Overcoming The Grid's Hosting Capacity Barriers

Power Session Webinar

23 January 2024

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Speaker – Ezra Beeman, Energeia

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Agenda

- Solar PV Adoption and Impacts
- Least Cost Integration Solutions
- Deep Dive into Dynamic Operating Envelopes
- Key Takeaways and Recommendations
- Q&A

This webinar is being recorded and distributed to all registrants along with this presentation.

Solar PV Adoption and Impacts

Penetration

Outlook

Impacts

Voltage Excursions

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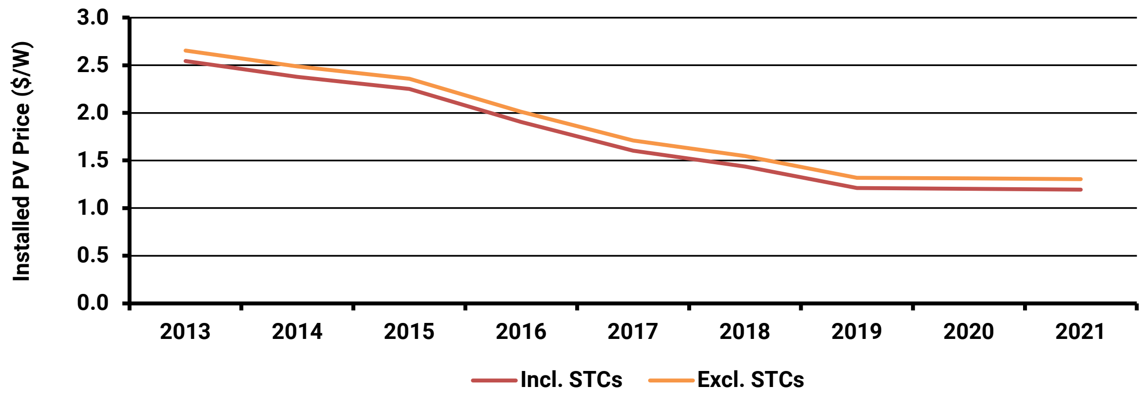
Rooftop Solar PV Costs vs. Residential Retail Electricity Prices

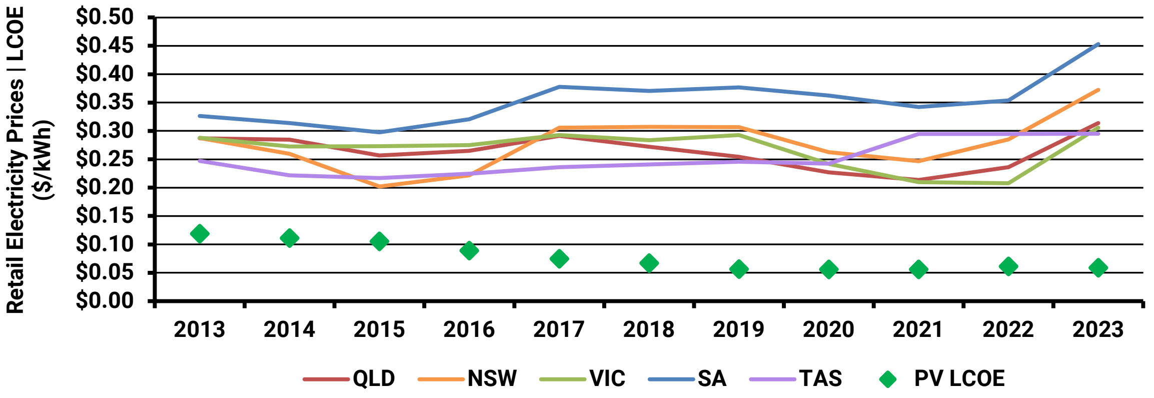
Solar PV Price Trends



Source: Energeia Modelling (2021)

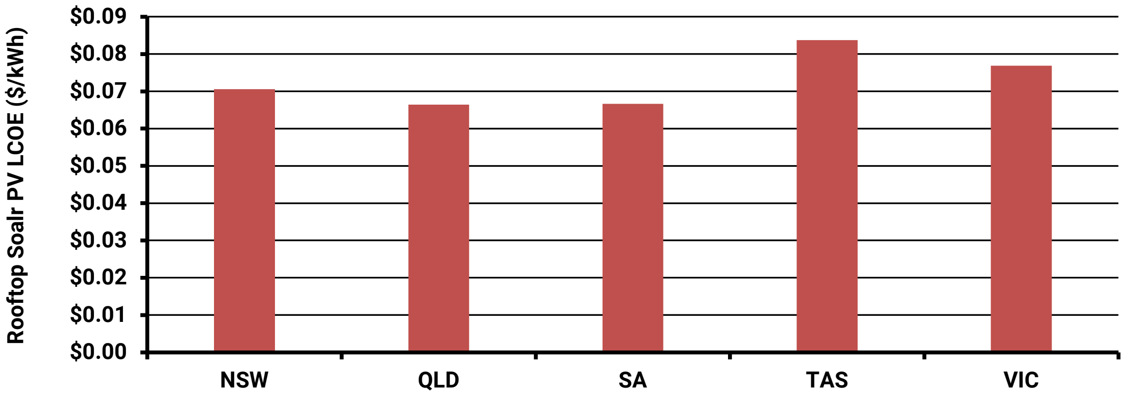
- Rooftop solar PV prices have continued to fall over the last 10 years, and the trend is expected to continue, albeit more slowly
- Retail electricity prices have been relatively flat over the same period, but are trending upwards since 2021
- Rooftop solar PV levelised cost of electricity (LCOE) or cost per kWhs is less than half of the average electricality prices
- While LCOE is based on output timing, and there is a mismatch to usage, it is driving strong demand rooftop solar PV

Australian Residential Retail Price Trends by State



Source: AEMC Residential Electricity Price Trends, Canstar Blue

Australian Residential PV LCOE Trends by State



Source: Energeia Modelling (2021), Note: Includes STCs

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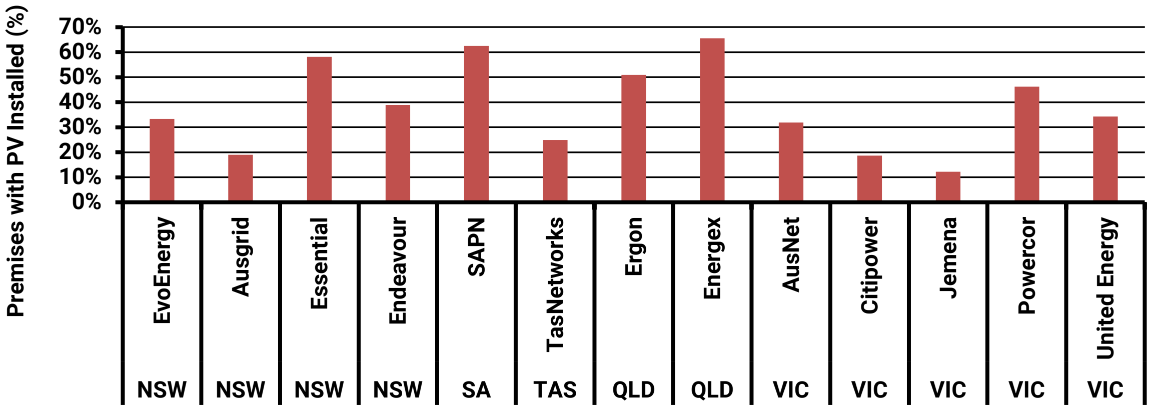
Solar PV Penetration Highest and Set to Continue to Grow

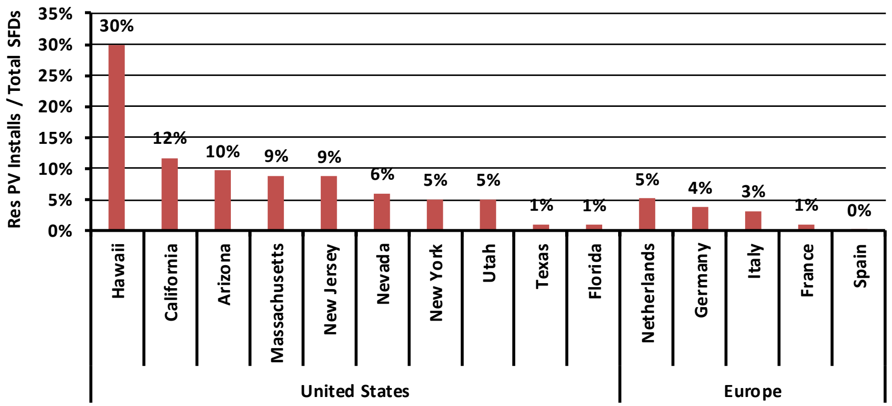
Rooftop Solar PV Penetration by DNSP



Source: APVI (2023)

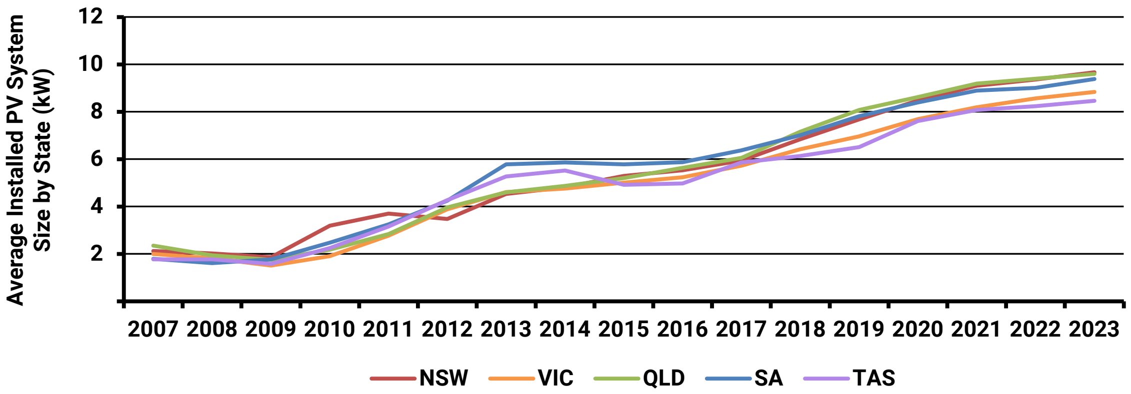
- Australia has some of the highest penetrations of rooftop solar PV systems in the world
- Leading overseas jurisdictions include Hawaii at 30%, with California in second with 12%
- Residential rooftop solar PV system sizes have been growing as residents seek to maximise the value of their investment
- Rising penetration and average sizes is leading to grid constraints

Overseas Rooftop Solar PV Penetration (2019)



Source: Energeia Research

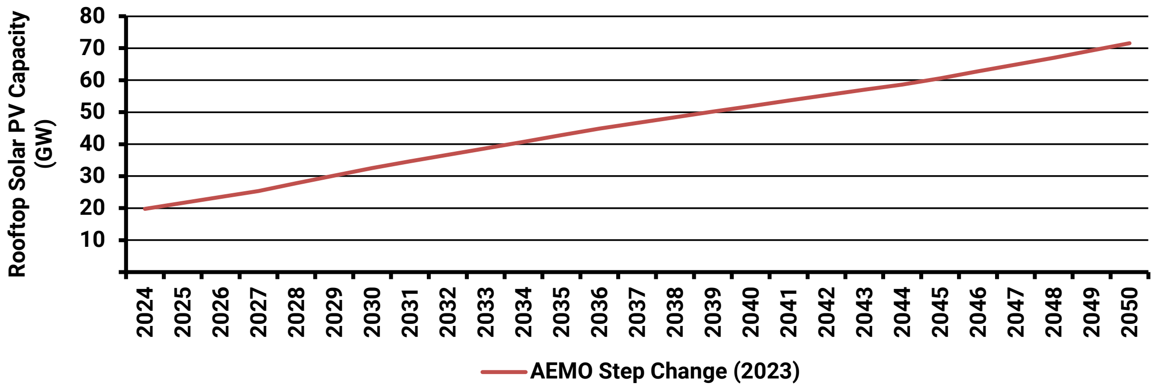
Average Size by State



Source: APVI (2023). Note: Average system size of systems under 15kW

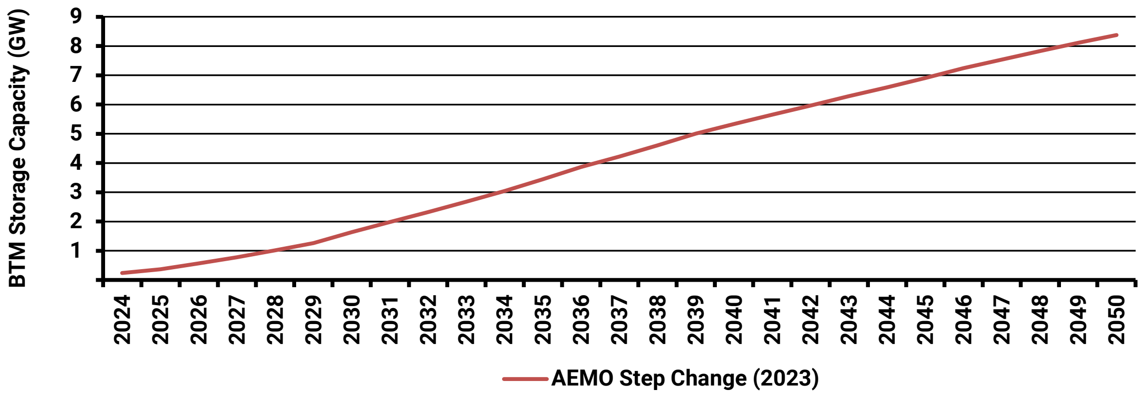
Outlook for Continued Growth in Rooftop Solar PV

Rooftop Solar PV Outlook



Source: AEMO (2023

Behind the Meter Storage Capacity Outlook



Source: AEMO (2023), Note: Assumed 4hrs of Storage Capacity

- The market operator’s most likely rooftop solar PV forecast sees continued growth for rooftop solar PV capacity to 2050
- Battery storage capacity is similarly expected to grow to 2050 driving by rising solar PV and EV adoption
- As solar penetration rises, so will the issues associated with rising levels of capacity and penetration

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Rooftop Solar PV Can Drive a Wide Range of Issues

Summary of Issues Associated with Rising PV Penetration

Stakeholder	Category	Issue	Impacts
Customers with Solar PV	Investment	Connection Limits	Connection standards can limit efficient investment choices in DER
		Export Limits	Connection standards can limit efficient operation of DER
		Inverter Curtailment	Inverter standards can reduce output and investment certainty
		Increased Energy Losses	Inverter standards can increase reactive power losses, reducing investment certainty
		Reduced Capacity	Inverter standards can increase reactive power, reducing inverter capacity and lifetime and investment certainty
		Reduced Lifetime	
Distribution Networks	Power Quality	Over-Voltage	Excess generation can increase voltage above allowed thresholds
		Under-Voltage	Generation can increase voltage range, leading to under-voltage
		Flicker	Intermittent generation can lead to voltage flicker
		Harmonics (THD)	Inverters can inject additional harmonics
	Reliability	Thermal Overload	Generation levels can exceed thermal rating limit
	Safety	Protection Maloperation	Changes in generation and load patterns can break some schemes
		Islanding	Inverters can fail to disconnect, creating safety issue
	System Security	Disturbance Ride-through	Inverters disconnect during disturbance, worsening the disturbance
		Under Frequency Shedding	Load shedding inverters can increase net load, worsening frequency
	Cost / Efficiency	Phase Imbalance	Inverters can be unevenly distributed, unbalancing the g rid
		Forecasting Error	Stochastic inverter uptake and output can reduce forecast accuracy
Generation, Transmission and Market Operations	Operability	Ramp Rate	Inverters can increase rate of change above system capabilities
	Security	Minimum Load	Generators require a minimum load to operate securely
	Reliability	Thermal Constraints	Large DER resources can overload thermal limits
	Safety	Fault Levels	Inverters can reduce fault current
	Cost / Efficiency	Forecasting Error	Uptake and operation can increase forecasting error
		Generation Curtailment	Curtailment of DER generation can increase wholesale market prices

Source: Energeia; Note: THD = Total Harmonic Distortion, 1. Grey indicates that issue is addressed by current inverter standards. 2. The lack of LV network monitoring means that there is limited visibility of the nature, scale and extent of LV network issues.

- Rising penetration of Rooftop Solar PV can give rise to a range of issues across customers, distribution networks, and the bulk power system
- The most common issues are highlighted in yellow
  - Voltage excursions are the key constraint driving distribution network costs
  - Minimum operating load is the key constraint driving market operator costs and risks
- Networks have responded in part by limiting connections and/or exports of new rooftop solar PV
- The market operator has responded in part by requiring new solar PV to be able to remotely curtailed
- These requirements have led to costs to existing and new rooftop PV customers
  - Limitations on new investments
  - Rising curtailment of existing investments

Least Cost Solar PV Hosting Solutions

Key Options and Unit Costs

Limits and Smart Inverters

Curtailment and Solution Costs

Cost Outlook

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Rooftop Solar PV Integration Solutions and Cost Estimates

Summary of Key Solution Cost Estimates by Category

Category	Solution		Capex	Opex	Units
Consumer	Water Heater Management – Retrofit Control		$150	$15	kW
	Level 2 Charger Management – Retrofit Control		$150	$15	kW
	Storage Management – Install New Controllable		$1k	$15	kW
Pricing	Coarse (e.g. ToU pricing), excl. smart meter		Negligible	$0	Customer
Signals	Granular (e.g. real-time pricing), excl. smart meter		$12m	$250k	DNSP
Technical Standards	Inverter Standards		Negligible	$0	DNSP
	Remote Inverter Configuration		Negligible	$0	Country
	Static Limitations		Negligible	$0	DSNP
	Dynamic Limitations		$6m	$250k	DNSP
Reconfiguration	Change Taps		Negligible	$1-2k	Trip
	Change Topology		$200k-$660k	$0	Feeder
	Change UFLS		$100k-$150k	$0	Feeder
	Change Protection		$1k	$0	Feeder
	Balance Phases		Negligible	$1.5-$2k	Trip
New Methods	Third Party Data	New Install	$500	$5	Customer
		Previous Install	Negligible	$5	Customer
	Better Long – Term Forecasts		$8m	$250k	DSNP
New Assets	LV Metering		$3,500	$30	Transformer
	Voltage Regulators		$300k	2.5% of capex	Regulator
	Larger Assets		$100k-$400k	2.5% of capex	Asset
	On-Load Tap Changer	Vault	$120k	$7k	Transformer
		Pole-Mounted	$60k	$7k	Transformer
	Harmonic Filters		$500k	$0	Substation
	Statcom (Single-Phase)		$5-8k	2.5% of capex	LV Phase
	Network Storage		$1.2k	2.5% of capex	kWh

Source: Energeia; Notes: 1. Changes deemed to be part of existing operations excluded, e.g. introduction of new price structures. 2. In-depth consultation with DNSPs would be required on to better understand costs on a jurisdictional basis. 3. Solutions are not mutually exclusive; the application of certain solutions may be limited by the absence of others i.e. electric water heaters must be in place to control their load.

- Energeia developed an estimate of rooftop solar PV impact mitigation solutions as part of the ECA funded Renew project
- Items in green were found to be low cost and widely applied:
  - Change offline transformer taps
  - Rebalance loads and generation by phase
  - Implement smart standards
- Items in orange were found to be high cost and typically applied once the low-cost options were exhausted
  - Static connection or export limitations
  - Add LV transformers to reduce impedance
  - Add network storage or statcoms
- Items in yellow were found to be among the lowest cost but least mature alternative options
  - Dynamic limitations = Dynamic Operating Envelops
  - Granular pricing signals
  - Control of key Consumer Energy Resource, incl. Water Heating, EV Charging and Storage

Green	Common, low cost
Yellow	Emerging
Orange	Conventional, higher cost

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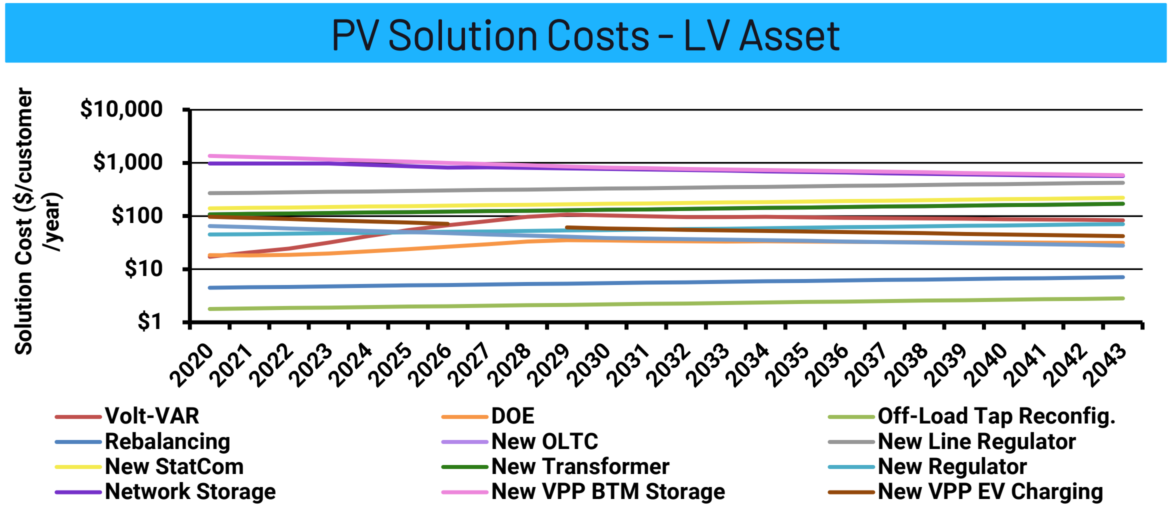
Analysis Showed DOEs a Key Solution



- For Project EDGE, Energeia updated its least-cost rooftop solar PV model developed for the Renew project
- The updated results for a suburban LV transformer scenario are reported at left
- The cheapest options remain offline tap changes and phase balancing – however, these are limited in their effect
- Smart inverter standards, e.g. Volt-Var, are among the cheapest options, but rise quickly due to the cost of curtailment
- Dynamic Operating Envelopes (DOEs) quickly becomes next least cost, but their cost rises with penetration over time
- By 2030, use of CER including EV charging becomes the least cost option

Source: Energeia

Dynamic Operating Envelope Deep-Dive

Overview

Key Impact Drivers

Value Optimisation Mechanisms

Forecast Limits

Forecast Impacts

Forecast Costs

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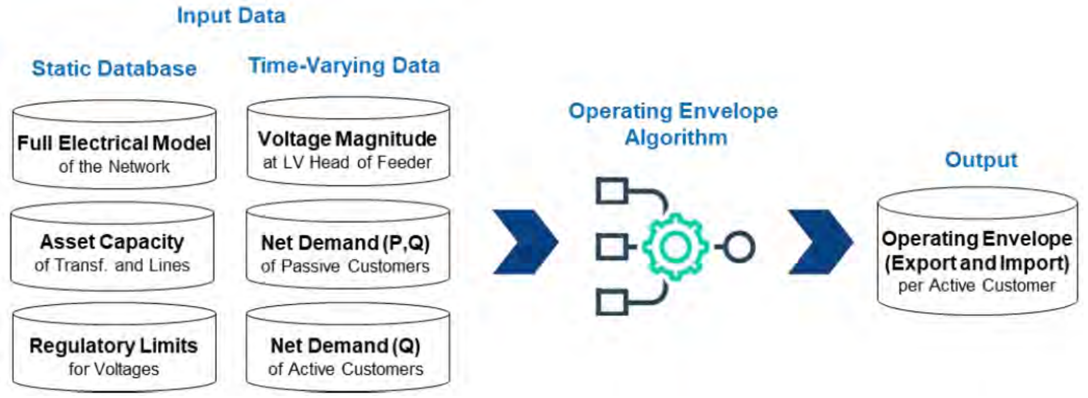
Dynamic Operating Envelopes

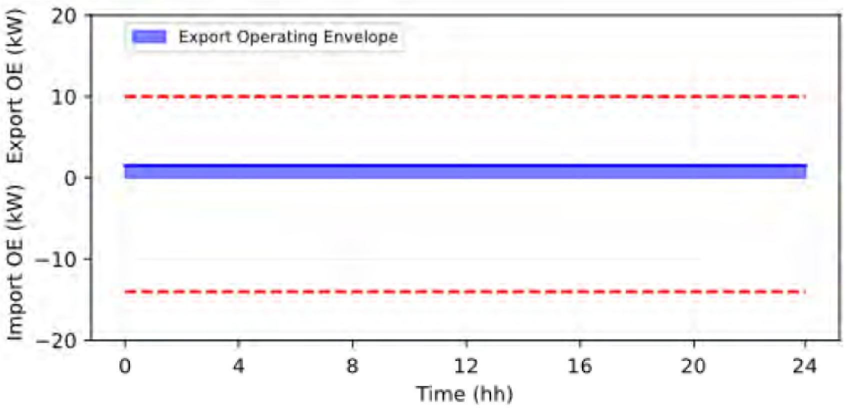
DOE Architecture



Source: Ochoa et al. (2023), Assessing the Benefits of Using Operating Envelopes to Orchestrate DERs Across Australia

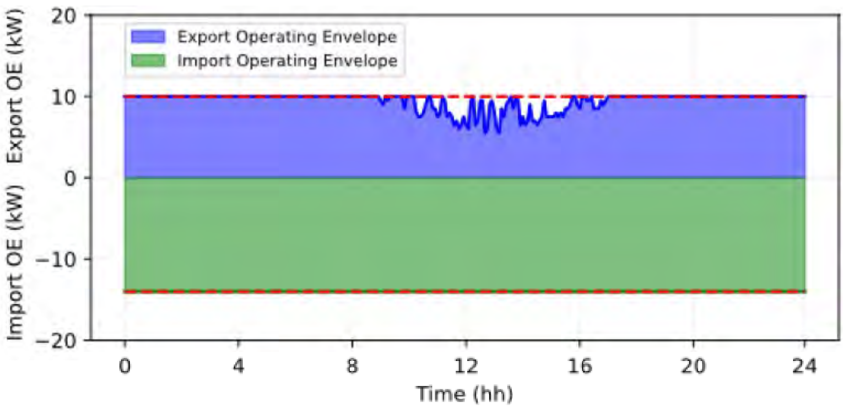
- DOEs allow networks to set restrictive import or export limits only during times of constraint
- This enables those with solar PV, storage, or EV charging to have greater access to the grid while ensuring security and reliability
- Their effectiveness is driven primarily by participation requirements and their objective function

Connection Level without DOE



Source: Ochoa et al. (2023), Assessing the Benefits of Using Operating Envelopes to Orchestrate DERs Across Australia

Connection Level with DOE



Source: Ochoa et al. (2023), Assessing the Benefits of Using Operating Envelopes to Orchestrate DERs Across Australia

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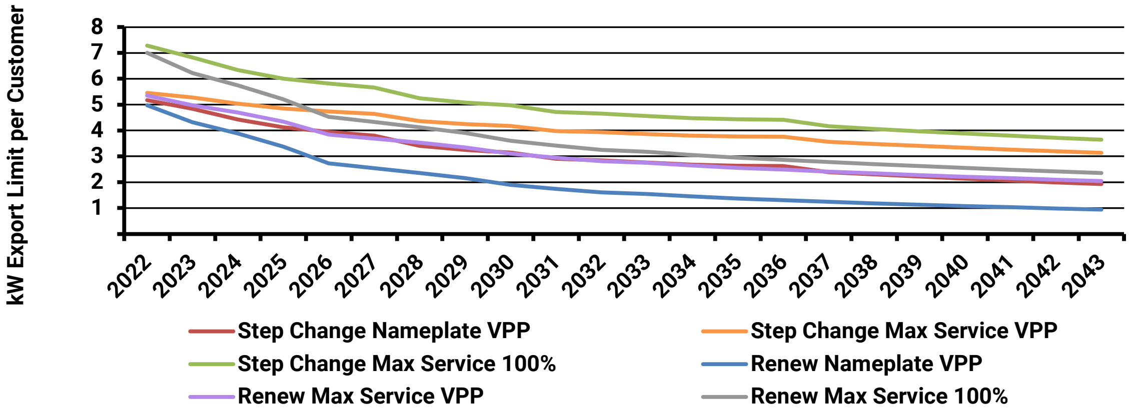
Project EDGE Export Limits by Scenario

EDGE Whole-of-System Scenarios

Scenario	Edge WoS TEM Element: DER Uptake	Edge WoS TEM Element: Objective	Edge WoS TEM Element: Participation	UoM TEM Element: Participation	UoM TEM Element: Objective
1	Step Change	Nameplate	VPP	Mid	Absolute Equal
2	Step Change	Max Service	VPP	Mid	Maximise NEM Export
3	Step Change	Max Service	100%	All	Maximise NEM Export
4	Renew	Nameplate	VPP	Mid	Absolute Equal
5	Renew	Max Service	VPP	Mid	Maximise NEM Export
6	Renew	Max Service	100%	All	Maximise NEM Export

Source: University of Melbourne, Energeia
Notes: WoS = Whole-of-System, DER = Distributed Energy Resources

Draft Export Limits by Scenario and Year



Source: Energeia

- Energeia used UoM data to develop an estimate of the export limits by scenario and over time
  - Scenarios determine DER by year
  - Mid scenario used for VPP participation
  - Absolute equal allocation used for nameplate
- Export limits are forecast to be higher initially, and fall significantly over time
- DOE basically doubles the amount of available capacity compared to the nameplate scenario
- 100% participation reduces allocations because non-participants assumed to have lower fixed limits

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DOE Optimisation Objective a Key Design Element

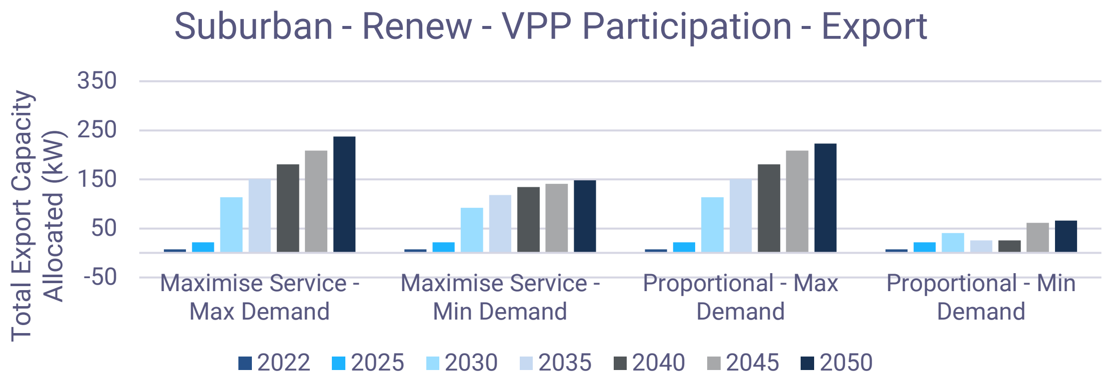
Dynamic Operating Objectives – Illustrative Examples

- DOE's can solve for a number of different 'objective' functions, shown at left
- These examples are not equivalent, i.e. the max service is showing more capacity than others in this case
- The main options considered include Maximise Service or Equality
- Equality is the level of export capacity where everyone gets an equal share

Source: James Naughton, Prof. Pierluigi Mancarella (2022), Project Edge, DOE Objective Functions

Project EDGE Estimated Impacts of CER Uptake, Participation and Objective Function

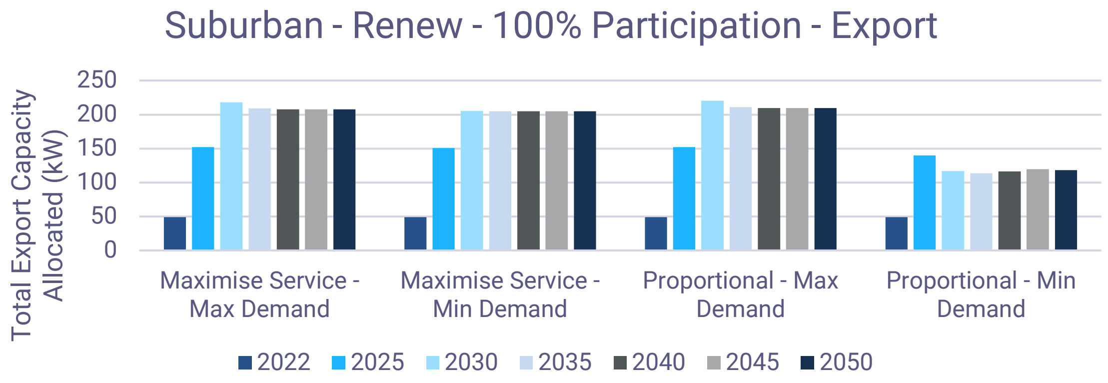
High Uptake, VPP Participation Only



James Naughton (2022), Project Edge, DOE Technoeconomic Modelling Results

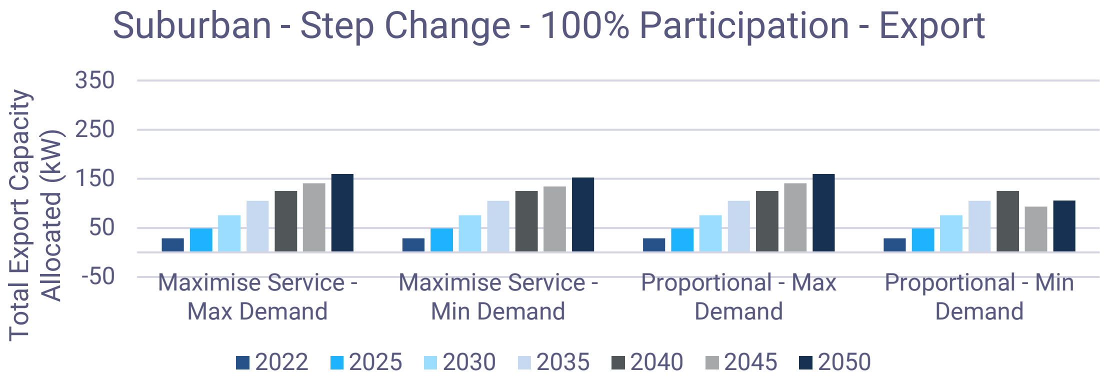
- Work by the University of Melbourne (UoM) on behalf of Project Edge estimated the min amount of capacity under a range of uptake scenarios, objective functions, constraint periods, and participation rules
- It showed that participation assumptions were a key driver of availability export capacity
- No major difference between max service and proportional, expect during min demand, where max service much higher

High Uptake, 100% CER Participation



James Naughton (2022), Project Edge, DOE Technoeconomic Modelling Results

Moderate Uptake, 100% CER Participation



James Naughton (2022), Project Edge, DOE Technoeconomic Modelling Results

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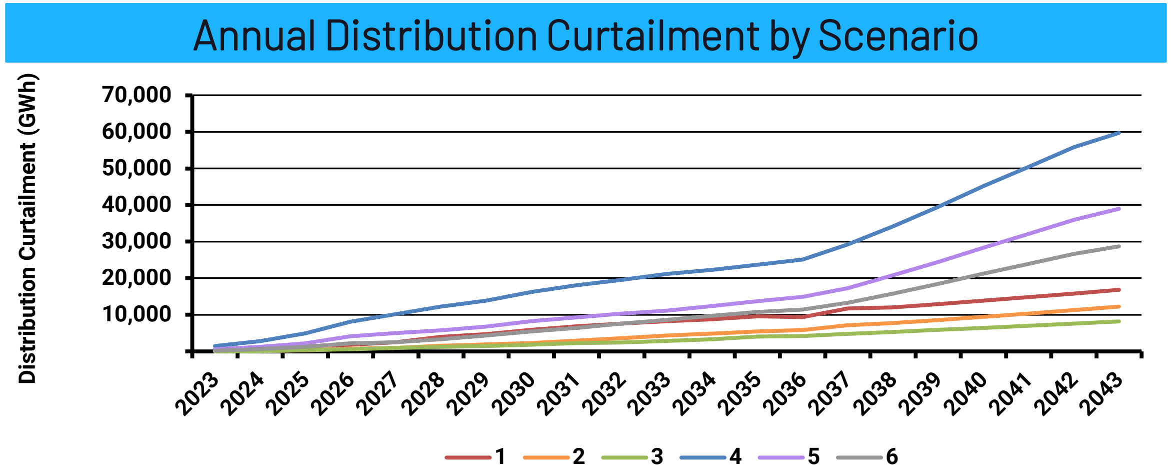
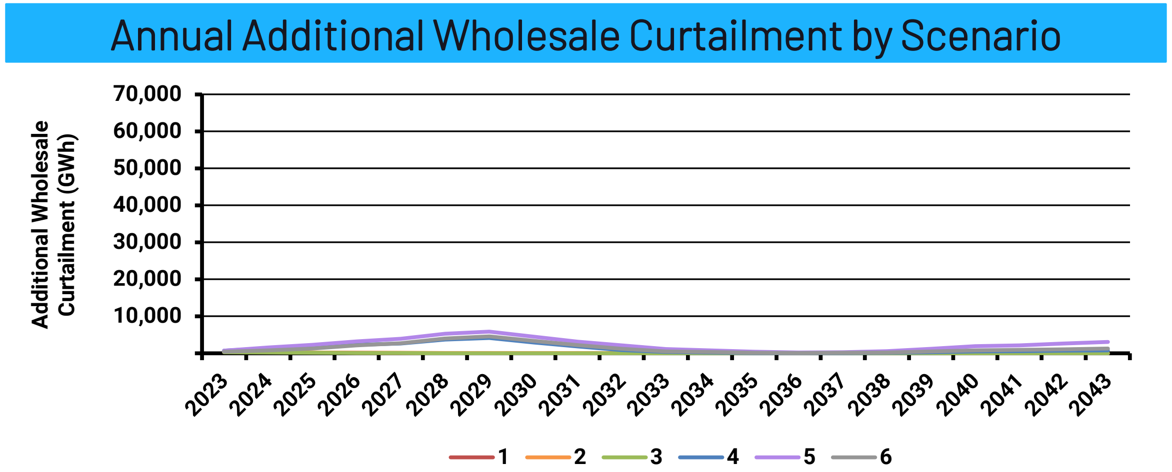
EDGE Forecast Market and Grid Curtailment Levels by Scenario



Source: Energeia



Source: Energeia

- Energeia forecast distribution-level curtailment per kW of solar PV, extrapolated to other networks based on relative PV uptake
- Distribution curtailment is prioritised over wholesale market curtailment
- Curtailment from network constraints much greater than curtailment required for min stable levels in wholesale market

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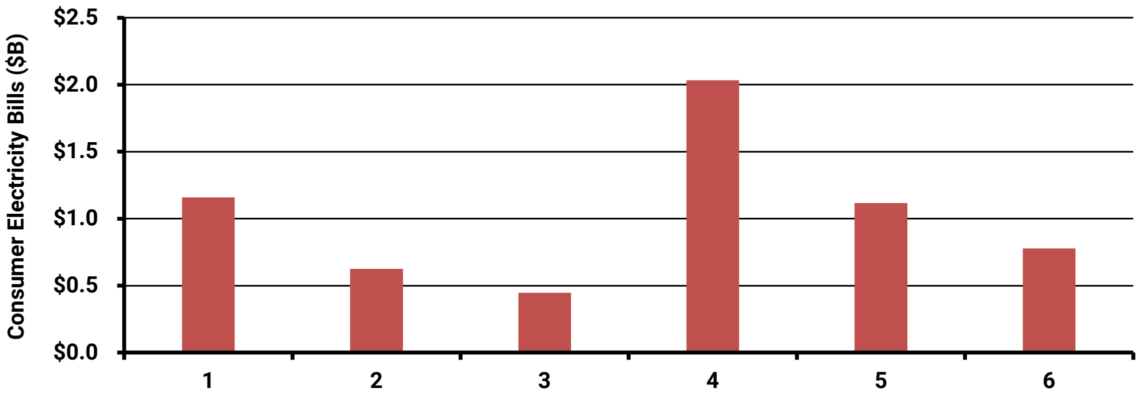
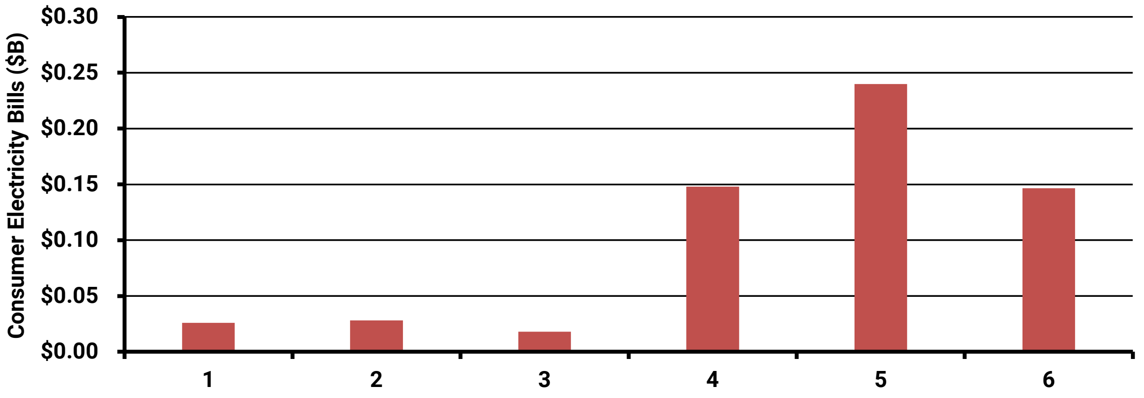
EDGE Forecast Market and Grid Curtailment Costs by Scenario

Network Curtailment Cost



Source: Energeia

Additional Wholesale Curtailment Cost



Source: Energeia

- Final scenario outcomes are shown as 20-year NPV
- Distribution curtailment decreases significantly with DOE participation and objective function enhancement
  - Static limit alternatives will reduce exports for customer
- VPP participation reduces wholesale market curtailment
  - More BTM load is shifted into the lower cost middle of the day
  - Maximising NEM exports requires more wholesale curtailment compared to nameplate, but less curtailment overall
- Best option under a high solar PV uptake scenario is scenario 6, i.e. 100% participation and max service DOE objective
- Max service means that CER may be curtailed more frequently at sites further away electrically
- A compensation system could help address this issue while delivering a higher net benefit to the wider community

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Key Takeaways and Recommendations

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Key Takeaways and Recommendations

- Key Takeaways
    - Solar PV forecast to continue to rise, and most of the lowest cost integration solutions are tapped out
    - Behind-the-meter storage and EV charging among the key next Customer Energy Resources (CER) needing integration solutions
    - Dynamic Operating Envelopes (DOEs) a key least cost solution for maximizing net benefits of solar PV and other CER
    - Full participation requirement and export maximization objective two key value drivers – trading rights needed for fairness
    - Advanced cost reflective pricing the next key solution needed to minimize Customer Energy Resource constraint mitigation costs
- Key Recommendations
    - Spatial forecasting of CER critical for anticipating potential issues arising and delivering a least cost solution over time
    - Phase balancing, offline transformer tap changes, smart inverter standards and basic cost reflective pricing key first line solutions
    - Key second line solutions include DOEs and advanced cost reflective prices
    - Ensuring full participation and export maximising optimisation key to maximising net community benefits
    - Max equal optimisation ensures equal access to the grid, and may be more popular – property rights and trade a potential gap here

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Q & A

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State of the Art in Virtual Power Plants (VPP)

19 March 2024
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- Where to find Energeia and Ezra Beeman
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Thank You!

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