A pathway to customer DER ubiquity:
Distribution voltage management, smart inverters and dynamic operating envelopes

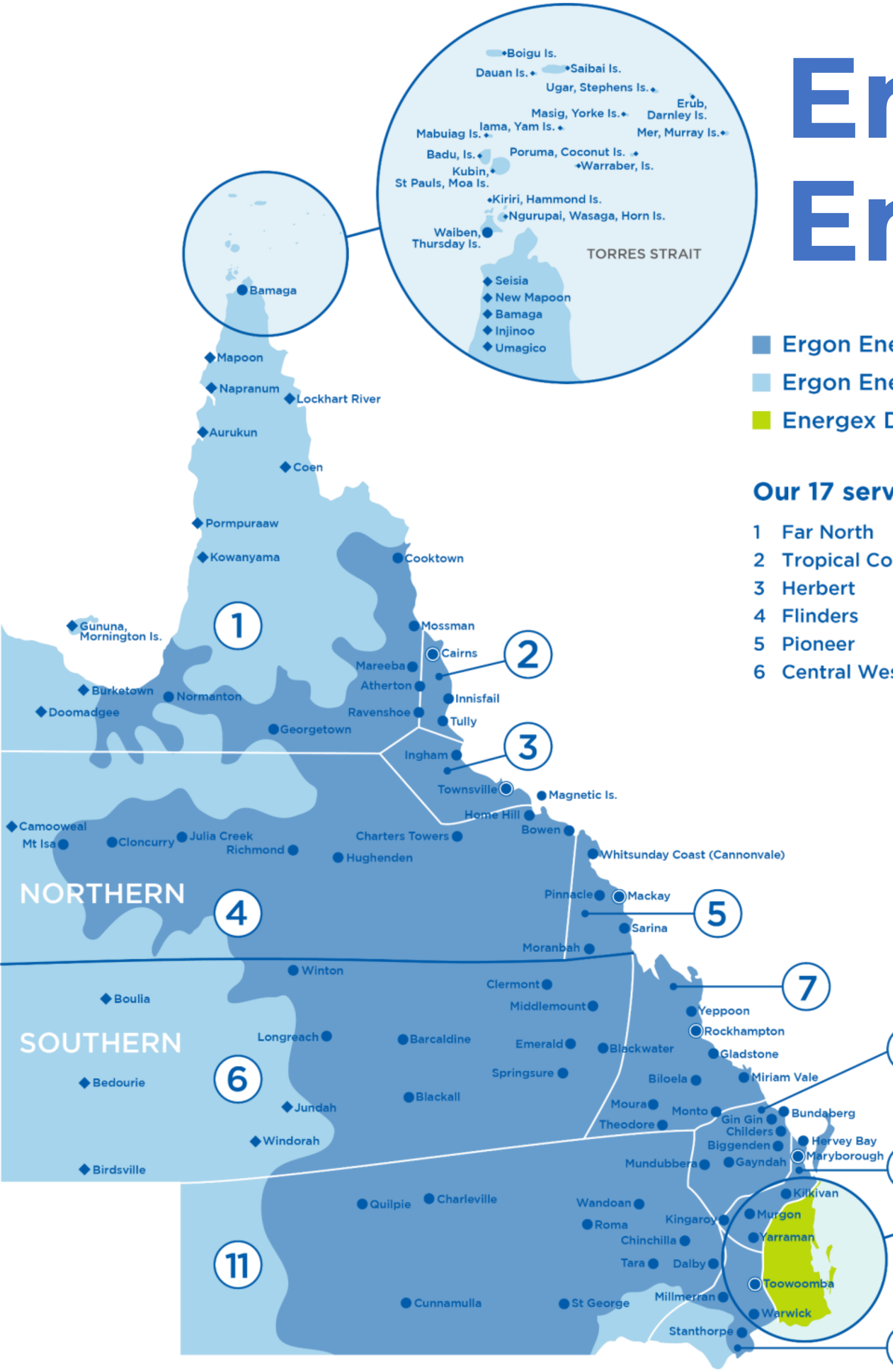
QUT, November 2023

ERGON ENERGY NETWORK | energex

Part of Energy Queensland

Acknowledgement of Country

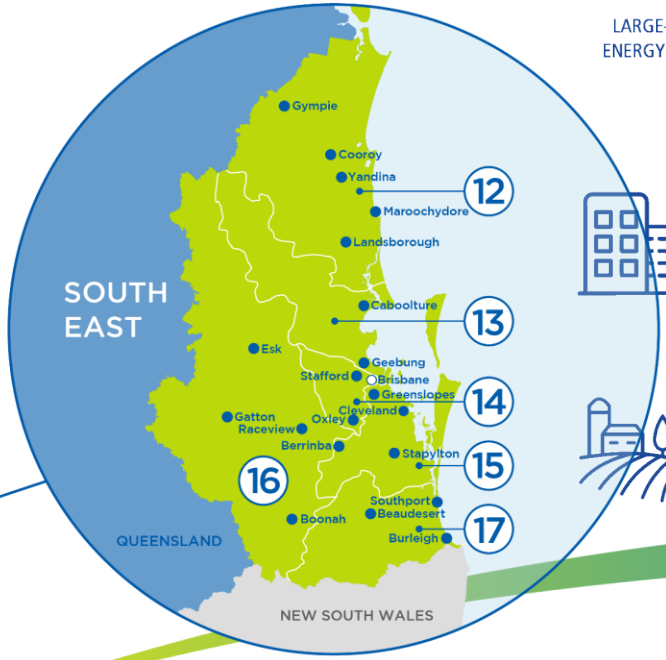
Ergon Energy Network & Energex



- Ergon Energy Distribution Network
- Ergon Energy Isolated Supply
- Energex Distribution Network
- Administration Centre
- Depots
- Isolated Supply

Our 17 service areas

1	Far North	7	Capricornia	13	Brisbane North
2	Tropical Coast	8	Bundaberg Burnett	14	Brisbane Central
3	Herbert	9	Fraser Burnett	15	Brisbane South
4	Flinders	10	Darling Downs	16	Ipswich Lockyer
5	Pioneer	11	South West	17	Gold Coast
6	Central West	12	Sunshine Coast		



210,000km POWERLINES (overhead and underground)

34 POWER STATIONS (including network-connected Barcaldine)

800,000 SOLAR ENERGY SYSTEMS CONNECTED

1.7million km² SERVICE AREA

43 LARGE-SCALE SOLAR ENERGY CONNECTIONS

1.7 million POWER POLES

ENERGEX

5,221 MW network-wide peak/ maximum demand

237 MW network-wide minimum demand

ERGON NETWORK

2,637 MW network-wide peak/ maximum demand

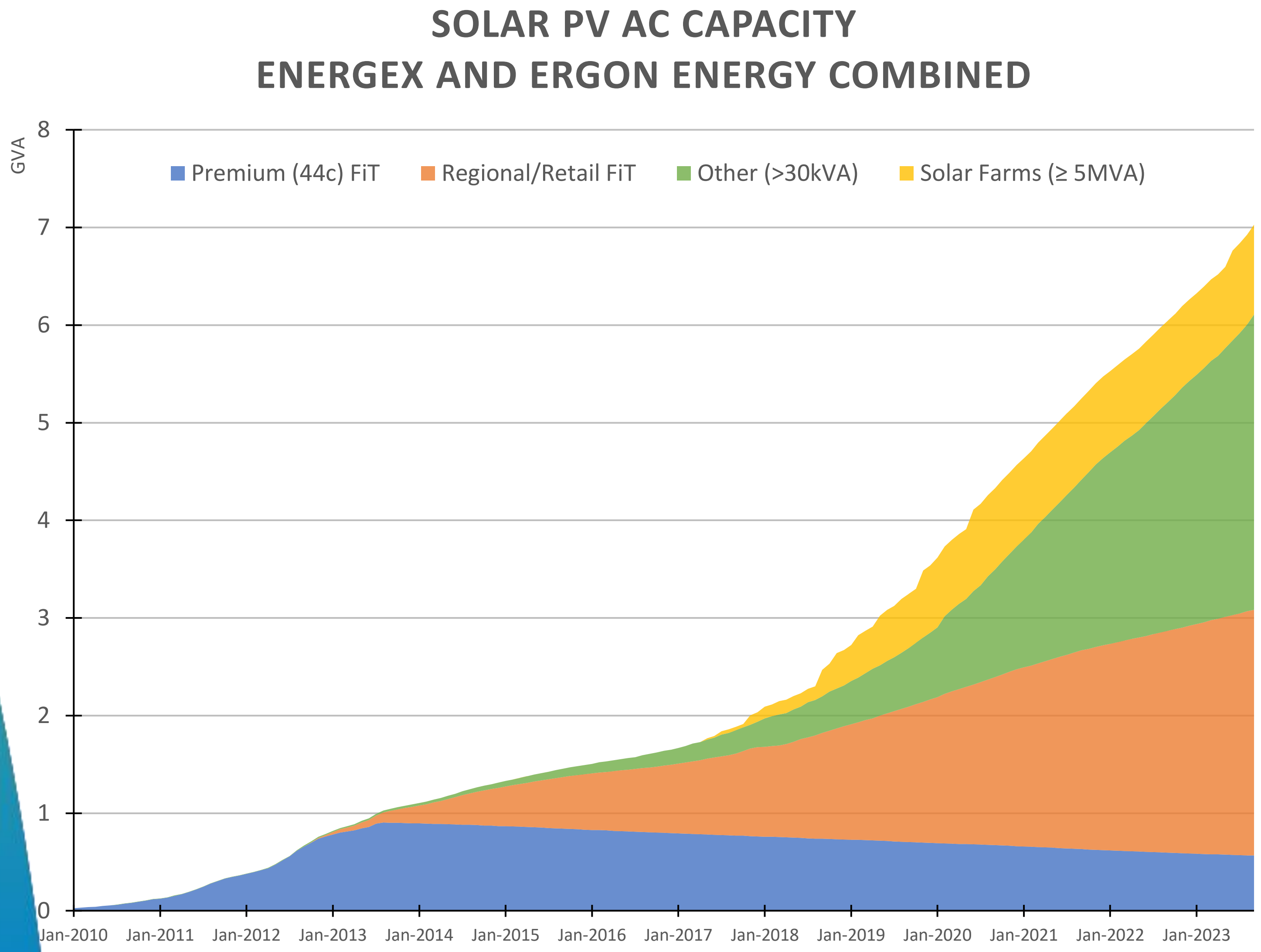
799 MW network-wide minimum demand

UNPLANNED OUTAGES

Energex	Ergon Network
0.66	2.15

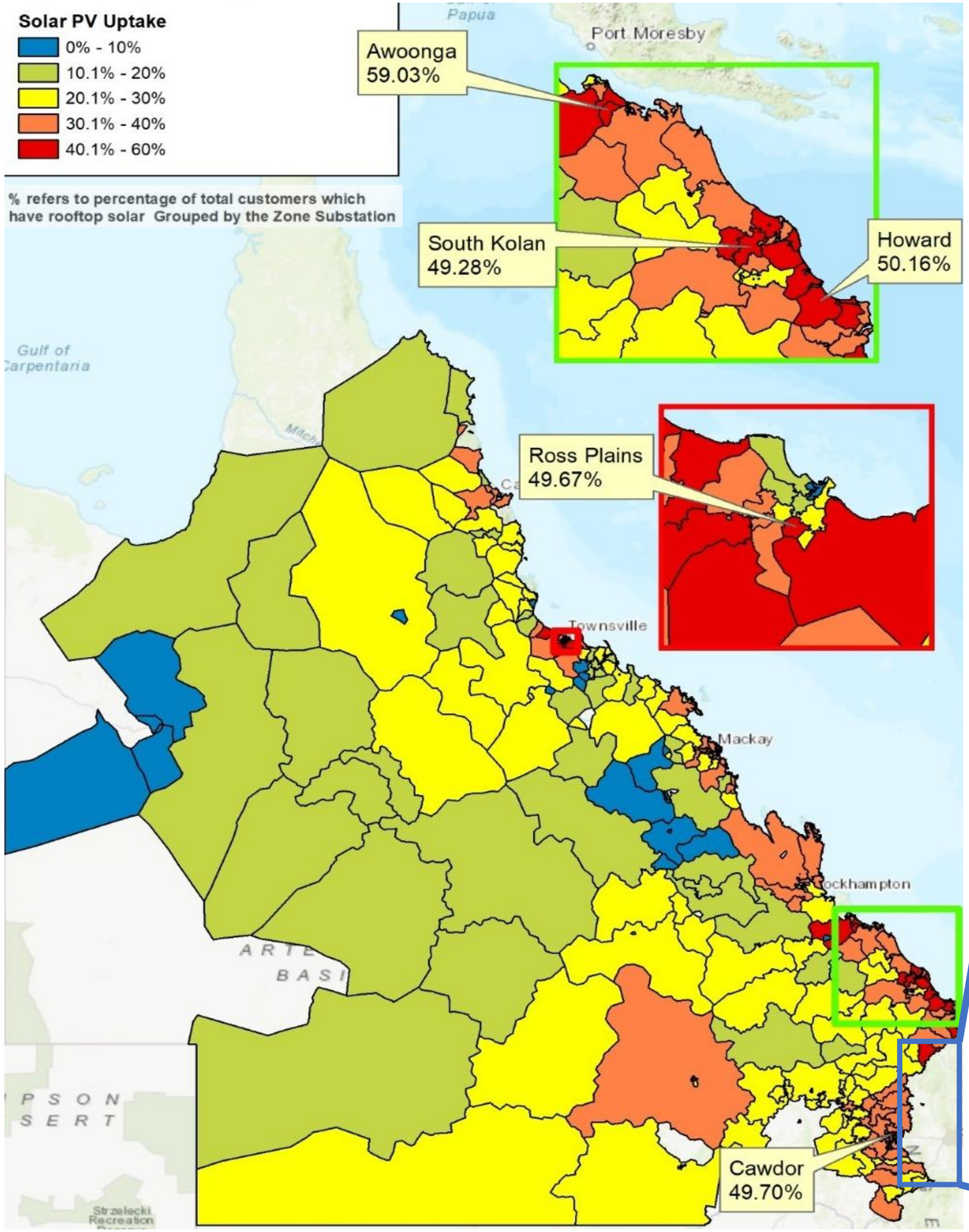
(average per customer a year)

Ongoing uptake of solar PV

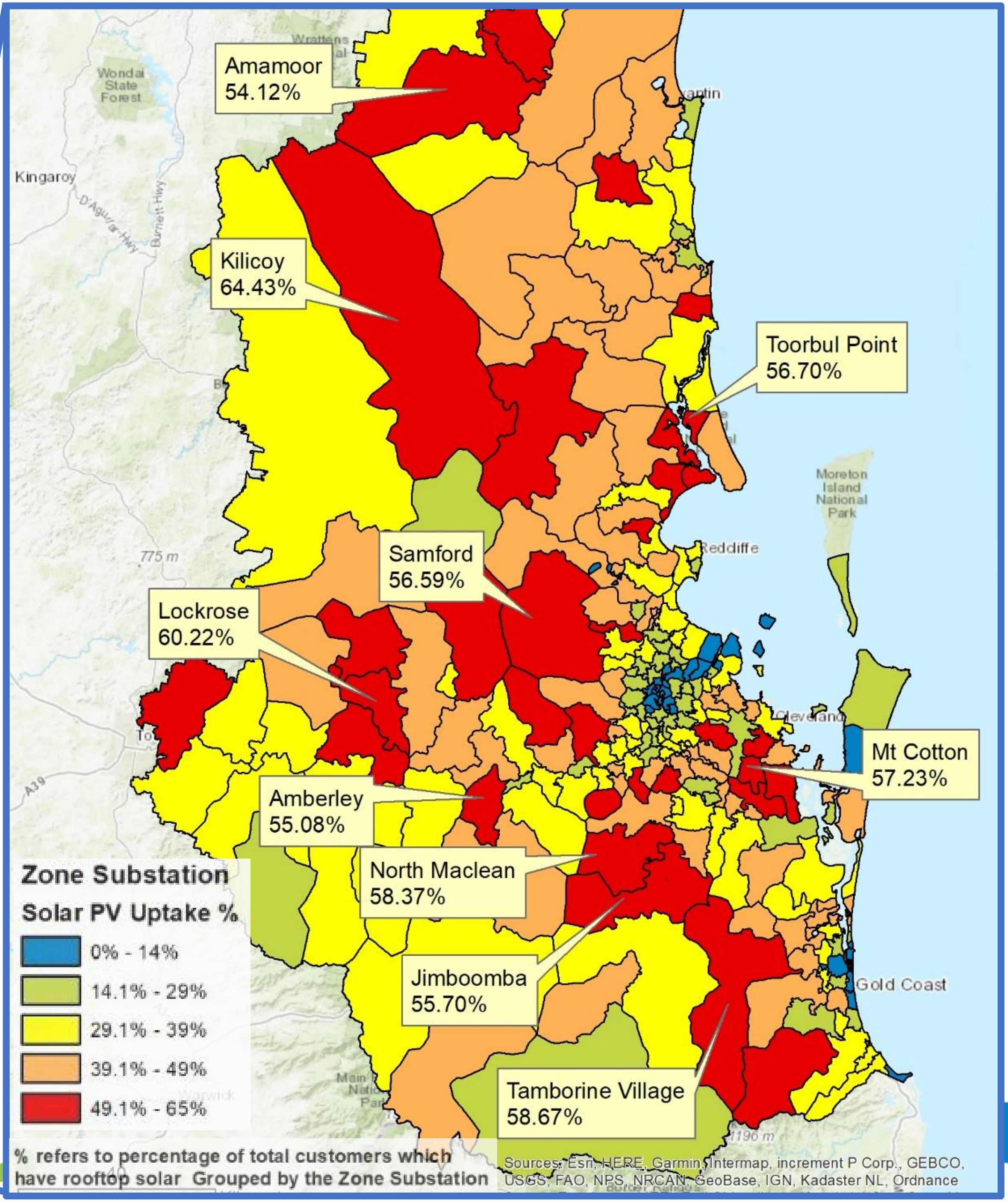


NB. Solar farms connected to Powerlink’s transmission network are not included

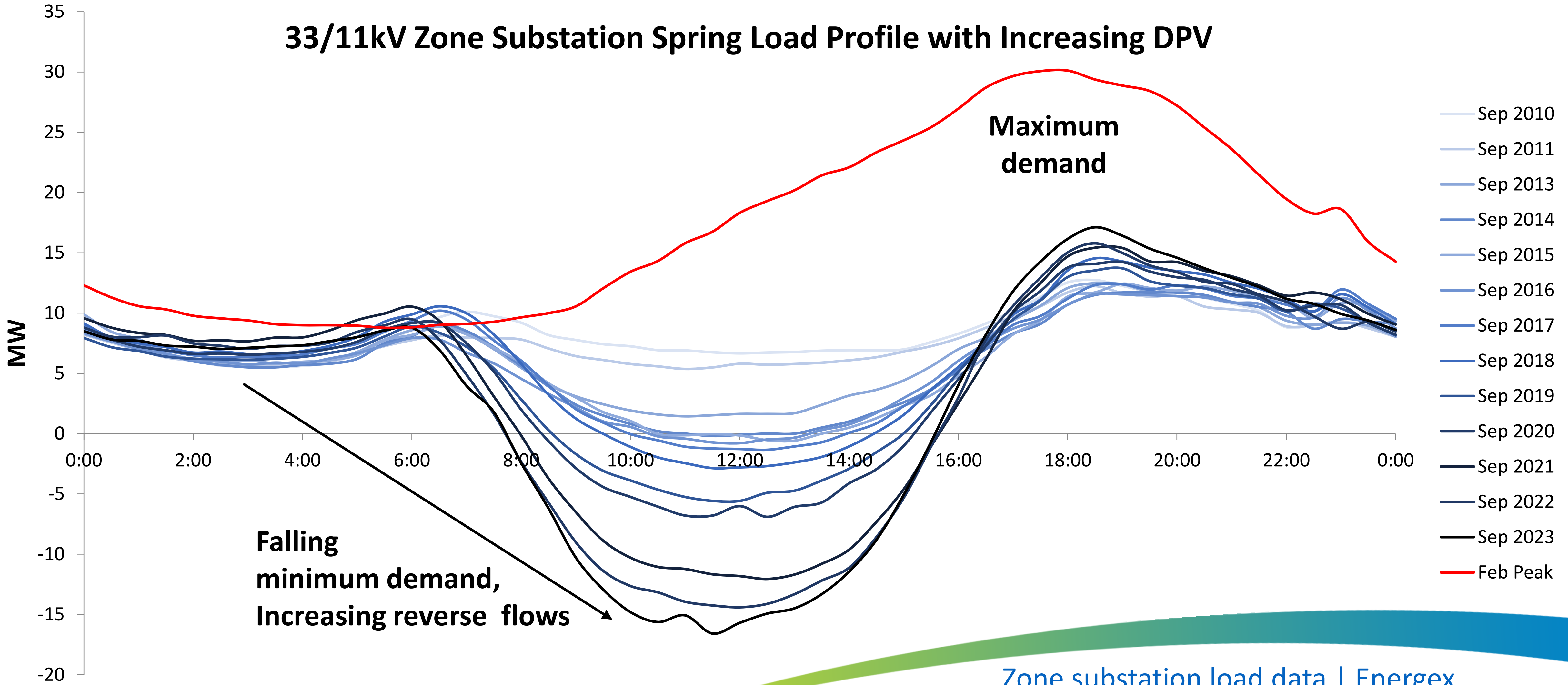
Regional Queensland



South East Queensland

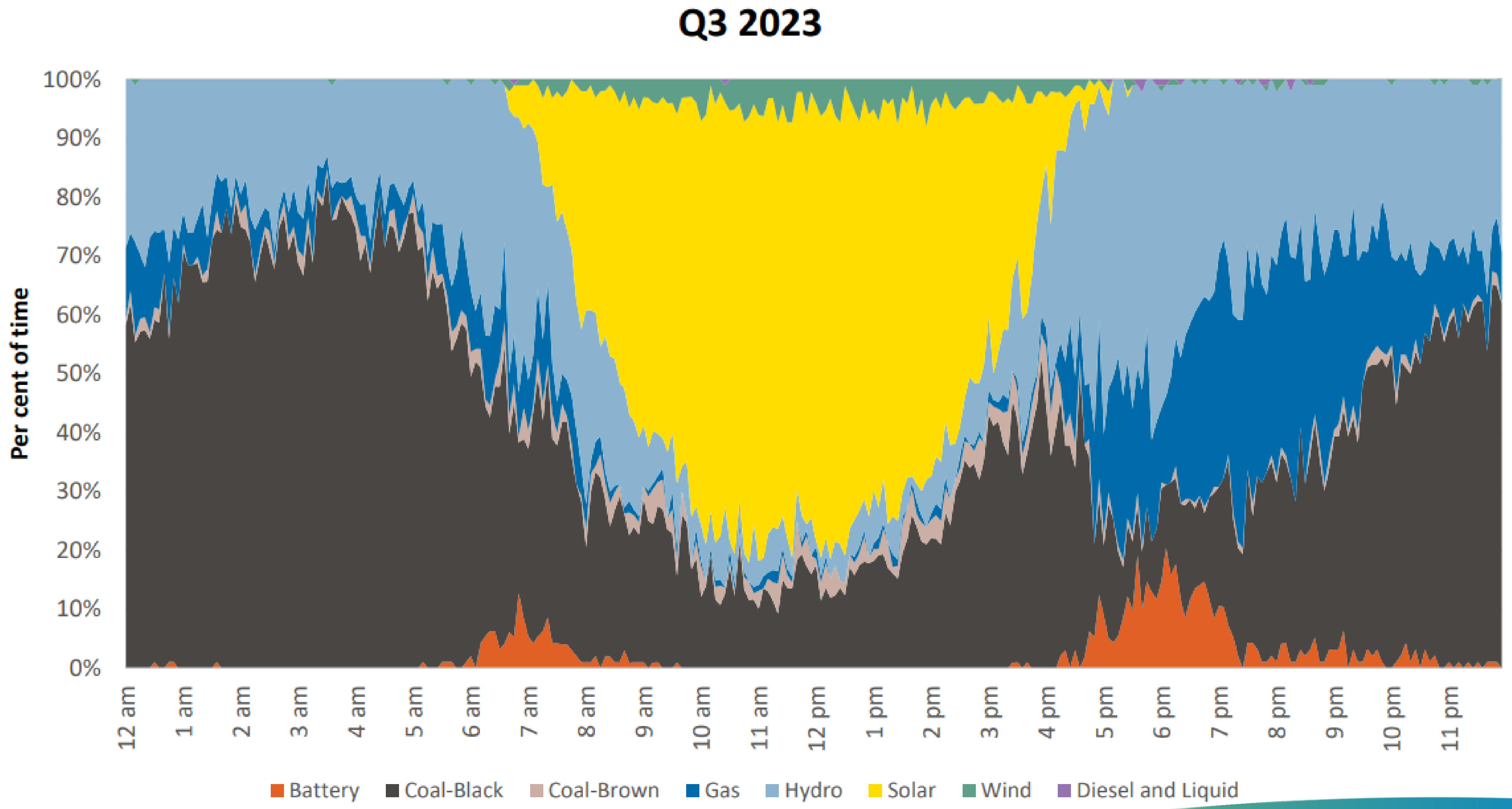


Distributed Solar PV (DPV) continues to increase reverse flows

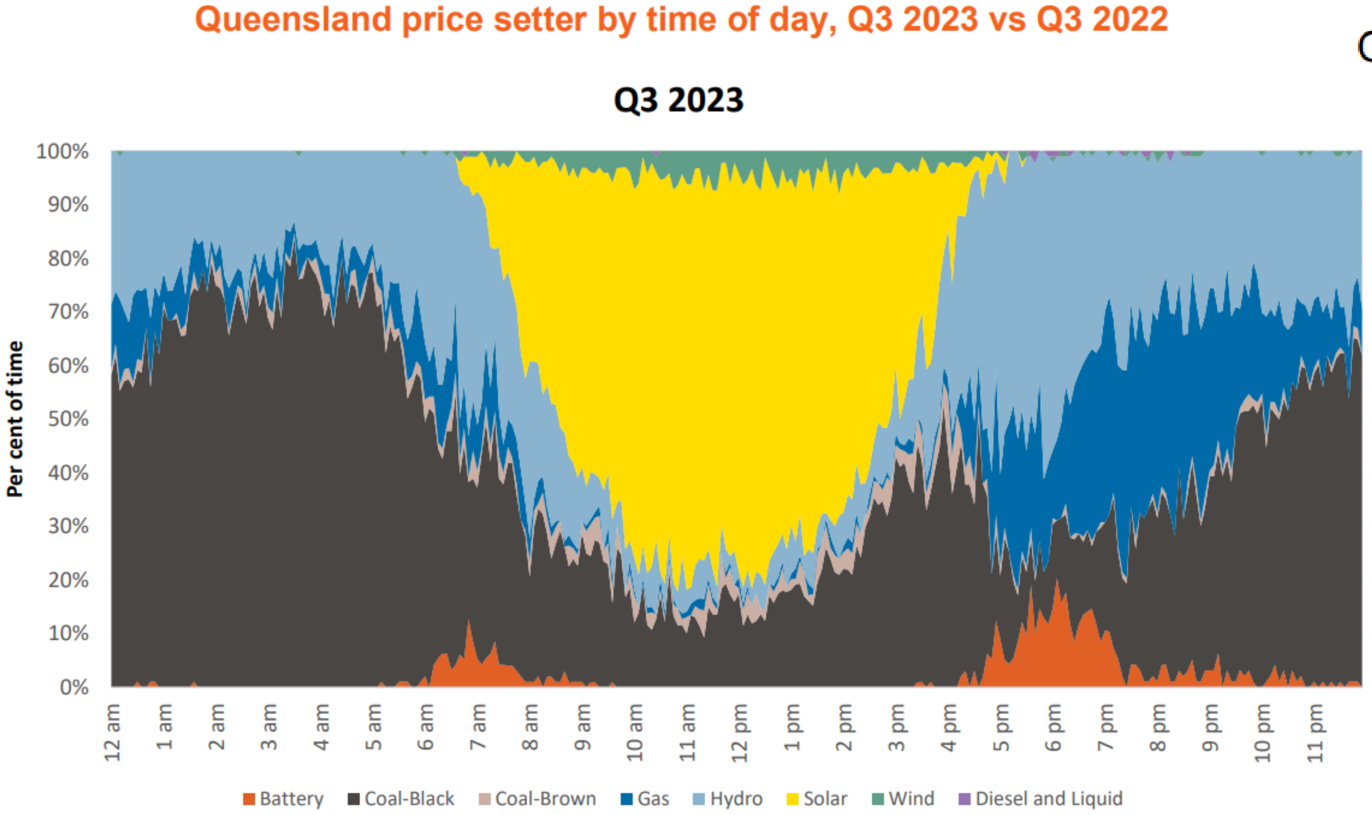


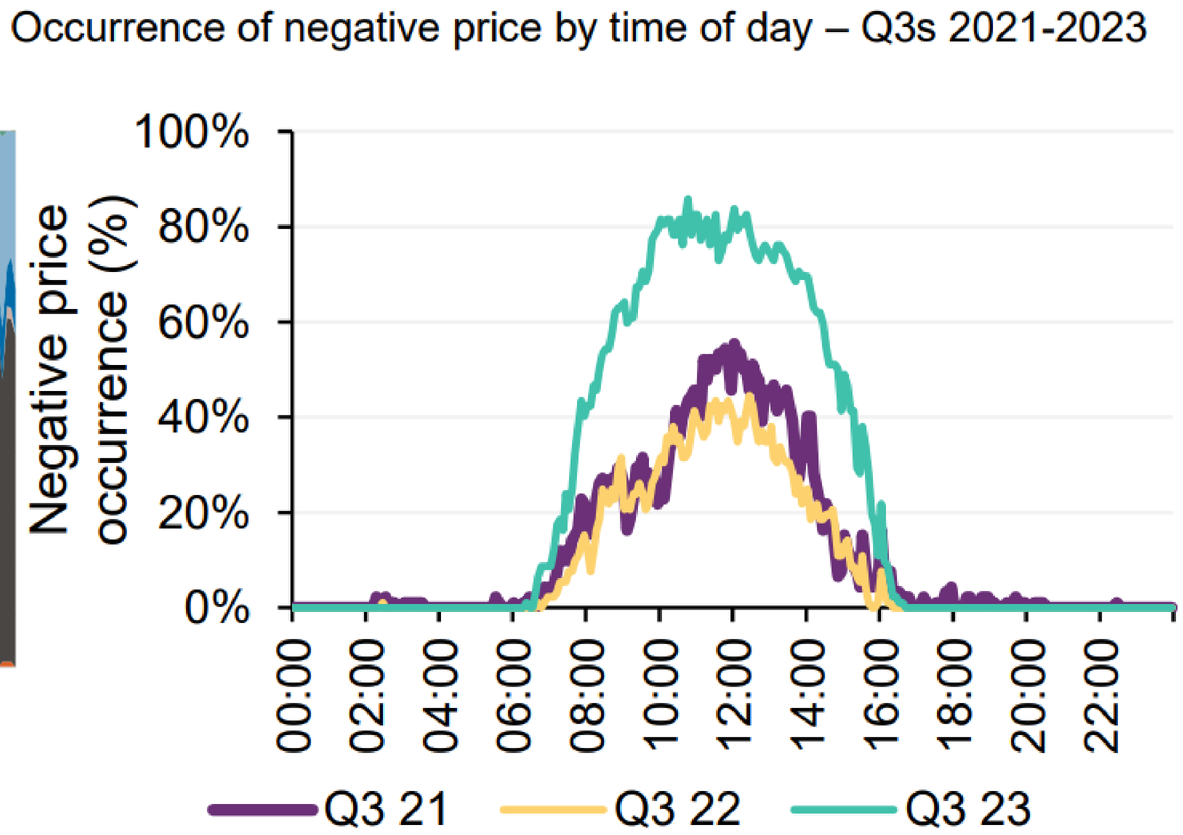
Zone substation load data | Energex

Queensland price setter by time of day, Q3 2023 vs Q3 2022



[AER Q3 2023 Wholesale markets quarterly report.pdf (aer.gov.au)]





Q3 2023 Wholesale markets quarterly report.pdf (aer.gov.au)

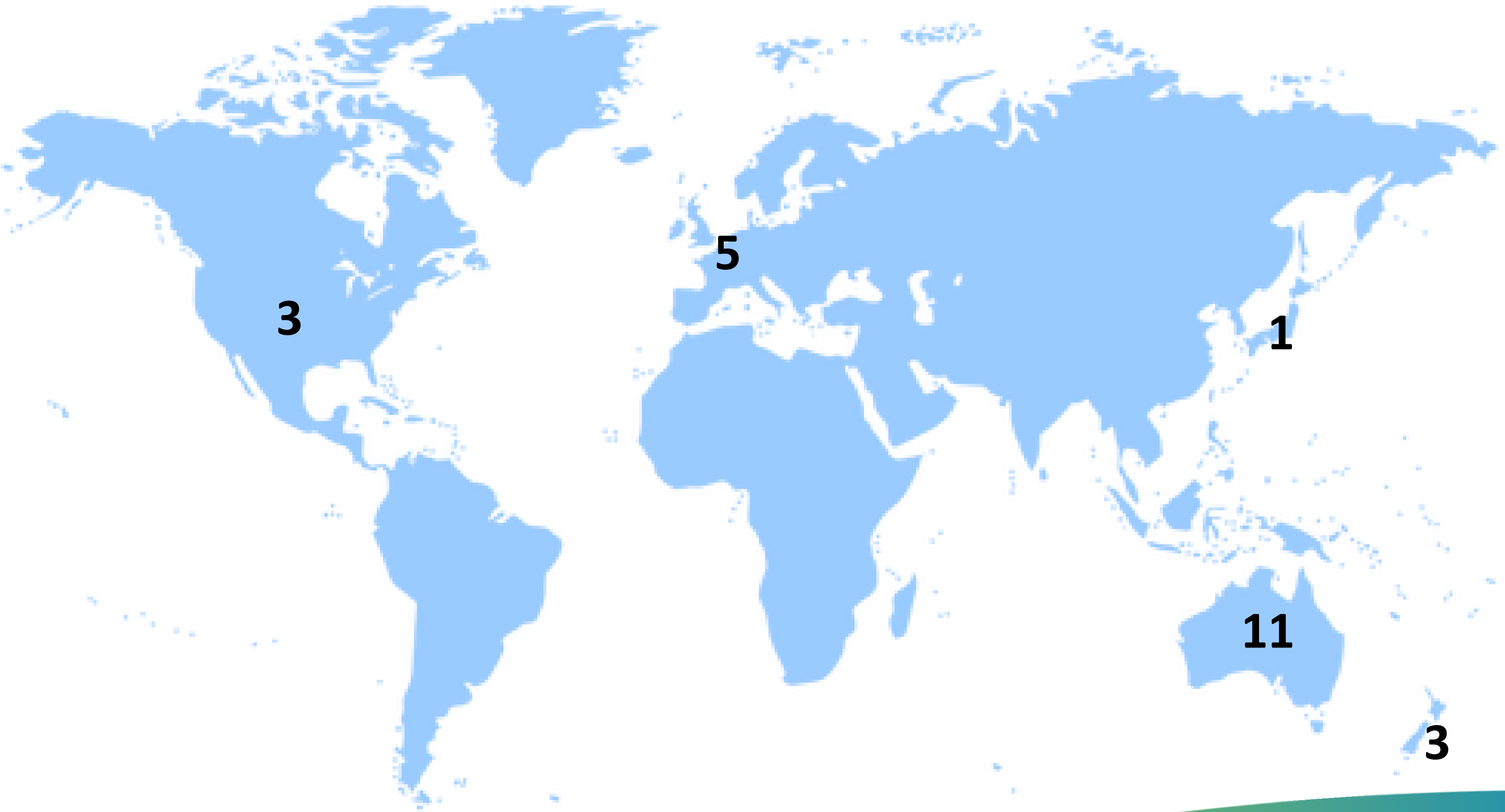
Quarterly Energy Dynamics Q3 2023 Report.pdf (aemo.com.au)

CIGRE AU C6 Survey on Distribution Voltage Management

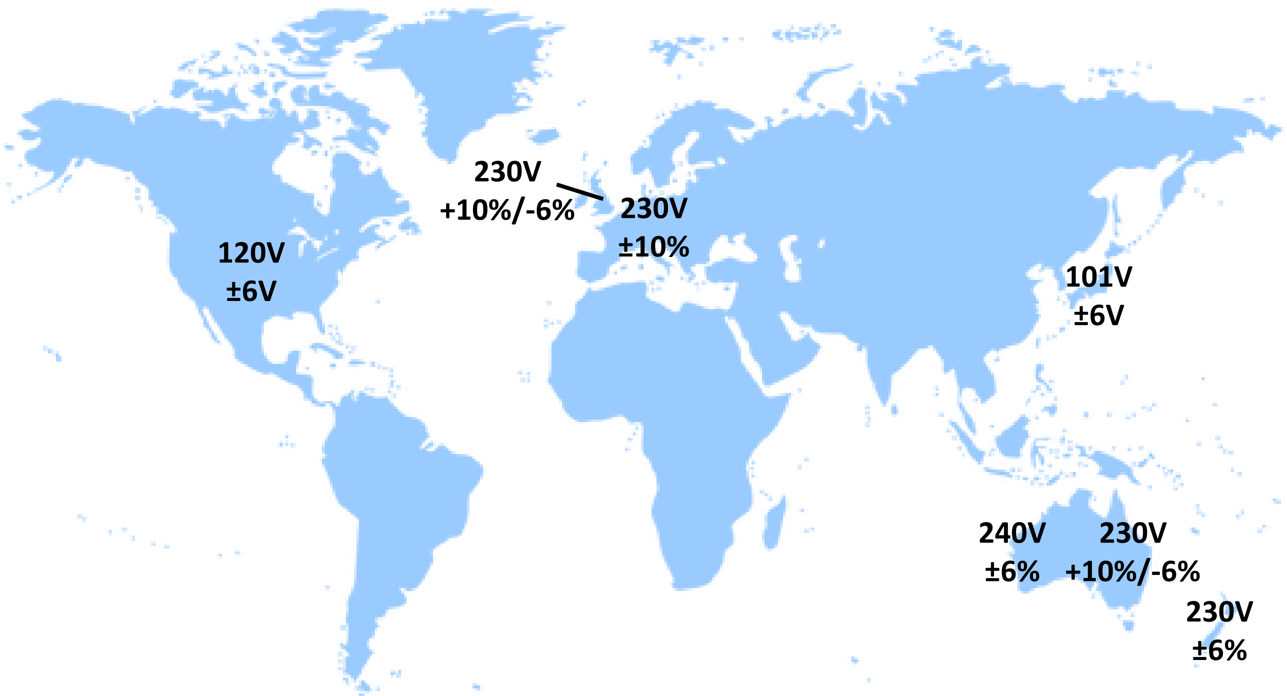
Global survey on distribution voltage management

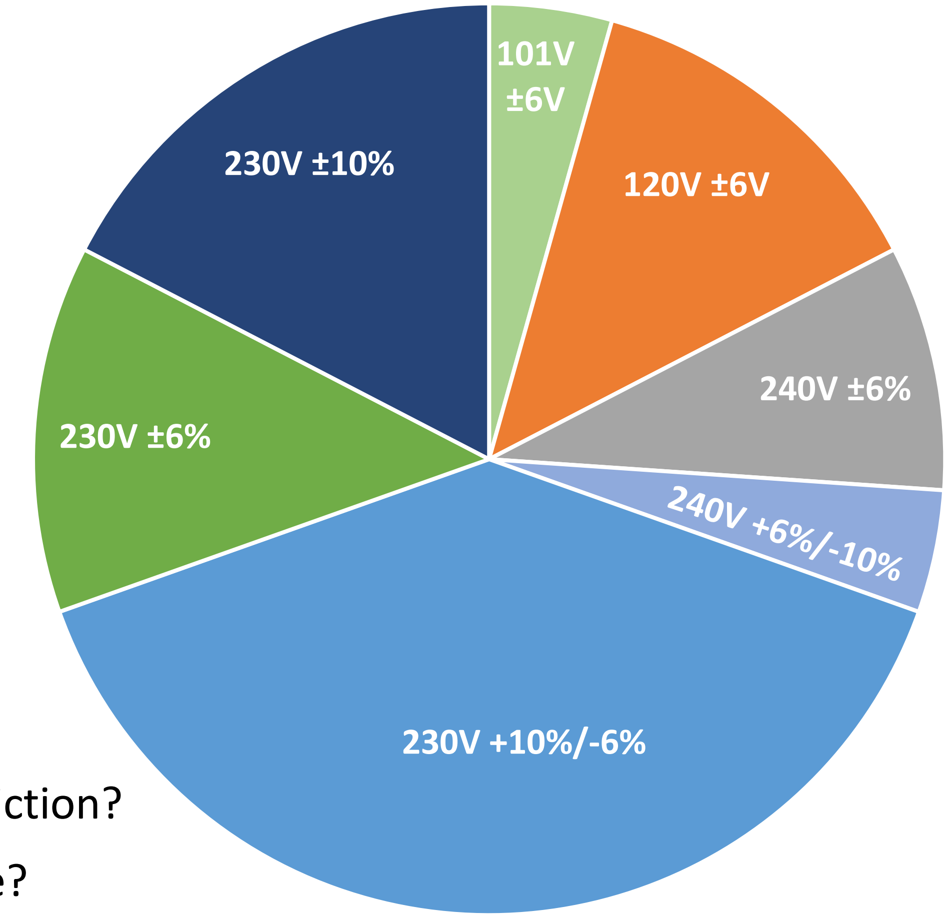
- Focused specifically on voltage management practices associated with the medium and low voltage electricity networks
- This is an area that has received increased attention and innovation, with the rise of DER, reverse flows and increasing customer awareness
- Voltage constraints have emerged first on distribution networks with growing distributed PV, spurring innovations in standards, voltage remediation, LV technologies, smart inverters and MV regulation
- This initially began as a survey of Australian DNSPs but with the support of CIGRE Australia extended to a global sample

Global distribution of respondents



Respondents' low voltage ranges

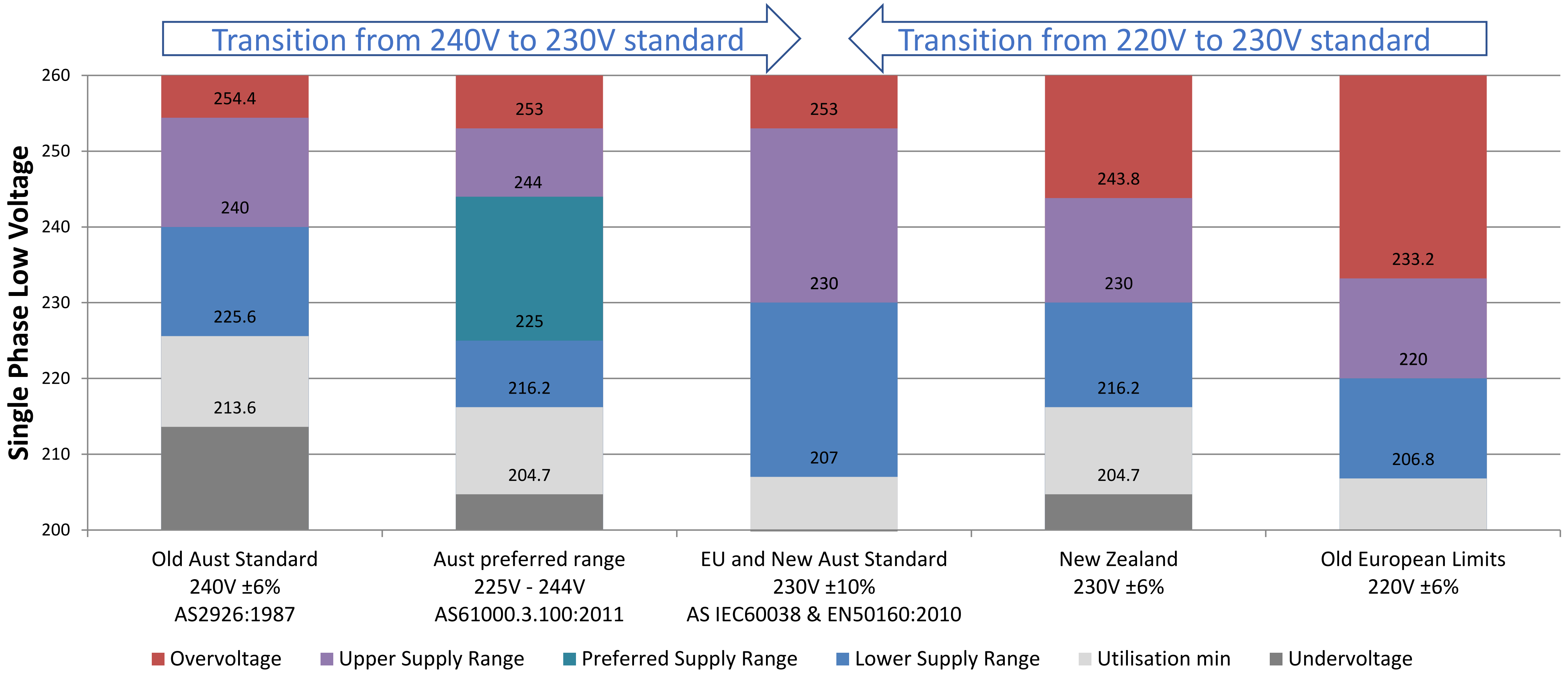




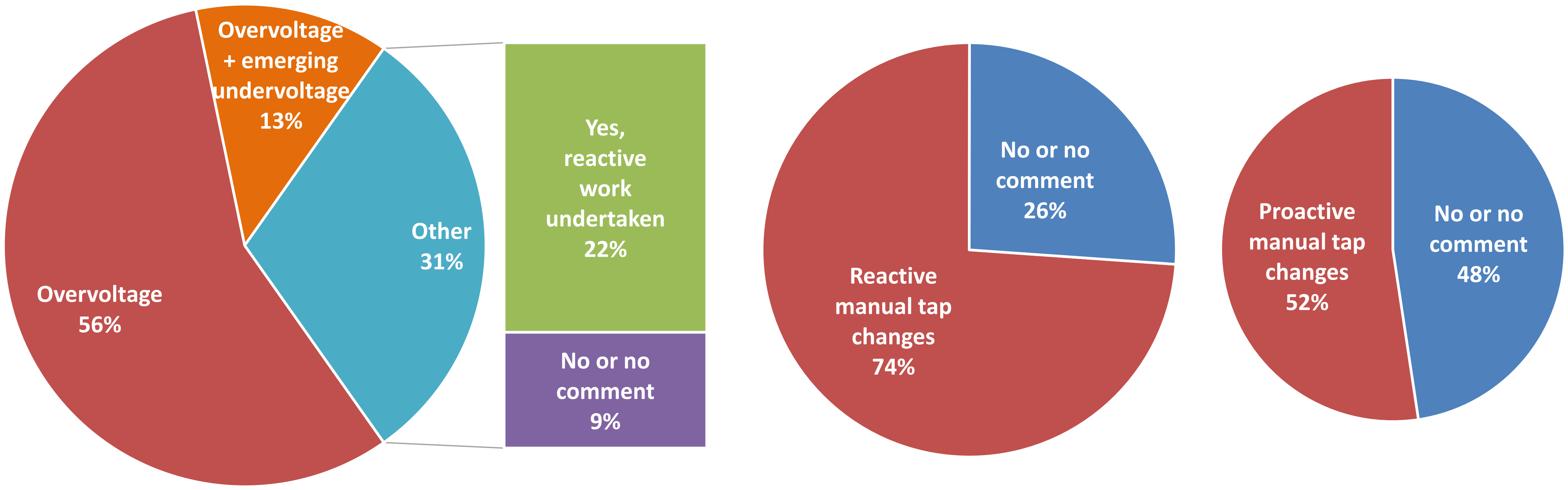
What is the current LV supply range in your jurisdiction?

Are there any plans to change the LV supply range?

4-wire low voltage standards



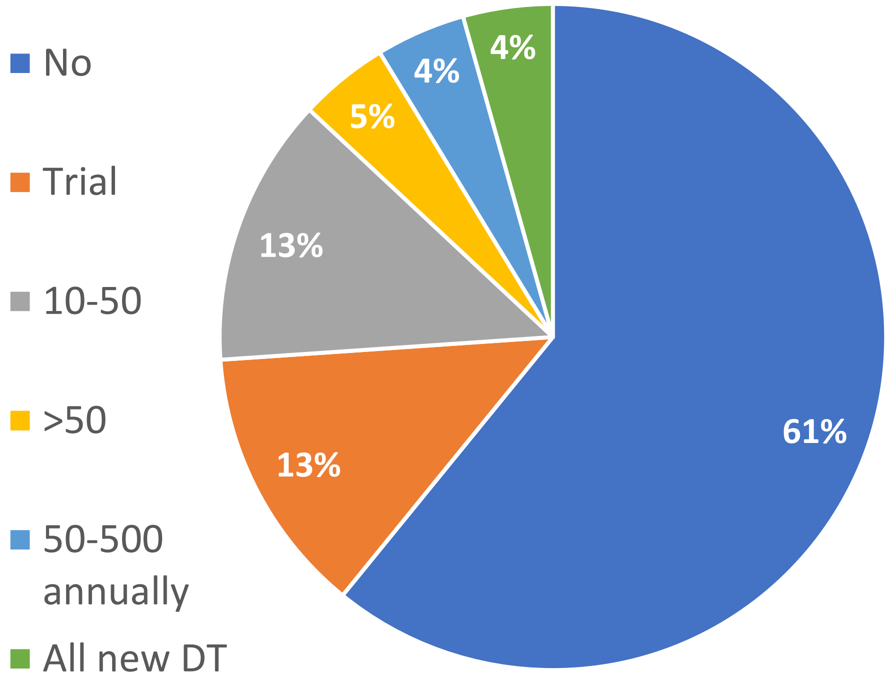
Reactive work mostly for overvoltage or undervoltage?



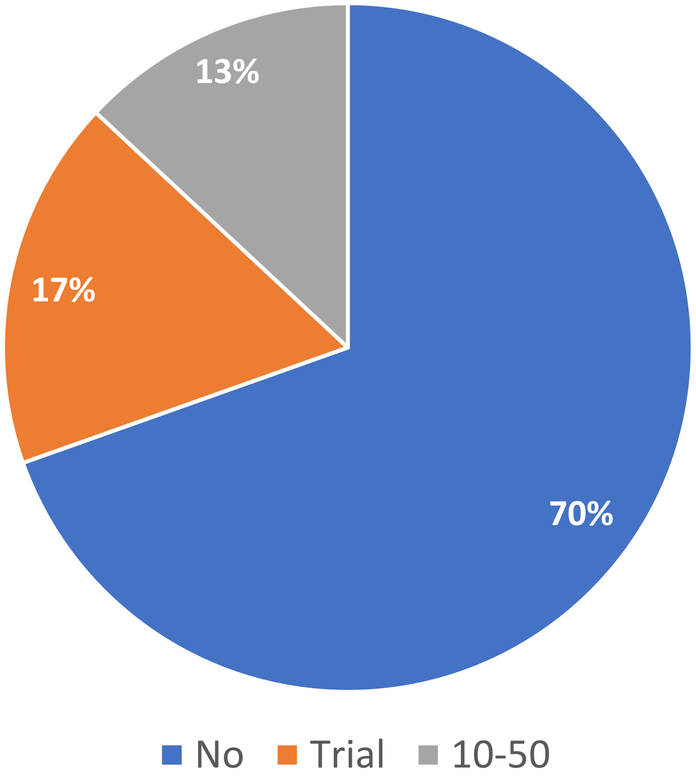
Does your organisation undertake reactive work more commonly to address undervoltage or overvoltage on LV networks?
Does your organisation undertake reactive manual tap changes of distribution transformers supplying LV networks where voltage constraints are identified?
Does your organisation undertake proactive manual tap changers of distribution transformers supplying LV networks where voltage constraints are expected/forecast ?

New LV distribution technologies

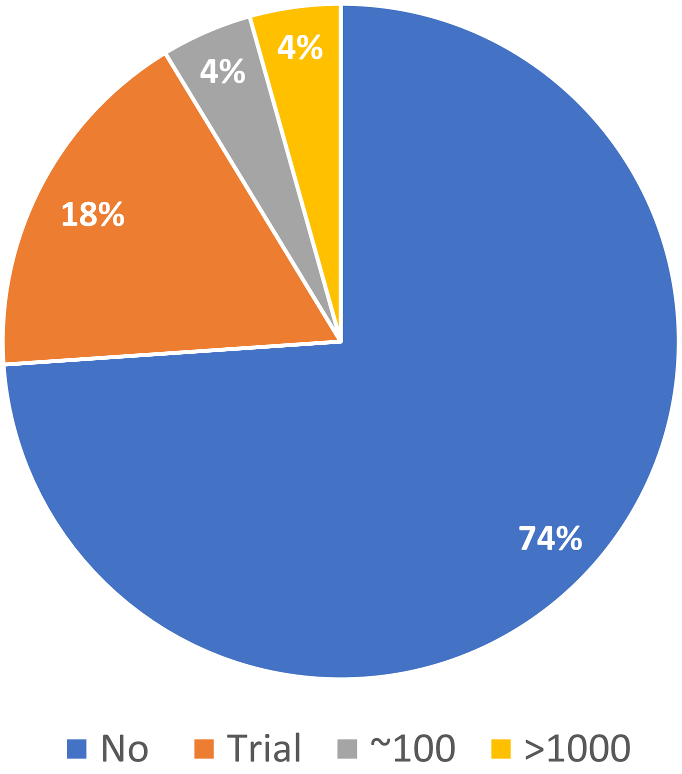
Voltage Regulating Distribution Transformers



LV Statcoms



LV Regulators

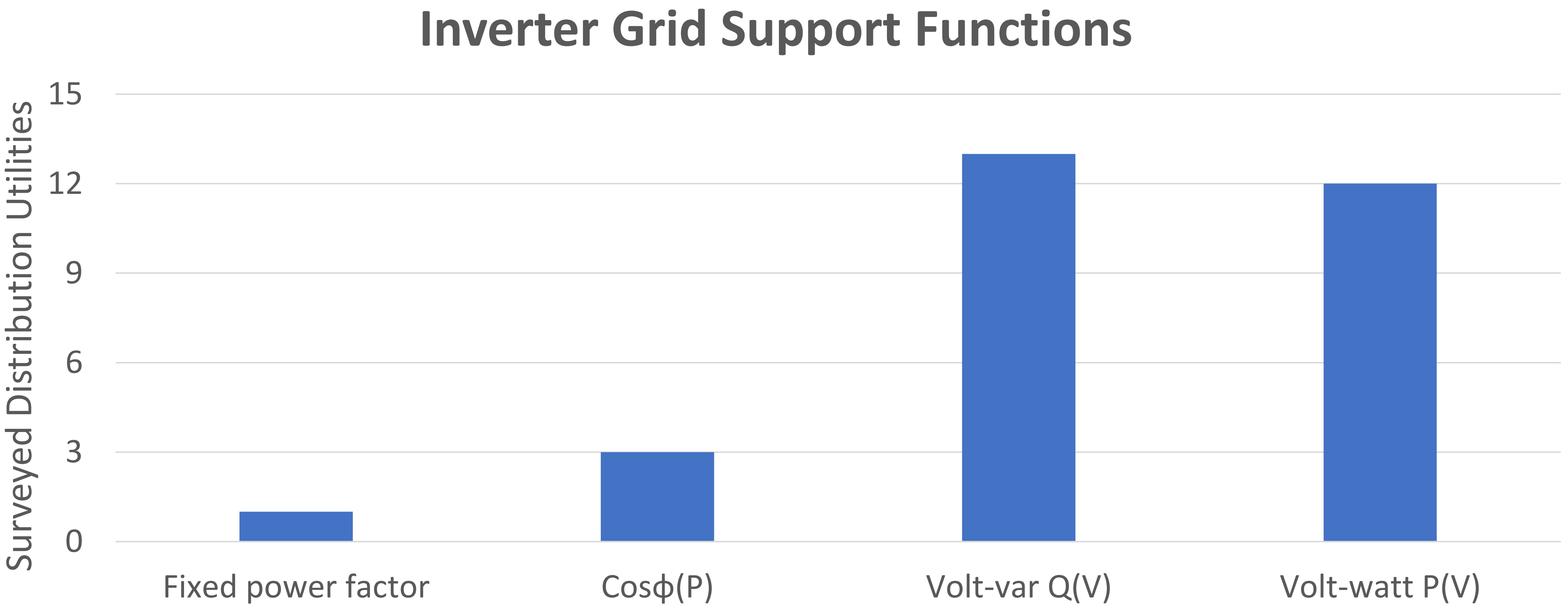


CIGRE AU C6 Survey

[Voltage Regulating Distribution Transformer (VRDT) – Use in Grid Planning and Operation (vde.com)]

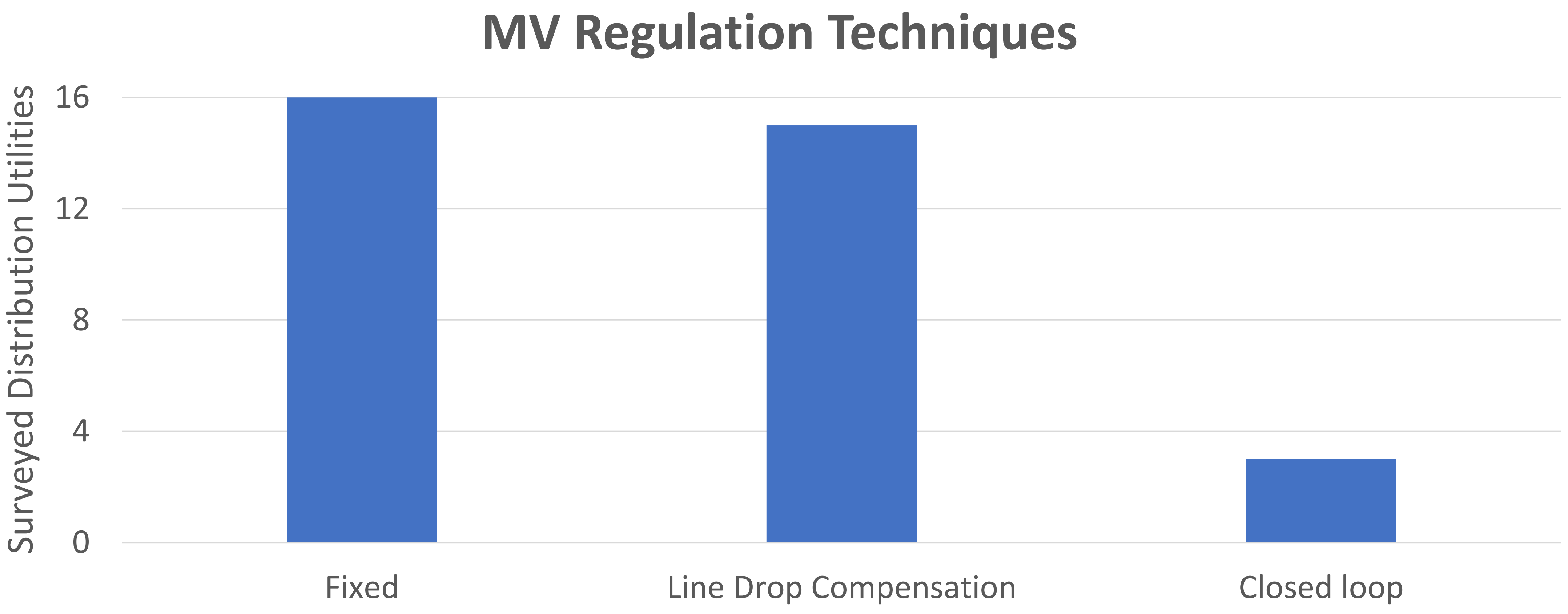
[Investigation into VM technologies for future Australian Suburban distribution networks (racefor2030.com.au)]

Smart inverter functions*



*heavily biased sample as a result of Australian regulations mandating AS/NZS 4777.2 with Q(V) and P(V)

MV regulation



Noteworthy takeaways from the survey

- Transitions to the 230V standard are progressing slowly but surely
- Overvoltage associated with PV has become the primary distribution voltage management constraint globally
- Undervoltage constraints associated with EV and heat pumps emerging
- VRDTs are leading LV regulators and LV statcom deployments, especially in Europe
- Australia [Q(V) & P(V)] and Germany [cos ϕ(P)] have the most consistent although distinct approaches to LV inverter grid support functions
- Both fixed MV regulation and line drop compensation are still widely used, with many reports of reducing set points/float levels, closed loop regulation is under development in a small but growing number of distribution utilities

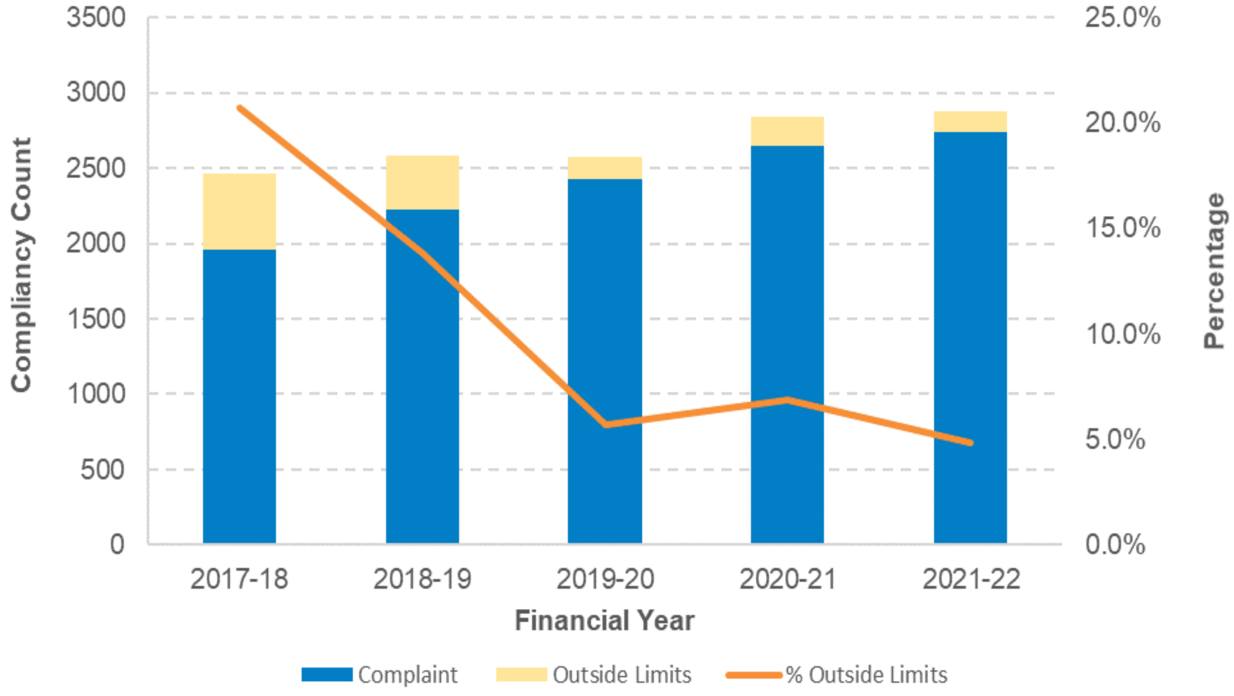
Distribution voltage management

Improved distribution voltage management

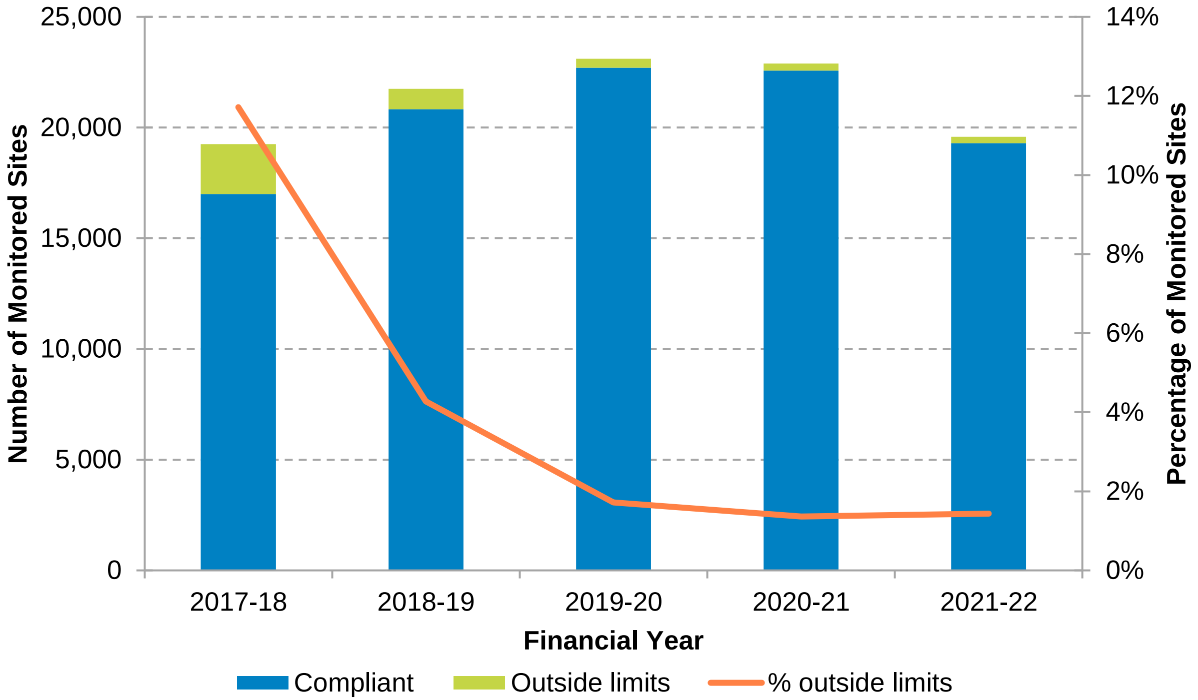
- Targeted distribution transformer tap reductions
  - Targeted at sites with high PV penetrations and modest peak demand voltage drop
- Widespread MV reductions to transition from the 240V standard to 230V
  - From 225.6-254.4V to 216-253V LV range
  - Increased voltage headroom for reverse flows
  - Median supply voltage compliance with Preferred range 225-244V (AS 61000.3.100)
- Application of line drop compensation to buck MV during reverse flow & minimum demand
  - Applied at zone substations and on MV feeder regulators
  - Reduces voltage spread at end of distribution feeders and accommodates additional feeder voltage rise
  - Constrained by buck tap range on some On Load Tap Changers (OLTCs)

"Voltage Management on Distribution Networks with High PV Penetrations" presented to QUT PECT by Mr Peter Kilby 2019

Ergon Energy

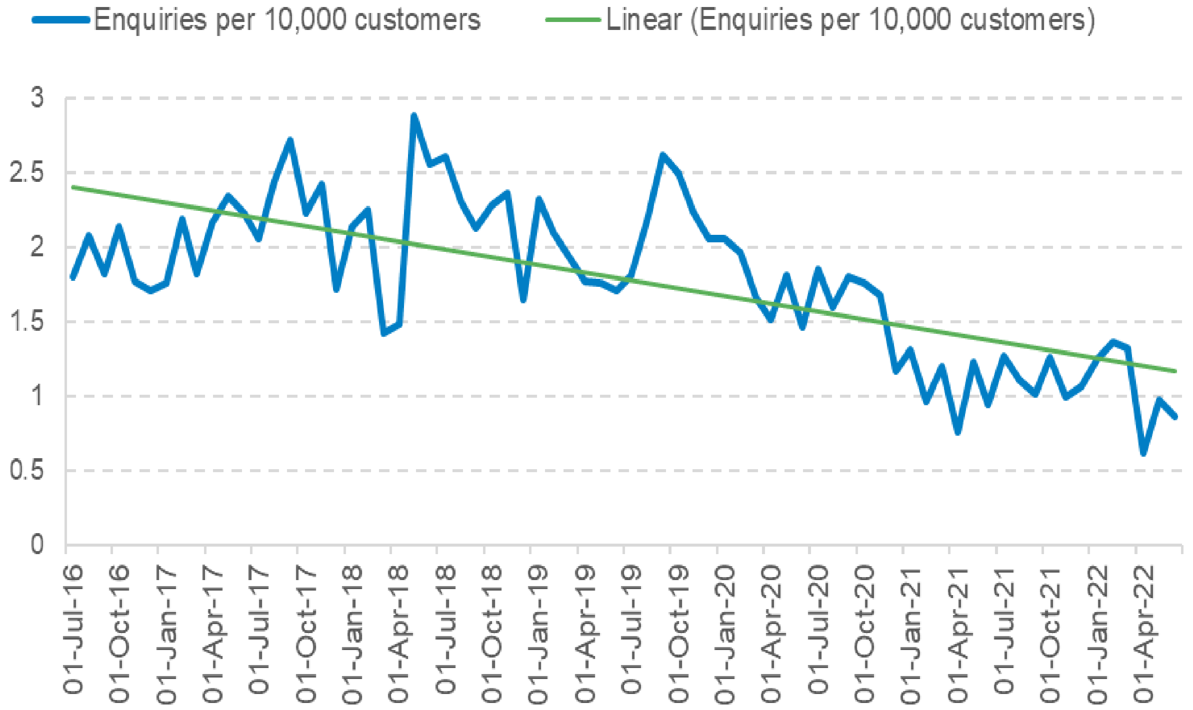


Energex

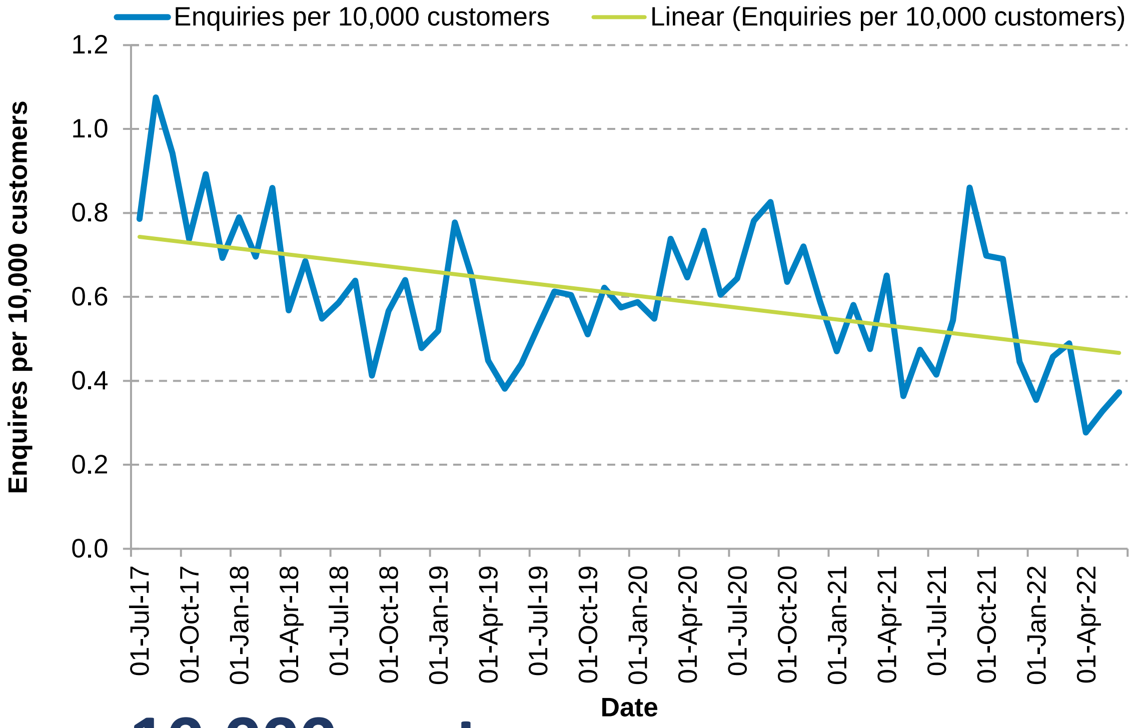


Overvoltage at the Transformer (V99% > 253V)

Ergon Energy Network

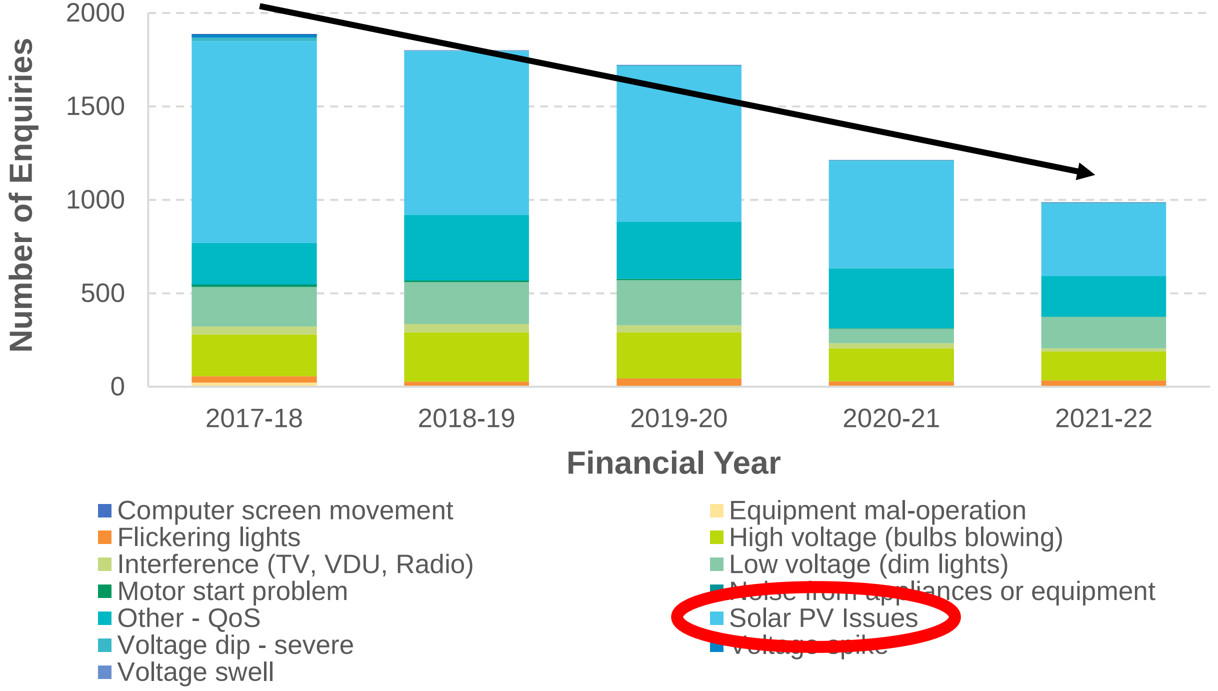


Energex

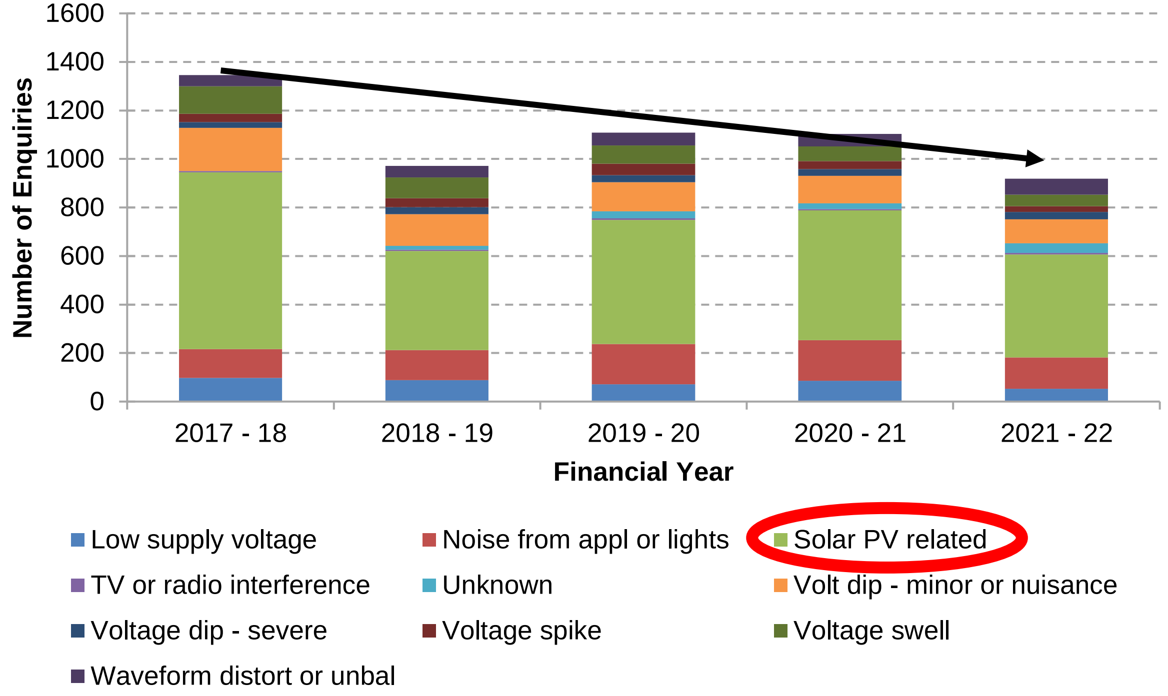


Quality of Supply Enquiries per 10,000 customers

Ergon Energy

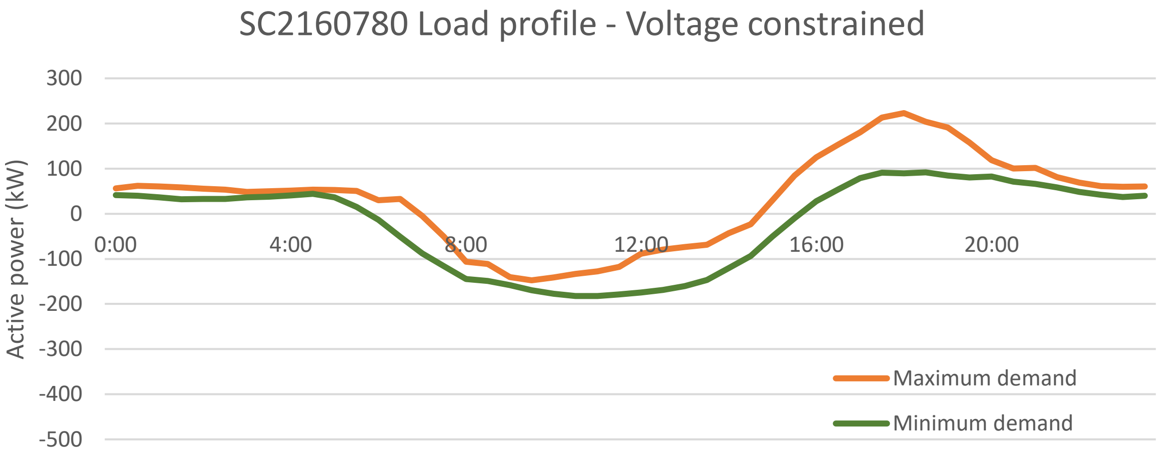


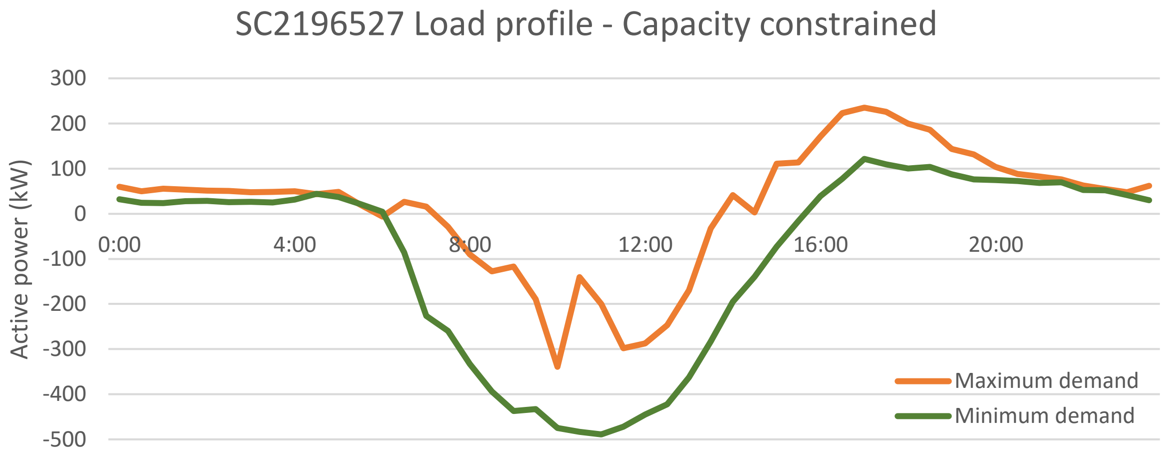
Energex

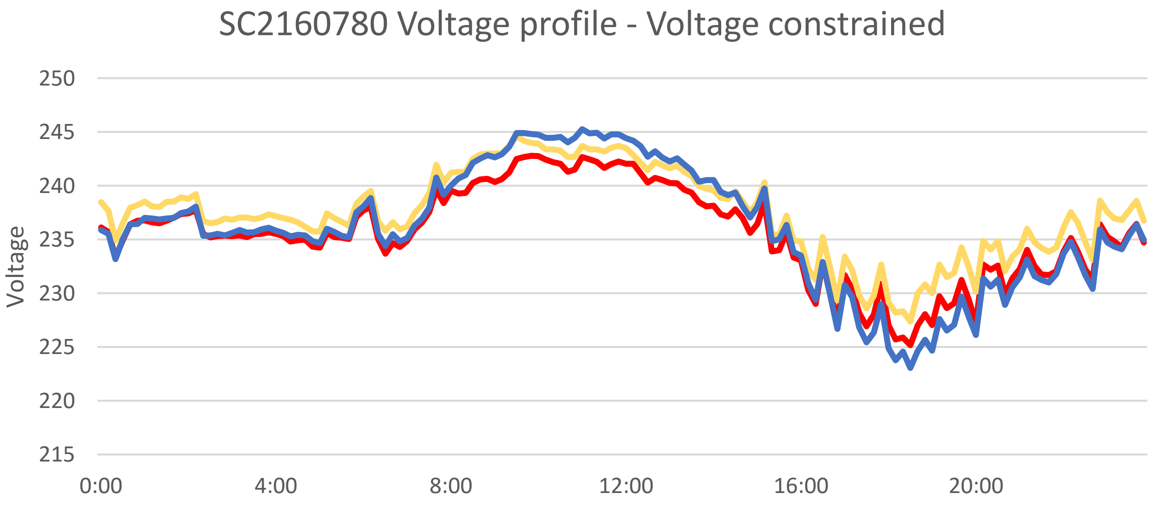


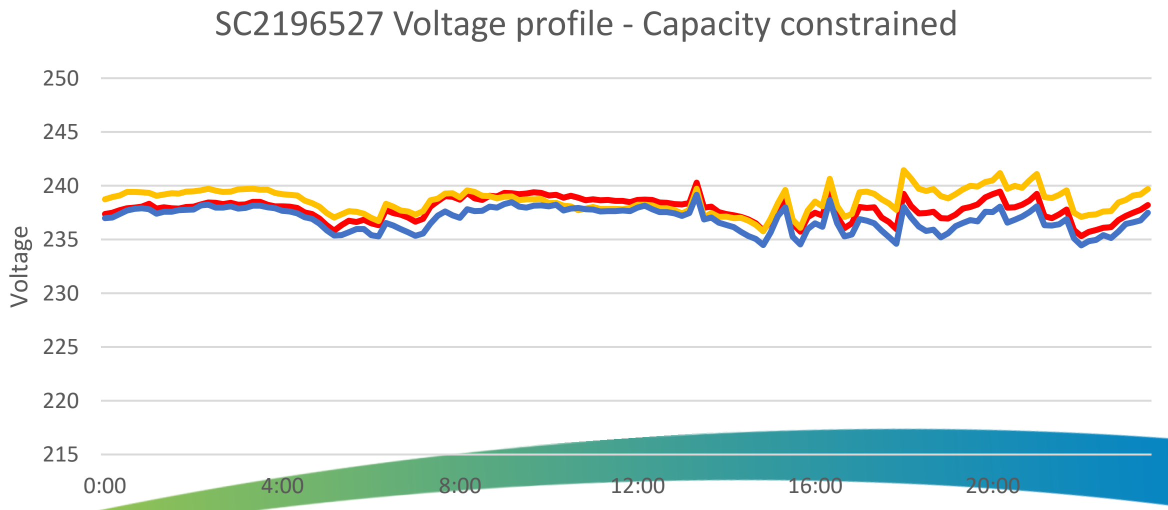
Quality of Supply Enquiry Categories

Voltage constrained VS Capacity constrained Distribution transformers





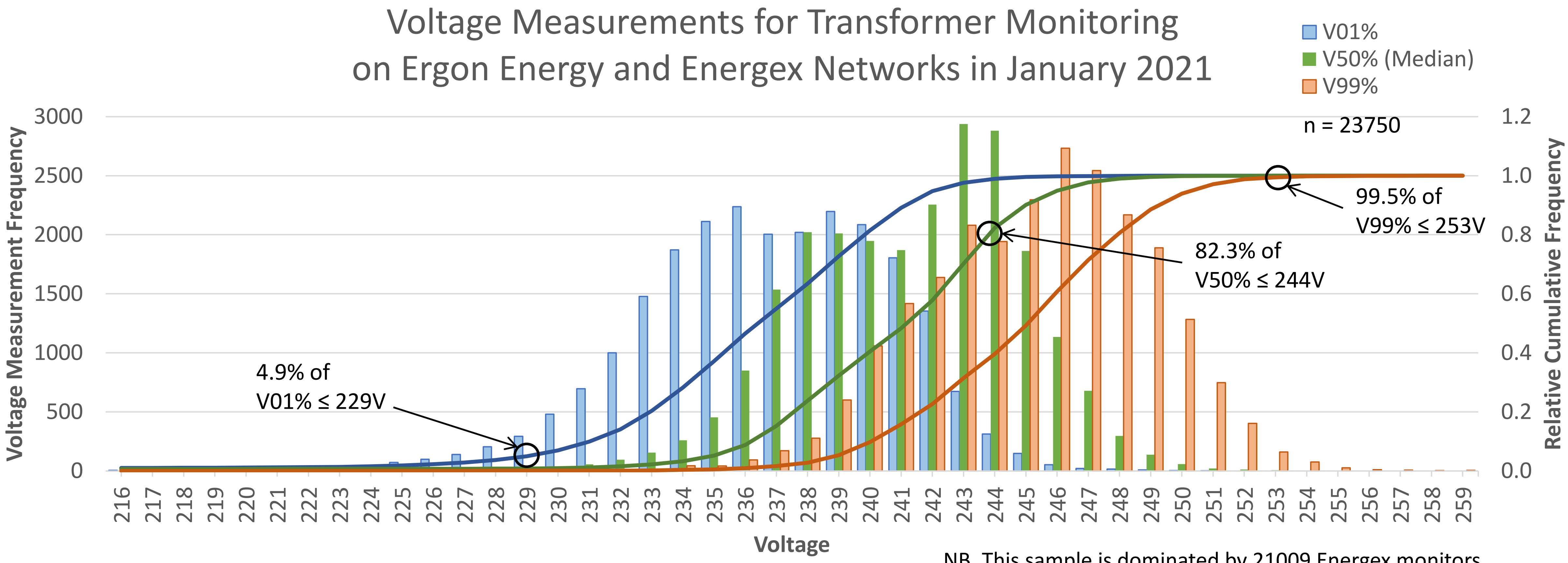




[Transformer monitoring data | Energex]

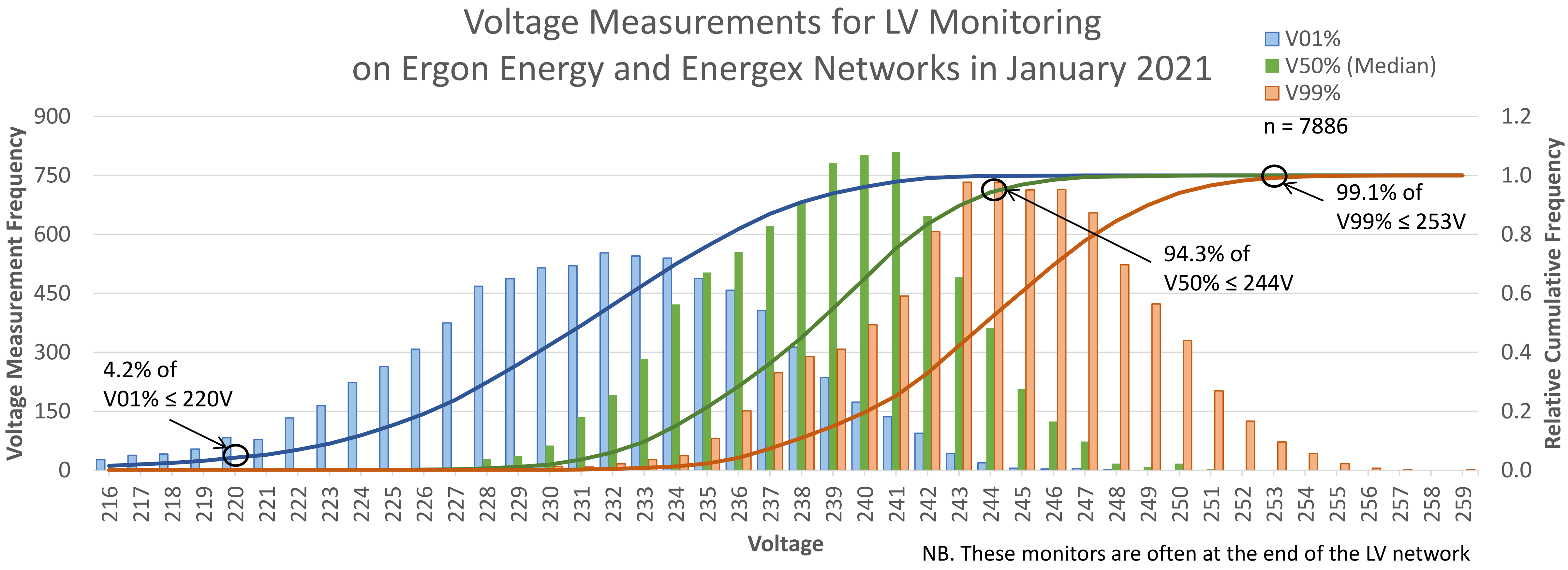
Steady-state voltage distribution

Transformer Monitoring – Jan 2021

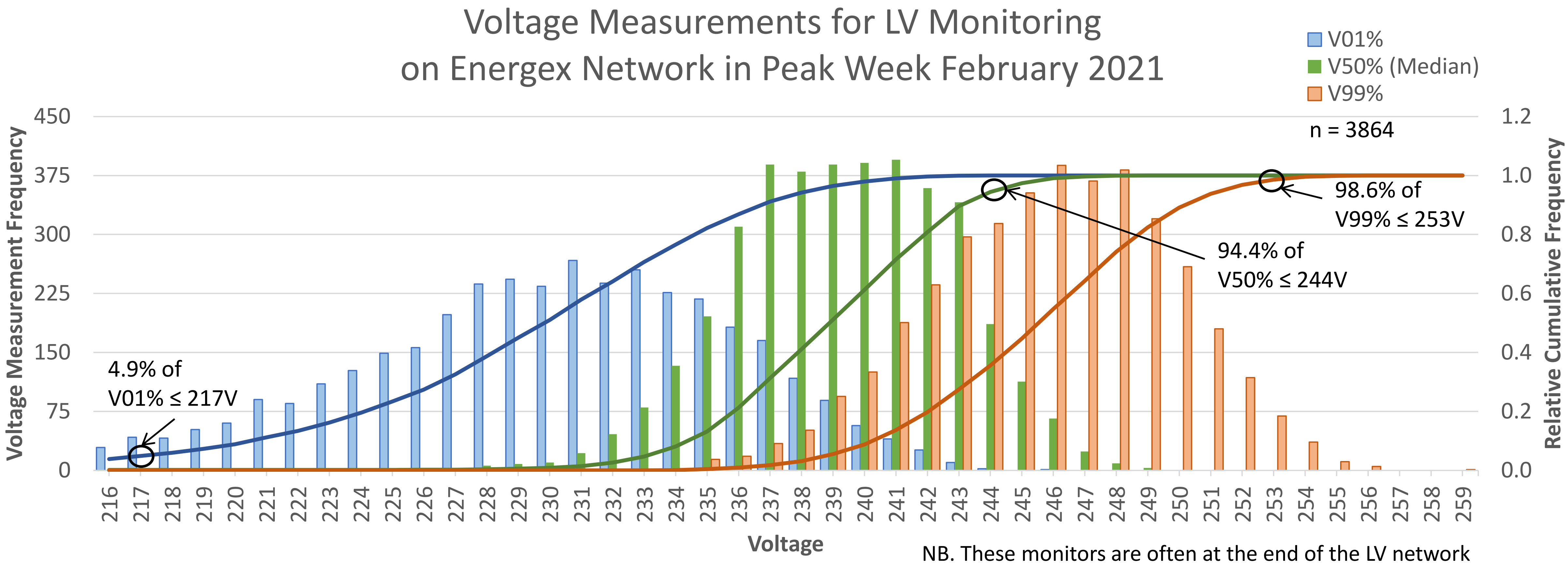


NB. This sample is dominated by 21009 Energex monitors

Low Voltage Monitoring – Jan 2021



Low Voltage Monitoring – Peak week Feb 2021



NB. These monitors are often at the end of the LV network

Smart Inverters and Grid Support Functions (GSF)

AS/NZS 4777.2:2020 Grid connection of energy systems via inverters, Part 2: Inverter requirements

Large Reactive Power Capability

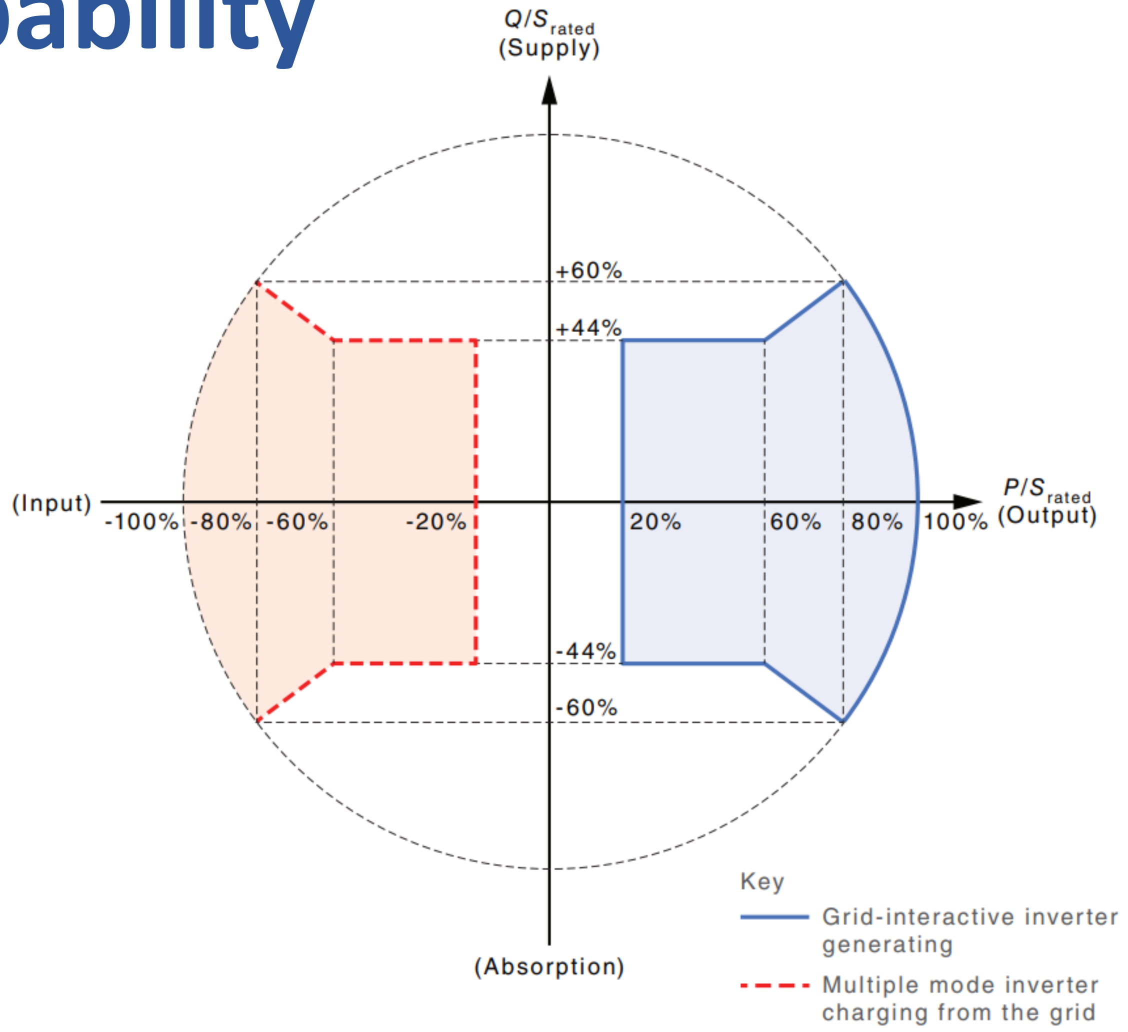


Figure 2.1 — Minimum reactive power capability

Volt-var response, mitigating voltage rise from reverse flow

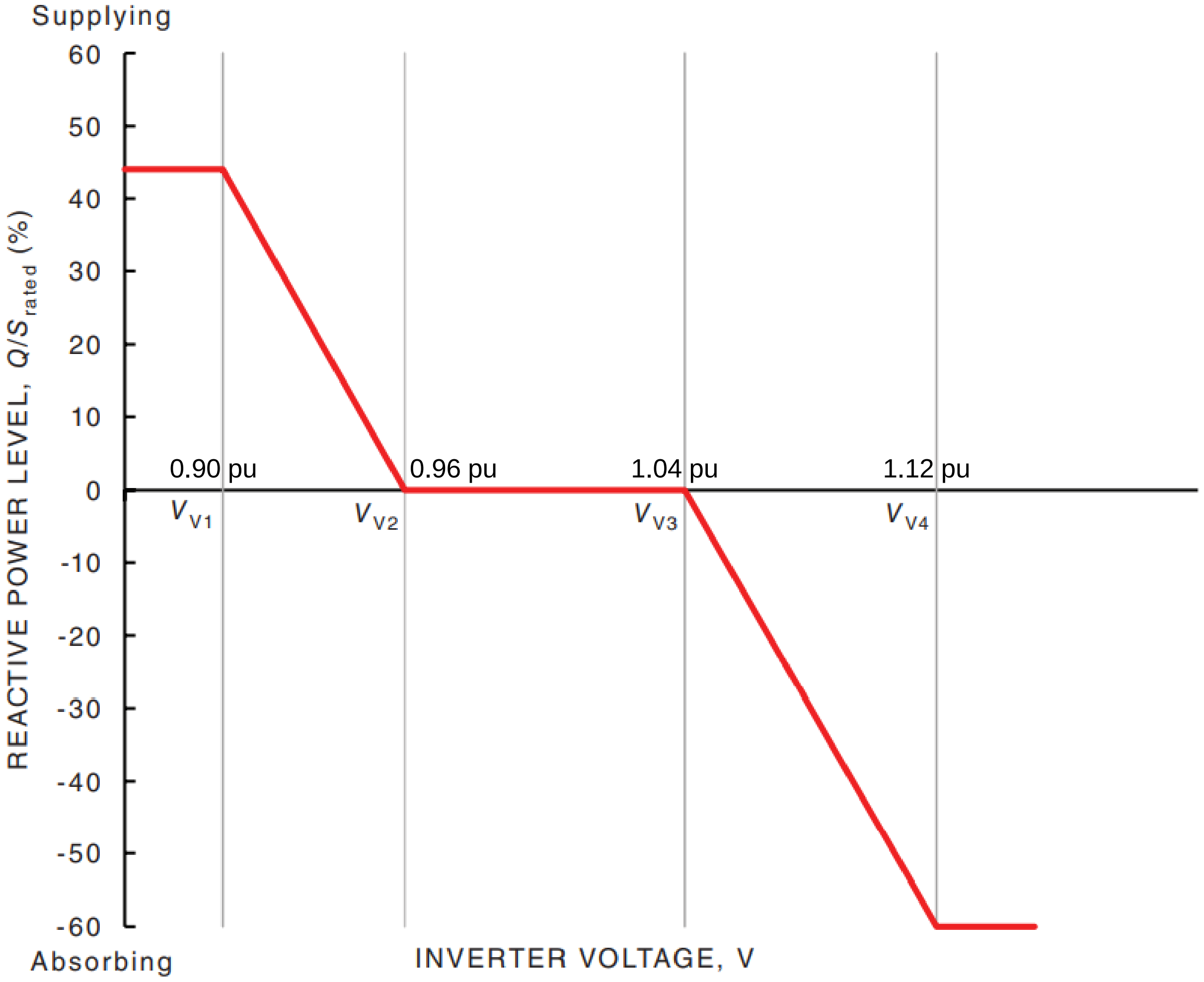


Figure 3.2 — Example curve for the volt-var control mode AS/NZS 4777.2:2020

Volt-watt response, limiting active power above 253V

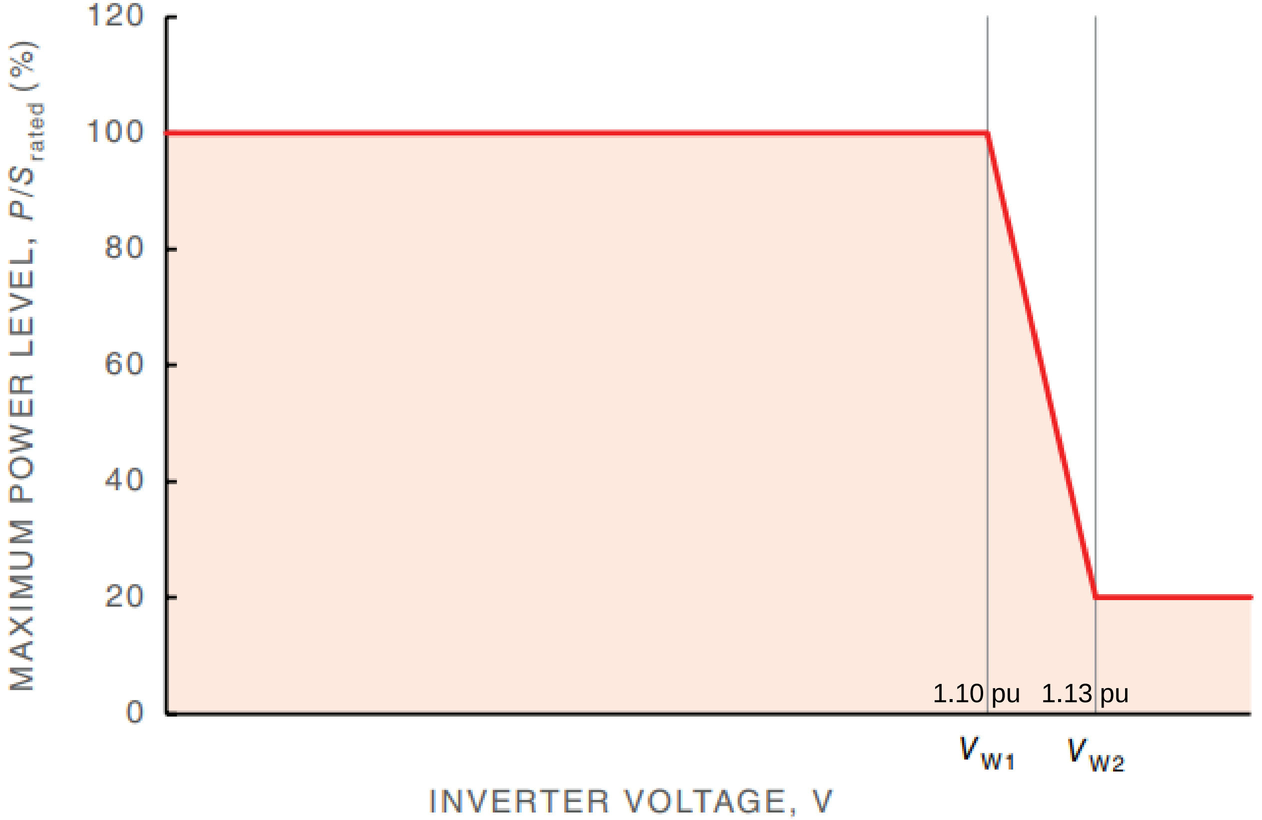
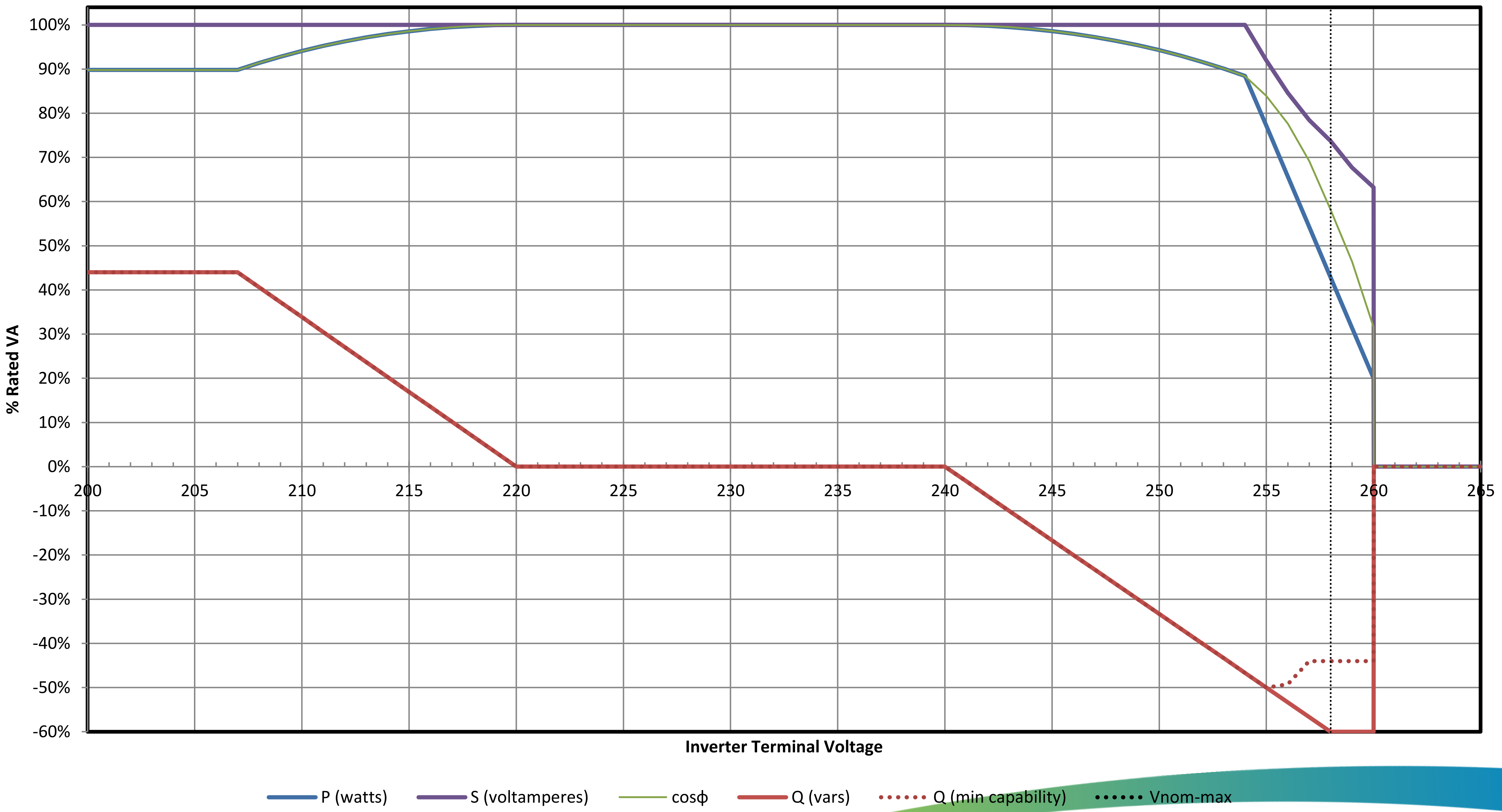


Figure 3.1 — Example curve for the volt-watt response mode

AS/NZS 4777.2:2020

Inverter Voltage Response – AS/NZS 4777.2 Australia A Region



For power system security, active power response to under and over frequency P(f)

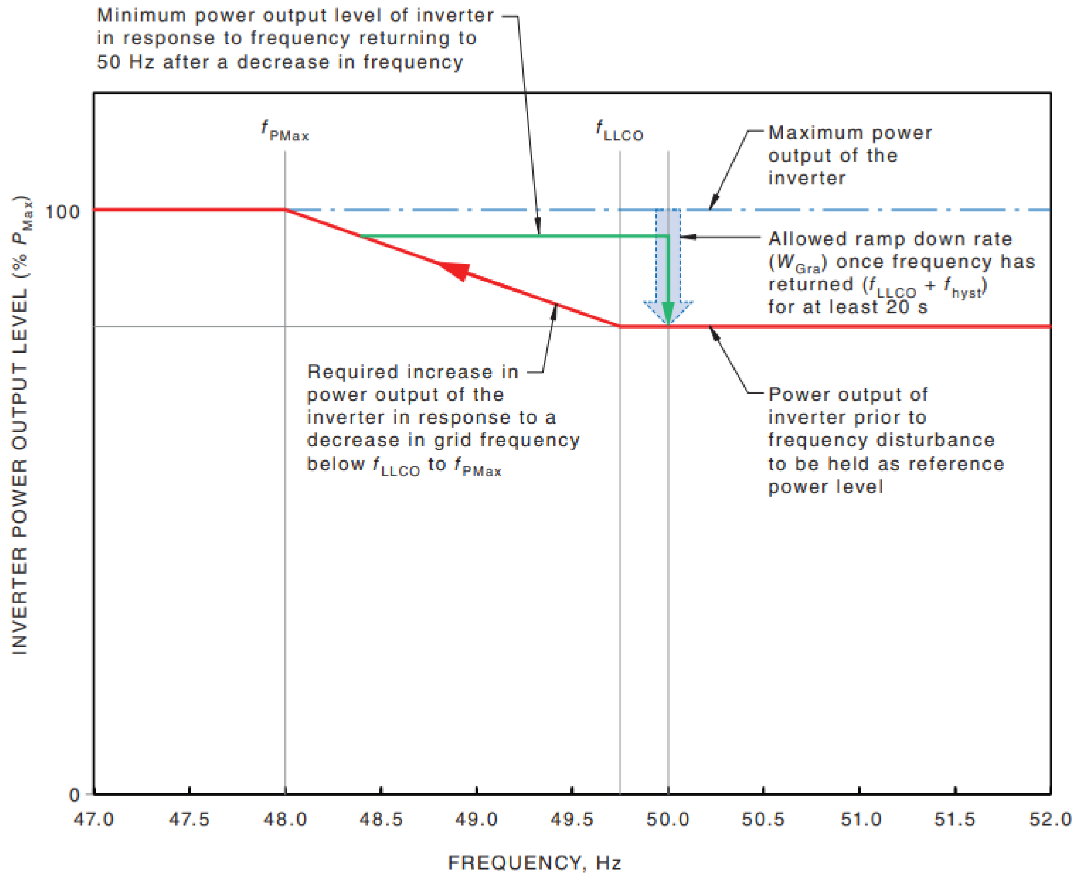


Figure 4.1 — Example frequency response for a decrease in frequency for an inverter that has a reduced output

+ Extensive voltage disturbance ride-through requirements

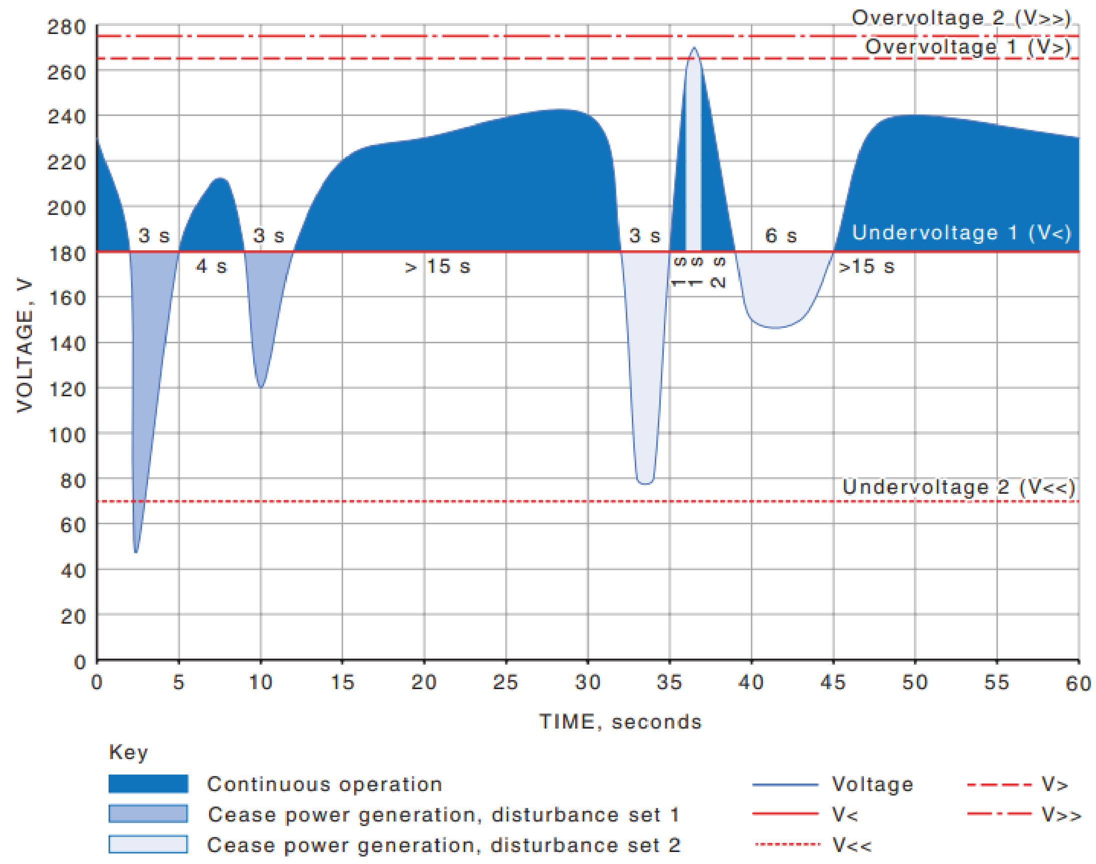


Figure 4.5 — Example of two multiple voltage disturbance events where the inverter is required to remain in continuous operation

Curtailment associated with volt-var and volt-watt

[Impacts of Voltage-Based Grid-Support Functions on Energy Production of PV Customers: Preprint (nrel.gov)]

TABLE II. IMPACT OF ACTIVATING GSF CONTROL ON PV SYSTEMS AND ENERGY CURTAILMENT AT DIFFERENT PENETRATION LEVELS

Metrics	GDML penetration levels					
	175%		370%		600%	
	VV	VV-VW	VV	VV-VW	VV	VV-VW
Max GSF Curt.	1.8%	2.3%	1.8%	3.7%	1.8%	5.7%
Ave. GSF Curt.	0.10%	0.07%	0.15%	0.13%	0.24%	0.23%
Ave. Incr. Gen.	2.1%	2%	2.7%	2.6%	2.7%	3%
Ave. Net Gen.	2%	1.9%	2.5%	2.4%	2.4%	2.8%

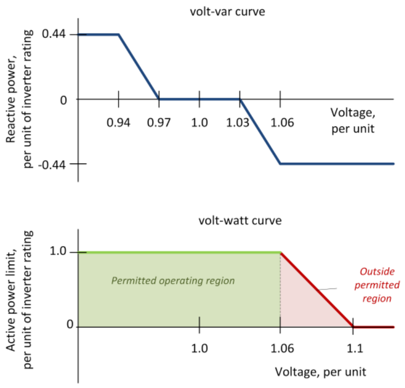


Fig. 1. The two voltage grid support functions and the settings used in this study

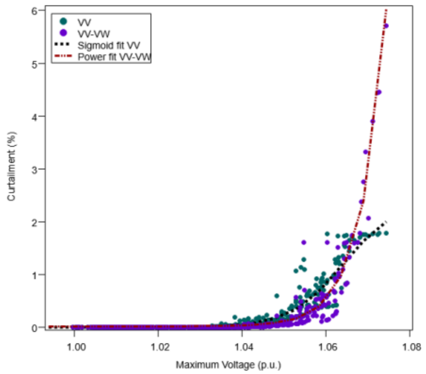


Fig. 6. Weekly customer energy curtailment versus maximum voltage for the high PV penetration case

[Real-world data analysis of distributed PV and battery energy storage system curtailment in low voltage networks - ScienceDirect]

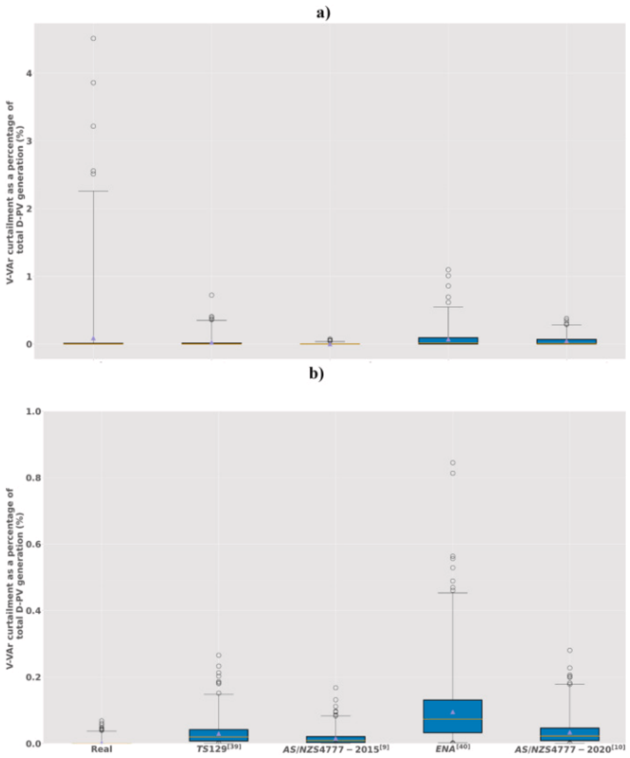


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Fig. 10. Measured and modelled V-VAr curtailment scenarios: a) D-PV only sites, b) D-PV coupled with BESS sites.

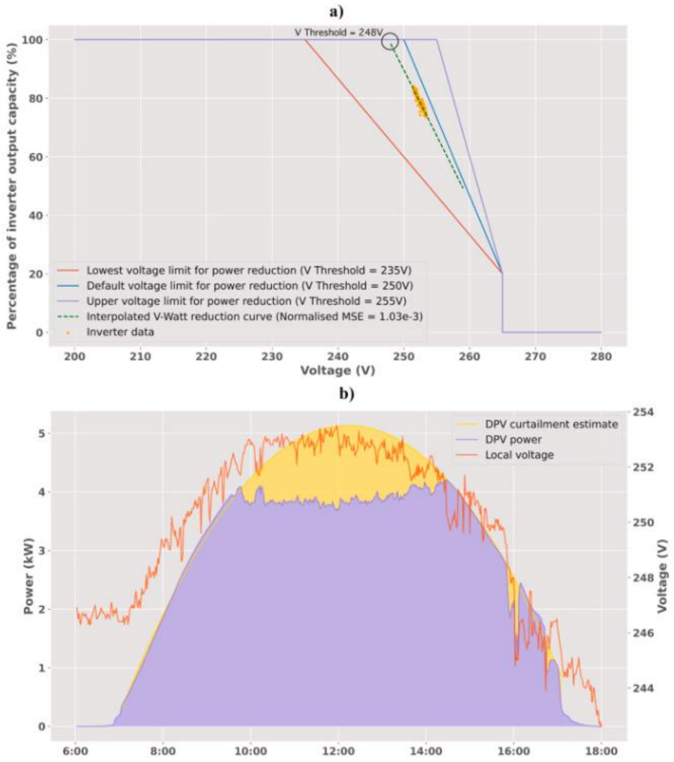

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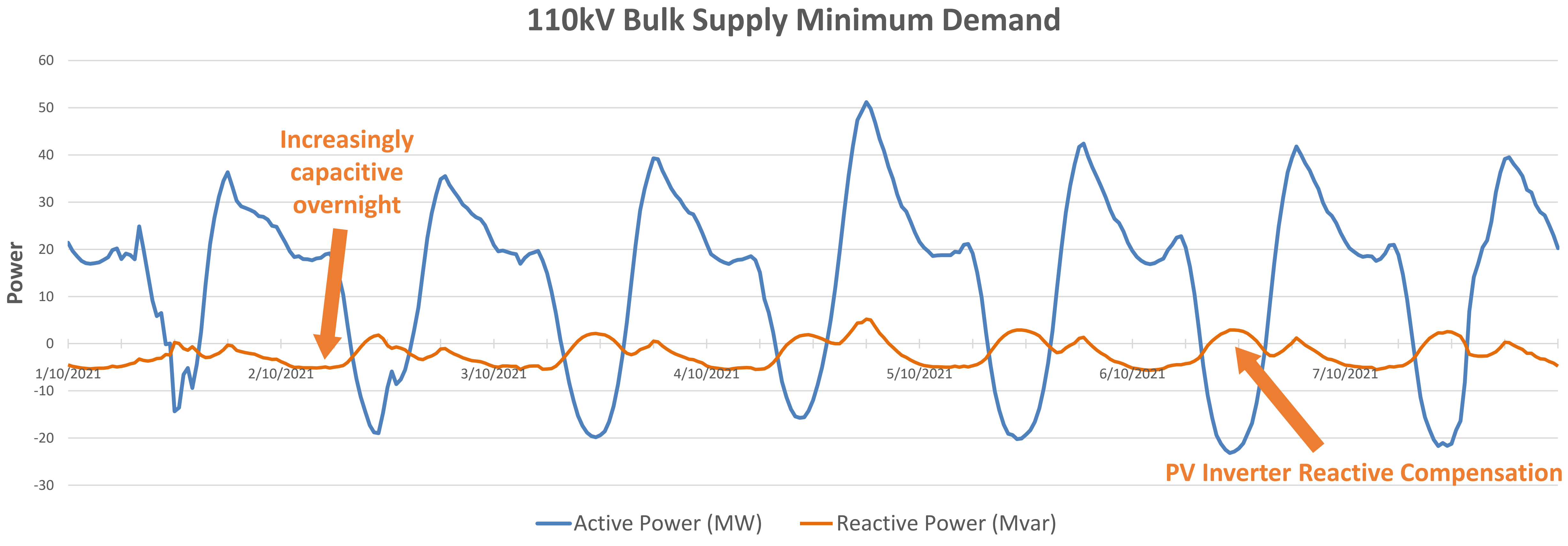
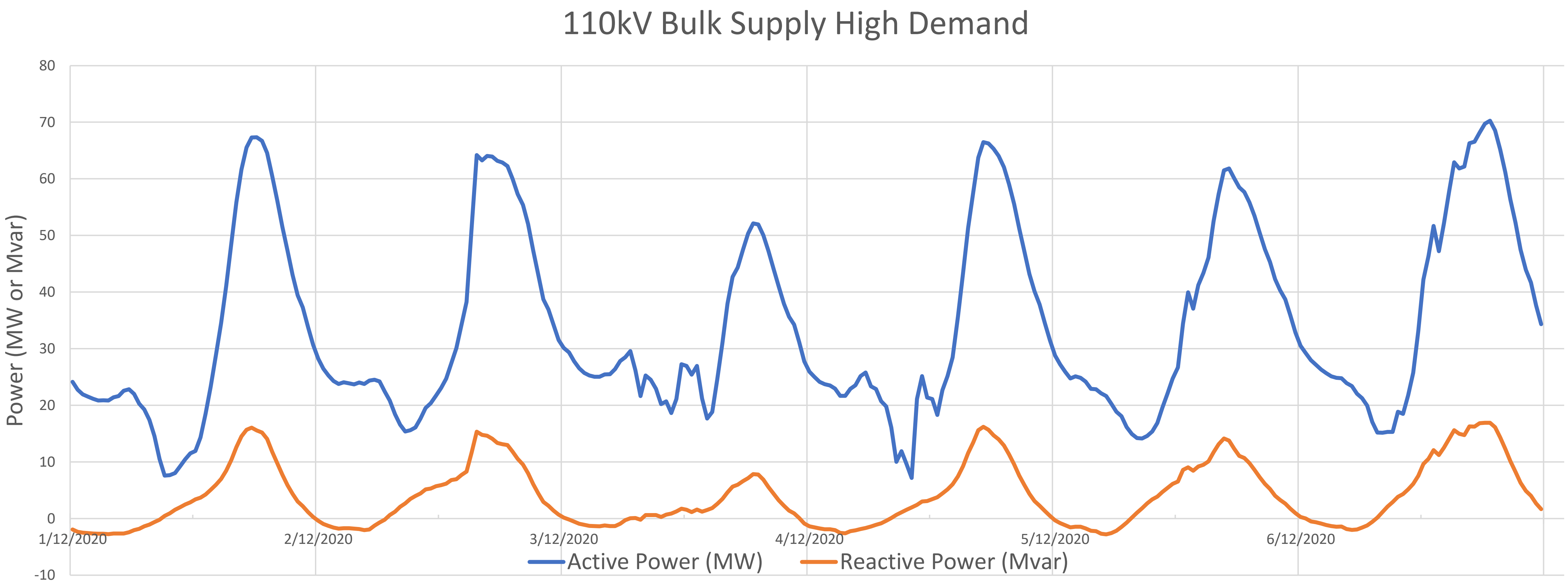
Fig. 11. a) V-Watt power reduction line and voltage threshold identification for a sample D-PV inverter, b) example daily operation with V-Watt curtailment.

Changing reactive power demand

PV inverters with GSF are absorbing reactive power at minimum demand

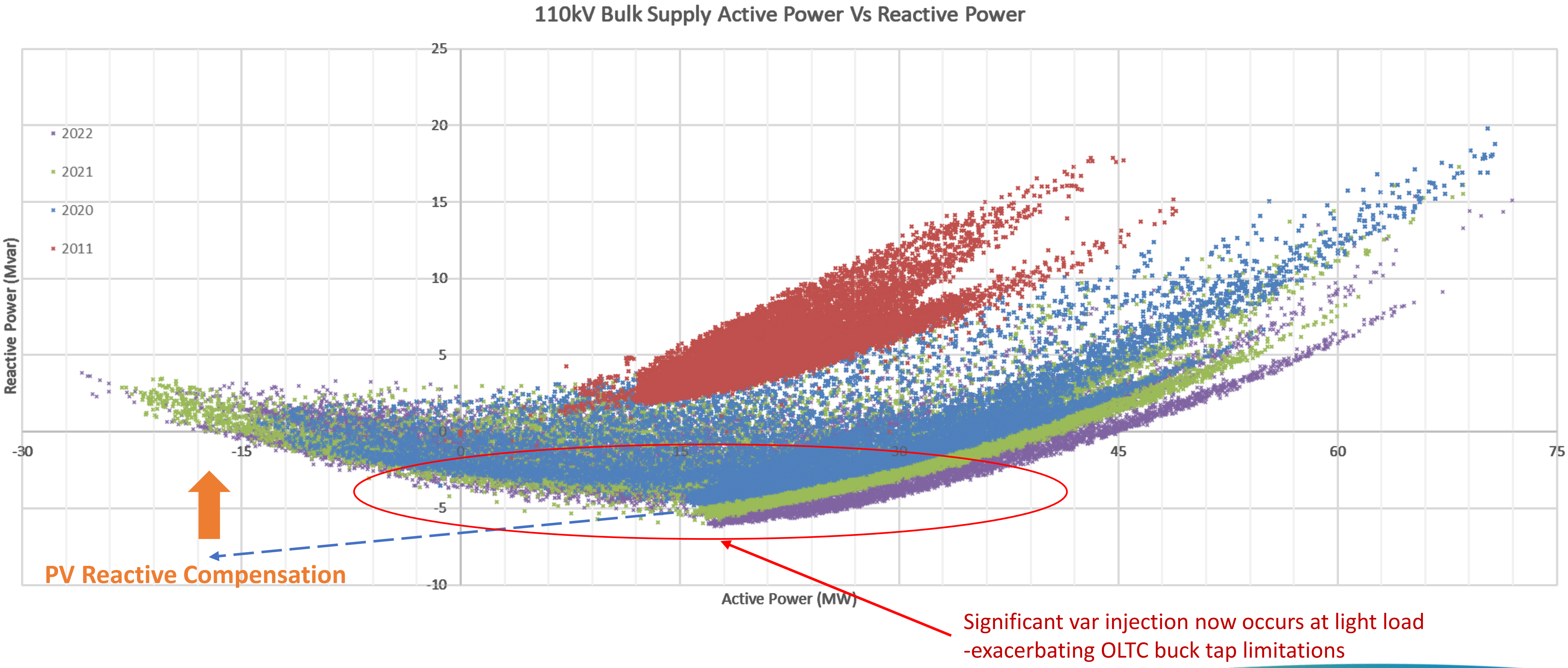


High Demand



110kV Bulk Supply High Demand
Power (MW or Mvar)
80
70
60
50
40
30
20
10
0
-10
1/12/2020
2/12/2020
3/12/2020
4/12/2020
5/12/2020
6/12/2020
Active Power (MW)
Reactive Power (Mvar)

Active Power Vs Reactive Power



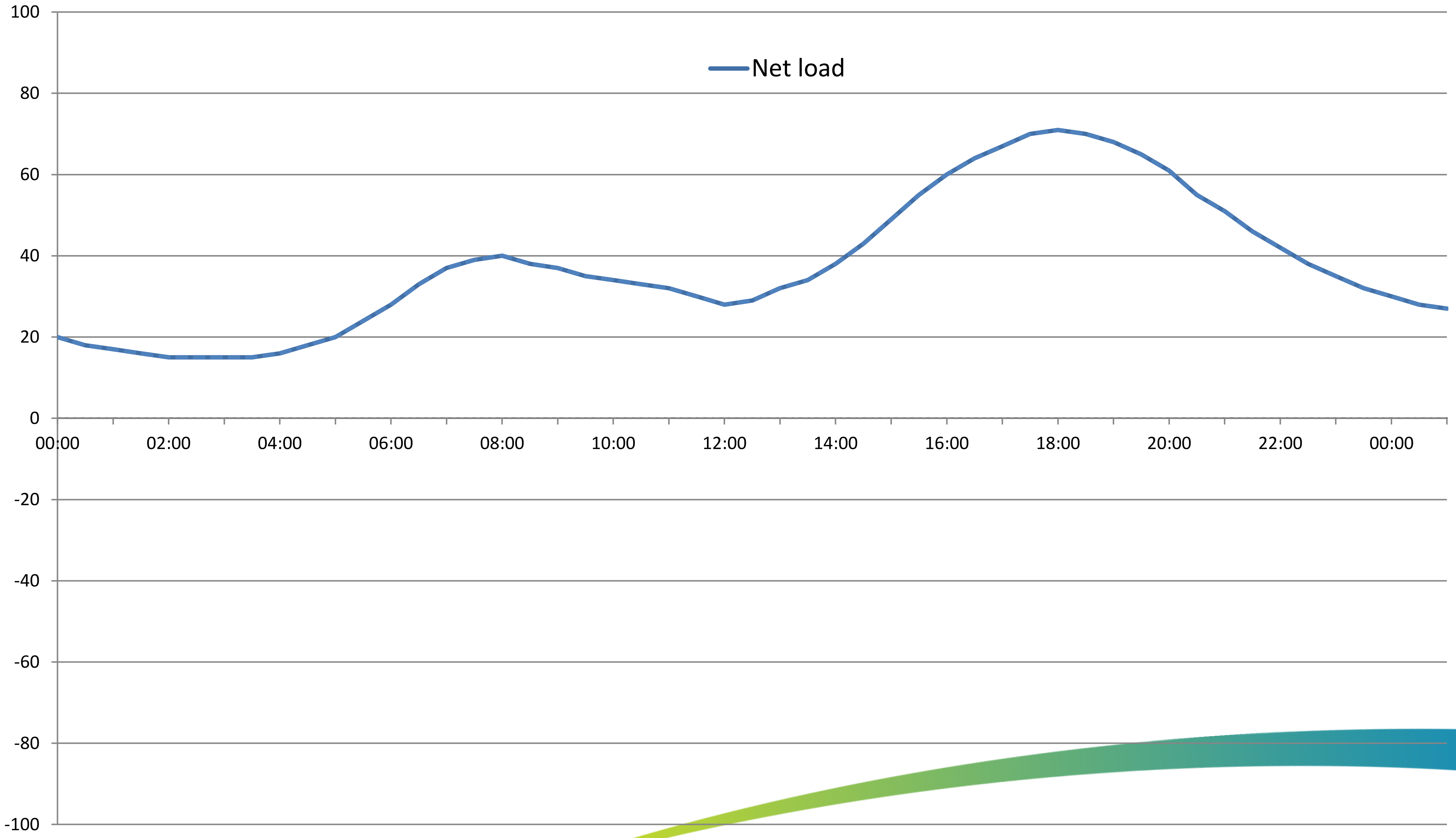
C.G. Kaloudas, L.F. Ochoa, B. Marshall, S. Majithia and I. Fletcher, "Assessing the Future Trends of Reactive Power Demand of Distribution Networks", IEEE Trans. on Power Syst., vol. 32, no. 6, 2017.

Dynamic Operating Envelopes (DOE)

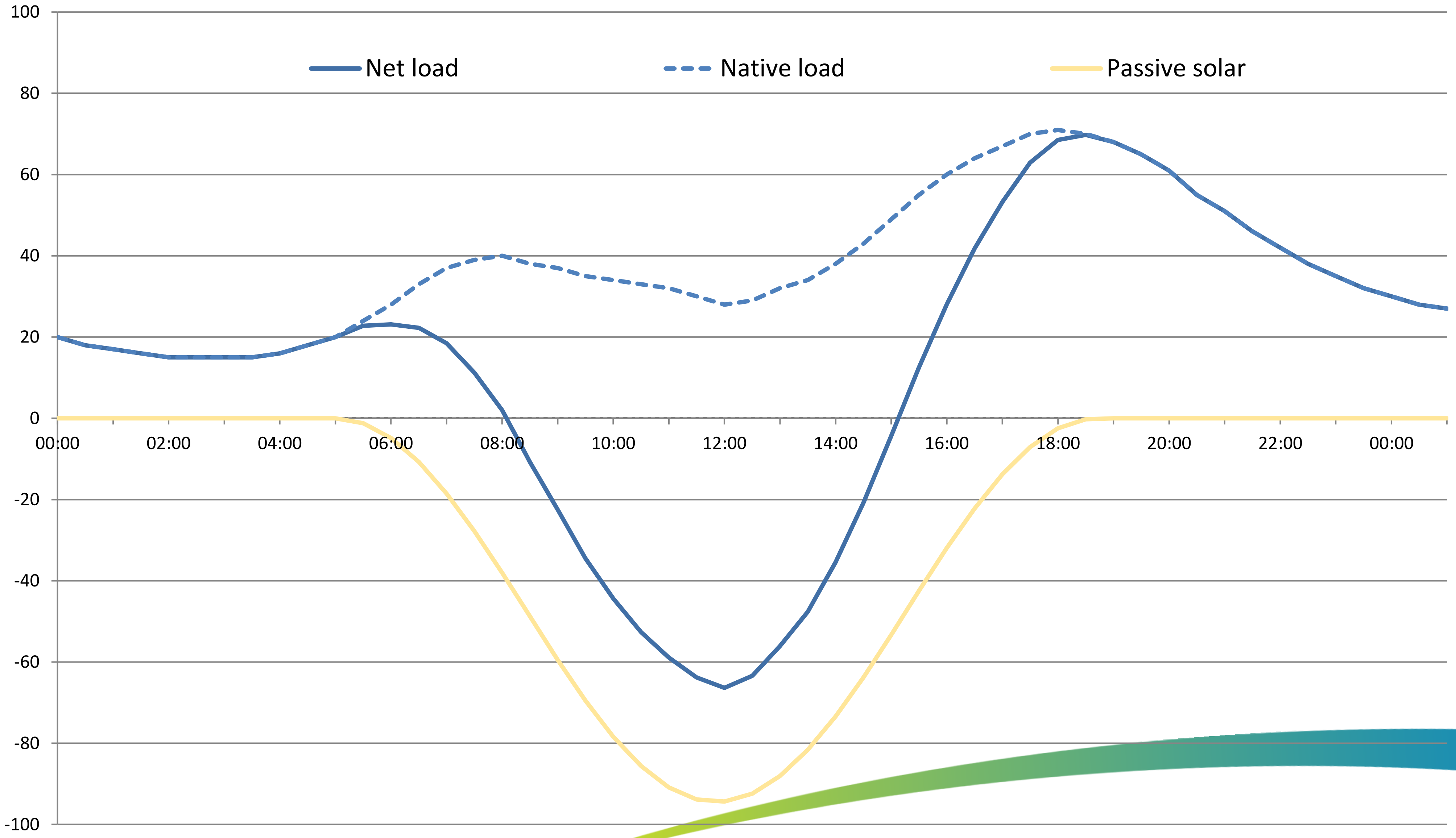
Dynamic Operating Envelopes

- A DOE specifies a varying operating range, typically at the connection point, for exports and/or imports.
- This can apply to a range of DER including PV, BESS and EV.
- It can be used in conjunction with autonomous DER responses to ensure network/system constraints are not breached by DER operation.
- DOE differ from demand response in that they do not dispatch or target a response; but specify the limits of active power import or export. Within the limits DER behaviour is unaffected.
- DOE also permit a range of behind-the-meter responses to achieve the specified limit – curtailment isn’t necessarily required.
- While DOE are initially limited by existing visibility and systems, as capabilities scale and grid visibility increases, the DOE we send to active DER can be optimised
- Now supported by two protocols IEEE2030.5 CSIP-AUS and OpenADR 3.0

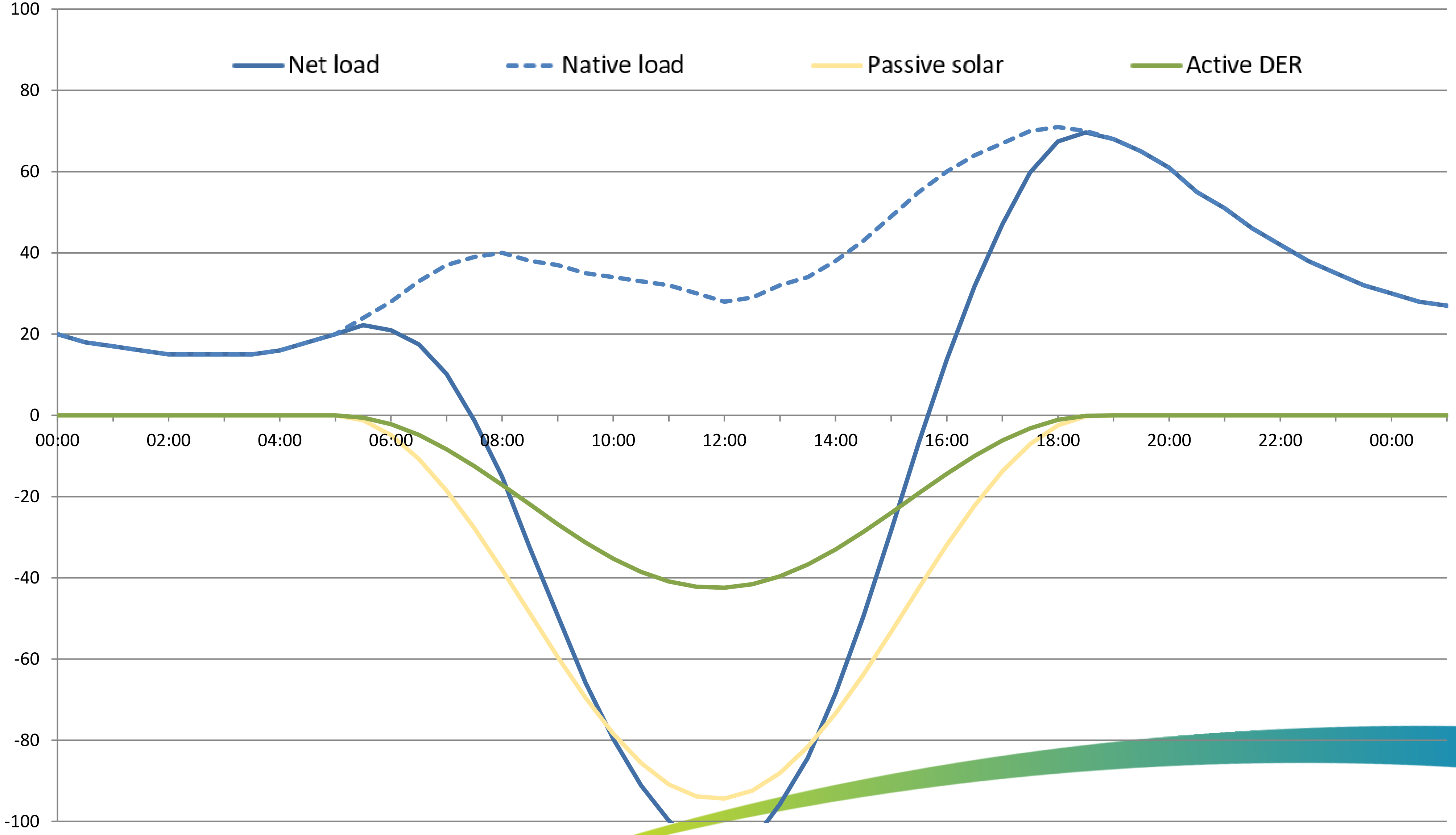
Native/underlying Load (before DER operation)



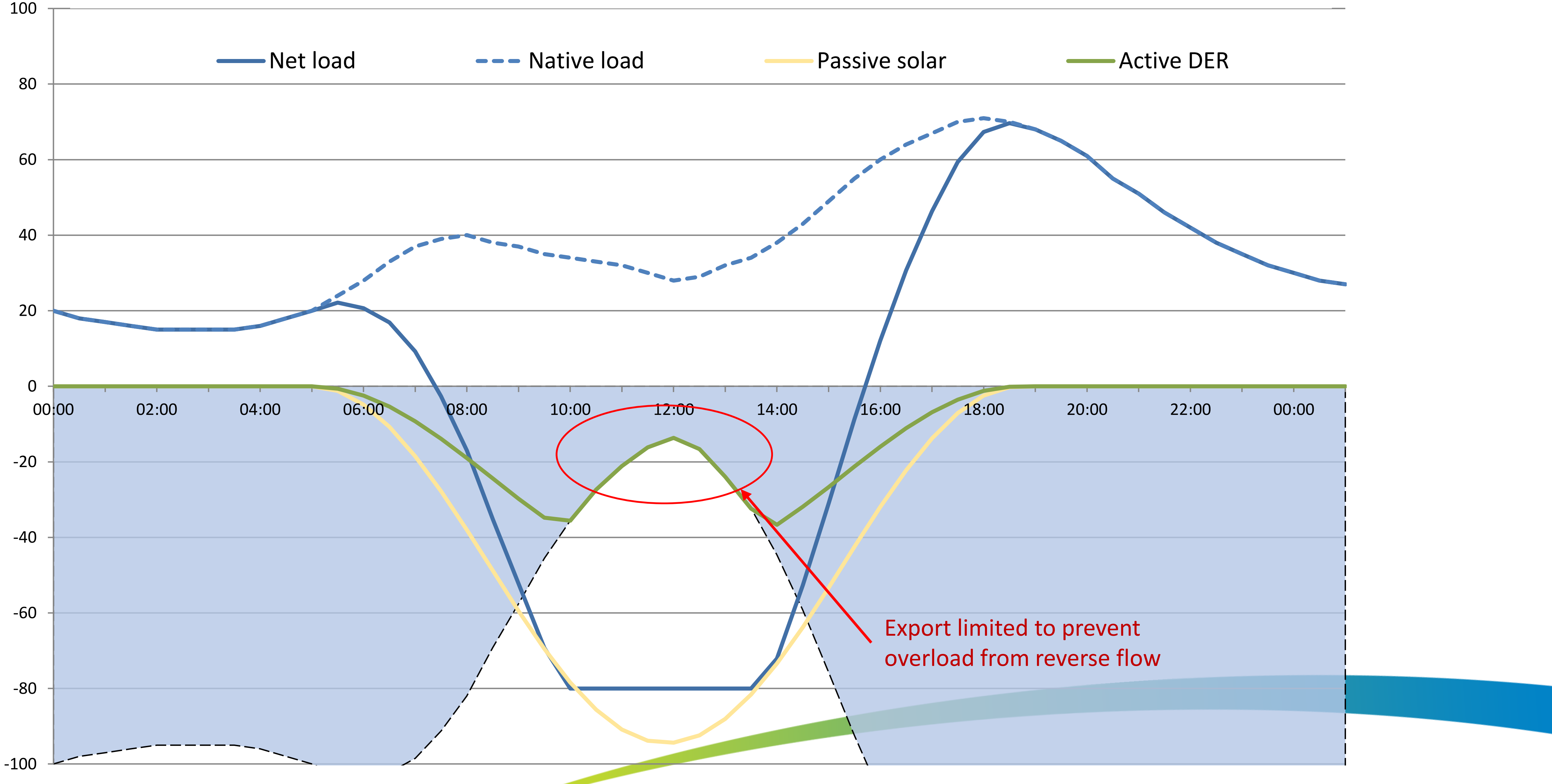
Net Load with significant PV generation



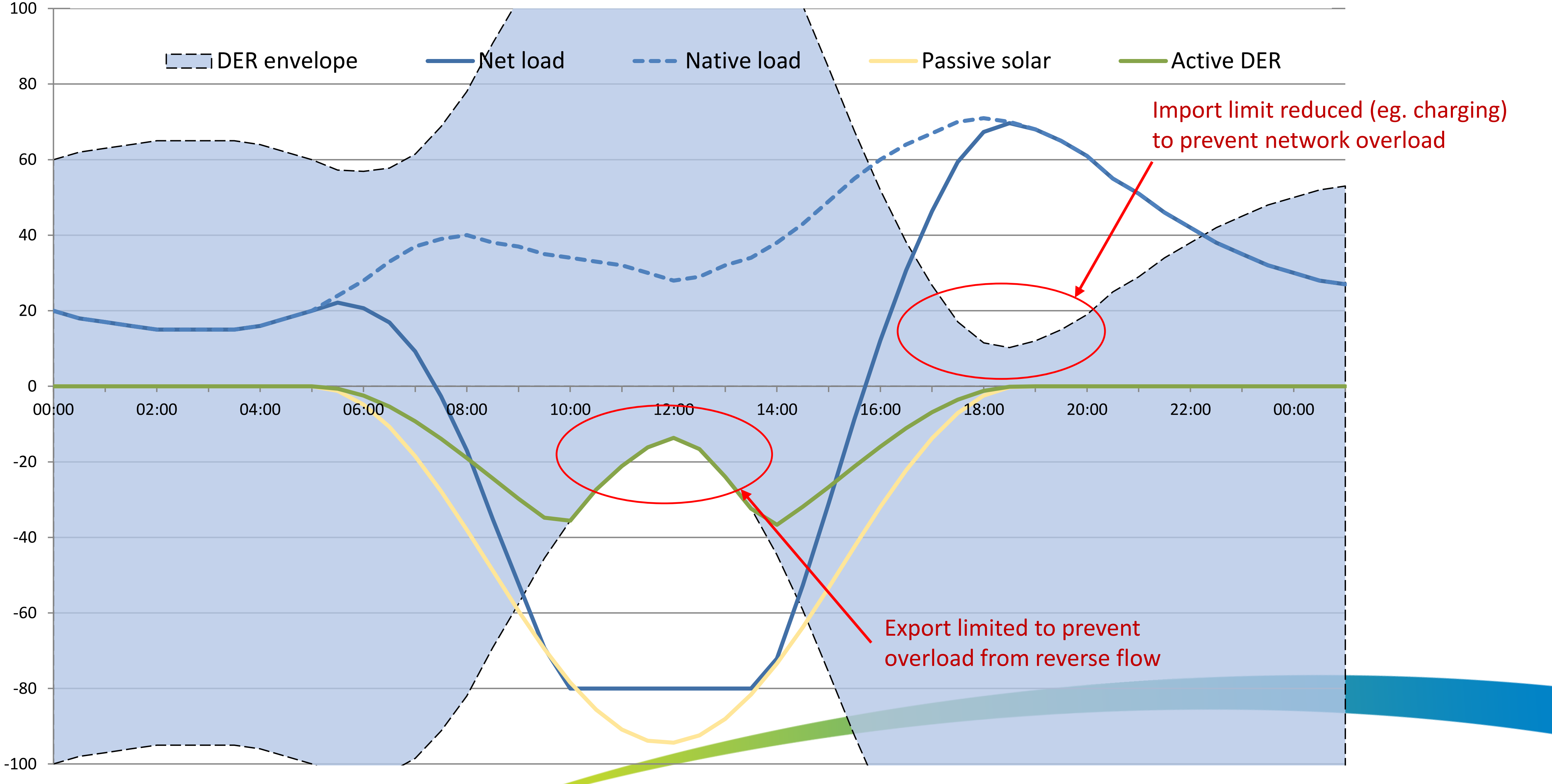
Net Load with additional PV generation can breach capacity constraints

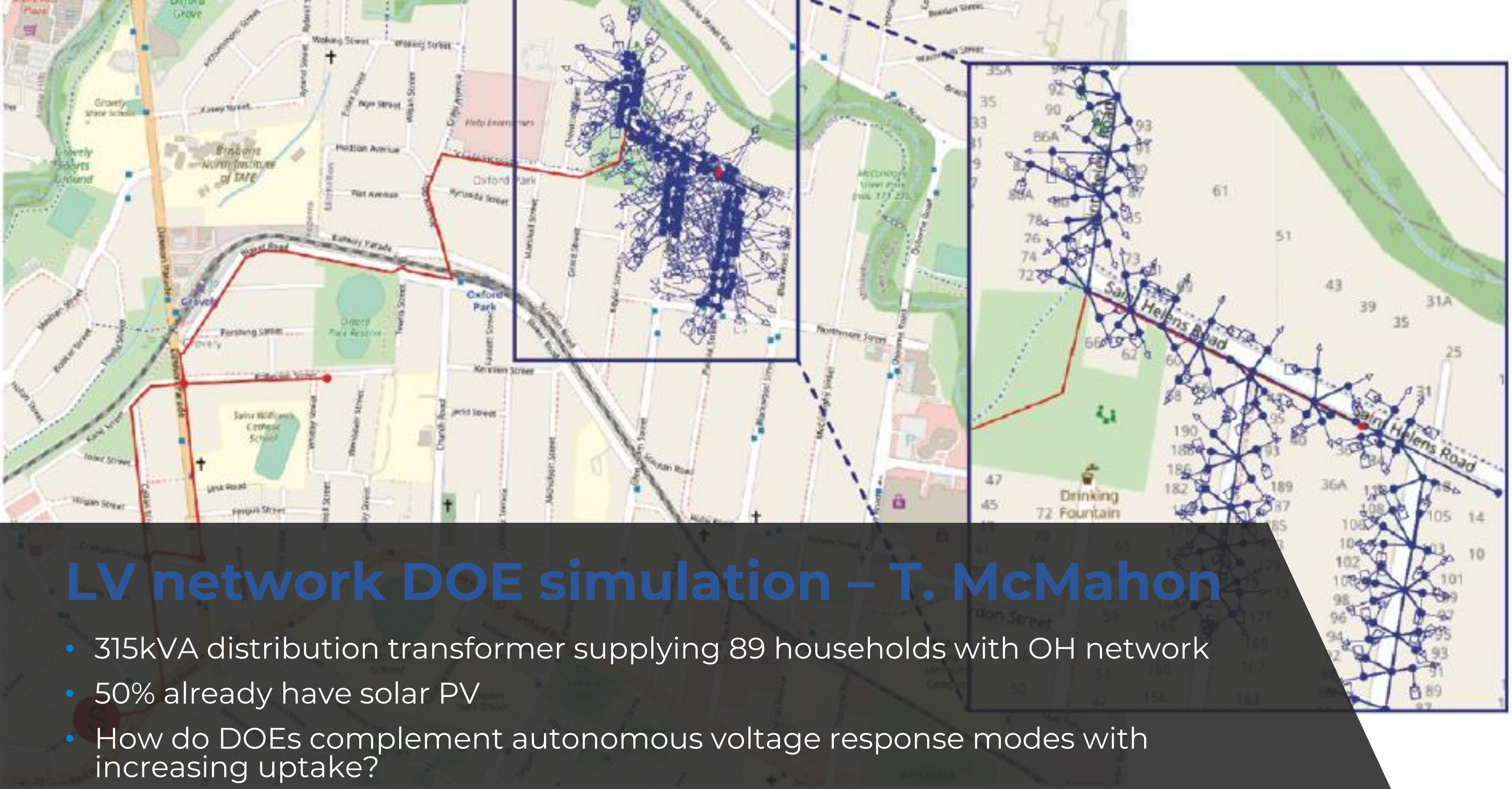


Net Load with significant PV generation
Newer PV managed with DOE



DOE can manage constraints associated with load also





LV network DOE simulation – T. McMahon

- 315kVA distribution transformer supplying 89 households with OH network
- 50% already have solar PV
- How do DOEs complement autonomous voltage response modes with increasing uptake?

Figure 5: Model developed in PowerFactory of study case on a section of the GLY15A

Existing 50% penetration

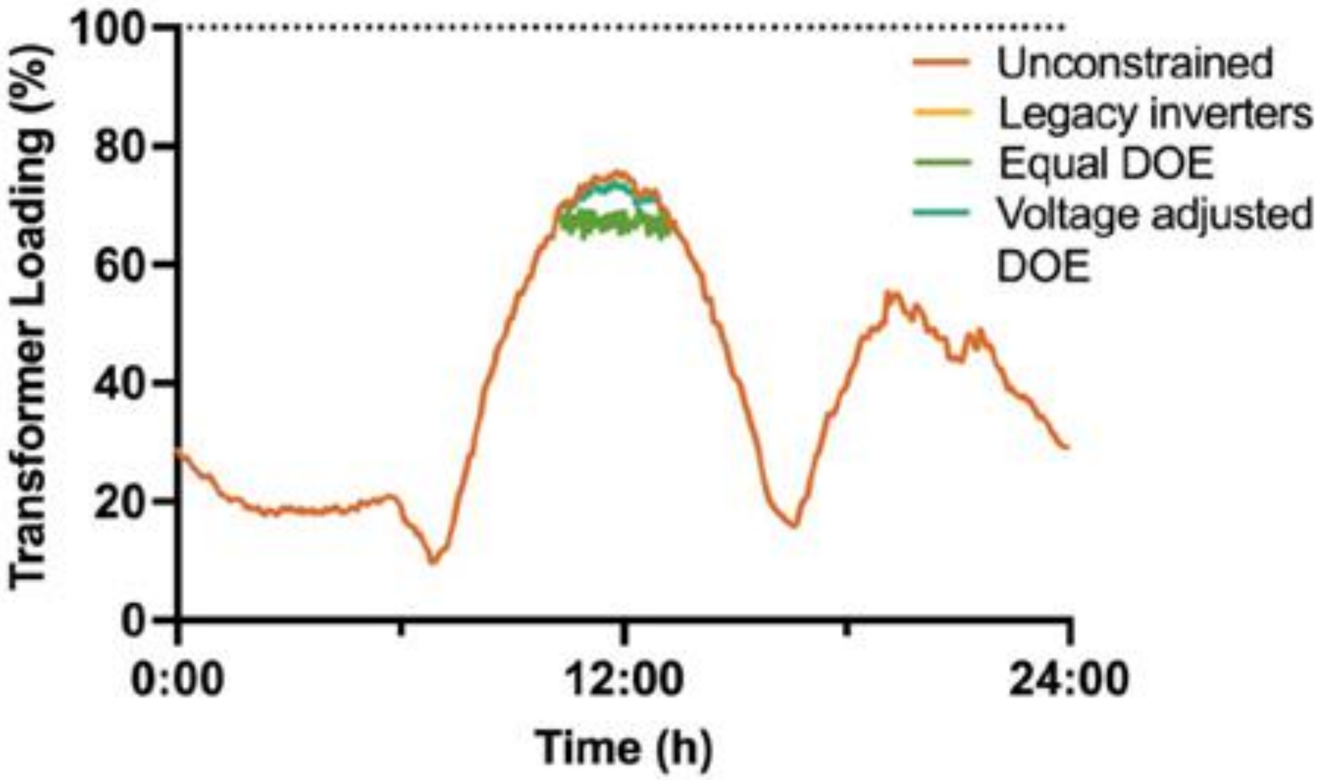


Figure 14: Transformer loading in existing solar PV scenario. Transformer loading threshold (black dotted line).

Simulating 100% PV penetration

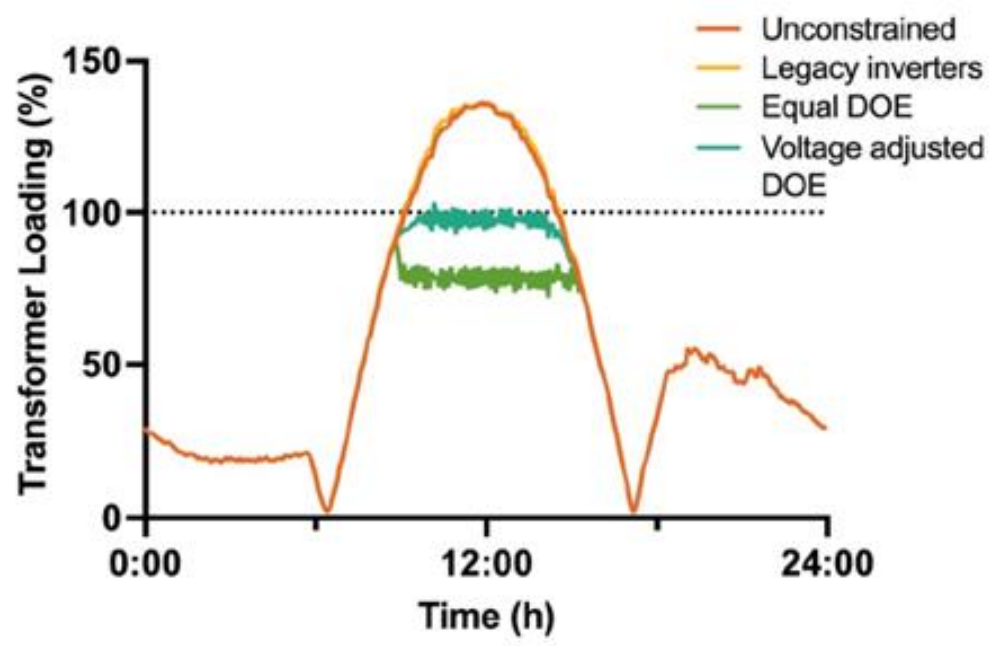


Figure 25: Transformer loading in 100% solar PV scenario. Transformer loading threshold (black dotted line).

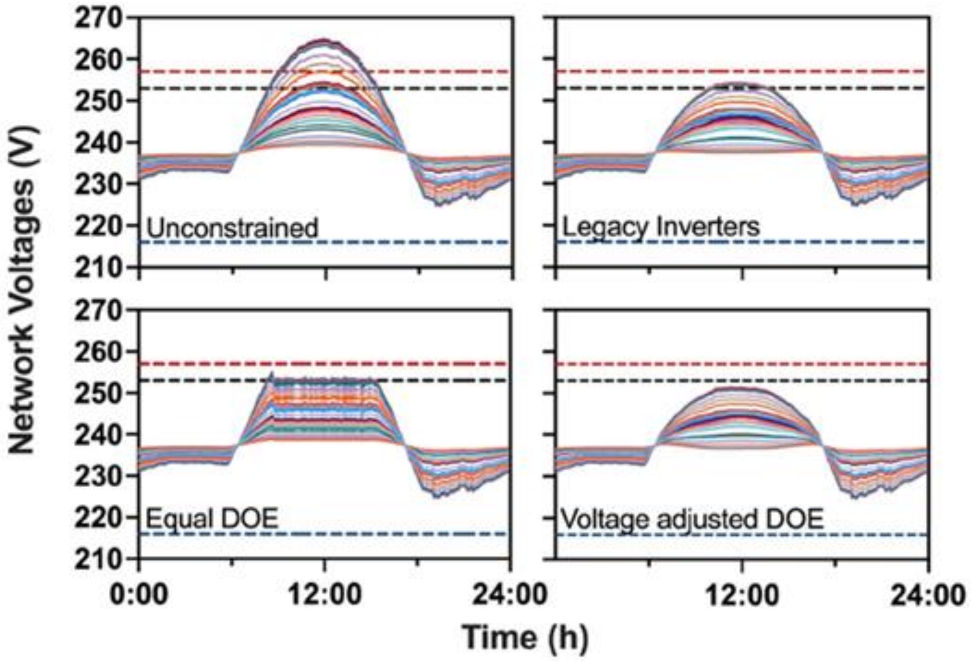
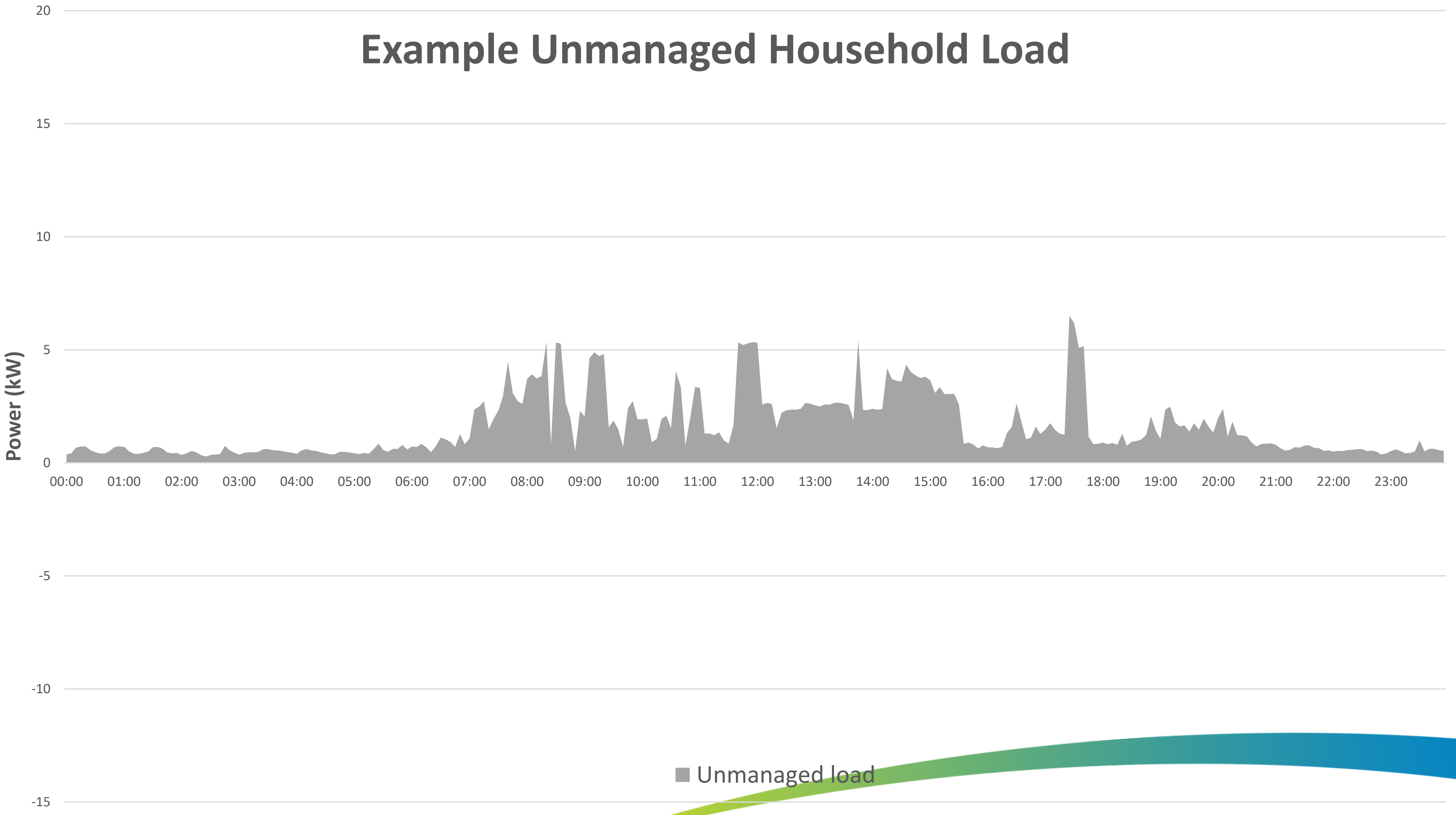


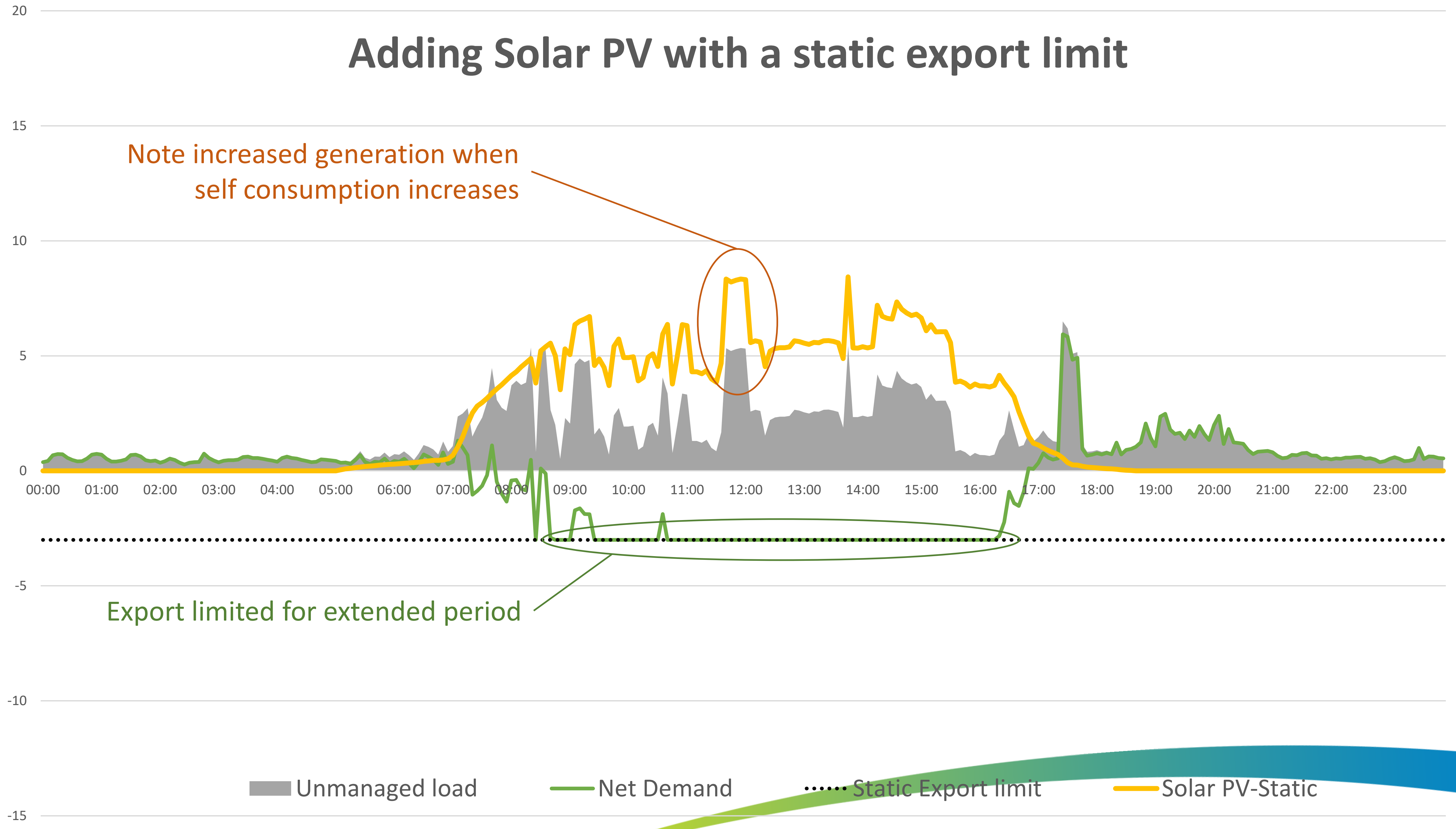
Figure 24: Network voltages (phase A) for all cases in 100% solar PV scenario. Overvoltage tripping limit 257 V (red dotted line), upper voltage threshold 253 V (black dotted line), lower voltage threshold 216 V (blue dotted line).

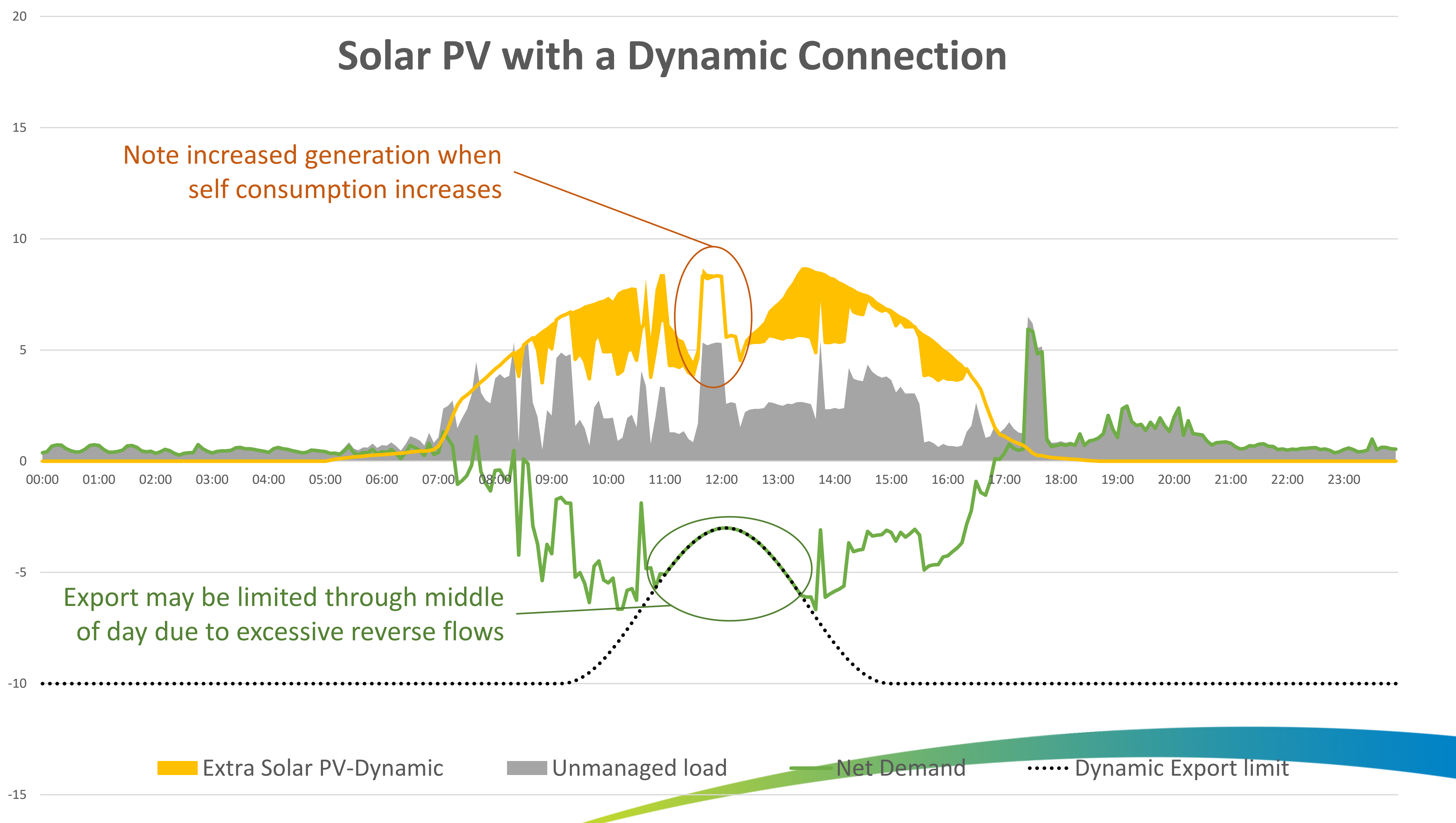
Example of a Dynamic Connection

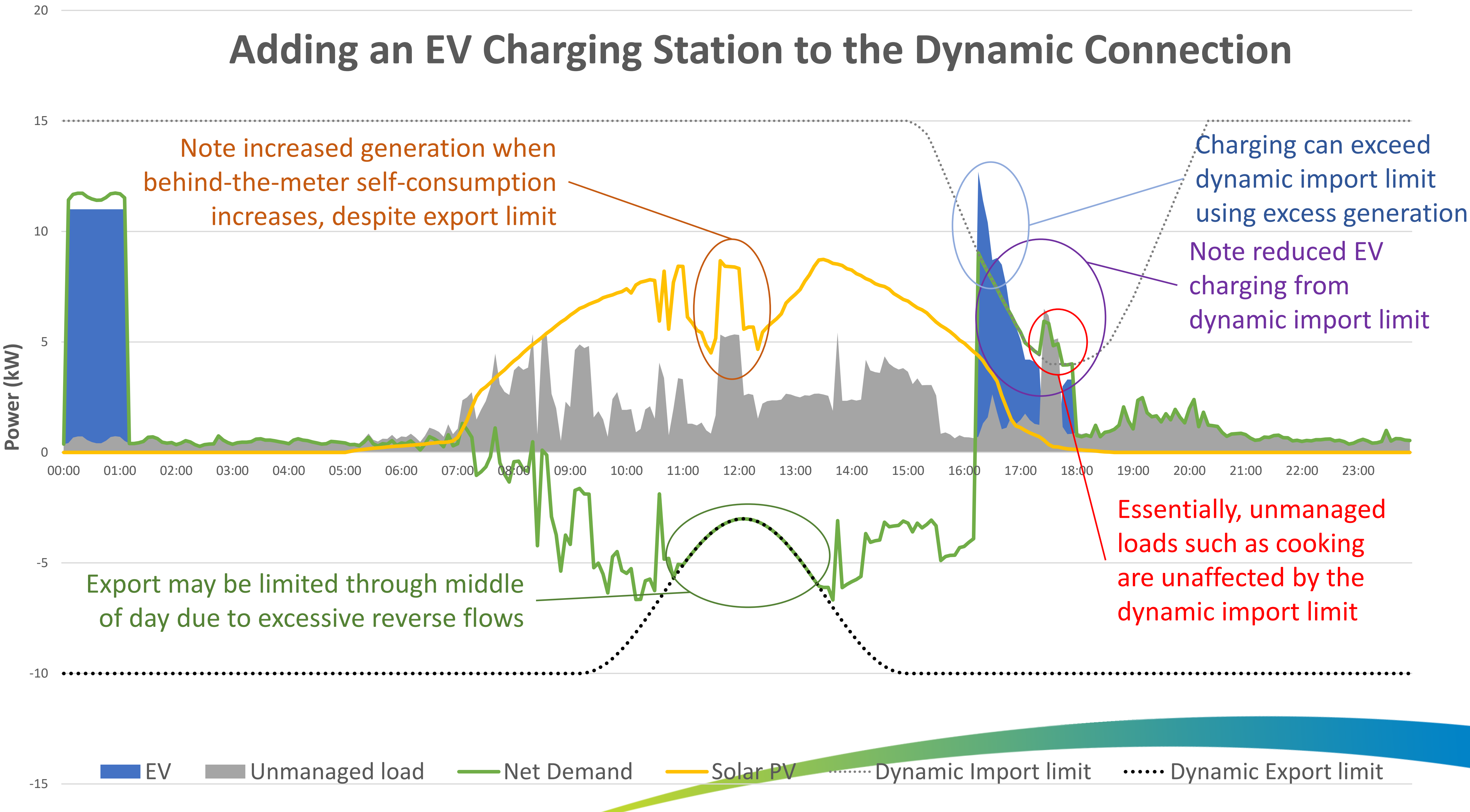
Example Unmanaged Household Load



Adding Solar PV with a static export limit




Solar PV with a Dynamic Connection
Note increased generation when self consumption increases
Export may be limited through middle of day due to excessive reverse flows
20
15
10
5
0
-5
-10
-15
00:00
01:00
02:00
03:00
04:00
05:00
06:00
07:00
08:00
09:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
18:00
19:00
20:00
21:00
22:00
23:00
Extra Solar PV-Dynamic
Unmanaged load
Net Demand
Dynamic Export limit



Adding an EV Charging Station to the Dynamic Connection
Note increased generation when behind-the-meter self-consumption increases, despite export limit
Charging can exceed dynamic import limit using excess generation
Note reduced EV charging from dynamic import limit
Essentially, unmanaged loads such as cooking are unaffected by the dynamic import limit
Export may be limited through middle of day due to excessive reverse flows
Power (kW)
20
15
10
5
0
-5
-10
-15
00:00
01:00
02:00
03:00
04:00
05:00
06:00
07:00
08:00
09:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
18:00
19:00
20:00
21:00
22:00
23:00
EV
Unmanaged load
Net Demand
Solar PV
Dynamic Import limit
Dynamic Export limit

Electrification – surfing CER wave

Electrification of residential & commercial loads also present opportunities for customer DER flexibility to reduce energy costs and curtailment

Figure 63 Components of Queensland residential electricity consumption forecast, ESOO Central scenario, 2023-24 to 2052-53 (TWh)

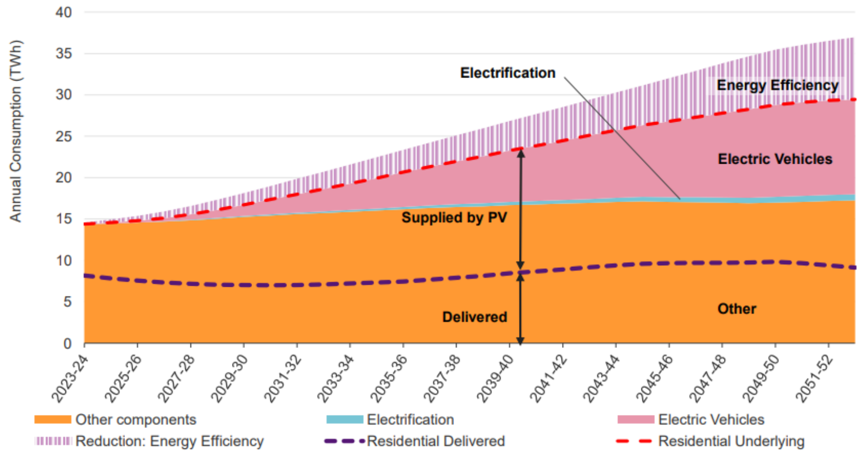
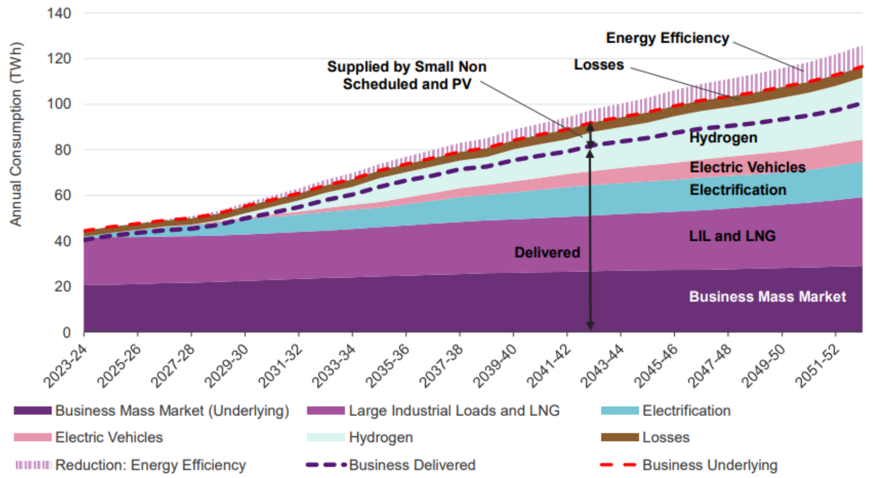
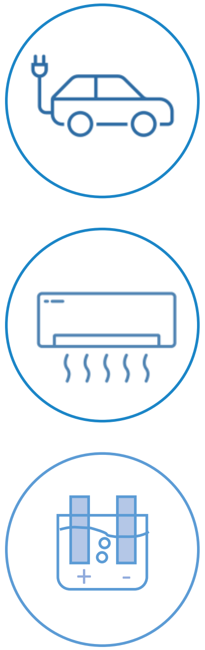


Figure 64 Components of Queensland business electricity consumption forecast, ESOO Central scenario, 2023-24 to 2052-53 (TWh)



Note: Small non-scheduled combines PVNSG and ONSG.



Most new electrified demand is flexible (suitable for demand management/smart charging via DERMS) limiting contribution to peak demand, and reducing curtailment, whilst increasing distribution network utilisation

2023 Electricity Statement of Opportunities (aemo.com.au)

Increasing DER integration supported by emerging DSO capabilities

- In a bit over a decade solar PV capacity in Qld has increased 1000 fold, primarily on the distribution network
- The 230V standard & improved distribution voltage regulation accommodates more voltage rise/PV
- Advanced autonomous inverter GSF mitigate impacts and maximise PV penetration
- DOE enables active DER management & DER service participation to maximise hosting capacity
- This and other DSO capabilities enable customers to surf the DER wave

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