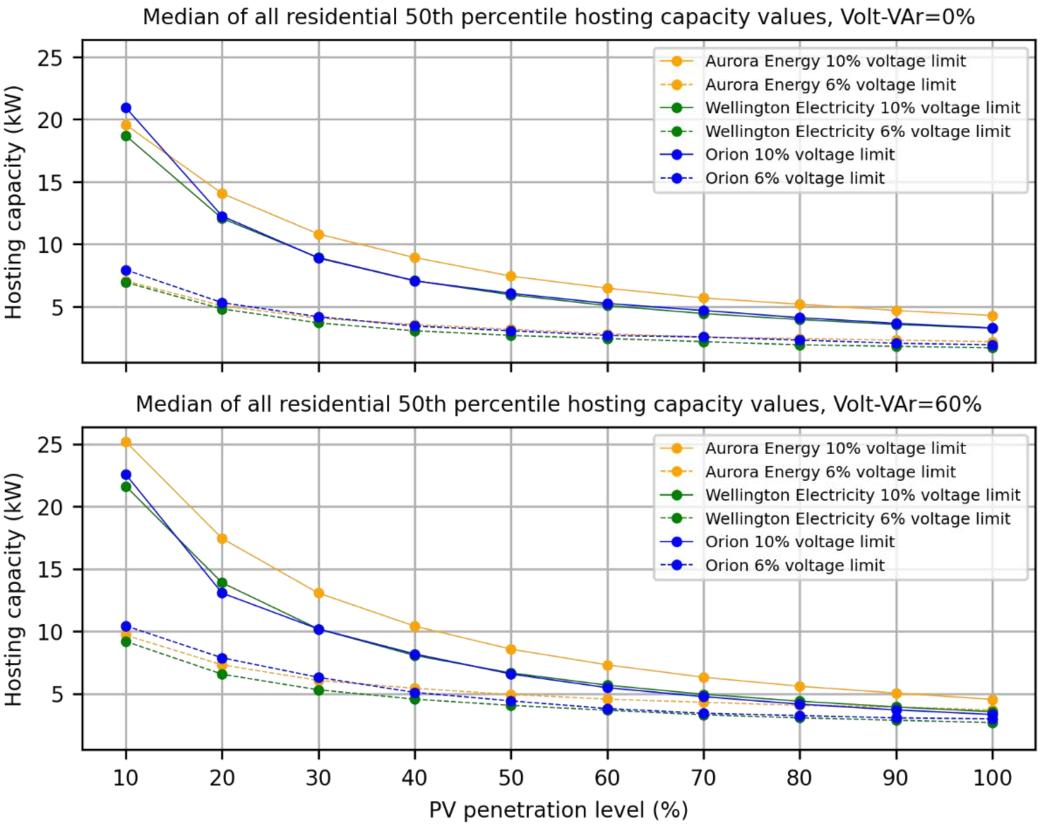


Figure 2: Hosting capacity of residential ICPs by penetration level at each upper voltage limit, with (top graph) and without (lower graph) Volt-VAr inverter responses. The hosting capacity given is the median of all ICPs, using the 50th percentile hosting capacity value (see Appendix One for a discussion of hosting capacity percentiles).

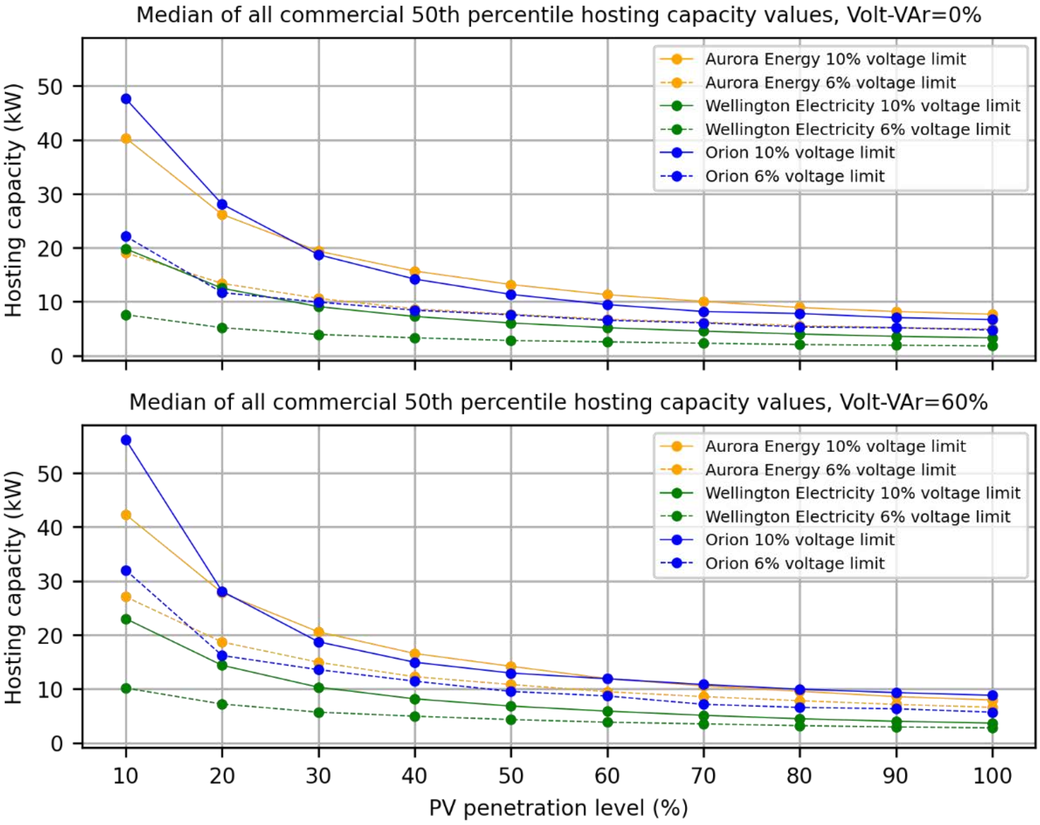


Figure 3: Hosting capacity of commercial ICPs by penetration level at each upper voltage limit, with (top graph) and without (lower graph) Volt-VAr inverter responses. The hosting capacity given is the median of all ICPs, using the 50th percentile hosting capacity value (see Appendix One for a discussion of hosting capacity percentiles).

Table 5: The percentage of Aurora's residential ICPs for which the circuit-level PV hosting capacity is constrained by the transformer (50th percentile, no Volt-VAr).

PV Penetration (%)	**% ICPs with circuit level PV hosting capacity constrained by the transformer**	
	+6%	**+10%**
10	0.6	6.7
20	1.7	19.9
25	2.3	22.0
30	2.6	27.2
40	4.1	32.9
50	6.3	39.5
60	7.2	42.8
70	8.8	47.1
75	9.6	45.9
80	10.7	51.3
90	12.8	55.0
100	16.5	62.0

Source: [full_results-with_analysis.xlsx]tables 19/08/2024 (0)

Figure 4 gives an indication of the distributions of residential ICP hosting capacities at the 50th hosting capacity percentile with an upper voltage limit of +6%. Figure 5 shows the same with an upper voltage of +10%. These only show the hosting capacity of ICPs with a hosting capacity less than or equal to 25kW to limit very high outliers, and thus show a lower median than the previous figures. These show similar distributions in interquartile range between Aurora and Orion, but a lower interquartile range in Wellington Electricity's results, again due to those LV networks being predominantly residential.

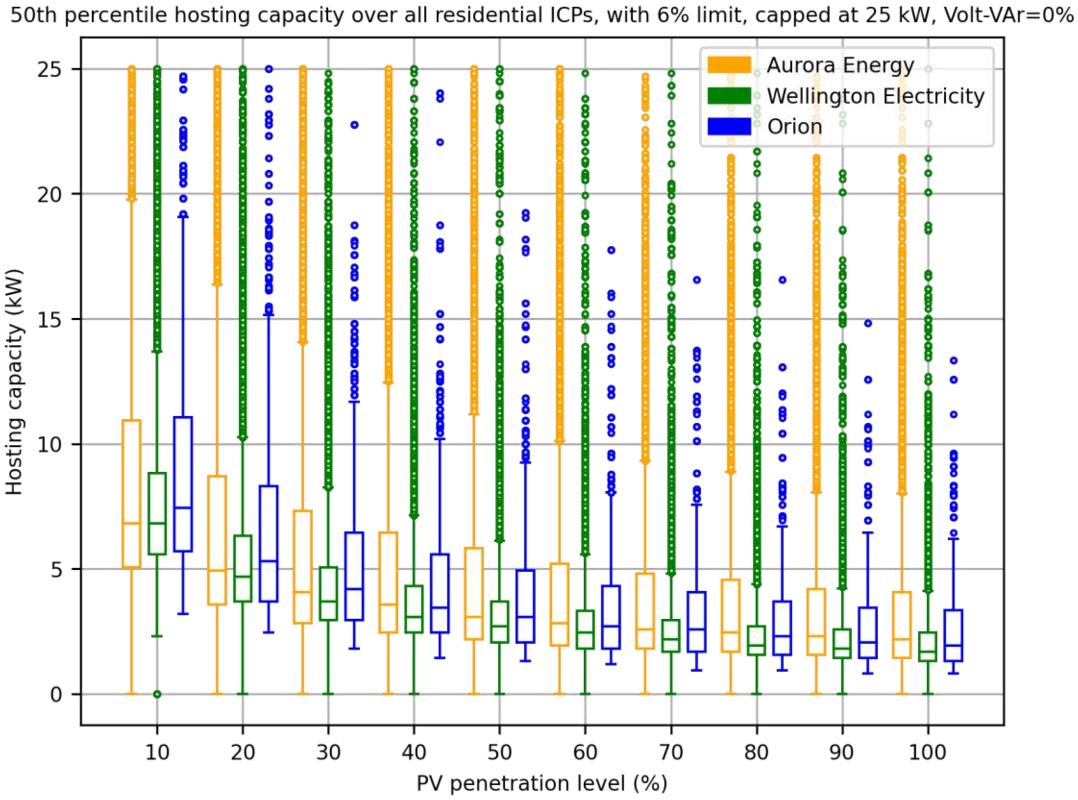


Figure 4: 50th percentile hosting capacity with an upper voltage limit of 6% for residential ICPs. Values have been capped at 25 KW due to some very high outlier hosting capacity values.

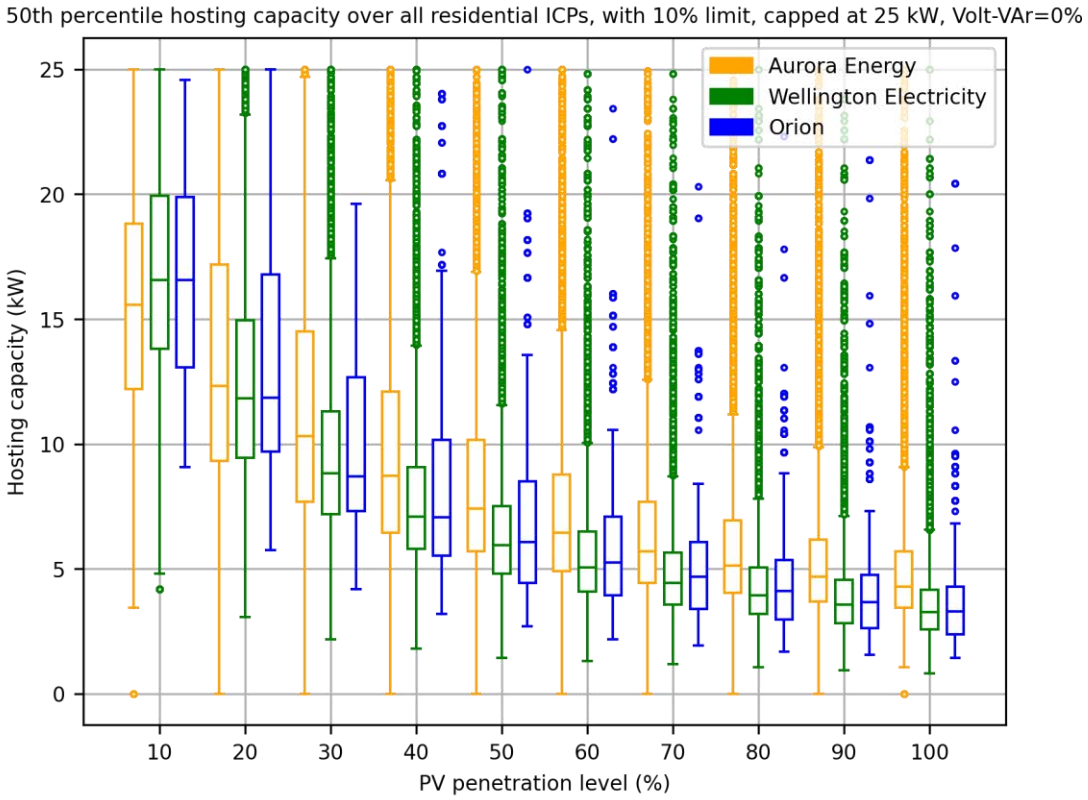


Figure 5: 50th percentile hosting capacity with an upper voltage limit of +10% for residential ICPs. Values have been capped at 25 KW due to some very high outlier hosting capacity values.

The increase in PV hosting capacity (kW) provides scope for additional energy (kWh) exports, discussed in the next section. Furthermore, it has several other implications important for PV system owners with batteries, as well as electricity consumers in general. First, it enables PV systems combined with batteries to export at higher capacity at times when energy or network capacity is scarce, such as during periods of peak demand. While it is unlikely voltage will be particularly high at such times, due to high demand, the hosting capacity may still set a limit on inverter exports due to a universal limit being applied. Despite this, it also enables PV systems with batteries to export at high capacities to provide instantaneous reserves, which could be at any time. Both of these will benefit owners of PV and battery systems through access to more revenue and/or another source of revenue, and will ideally lower the cost of reserves to all consumers.

3.2 Additional energy (kWh) exports

3.2.1 High level national results and selection of the base EDB

The estimated national additional export from increasing the upper voltage limit from +6% to +10% is shown Table 6. The results in Table 6 are for each base EDB against penetration level for 50th percentile hosting capacity results and Volt-VAr response off. They are shown as absolute values – Section 3.2.4 discusses this increase relative to existing export. The base EDB is the EDB whose hosting capacity results would be used for each region, as if their LV networks represent the LV networks within each region.

Table 6: Estimated national additional export (GWh per annum) resulting from increasing the upper voltage limit from +6% to +10% calculated across all ICPs in each Base EDB's network and scaled by the penetration level. Volt-VAr response is off (0%) and the 50th percentile hosting capacity value is used in these tables. (a) residential ICPs; (b) commercial ICPs.

(a) Residential ICPs

PV penetration (% of ICPs)	Additional National PV Export (GWh/year) - residential, P50, 0% Volt-VAr Base EDB		
	Aurora Energy	Wellington Electricity	Orion
10	2	1	0
20	28	12	14
30	106	74	89
40	241	218	239
50	423	439	453
60	655	740	712

Source: [raw_results.xlsx]raw 16/08/2024 (3a)

(b) Commercial ICPs

PV penetration (% of ICPs)	Additional National PV Export (GWh/year) - commercial, P50, 0% Volt-VAr Base EDB		
	Aurora Energy	Wellington Electricity	Orion
10	175	309	173
20	402	556	374
30	614	706	513
40	790	799	672
50	933	858	765
60	1,061	908	863

Source: [raw_results.xlsx]raw 16/08/2024 (3b)

The results in Table 6(a) show that with Aurora Energy as the base EDB, the increase in the upper voltage limit results in higher estimated additional export from residential ICPs at low penetration levels, but that this roughly equalises with both Wellington Electricity and Orion at around 40-50% PV penetration. However, Aurora Energy based estimates of additional export from commercial ICPs (Table 6(b)) are lower than Wellington Electricity based estimates at low PV penetration levels, but similar to Orion based estimates. At higher PV penetration levels Aurora Energy based estimates exceed both Wellington Electricity and Orion based estimates. What is also obvious is that the increase from commercial ICPs is much higher than the increase from residential ICPs.

The Aurora Energy value for residential ICPs (Table 6(a)) is likely higher at lower penetration levels due to small LV networks with very few ICPs that have higher hosting capacity. This represents an urban-rural split, with the LV networks giving rise to Aurora Energy's results representing both urban and rural LV networks. In comparison, the subset of LV networks used in the original Wellington Electricity and Orion studies included very few small LV networks.

The different Aurora Energy value for commercial ICP energy export increase is due to Aurora Energy's more complete representation of commercial ICPs, as shown in Table 1. The greater increase in exported energy from commercial ICPs is largely due to higher commercial PV capacity. However, the increase in estimated energy from commercial ICPs slows as penetration level increases, as shown in Table 7 and Figure 6.

As shown in Figure 3, the increased hosting capacity at +10% upper voltage and at a 10% PV penetration level for commercial ICPs is close to the average commercial PV capacity in most regions. Further, the increased hosting capacity reduces to below the average PV capacity figure at higher PV penetration levels. By contrast, the residential PV hosting capacity at +10% is higher than the average residential PV capacity by a factor of roughly four times at 10% PV penetration, as shown in Figure 2. While the +10% residential hosting capacity does reduce with PV penetration, it remains higher up to about 60% PV penetration. This higher residential hosting capacity provides scope for increased energy exports from residential ICPs at higher PV penetration levels compared to commercial ICPs. It explains the slowing of additional commercial ICP exports at higher PV penetration levels in Figure 6. Essentially the slowing of commercial ICP exports is caused by thermal constraints in conductors and, in particular, transformers reaching constraint sooner with the increased upper voltage limit.

In any case, given the estimates of commercial ICP numbers used to make this assessment, it is considered prudent to assume lower commercial ICP PV uptake than that of residential consumer PV uptake. As shown in Table 6(b), this makes the Aurora Energy based estimates the lowest at PV penetration levels below 30%. Even 20% of commercial ICPs with PV gives rise to about 1.6 GW of installed PV capacity on commercial buildings, as shown in Table 4. Combined with the residential PV penetration of a similar amount gives a total installed capacity of about 3.5 GW.

It is concluded from the above assessment that Aurora Energy's results are the best choice as Base EDB, providing a more balanced representation of both urban and rural ICPs, and of residential and commercial ICPs. Table 7 shows the results for Aurora Energy as the Base EDB for both residential and commercial ICPs.

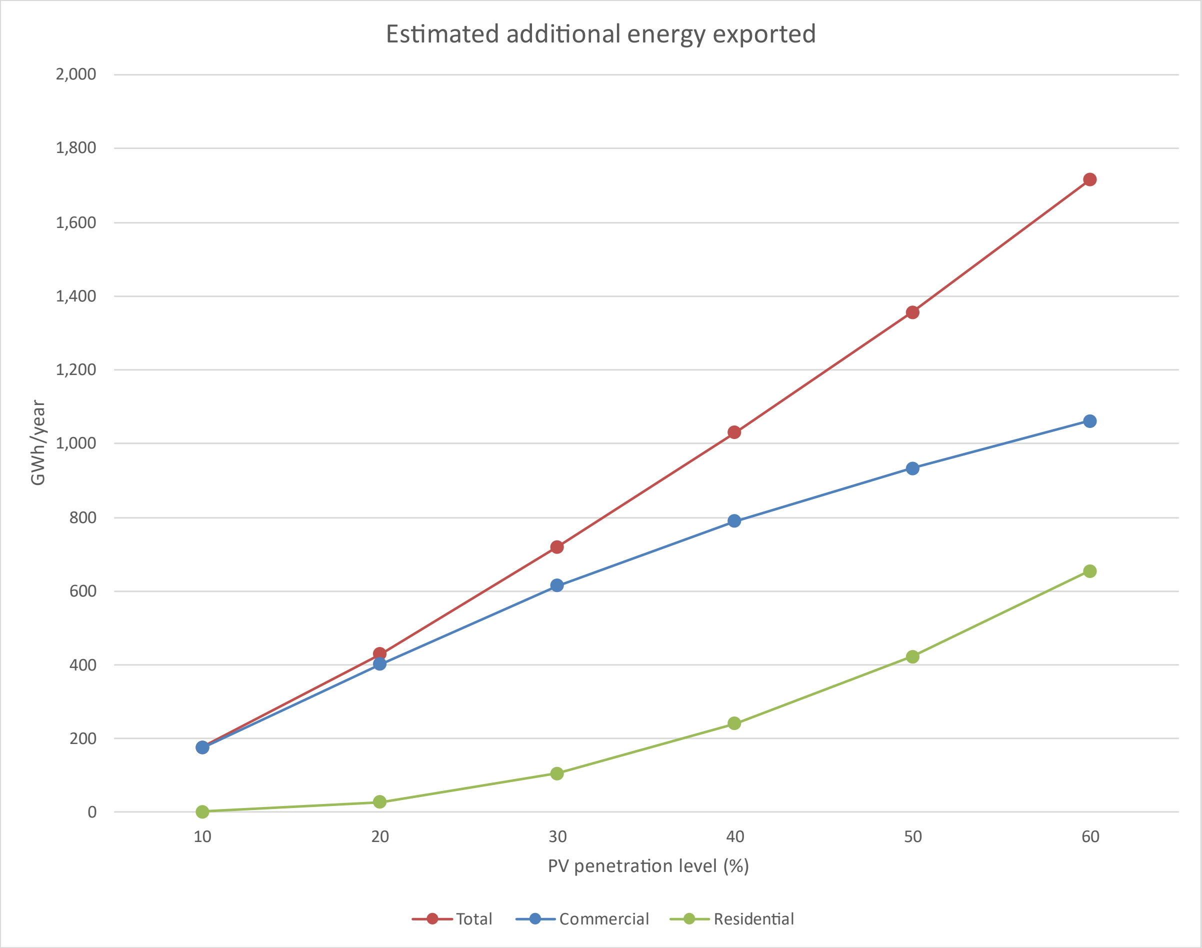


Figure 6: Estimated national additional export (GWh per annum) resulting from increasing the upper voltage limit from +6% to +10% calculated across all ICPs with Aurora Energy as the Base EDB, scaled by the penetration level (graphical representation of Table 7).

Table 7: Estimated national additional export (GWh per annum) resulting from increasing the upper voltage limit from +6% to +10%, calculated across all ICPs with Aurora Energy as the Base EDB, scaled by the penetration level Volt-VAr response is off (0%) and the 50th percentile hosting capacity value is used.

PV penetration (% of ICPs)	Additional National PV Export (GWh/year), Base EDB: Aurora, P50, 0% Volt-VAr ICP type		
	Residential	Commercial	Total
10	2	175	177
20	28	402	430
30	106	614	720
40	241	790	1,031
50	423	933	1,356
60	655	1,061	1,716

Source: [raw_results.xlsx]raw 16/08/2024 (4a)

3.2.2 Sensitivity of the national increase in energy export

Having selected the base EDB and extrapolated the results to the national scale at each penetration level, the effect of hosting capacity percentile is assessed. This provides an indication of the sensitivity of results to location of PV in LV networks and to demand coincident with PV generation, since percentiles represent different configurations of both factors. In general:

- The 25th percentile represents ICPs with PV located further away from the distribution transformer and/or installed on ICPs with lower demand.
- The 75th percentile represents ICPs with PV located closer to the distribution transformer and/or installed on ICPs with higher demand.

On average, across all LV networks, the 50th percentile hosting capacity is chosen to represent an average PV installation and ICP demand configuration. Since this is across many thousands of ICPs and LV networks, it is considered reasonable. However, the percentiles give an indication of results if all PV installations and ICP demand deviate from the median in the same direction across all LV networks. The results at these hosting capacity percentiles are given in Table 8.

Table 8: Assessing hosting capacity percentile effect on estimated national additional export (GWh per annum) resulting from increasing the upper voltage from +6% to +10% (calculated across all ICPs with Aurora Energy as the Base EDB, scaled by the penetration level). Volt-VAr response is off (0%) and the 50th percentile hosting capacity value is used.

(a) Residential ICPs

PV penetration (% of ICPs)	Additional National PV Export (GWh/year) - residential, Base EDB: Aurora, 0% Volt-VAr Hosting capacity percentile		
	25th	50th	75th
10	8	2	0
20	66	28	11
30	194	106	55
40	382	241	147
50	608	423	286
60	871	655	482

Source: [raw_results.xlsx]raw 16/08/2024 (5a)

(b) Commercial ICPs

PV penetration (% of ICPs)	Additional National PV Export (GWh/year) - commercial, Base EDB: Aurora, 0% Volt-VAr Hosting capacity percentile		
	25th	50th	75th
10	214	175	138
20	457	402	339
30	682	614	536
40	861	790	698
50	1,003	933	822
60	1,122	1,061	948

Source: [raw_results.xlsx]raw 16/08/2024 (5b)

(c) All ICPs

PV penetration (% of ICPs)	Base EDB: Aurora, residential & commercial, 0% Volt-VAr (GWh/year) Hosting capacity percentile		
	25th	50th	75th
10	222	177	139
20	523	430	350
30	875	720	591
40	1,242	1,031	845
50	1,611	1,356	1,107
60	1,993	1,716	1,430

Source: [raw_results.xlsx]raw 16/08/2024 (5c)

As shown in Table 8, the lower hosting capacity percentile results in relatively large increases in additional exports at lower PV penetration levels on residential ICPs, but not as large on commercial ICPs. The increase diminishes at higher PV penetration levels in both cases. Initially this seems counterintuitive, since the 25th hosting capacity percentile leads to lower hosting capacity values (as shown in Appendix Three Figure 14 and Figure 16). However, this is in fact the reason for such a large increase: at the +6% upper voltage limit, the 25th percentile hosting capacity is lower than the 50th percentile hosting capacity, giving less scope for exports. At the +10% upper voltage limit, the increase in hosting capacity at the 25th percentile is still substantial, enabling even more export of PV energy.

The 75th percentile hosting capacity results in a decrease in additional exports for the opposite reason – that the +6% upper voltage limit hosting capacity at the 75th percentile is higher, leaving less scope for increase in exports at the +10% upper voltage limit. The decreases relative to the 50th percentile value are not quite as much as the increases at the 25th percentile for residential ICPs.

Commercial ICPs do not increase by as much, because the constraints are dominated by capacity of either conductors or transformers, due to the higher PV capacity and exports. By contrast, residential ICP hosting capacity limits are dominated by voltage, with the location of export occuring on an LV network affecting the voltage rise. Thus the sensitivity of residential ICPs to percentile, which partly represents location, is greater than that of commercial ICPs.

3.2.3 Effect of Volt-VAr and increased upper voltage

Since the Volt-VAr power quality response of PV inverters can be used to control voltage to some extent, the impact of increasing the upper voltage limit in combination with this response is assessed. The results are given in Table 9.

Table 9: Assessing the effect of the Volt-VAr inverter response on estimated national additional export (GWh per annum) resulting from increasing the upper voltage from +6% to +10% (calculated across all ICPs with Aurora Energy as the Base EDB, scaled by the penetration level). The 50th percentile hosting capacity value is used.

(a) Residential ICPs

PV penetration (% of ICPs)	Additional National PV Export (GWh/year) - residential, Base EDB: Aurora, P50, Volt-VAr level:	
	0%	60%
10	2	1
20	28	10
30	106	37
40	241	84
50	423	146
60	655	227

Source: [raw_results.xlsx]raw 16/08/2024 (7a)

(a) Commercial ICPs

PV penetration (% of ICPs)	Additional National PV Export (GWh/year) - commercial, Base EDB: Aurora, P50, Volt-VAr level:	
	0%	60%
10	175	136
20	402	313
30	614	454
40	790	544
50	933	601
60	1,061	631

Source: [raw_results.xlsx]raw 16/08/2024 (7b)

(a) All ICPs

PV penetration (% of ICPs)	Additional National PV Export (GWh/year) - residential & commercial, Base EDB: Aurora, P50, Volt-VAr level:	
	0%	60%
10	177	137
20	430	323
30	720	490
40	1,031	628
50	1,356	747
60	1,716	858

Source: [raw_results.xlsx]raw 16/08/2024 (7c)

As shown, the effectiveness of increasing the upper voltage limit to +10% decreases when Volt-VAr responses are used in conjunction. As shown in Figure 2 for example, the Volt-VAr response provides some additional capacity for export at the +6% upper voltage limit. Thus, this has a similar effect to the 75th percentile hosting capacity – the +6% upper voltage limit hosting capacity with Volt-VAr on is higher, leaving less scope for increase in exports at the +10% upper voltage limit. However, there are two important factors than must also be considered:

- The simulations assume that the PV inverters are operating at their rated power level, and that reactive power (kVAr) absorption by the inverter takes precedence over active power (kW) export. This means that the active power must be reduced as the reactive power absorption increases (up to 20% active power reduction at 60% Volt-VAr), and is part of the reason why Volt-VAr is so effective across all networks, even those with higher resistances/lower X/R ratios. This will change somewhat if the inverters have in-built headroom to allow them to absorb maximum reactive power (VArs) at the same time as they export maximum active power (Watts). However, in this analysis the inverters do not have any headroom, and therefore an increase in PV exports will not occur to the extent suggested in Table 9.
- Moreover, the selection of Volt-VAr parameters should change as an inverter is oversized (higher than the EDB set export limit). This is because it calls into question whether the EDB set export limit or the higher inverter rating should be used in setting the Volt-VAr parameters. If the latter, even larger amounts of reactive power will be absorbed, exacerbating the next point.
- If many inverters are absorbing reactive power to control voltage at midday when PV generation is at a maximum on a sunny day, large amounts of reactive power may flow in LV networks and ultimately in distribution, sub-transmission and transmission networks. For example, if 50% of 5 kVA inverters are controlling at their maximum at a 60% PV penetration level over 130,000 consumers (such as in Wellington), a combined 117 MVAr of reactive power will result, compared to an estimated summer midday load of 100 MW. The increase in reactive power flow will lead to additional losses at the very least.

In summary, increasing the upper voltage limit is preferable because it will avoid the Volt-VAr response and therefore allow more kWh export. Furthermore, it will avoid large amounts of reactive power flow and associated losses from the Volt-VAr inverter operation. Therefore, results reported are without the Volt-VAr response.

3.2.4 Increases relative to existing exports

Table 10 assesses the increase in PV export afforded by increasing the upper voltage limit to +10% from +6%. As shown, the increase for residential ICPs is small at lower PV penetration levels, in part because of the relatively low PV penetration, but largely because the absolute increase at lower PV penetration levels is small. However, as PV penetration increases, the relative increase in export becomes more significant. For commercial ICPs, the increase is significant at all penetration levels, although the rate of increase declines at higher PV penetration levels. As discussed in Section 3.2.1 this is due to more thermal transformer constraints than voltage constraints at higher PV penetration levels. As also discussed in Section 3.2.1, such high commercial PV penetration levels are likely unrealistic, with 20% or below being a prudent maximum. At this level the increases are significant at around 24%.

Table 10: Increase in PV production relative to PV production capped at the +6% upper voltage hosting capacity limit.

(a) Residential ICPs

PV penetration (% of ICPs)	Additional National PV Export (GWh/year) - residential, Base EDB: Aurora, P50, 0% Volt-VAr		
	Capped at +6% limit	Additional export from the +10% increase	Proportion increase
10	1,188	2	0%
20	2,352	28	1%
30	3,464	106	3%
40	4,519	241	5%
50	5,527	423	8%
60	6,485	655	10%

Source: [raw_results.xlsx]raw 16/08/2024 (8a)

(b) Commercial ICPs

PV penetration (% of ICPs)	Additional National PV Export (GWh/year) - commercial, Base EDB: Aurora, P50, 0% Volt-VAr		
	Capped at +6% limit	Additional export from the +10% increase	Proportion increase
10	849	175	21%
20	1,646	402	24%
30	2,457	614	25%
40	3,306	790	24%
50	4,186	933	22%
60	5,082	1,061	21%

Source: [raw_results.xlsx]raw 16/08/2024 (8b)

3.2.5 Increases by time of year and region

Table 11 and Table 12 give the estimated increase in PV exports by region and time of year for 20% commercial ICP PV penetration and 30% and 50% residential PV penetration respectively. As expected, the energy increase varies by area, although the increase from PV energy varies by a different ratio due to matching of solar generation to each region as close as possible (i.e. regions with better solar resource increase in greater proportion). The tables show several items of interest:

1. The summer (January) contribution is higher, by a factor of about four to five times compared to winter (June). This is due to the combination of higher ICP load and lower solar resource in winter compared to summer. Figure 1 helps explain this difference. Even at the high penetration level in Table 12, the estimated increase in winter generation over the whole month of June contributes roughly 20% of daily electricity demand.
2. With 20% commercial PV uptake (1.6 GW from Table 4) and 30% residential PV uptake (2.8 GW from Table 4) the combined increase in annual generation is about 507 GWh, lifting PV's contribution from 11.6% of annual national generation to 12.8%.[1]
3. With 20% commercial PV uptake and 50% residential PV uptake (4.7 GW from Table 4) the combined increase in annual generation is about 825 GWh, lifting PV's contribution from 16.3% of annual generation to 18.2%.

---

[1] Using annual generation of 44,000 GWh from the June 2023 quarter to March 2024 quarter (from MBIE's Electricity Statistics).

Table 11: Increase in PV exports (GWh) by month with 30% residential PV penetration and 20% commercial PV penetration.

	Additional National PV Export (GWh/year), Base EDB: Aurora, residential (30% PV penetration) & commercial (20% PV penetration), P50, 0% Volt-VAr Month											
Region	January	February	March	April	May	June	July	August	Setpember	October	November	December	Total
Northland Region	2	2	2	1	1	0	1	1	1	2	2	2	16
Auckland Region	22	17	17	11	8	6	7	10	13	17	19	22	169
Waikato Region	7	5	5	3	2	2	2	3	4	5	6	6	49
Bay of Plenty Region	4	3	3	2	1	1	1	2	2	3	4	4	31
Gisborne Region	0	0	0	0	0	0	0	0	0	0	0	0	2
Hawke's Bay Region	2	2	1	1	1	0	0	1	1	2	2	2	15
Taranaki Region	2	1	1	1	0	0	0	1	1	1	2	2	12
Manawatu-Wanganui Region	4	3	3	2	1	1	1	1	2	3	3	4	27
Wellington Region	9	7	6	4	3	2	2	3	5	7	7	8	63
Tasman Region	1	1	1	0	0	0	0	0	0	1	1	1	6
Nelson Region	1	1	1	0	0	0	0	0	0	1	1	1	6
Marlborough Region	1	0	0	0	0	0	0	0	0	0	1	1	4
West Coast Region	0	0	0	0	0	0	0	0	0	0	0	0	2
Canterbury Region	10	8	7	4	3	2	2	4	6	8	9	10	74
Otago Region	3	3	2	1	1	1	1	1	2	3	3	3	24
Southland Region	1	1	1	0	0	0	0	0	1	1	1	1	8
Total	70	55	48	32	22	15	18	27	39	53	61	66	508

Source: [raw_results.xlsx]raw 16/08/2024 (9c)

Table 12: Increase in PV exports (GWh) by month with 50% residential PV penetration and 20% commercial PV penetration.

	Additional National PV Export (GWh/year), Base EDB: Aurora, residential (50% PV penetration) & commercial (20% PV penetration), P50, 0% Volt-VAr Month												
Region	January	February	March	April	May	June	July	August	Setpember	October	November	December	Total
Northland Region	4	3	3	1	1	1	1	1	2	3	3	4	28
Auckland Region	36	27	25	16	11	7	9	14	20	26	30	35	256
Waikato Region	12	8	8	5	3	2	3	4	6	8	10	10	78
Bay of Plenty Region	8	6	5	4	2	2	2	3	4	6	7	7	56
Gisborne Region	1	1	0	0	0	0	0	0	0	1	1	1	5
Hawke's Bay Region	4	3	2	2	1	1	1	1	2	3	4	4	28
Taranaki Region	3	3	2	1	1	0	0	1	2	2	3	3	21
Manawatu-Wanganui Region	7	5	4	3	1	1	1	2	3	5	6	6	44
Wellington Region	14	11	9	5	3	2	2	4	6	10	12	13	92
Tasman Region	2	2	1	1	0	0	0	1	1	1	2	2	12
Nelson Region	2	1	1	1	0	0	0	0	1	1	1	1	10
Marlborough Region	1	1	1	1	0	0	0	0	1	1	1	1	8
West Coast Region	1	1	0	0	0	0	0	0	0	1	1	1	6
Canterbury Region	17	14	10	7	4	3	3	6	9	14	16	16	119
Otago Region	6	5	4	2	1	1	1	2	3	5	6	6	42
Southland Region	3	2	1	1	0	0	0	1	1	2	2	2	17
Total	121	93	79	49	31	20	25	40	62	89	103	113	825

Source: [full_results-with_analysis.xlsx]tables 16/08/2024 (9c)

3.2.6 Increased PV generation from behavioural changes

While this study is a technical analysis of the additional PV export enabled by hosting capacity increase from raising the upper voltage limit, it is possible that behavioural changes may also occur. For example, consumers may install larger PV systems, knowing that they can export more, or as pointed out earlier, they may install the same size inverters as the historical average, but with more PV panels. This is complex to predict, with other factors such as capital cost, buyback rate and housing suitability (roof space) contributing to the decision. Nevertheless, to gain some idea of the additional PV energy production if such a change was to occur, this section investigates an average increase in residential PV capacity. Only residential PV capacity is assessed, since commercial PV capacity is already large. A 25% increase in residential PV capacity is investigated (the roughly 4 KW average installations increase to 5 kW), with results summarised in Table 13.

This shows that even with the hosting capacity remaining at the +6% voltage limit there is some increase in PV production (Column 3). This will be from broadening the shoulders of the PV generation curve below the +6% limit hosting capacity – imagine the bounds of the blue and green hashed areas in Figure 1 moving further to the left and right. It also shows that there is an increase in exported energy at the new hosting capacity with the +10% voltage limit (Column 5), and that this increase is roughly twice the exported energy of the original PV capacity and +10% limit. In other words, with the +10% voltage limit and resulting hosting capacity increase, a 25% increase in PV capacity results in a 50% increase in exported energy at penetration levels above 30%, and an even greater increase at lower penetration levels. In these results the 'backstop' EDB export limit of 5 kW is maintained. Increasing this to 10 kW made no difference to the results. This is not surprising, as the export from the increased installed PV capacity, after netting off household load, will not reach this 5 kW export limit. However, this situation would change if even larger PV systems were installed.

This study has assumed an inverter loading ratio of 1.0. If the inverter loading ratio of PV systems increased at their existing inverter capacity, or both with an increased inverter capacity and inverter loading ratio, the increase in PV exports would be even higher than indicated in Table 13 and later results. This is due to 'squaring off' of the solar generation profile and more generation closer to the inverter capacity. Referring to Figure 1 again, this would lead to an increase in the yellow hashed area.

Table 13: Increased PV energy production (Column 3) and PV exports (Column 5) from increasing the average installed PV capacity by 25% (roughly 4 kW to 5 kW).

PV Penetration (%)	Additional National PV Export (GWh/year) - residential, Base EDB: Aurora, P50, 0% Volt-VAr, 5 kW export limit				
	Energy from PV, with export capped at the +6% voltage limit hosting capacity		Additional exported energy from the higher hosting capacity resulting from an increase in voltage limit to +10%		Total increase from a 25% increase in PV capacity and the upper voltage increasing to +10%
	Original PV capacity	Original PV capacity increased by 25%	Original PV capacity	Original PV capacity increased by 25%	
10	1,188	1,473	2	9	293
20	2,352	2,880	28	83	610
30	3,464	4,182	106	262	980
40	4,519	5,398	241	527	1,406
50	5,527	6,559	423	848	1,880
60	6,485	7,662	655	1,226	2,403

Finally, the increase in residential exports as a proportion of PV production capped by the hosting capacity at the +6% voltage limit are shown in Table 14. This is the same as Table 10(a) but for residential PV capacity 25% higher. This shows an increase of 13% in PV generation (PV penetration of 50%) resulting from both the increase in hosting capacity due to an increased upper voltage of +10% and an increase in PV capacity resulting from this.

Table 14: Increase in PV production relative to PV production capped at the +6% upper voltage hosting capacity limit resulting from both the upper voltage limit increase to +10% and residential consumers installing larger PV systems.

PV penetration (% of ICPs)	Additional National PV Export (GWh/year) - residential +25%, Base EDB: Aurora, P50, 0% Volt-VAr		
	Capped at +6% limit	Additional export from the +10% increase	Proportion increase
10	1,473	9	1%
20	2,880	83	3%
30	4,182	262	6%
40	5,398	527	10%
50	6,559	848	13%
60	7,662	1,226	16%

Source: [full_results-with_analysis.xlsx]tables 16/08/2024 (8a)

4 Conclusions, Discussion, and Recommendations

From this study the following conclusions are made:

1. Raising the upper voltage limit from +6% to +10% increases the PV hosting capacity (kW) of LV electricity networks by a factor of about three times for residential consumers and about two times for commercial consumers at 10% PV penetration. This increase diminishes as penetration level increases, particularly for commercial ICPs, due to the nature of constraints moving from voltage constraints to thermal constraints on transformers.

2. Raising the upper voltage limit from +6% to +10% allows PV exports (kWh) to increase for both residential and commercial consumers, especially residential consumers. The exports increase rapidly with PV penetration level for residential ICPs, starting out modestly at 10% PV penetration, and rising to quite high increases at 50% PV penetration (giving an 8% increase in PV production per residential ICP on average at 50% PV uptake and a 24% increase in PV production per commercial ICP on average at 20% PV uptake).

3. Despite the increase in energy exports being modest at low penetration levels, the additional PV hosting capacity (kW) provides several additional benefits when PV systems are paired with battery storage systems:

    a. It enables PV systems with batteries to export at higher capacity at times when energy or network capacity is scarce, such as during peak demand. This could help alleviate additional network voltage and loading constraints, as well provide further benefit to battery system owners ('value stacking'). However, there is a question over what impact this may have on voltage levels and overvoltage constraints at these times, and how battery exports should best be managed and controlled.

    b. It enables PV systems with batteries to export at high capacities to provide instantaneous reserves. This will again benefit owners of such systems through access to another source of revenue, and will lower the cost of reserves to all consumers.

4. Raising the upper voltage limit will provide the benefits outlined above, as well as avoid network expenditure to upgrade conductors to relieve voltage constraints. Over the many thousands of LV networks in New Zealand, this could amount to a substantial avoided investment. Such avoided investments can be assessed with ANSA's constraint risk and LV Capex Model, together with other demand changes such as EV uptake and gas-to-electricity transition. Since constraints arising from EV and gas-to-electricity can be driven by winter demand, they may be required ahead of the PV driven investments. This highlights the importance of considering all changes in network use together.

5. For both hosting capacity (kW) and export increase (kWh), there was good agreement between the results of three of ANSA's clients for the LV networks assessed, considering the different ICP types assessed. This supports the selection of a preferred set of LV networks and extrapolating those to a national estimate.

6. Estimated PV export increase varies by time of year, with the greatest increase in exports occurring in the summer. There is some increase in the winter, but this is limited due to higher daytime household demand and lower overall PV generation in the winter.

7. There is some increase in exported energy over a year, roughly equal to:

    a. About 24% for commercial ICPs with 20% PV uptake and 3% for residential ICPs with 30% PV uptake. The combined increase in annual generation is about 507 GWh, lifting rooftop PV’s contribution from 11.6% of annual national generation to about 12.8%.
    b. At 50% residential PV uptake and the same 20% commercial PV uptake as above, the increase is about 8% for residential ICPs. The combined increase in annual generation is about 825 GWh, which lifts rooftop PV’s contribution from 16.3 % of annual generation to about 18.2% of annual generation.

   While these numbers are relatively small increases, especially at the lower PV penetration levels, the increases will benefit those with PV. There is a further benefit in terms of lower capital expenditure required by EDBs to release this additional PV energy. This in turn will benefit all consumers through more available renewable energy lowering energy prices and avoiding the need to fund the capital expenditure through higher charges to consumers. The primary capital expenditure avoided is conductor upgrades to relieve voltage constraints. Use of reactive power generation equipment such as advanced inverter controls to regulate voltage is questionable at high PV penetration levels, as it will give rise to large reactive power flows, higher losses, and potentially overload equipment thermal ratings sooner.

8. If a behavioural change in PV installation was to occur in conjunction with the lifting of the upper voltage limit to +10%, combined with EDBs increasing the allowable PV capacity on residential installations, the additional energy produced by residential rooftop PV could be in the order of 293 GWh at 10% PV penetration (0.7% of New Zealand’s current annual electricity generation) and 1,406 GWh at 40% PV penetration (3.2% of New Zealand’s current annual electricity generation). This assumes that, on average, the capacity of residential PV installations increases by 25%.
9. As PV penetration level increases further, beyond about 60% for residential ICPs (Figure 2) and 50% for commercial ICPs (Figure 3) the increase in the upper voltage limit to +10% diminishes in effectiveness as transformers become the constraining element in LV networks (Table 5). EDBs will then face the decision of whether to upgrade transformers to allow more PV export. Finding local uses for the locally produced PV energy should provide a more cost-effective option for all consumers. For example, load could be managed by shifting storage hot water heating and EV charging demand to coincide with periods of high PV generation.
10. Following a rise in the upper voltage limit to +10%, EDBs may change transformer tap settings to boost LV voltages even higher than they are now to allow for more voltage fall at times of high demand, such as evening peaks with coincident EV charging. This will diminish the benefits of additional PV generation reported herein. Moreover, such a tap setting change may be avoided by also lowering the lower voltage limit to -10% from -6%. However, as explained, the effectiveness of this in supplying larger loads will be limited due to constraints being dominated by transformer thermal constraints rather than voltage reducing below the -6% limit.

From this investigation the following recommendations are made:

1. Increasing the upper voltage limit from +6% to +10% allows consumers to continue to install PV without constraining voltages in LV networks.

2. Prior to proceeding with the upper voltage increase, there are other aspects not addressed in this study that should be investigated. One is investigating the impact on other equipment connected to LV networks.
3. If proceeding with increasing the upper voltage limit from +6% to +10%, an analysis of the avoided capital expenditure should be undertaken, as this is likely to be high given how many voltage constraints there are at +6%.

5 Appendix One – Background on Low Voltage Networks and PV

5.1 Low voltage electricity networks that directly supply consumers

Figure 7 illustrates an overhead low voltage (LV) distribution network – the type that supplies the majority of electricity consumer premises. Almost all LV networks are three-phase four-wire networks, with three-phase conductors, and a fourth neutral conductor.[2] The network shown is overhead, but many are underground (with cables carrying the four conductors, or four separate cables), or are a combination of overhead and underground. Some LV networks contain multiple circuits from the distribution transformer, and some of those circuits branch multiple times, as illustrated in Figure 8.

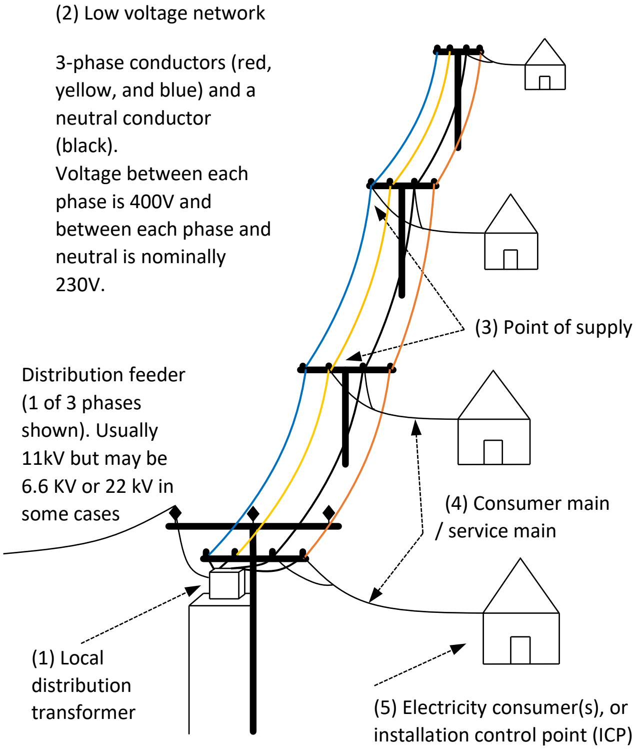


Figure 7: Illustration of an overhead low voltage network with the medium voltage distribution feeder supplying it. Most consumers are supplied from low voltage networks, which may be overhead, underground cables, or a combination of overhead and underground.

---

[2] The reason for three phases dates back to Nikola Tesla's invention of alternating current (AC) generators, AC electricity reticulation, and the induction motor in the 1800s. The three phases electrically represent the mechanical rotating alternators used to generate electricity, and have historically been necessary for the functioning of induction motors. Induction motors are ubiquitous in modern industry, used in such applications as water pumping and irrigation, cement production, wood processing, conveyor systems, air movement and extraction, heat pumps and air conditioners, and relatively recently in Tesla Motors' electric vehicles. The advent of modern power-electronics is replacing the direct connection of three-phase to induction motors, but three-phase supply is generally still required for high power users because it has the ability to deliver more power.

(a) An LV network with multiple circuits coloured.

(b) The same LV network, with its extent coloured (orange).

(c) The same LV network with conductor types coloured.

Figure 8: An illustration of LV networks, with the distribution transformer of one particular LV network shown (the triangle left of centre) as well as service mains to ICPs: (a) multiple circuits from the distribution transformers, (b) the extent of each LV network coloured, and (c) the types of conductor coloured (orange is overhead/lines, blue is underground/cables), with ICPs shown as red dots. Source of images: ANSA's LV Visibility Dashboard, using Aurora Energy's LV network data.

Figure 8 shows LV networks that supply residential consumers in a relatively dense urban area, with a few commercial consumers as well. The number of consumers connected to LV networks can vary considerably, especially between urban and rural networks. Figure 9 illustrates this for two different Electricity Distribution Businesses (EDBs) distribution networks. Rural LV networks are commonly a single pole-mounted transformer supplying one or two ICPs, whereas urban LV networks can supply hundreds of ICPs.

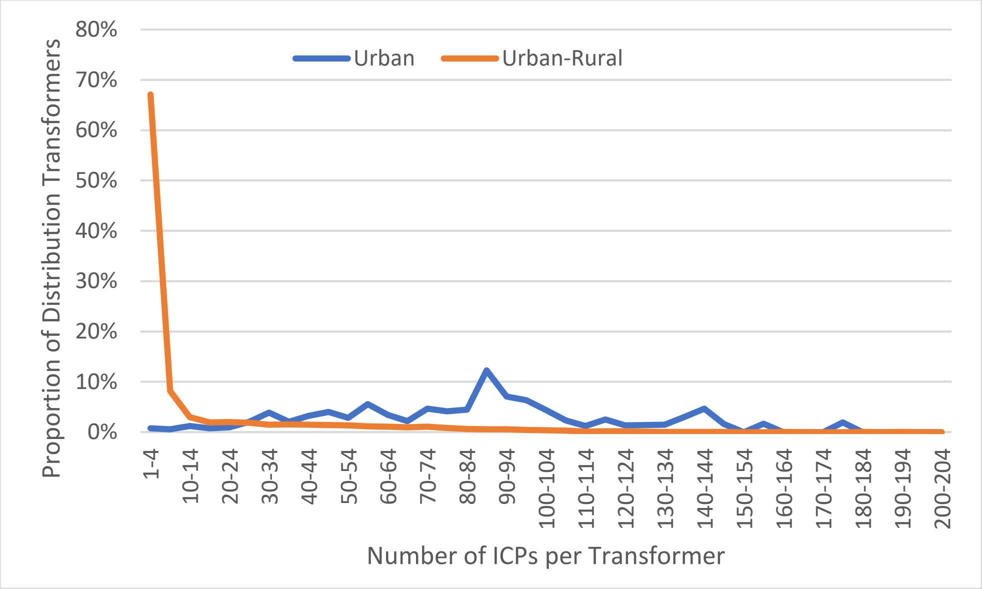


Figure 9: ICPs per distribution transformer, illustrating the difference between urban and urban-rural LV networks.

5.2 Voltage on LV networks

The voltage along an electrical conductor, such as those in an electricity distribution network, decreases in the direction of net power flow, as shown in Figure 10. In traditional networks, power flow is always away from the transformer towards the last house on the network. This is changing due to the introduction of PV and potentially battery storage. The presence of both EVs and PV create even more challenges for EDBs in achieving balance of consumers on the network. That is because some consumers may generate during the day (with PV), while others may consume more during the night (with EVs). New technologies, such as 'smart' EV chargers, newer PV inverters with advanced power quality controls, potentially 'smart' distribution transformers, and ultimately storage batteries may alleviate some of these issues and increase network hosting capacity for both EV and PVs by managing local network peaks and balancing load on the network.

The rate at which voltage reduces with distance along the conductors from the distribution transformer depends on how large the power flow is and the size of the conductors. A small diameter conductor (having a high resistance, or impedance, to electrical current flow) experiences a higher voltage drop. By contrast, a larger diameter conductor (having lower impedance to current flow) experiences a lower voltage drop. Older overhead networks often have smaller conductors, whereas newer underground cable networks may have larger conductors. The voltage drop is generally proportional to the power flow – the higher the power flow the greater the voltage drop. Complicating voltage on each of the three phases of an LV network is balance of loading. Imbalanced loading can lead to current flow in the neutral conductor, giving rise to particularly high voltages on some phases. In some LV networks, the neutral conductor has a lower rating than the phase conductors, which exacerbates voltage imbalance. PV on some phases may give rise to substantial imbalance during times when PV is exporting.

Figure 10 shows how voltage might decrease with distance from the local supply transformer. When lightly loaded (such as in the early hours of the morning), the voltage only falls a small amount, as shown by the top voltage profile (blue line). When heavily loaded (such as during a winter evening peak), voltage falls a lot more, as shown in the bottom voltage profile (green line).

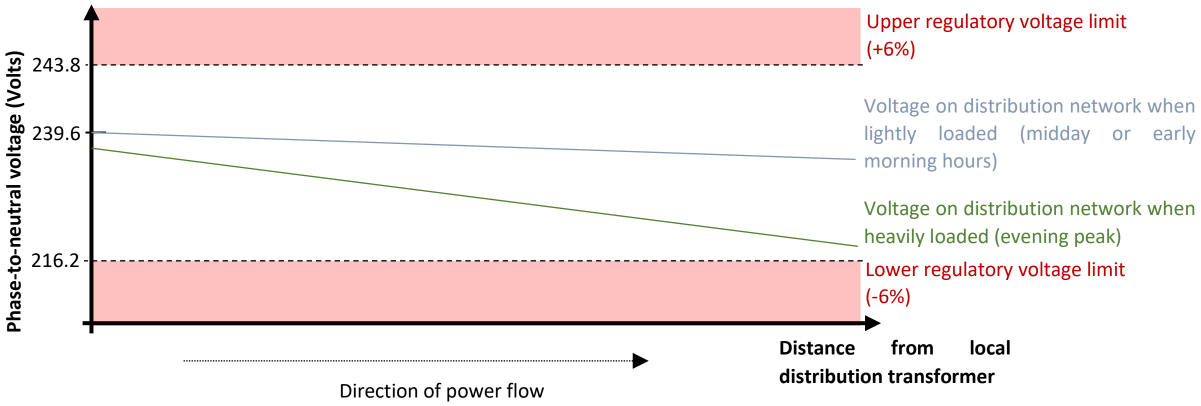


Figure 10: Single-phase voltage profile on a low voltage electricity distribution network under traditional consumer load.

Distribution networks have traditionally been designed to boost the voltage at the start of the low voltage lines. This is achieved using the 11 kV/400 V local distribution transformer by manually adjusting its tap setting to boost the voltage on the secondary 400 V side. As shown in Figure 10, the voltage is boosted to 415 V phase-to-phase (239.6 V balanced phase-to-neutral), which is standard practice on most New Zealand distribution networks and is known as a ‘boost’ tap on the secondary. This ensures that the voltage at the beginning of the low voltage line is high, but not so high as to exceed the regulatory limit (239.6 V phase-to-neutral is 4.17% above the nominal 230 V, but below the 6% upper regulatory limit). This boosting of voltage primarily ensures that when heavily loaded the voltage can fall by more than 6% along the network’s length without going below the lower regulatory limit. It also deals with voltage drop across the medium voltage 11 kV distribution network. Secondary ‘boost’ taps, and this method of voltage management, is a widespread practice; so widespread that distribution transformers are usually supplied by manufacturers in New Zealand with the secondary tap set to boost to 415 V (239.6 V phase-to-neutral) as shown in Figure 10.

5.3 The effect of PV on voltage

With regard to PV and EVs, the effect they can have on voltage profiles are the exact opposite of one another. In the case of PV, the effects are particularly pronounced because of the traditional design of distribution networks based on boosting voltage at the start of the low voltage network, as discussed earlier. This is illustrated in Figure 11, where the penetration of PV is sufficient that when irradiance conditions are high enough, and load of each consumer low enough, power flow reverses. This causes some rise in voltage at or near the end of the network (the blue line). As PV uptake increases, power flow reverses even more, and voltage rises even more at the end of the network, to the point where it reaches the upper voltage limit. Because of the boost design of the transformer, there is less margin between the starting voltage and the upper limit. Thus, PV tends to constrain at quite low uptake levels, and tends to constrain on voltage before overloading the distribution transformer or network conductors.

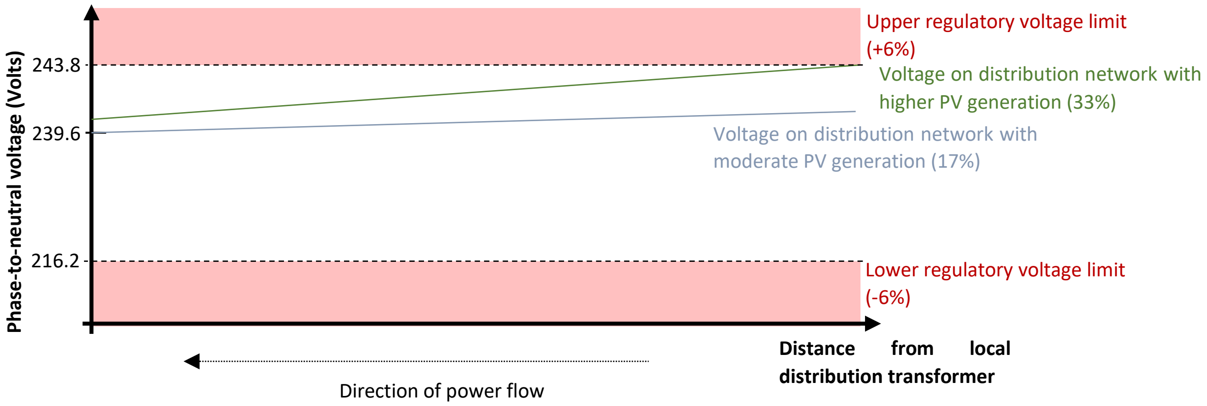


Figure 11: Single-phase voltage profile on a low voltage electricity distribution network resulting from reversal of power flow, as occurs when load is low and PV generation is high, such as around midday.

In the example shown in Figure 11 the PV is distributed evenly across the length of the network, and evenly between the three phases of the network – the ideal case, but difficult to achieve in practice. Voltage rise can be pronounced on some phases when PV is predominantly installed on one particular phase of a network, leading to imbalance. Voltage rise would also be far worse if all the PV was installed by consumers towards the end of the network, but better if all PV was installed by the consumers closest to the distribution transformer. Figure 12 gives an example for the same LV networks of where constraints are likely to occur due to PV generation.

The exact voltage profile is highly dependent on:

- where the PV is installed along the network and on which phases of the network;
- balance of PV and load across phases;
- PV generation level;
- the load of each consumer coincident with maximum PV generation;
- type of network (overhead or underground);
- branching nature of the network; and
- the type of conductors used in the network (large or small conductors).

Hence when studying the possible effects of PV it is necessary to know the network details, and to model a range of different scenarios of PV and load distribution on the network. Given the large number of variables, probabilistic modelling is used. This commonly takes the form of Monte Carlo simulation, in which PV is randomly assigned to each consumer for each scenario. While PV can congest networks, advanced controls in PV inverters can be used to improve network hosting capacity for PV. ANSA's hosting capacity models accommodate all the information outlined above, and model advanced inverter controls (Volt-VAr responses) in conjunction with consumer mains to understand how they might mitigate voltage congestion.

Undertaking network hosting capacity studies requires certain information about low voltage networks, which is derived from the list above. The probabilistic nature of the studies results in a probability density function of hosting capacity, with an example output shown in Figure 13.

(a) Constraint map with 230 V + 6% upper voltage limit. *(b) Constraint map with 230 V + 10% upper voltage limit.*

Figure 12: Constraint maps showing constraints in the LV network arising from generation (PV export) from ICPs: (a) with the 6% upper voltage limit, showing voltage constraints near the outer extent of the LV network (indicated by the red colour on the outside of the conductors – the inner colour represents conductor loading); (b) with the +10% upper voltage limit, showing reduced voltage constraints on the LV network. Source of images: ANSA's LV Visibility Dashboard, using Aurora Energy's LV network data.

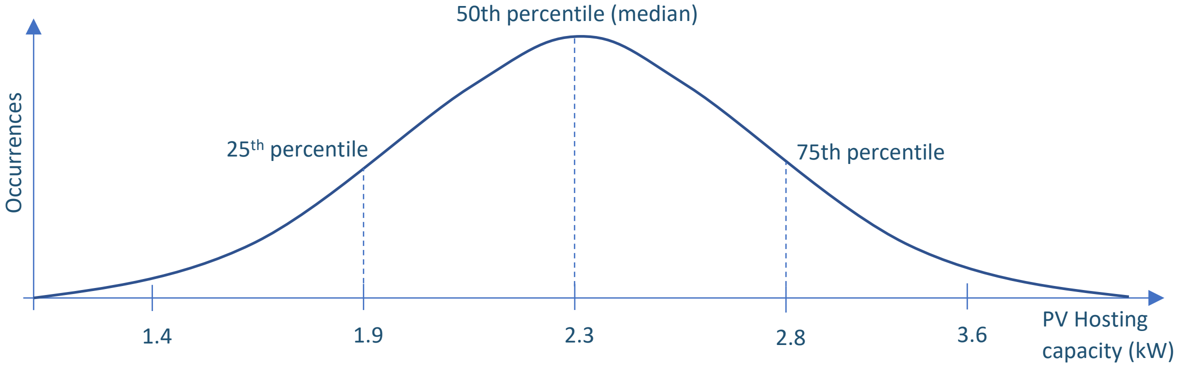


Figure 13: An example output of PV hosting capacity on a given circuit, for a given PV penetration level and Volt-VAr level. The normal distribution shape is representative – the hosting capacity on any given circuit may not follow this shape.

6 Appendix Two – Process/logic applied to assess additional energy exported for each ICP

The full process and logic applied in assessing the additional energy exported for each ICP is set out below. Figure 1 may be useful in understanding this logic.

1. If the ICP has PV already, use the capacity of the ICP's installed PV, otherwise use the average installed solar capacity for either residential or commercial ICPs for the EDB's region from 2023 and 2024 to June (data obtained from the Electricity Authority's EMI dataset). As a proxy for residential ICPs, PV installations less than or equal to 10 kW were used to determine the average residential PV capacity by region. For commercial ICPs, SMEs were used to determine the average commercial PV capacity by region. Table 3 gives the average PV installation capacities by ICP.
2. Using the PV capacity and a typical meteorological year (TMY) of hourly normalised solar generation data for the relevant region (both set out in Table 3), scale the TMY solar generation data by the PV capacity to give region specific solar generation.
3. Determine the ICP's daytime load, obtained from the distributions used to determine hosting capacity, and scale ICP daytime load by the seasonal demand ratio.[3]
4. Determine solar minus load.
5. If the hosting capacity value at 6% upper voltage exceeds the export limit, do not proceed to calculate any additional export, since any export will be capped at the export limit (see Figure 1 for these quantities).
6. Cap the hosting capacity at +10% upper voltage at the export limit, since the export limit sets a firm export limit.
7. Cap solar minus load at the capped +10% upper voltage hosting capacity, since it is not possible to export more than this amount. This is the upper horizontal limit on the yellow hashed area in Figure 1(a).
8. Find all solar minus load that exceeds the 6% upper voltage hosting capacity value and, from above, is below the capped +10% upper voltage hosting capacity value. This gives the hashed yellow area in Figure 1(a) and (b).
9. Sum all hourly values of the yellow hashed area and record them by month to give the total delta export over all ICPs for a given type (residential or commercial).
10. After determining monthly total delta export over all ICPs, scale the monthly total by the penetration level. This approach was taken, rather than selecting a sample of ICPs based on the uptake level, to include all ICPs in the analysis, as selecting a sample may not represent all ICPs.
11. Scale the base EDB's monthly total delta export scaled by penetration level by a regional city scaling factor, equal to the building count for the region divided by the number of ICPs in the base EDB's dataset. For residential ICPs the building count is the number of dwellings by region, obtained from the 2023 Census (see Table 3). The number of dwellings was used rather than the total number of ICPs to avoid including small ICPs such as street-lighting, communications cabinets, pumping stations, etc. in the data since we are only interested in residential houses. For commercial ICPs no information was available on the number of commercial buildings by region or city. Hence the ratio of commercial ICPs to residential ICPs

---

[3] Seasonal demand ratio is the ratio of average midday demand in a month to the average midday demand in the minimum demand month for which hosting capacity was determined. The hosting capacity and ratio were determined using load profiles provided for the hosting capacity study for the selected base EDB.

was calculated for Aurora Energy's data set and applied to all cities/regions. Aurora Energy's data set was used, since this provided the largest sample of ICPs that covered all consumer types (it was not selected to focus on one consumer type). The ratio calculated and applied is commercial building = 10% of residential dwellings. Table 3 gives the values used.

7 Appendix Three – hosting capacity changes at different hosting capacity percentiles

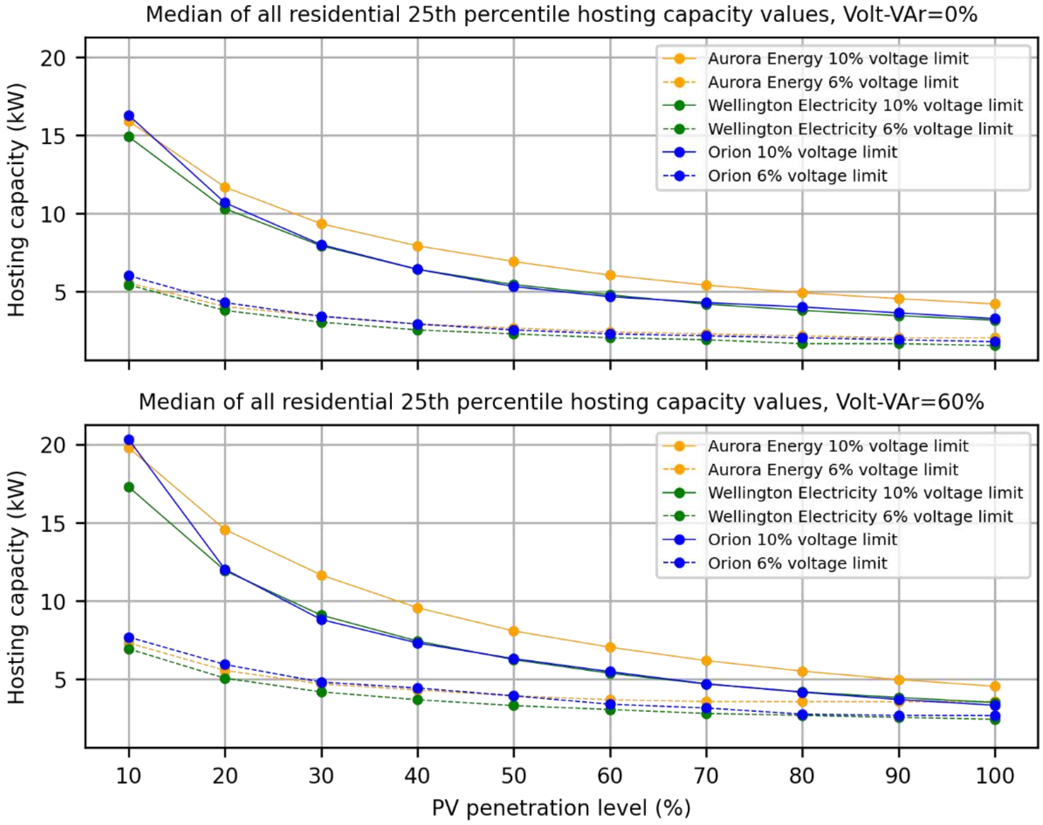


Figure 14: Median of the 25th percentile hosting capacity values for residential ICPs, showing hosting capacity values roughly 25% lower than the 50th percentile hosting capacity values in Figure 2.

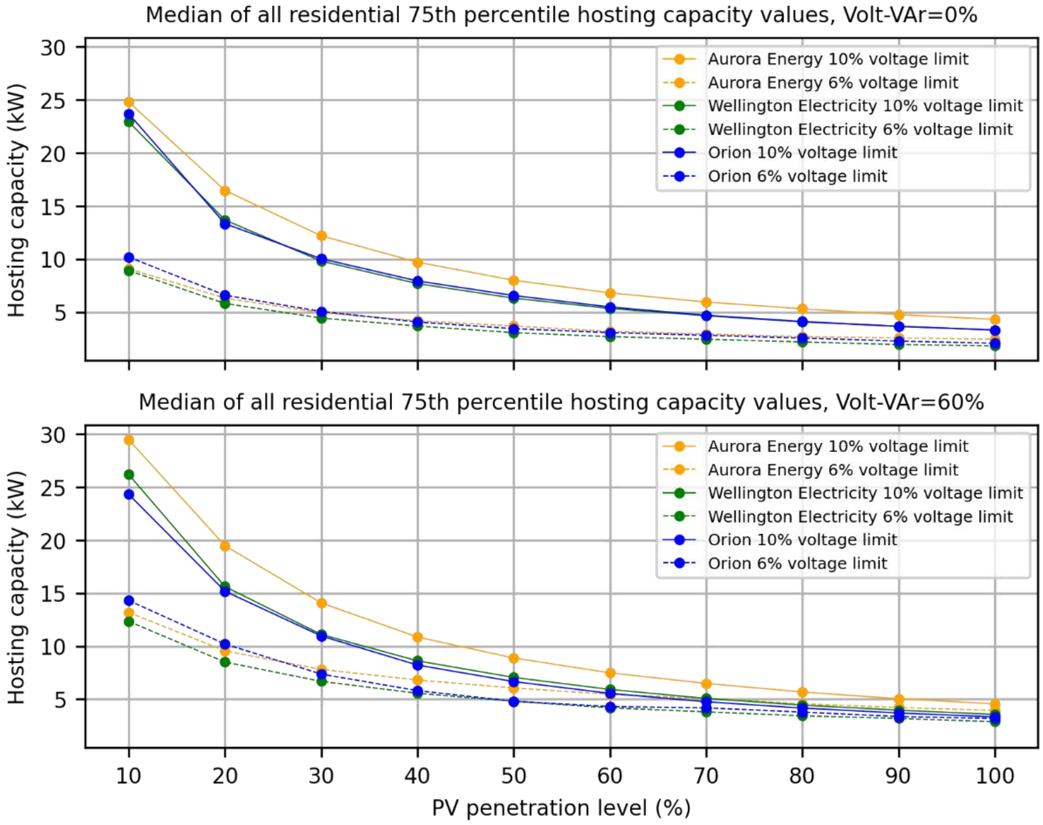


Figure 15: Median of the 75th percentile hosting capacity values for residential ICPs, showing hosting capacity values roughly 25% higher than the 50th percentile hosting capacity values in Figure 2.

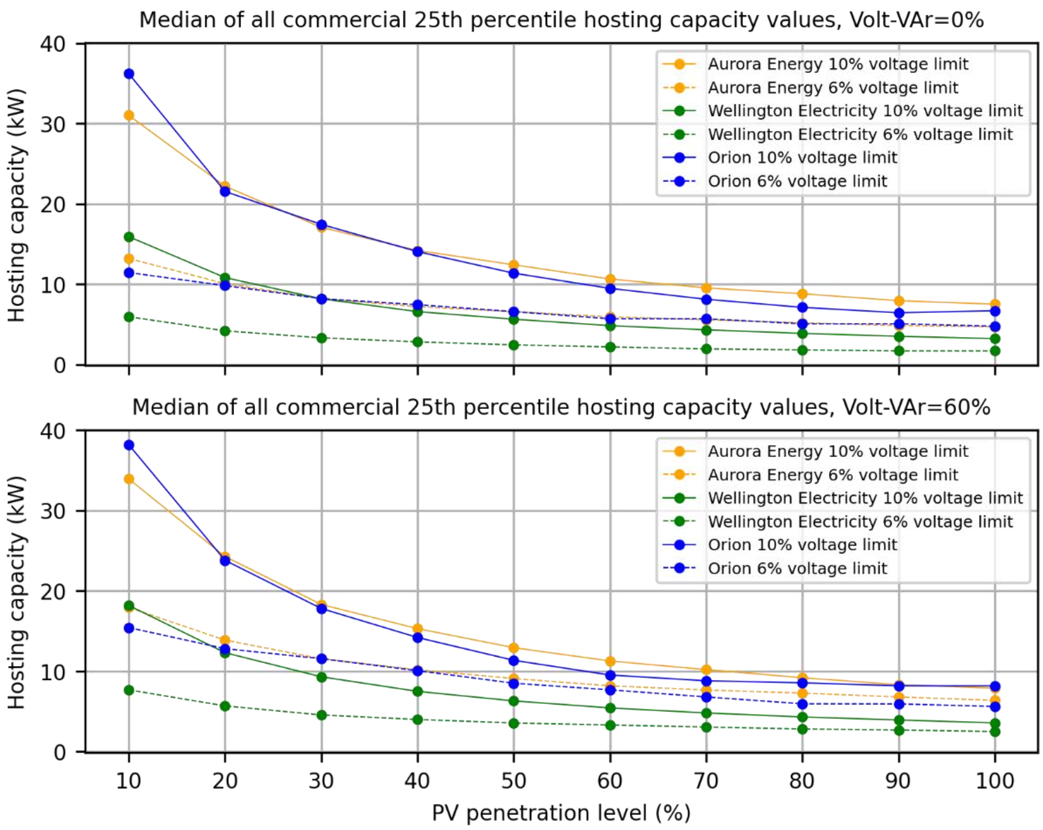


Figure 16: Median of the 25th percentile hosting capacity values for commercial ICPs, showing hosting capacity values roughly 25% lower than the 50th percentile hosting capacity values in Figure 3.

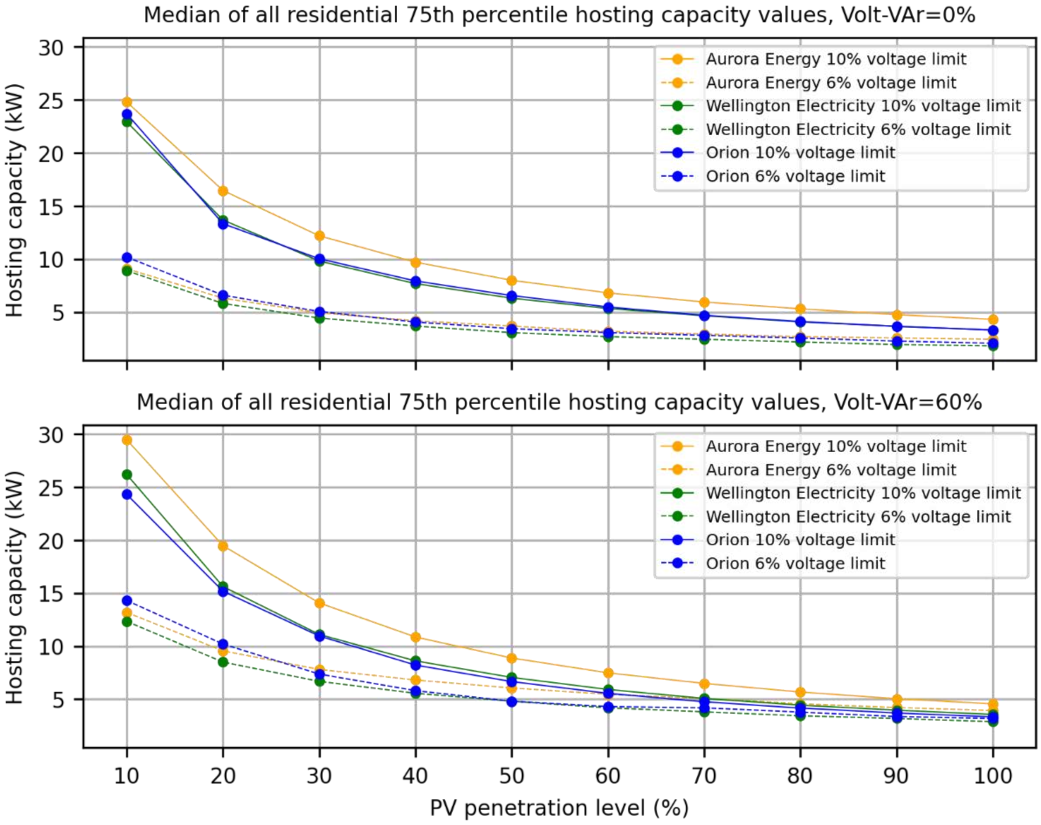


Figure 17: Median of the 75th percentile hosting capacity values for commercial ICPs, showing hosting capacity values roughly 25% higher than the 50th percentile hosting capacity values in Figure 3.