Security, reliability and resilience in low-carbon power systems

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Professor of Smart Energy Systems, The University of Manchester

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IEEE Power and Energy Society Distinguished Lecturer Program

“Vuelta a Espana” 2025

UPV/EHU School of Engineering, Bilbao, 19th June 2025

Melbourne base, global outlook

The City of Melbourne

Consistently ranked among the world's most liveable cities

(#1 for many years in a row)*

Top 5 Student-friendly city**

(*Walk and bike everywhere*!)

*The Economist Intelligence Unit
**QS Best Student Cities 2023

Multicultural and vibrant: unique mix of Mediterranean and Asian culture

Australia's and one of the world's greatest sporting and cultural capital

Source: iStock

The University of Melbourne

1861 15 students enrol in Australia's first Engineering course at the University of Melbourne

1942 First female engineering graduate

1955 CSIRAC: 1st Australian-built computer housed at the University of Melbourne

Top #20-#30 University in the world

#1 University in Australia

50,000+ student population

40% International students

Power and energy systems at UniMelb

The energy sector is undergoing revolutionary changes to deliver energy that is affordable, reliable and clean. Electrical networks are the backbone of the future energy infrastructure. transition towards low-carbon power and energy systems is being enabled, particularly in Australia, by rapid developments of renewable energy sources (solar and wind) as well as different Smart Grid technologies (different types of energy storage, advanced control of networks and loads). The scale of the changes introduces unprecedented challenges for operating and planning future power and energy systems.

We perform modelling activities, develop tools, and carry out studies to support decision-making across the energy supply and value chains. We work closely with industrial partners and policy makers, and are actively involved in national and international research collaborations and activities with leading institutions. Our research has strong links with different energy-related research groups within the University.

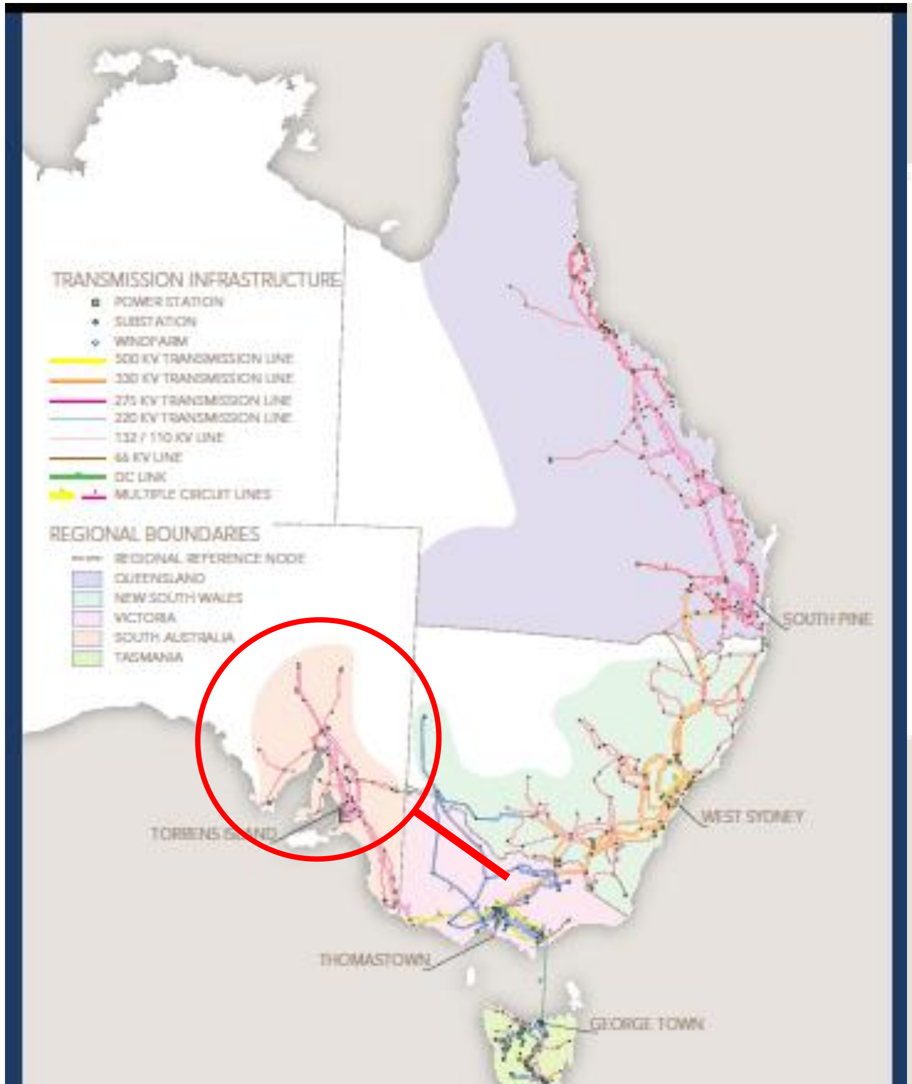
https://electrical.eng.unimelb.edu.au/power-energy

MANCHESTER 1824

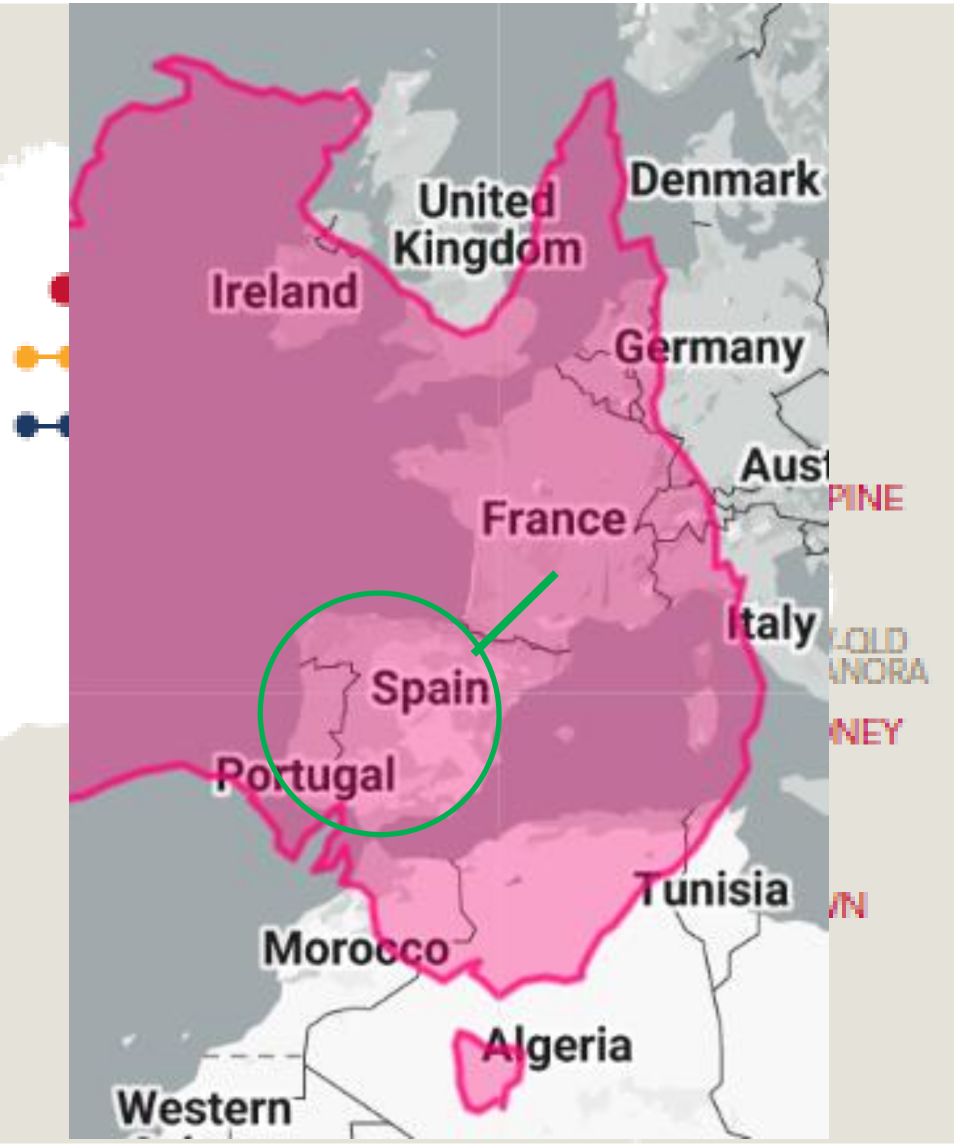
The University of Manchester

THE UNIVERSITY OF MELBOURNE

The Australian East Coast power system and the National Electricity Market (NEM)



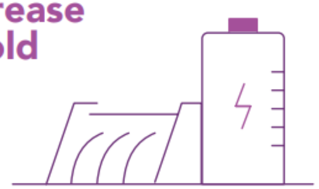
Source: AEMO



Vision for a new grid

NEM forecast installed generation capacity to 2050, "Step change" scenario

Grid-scale wind and solar
to increase 6-fold

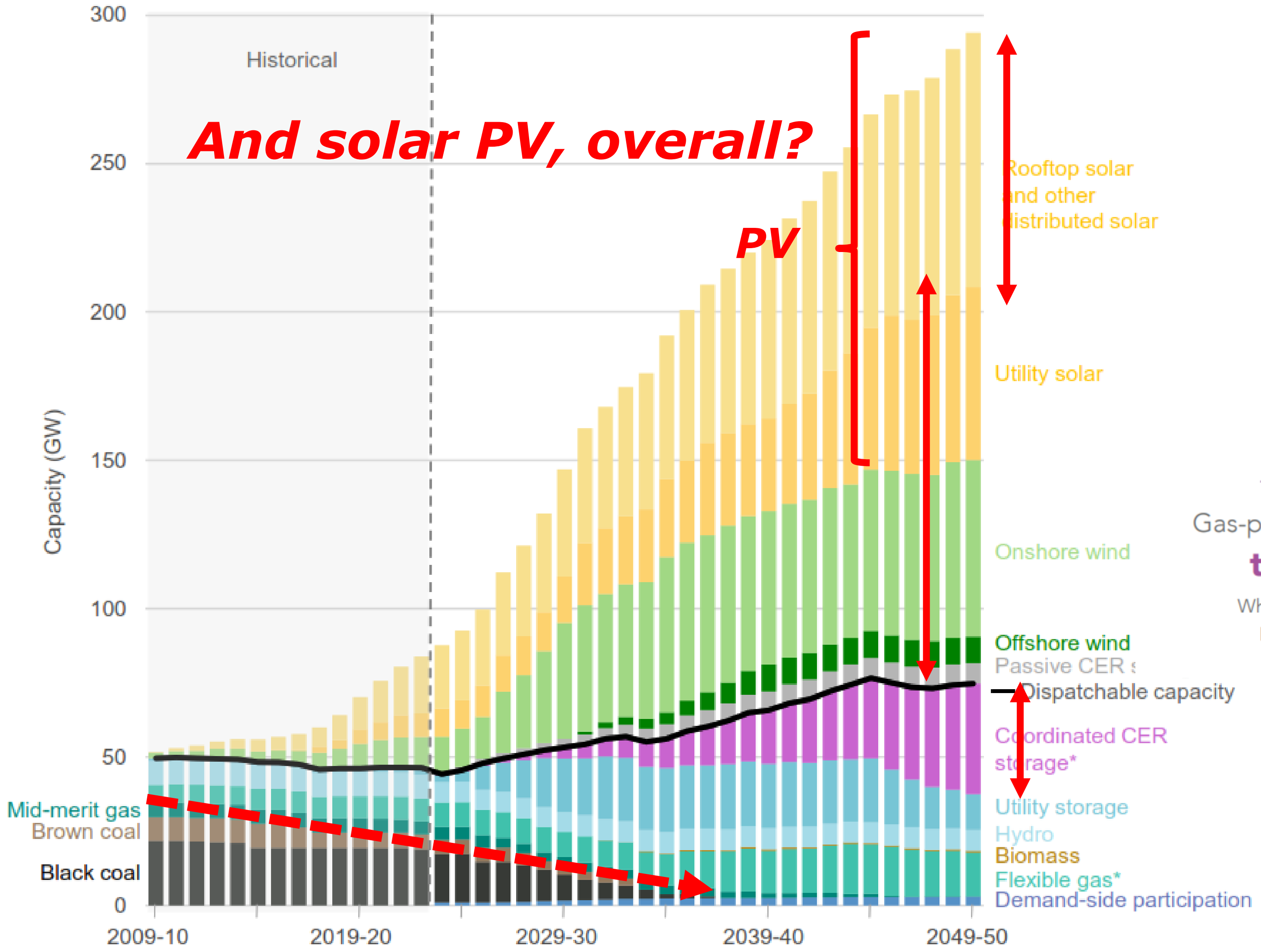


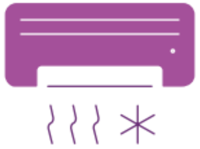
Storage capacity
to increase significantly

Batteries, virtual power plants, pumped hydro

Distributed solar PV
to increase 4-fold

Rooftop solar, other distributed solar





Electricity consumption from the grid
to nearly double

Gas-powered generation
to increase

While current mid-merit plants will within tha

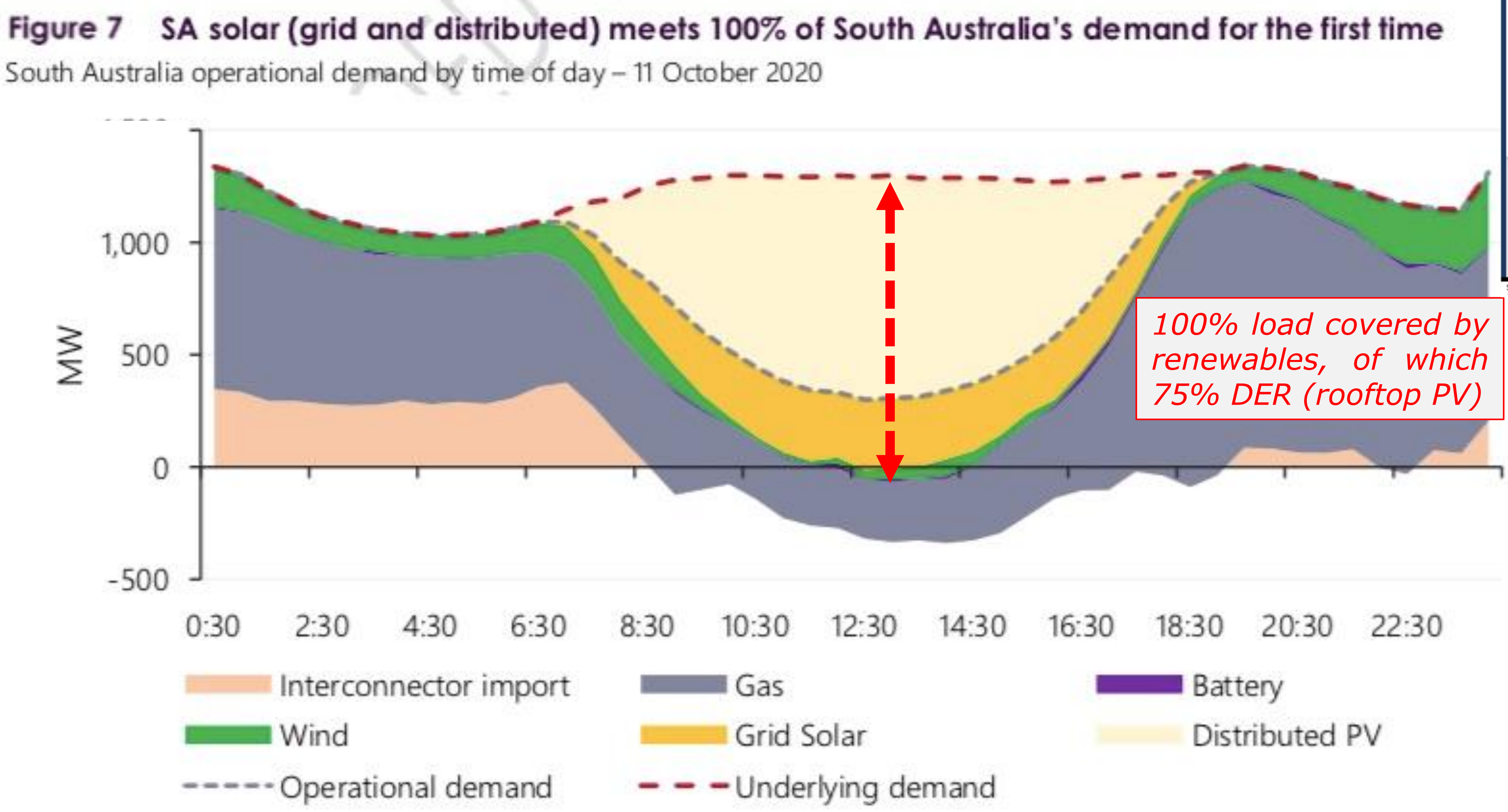
Coal generation
to be withdrawn

Capacity to be retired by:

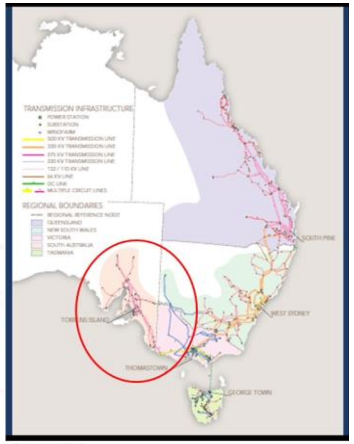
https://aemo.com.au/-/media/files/major-publications/isp/2024/2024-integrated-system-plan-isp.pdf?la=en

Source: AEMO, ISP 2024

A postcard from the future:
100% demand supply from solar in South Australia…
Five years ago!



100% load covered by renewables, of which 75% DER (rooftop PV)



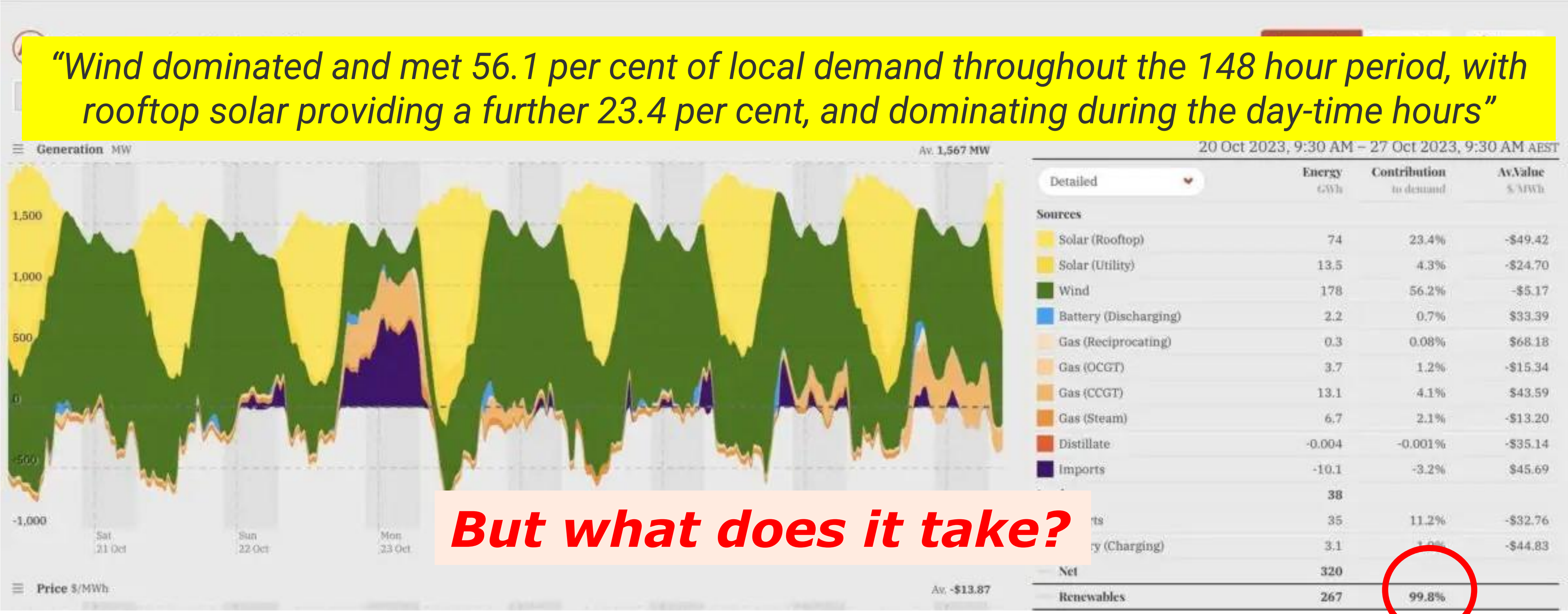
Source: AEMO

:e: AEMO and OpenNEM

Fast-forward to the future!
BAU *net-zero* operation in South Australia…

"South Australia grid operates at 99.8 per cent wind and solar over past seven days" (Oct 2023)

RenewEconomy, https://reneweconomy.com.au/south-australia-grid-operates-at-99-8-per-cent-wind-and-solar-over-past-seven-days/

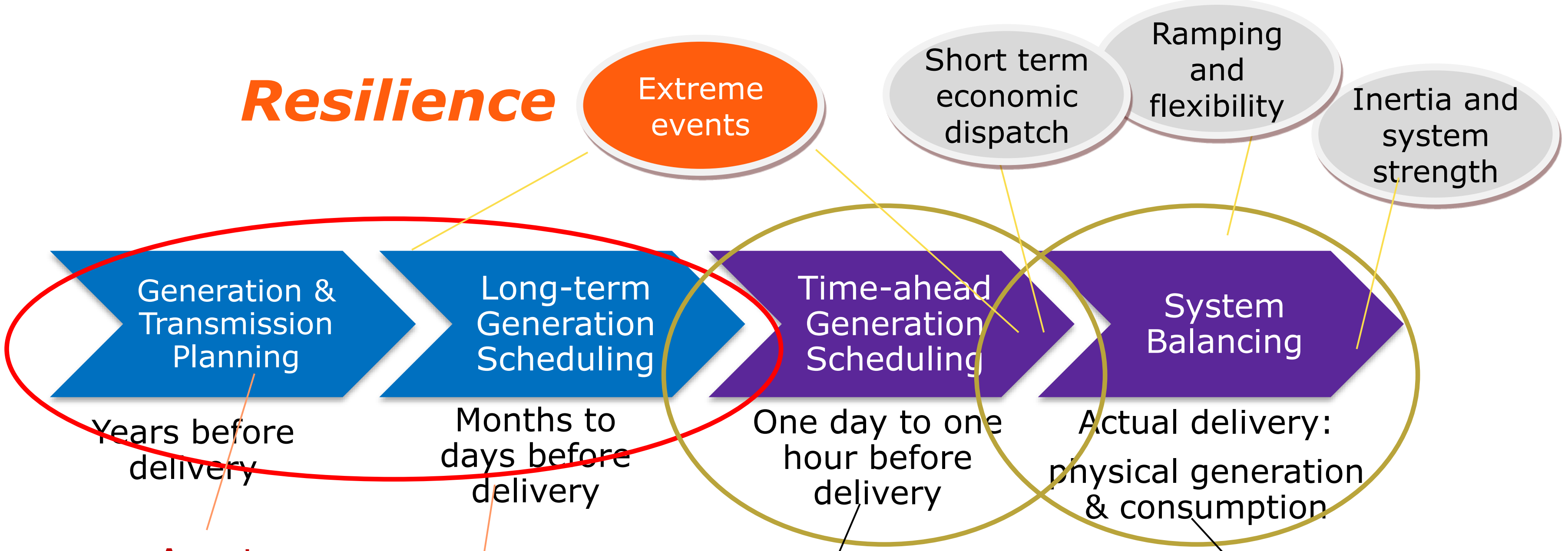


Source: AEMO and OpenNEM, October 2023

A changing landscape

Balancing supply and demand at all times to guarantee system reliability

Resilience



Asset investment

Fuel contracts

Maintenance planning

Economic dispatch and UC

Time-ahead markets

Primary and secondary FR and tertiary reserves

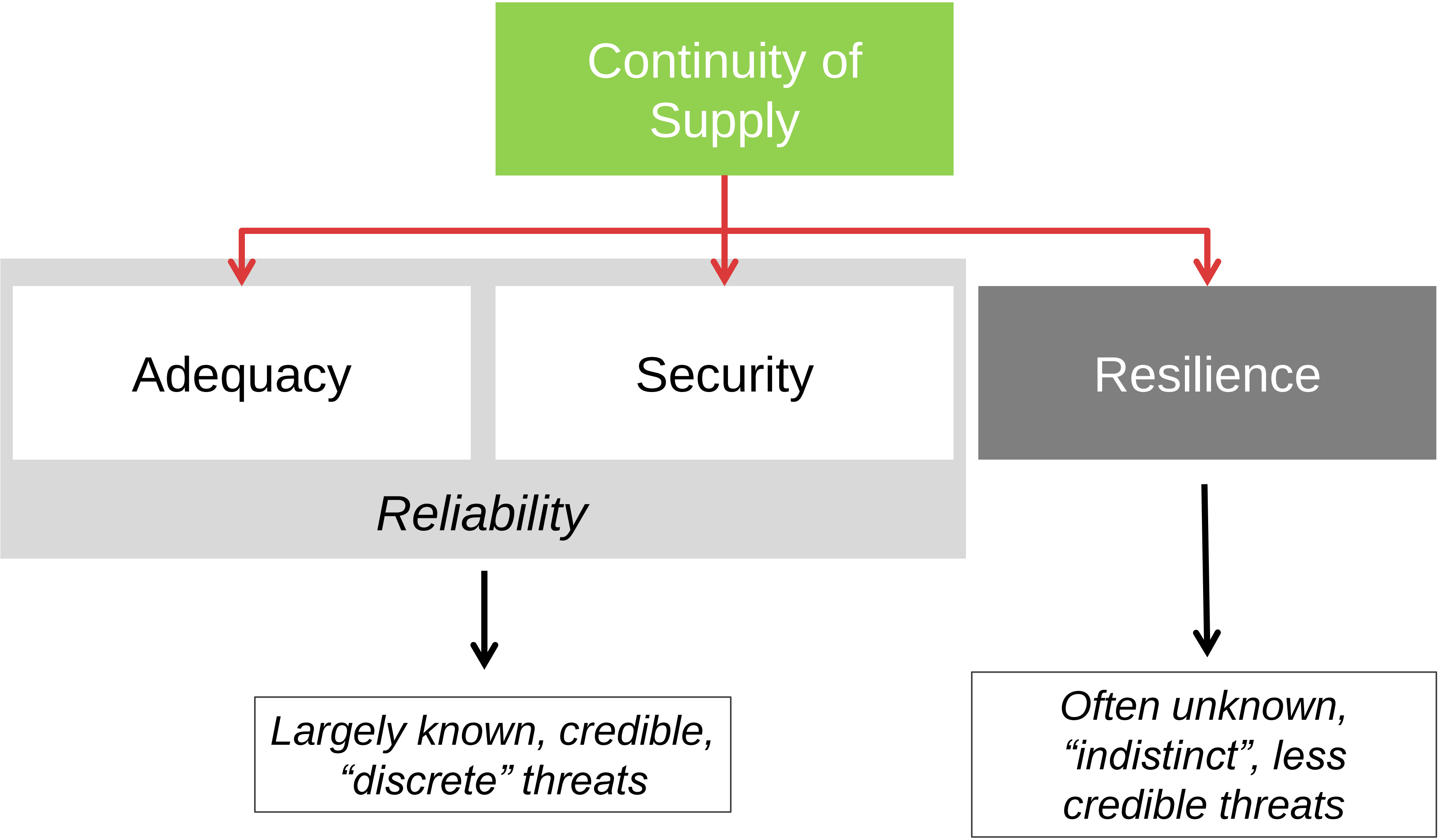
Regulation/load following

Balancing markets

Planning for adequacy

Operating with security

Reliability, resilience and continuity of supply



Reliability, resilience and continuity of supply

Continuity of Supply

“Rara avis in terris nigroque simillima cygno”
Juvenal, 82 AD

Ad

y

Largely known, credible, “discrete” threats

Often unknown, “indistinct”, less credible threats

The "new physics"

Risk	Emerging issues	Possible Mitigations
Frequency control and inertia	- Sustained frequency excursions (regulation) - High ROCOF following contingency - Insufficient regional inertia - Insufficient PFR - Risk of low-inertia and insufficient PFR after separation	- Minimum inertia levels - Compulsory droop response - Additional amount of PFR - Co-optimization of energy, frequency response, and (regional and system-level) inertia - Regional allocation of reserves - New sources of fast frequency response (e.g., batteries, electrolysers) - Management of largest contingency and interconnector flows (system at risk of regional separation)
Variability, uncertainty and visibility	- Large variation in net demand - Insufficient short- and medium-term and ramping reserves - Visibility of Distributed Energy Resources (DER)	- Better forecasting - Artificial intelligence to assess reserves (e.g., dynamic Bayesian belief network tools) - Use of more flexible resources including energy storage (e.g., pumped hydro)
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P. Mancarella and F. Billimoria, 'The Fragile Grid – The physics and economics of security services in low-carbon power systems", *IEEE Power and Energy Magazine*, 2021

The "new physics"

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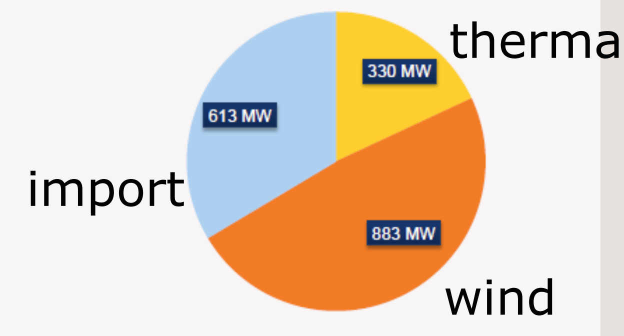
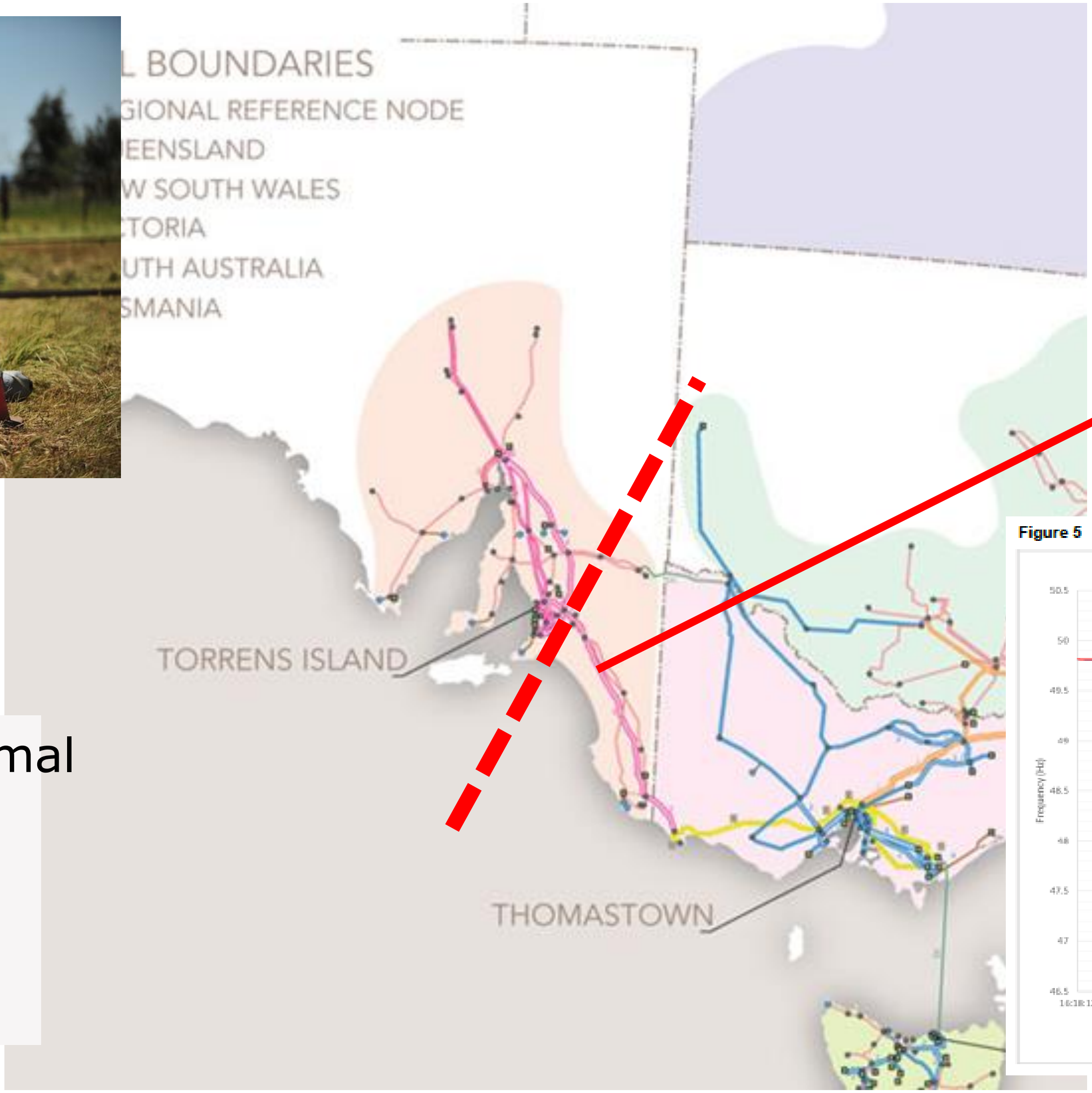
P. Mancarella and F. Billimoria, 'The Fragile Grid – The physics and economics of security services in low-carbon power systems", *IEEE Power and Energy Magazine*, 2021

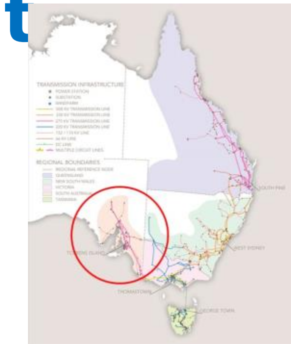
A textbook example: The 2016 "black system" event

Source: ABC

Source: AEMO

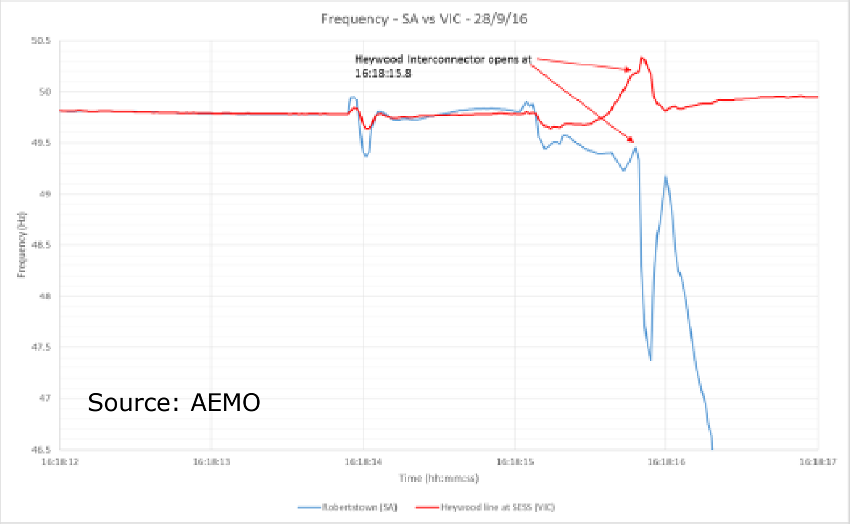






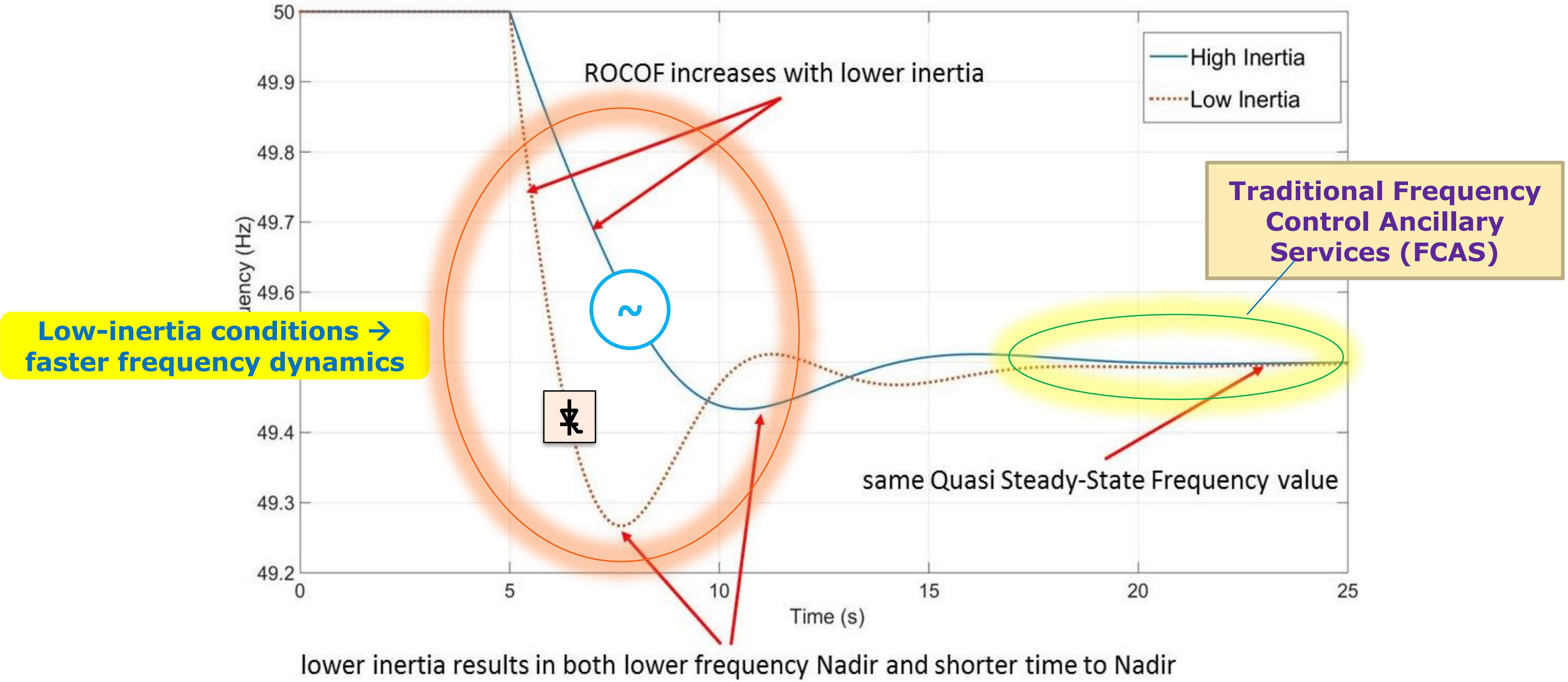
Heywood AC Interconnector

Figure 5 SA frequency compared to Victoria during event



Source: AEMO

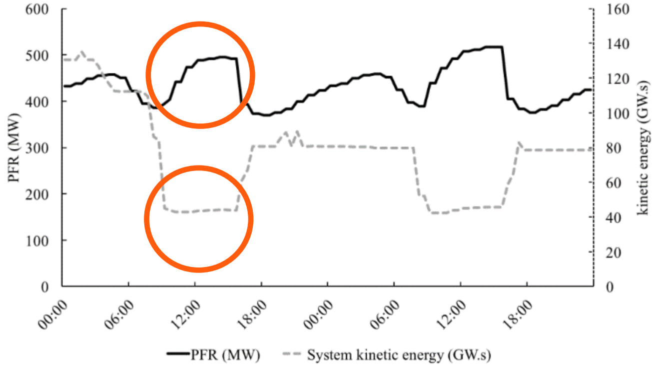
Frequency control challenges in renewables-rich systems

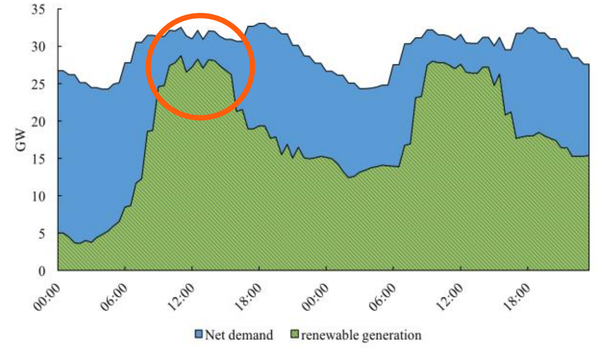


P. Mancarella et al., "*Power system security assessment of the future National Electricity Market"*, Report in support of the "Finkel Review", June 2017

The dawn of new frequency control and inertia services and markets

Co-optimization of energy, frequency control ancillary services, and inertia





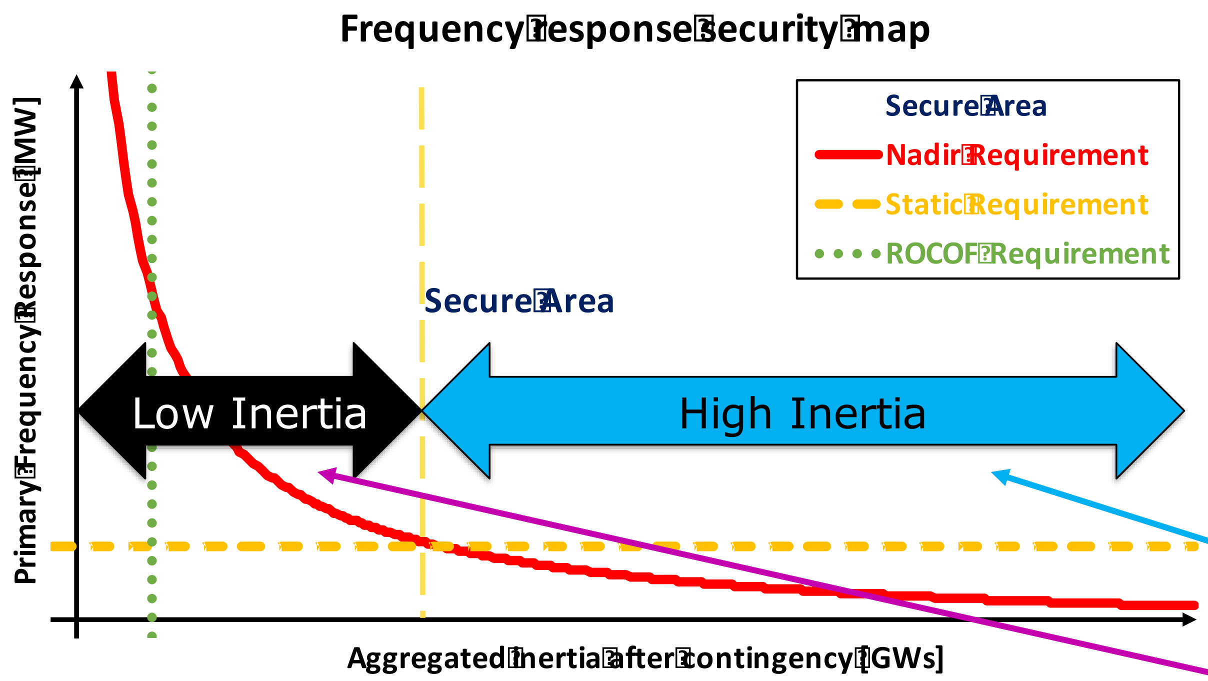
Power system security assessment of the future National Electricity Market

A report by the
Melbourne Energy Institute
at the
University of Melbourne
in support of the
'Independent Review into the Future Security of the National Electricity Market'

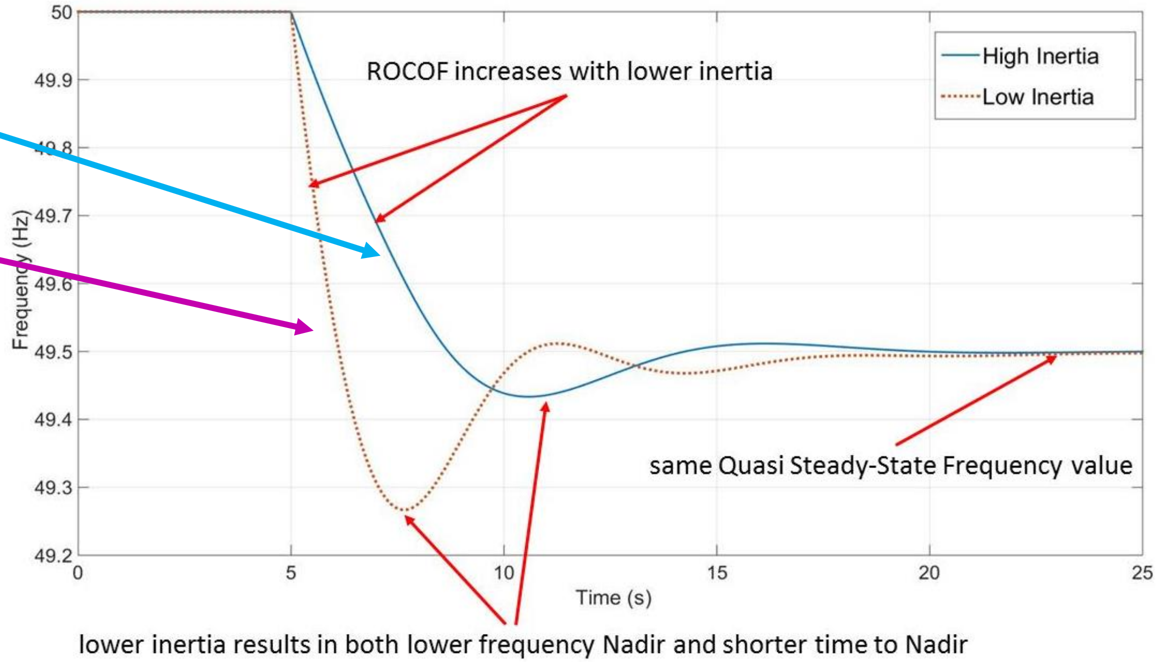
June 2017

P. Mancarella et al., "*Power system security assessment of the future National Electricity Market"*, Report in support of the "Finkel Review", June 2017

Frequency response security maps



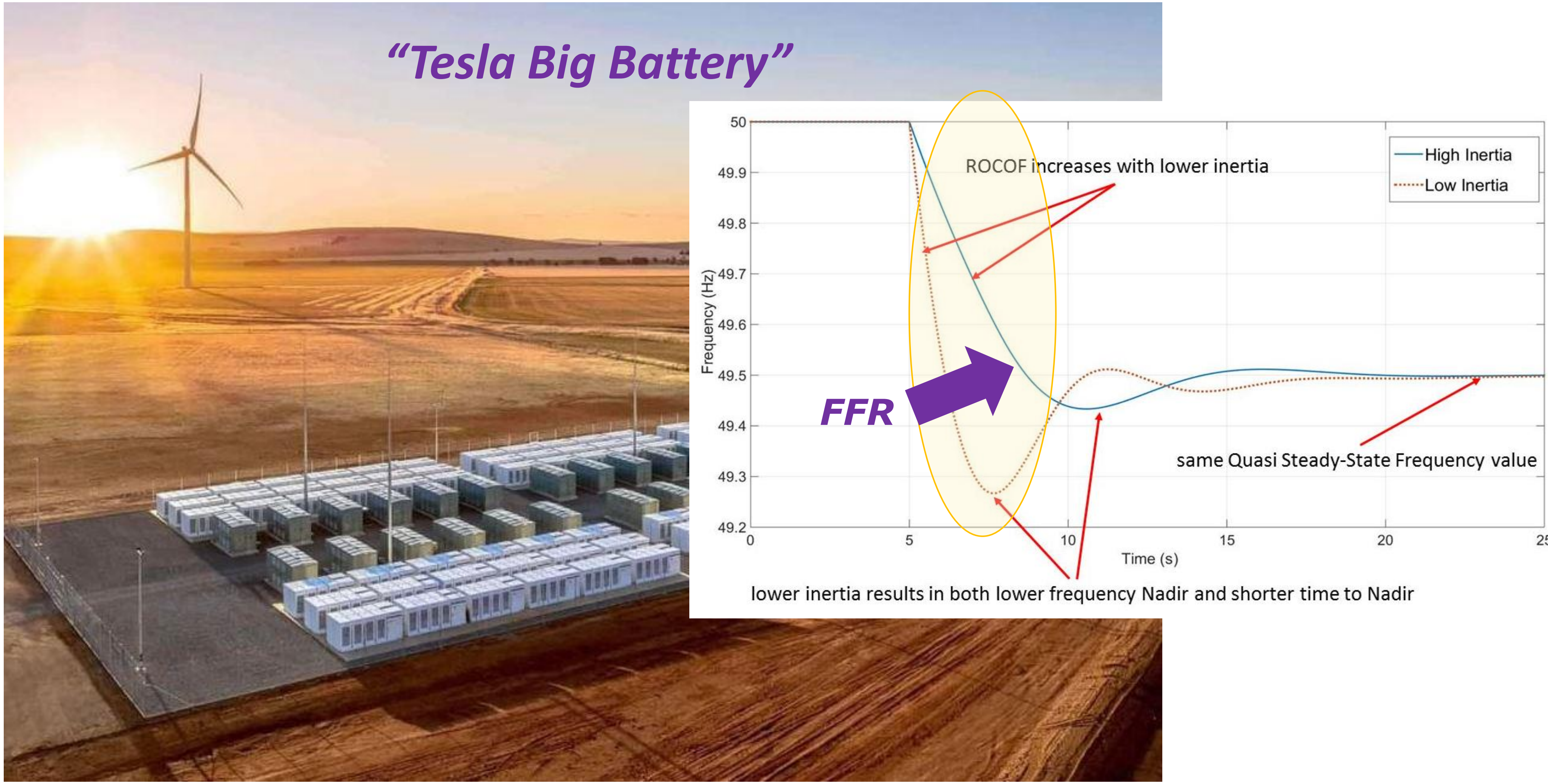
Adapt controls (and markets!) to the new physics!

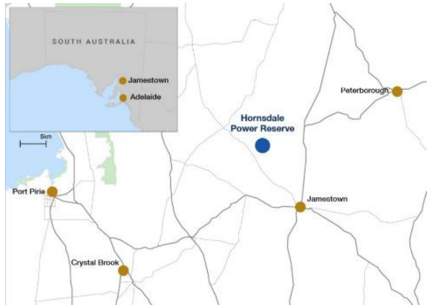


P. Mancarella et al., "*Power system security assessment of the future National Electricity Market*", Report in support of the "Finkel Review", June 2017

Making history: Engineering the grid of the future

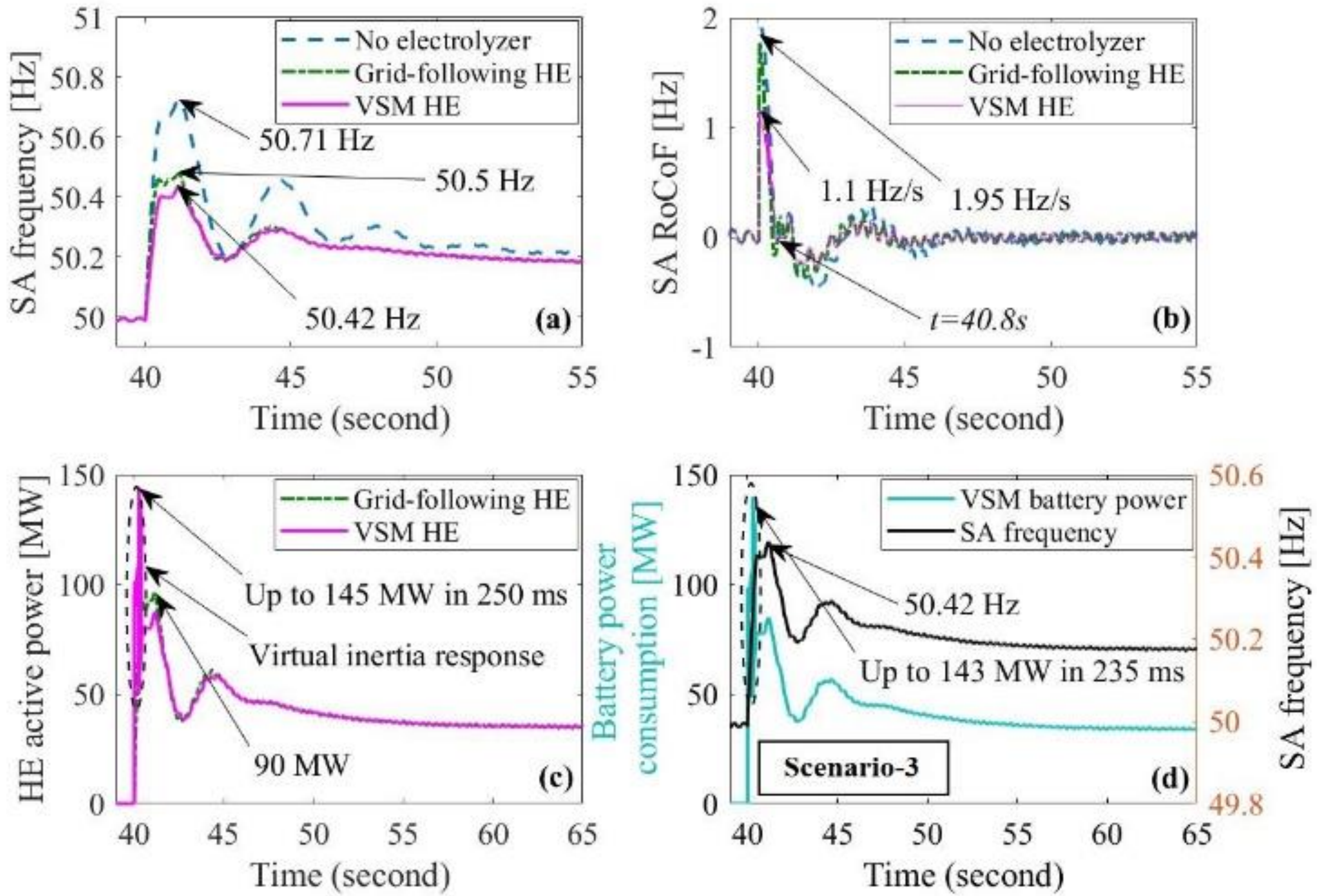
Hornsdale Power Reserve, Jamestown, South Australia





Source: Neoen, PV Magazine Australia

Not only batteries!



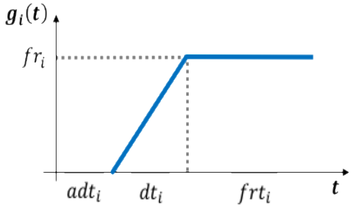
M. Ghazavi Dozein, *et al.*, "**Fast frequency response** from utility scale hydrogen electrolysers", *IEEE Trans. Sustainable Energy*, 2021

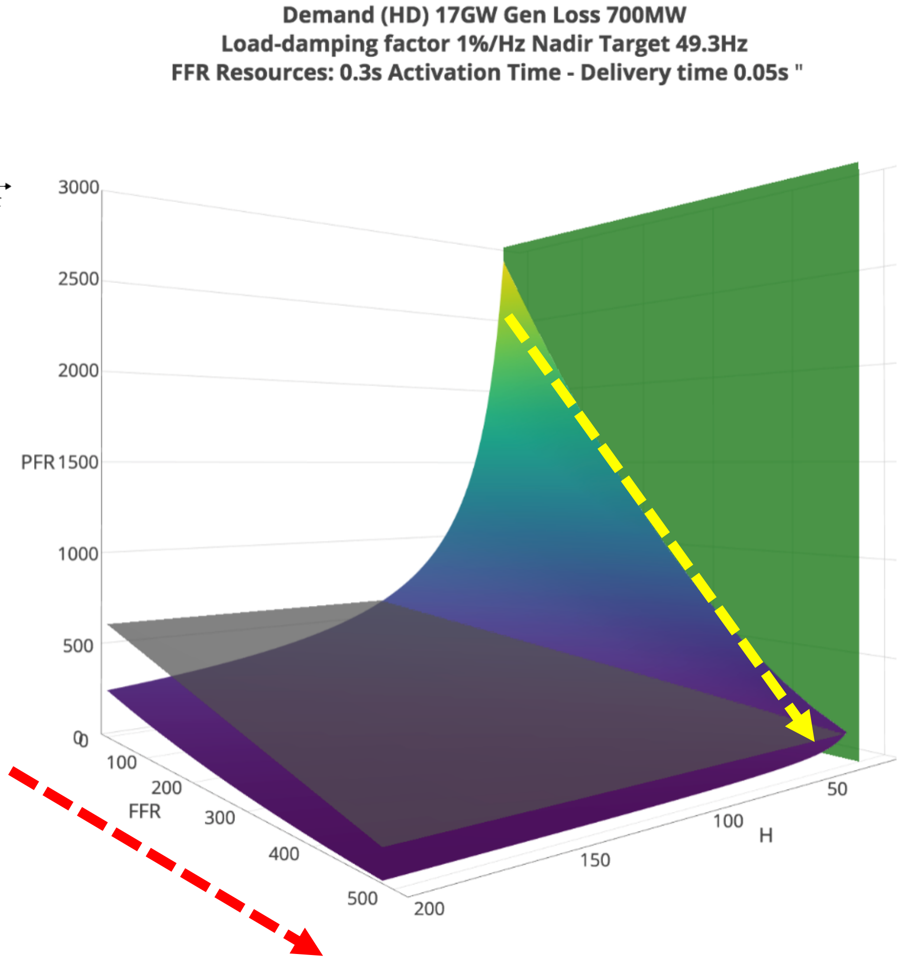
M. Ghazavi Dozein, *et al.*, "**Virtual Inertia** Response and Frequency Control Ancillary Services from Hydrogen Electrolyzers", *IEEE Tran. on Pow. Syst*, 2022

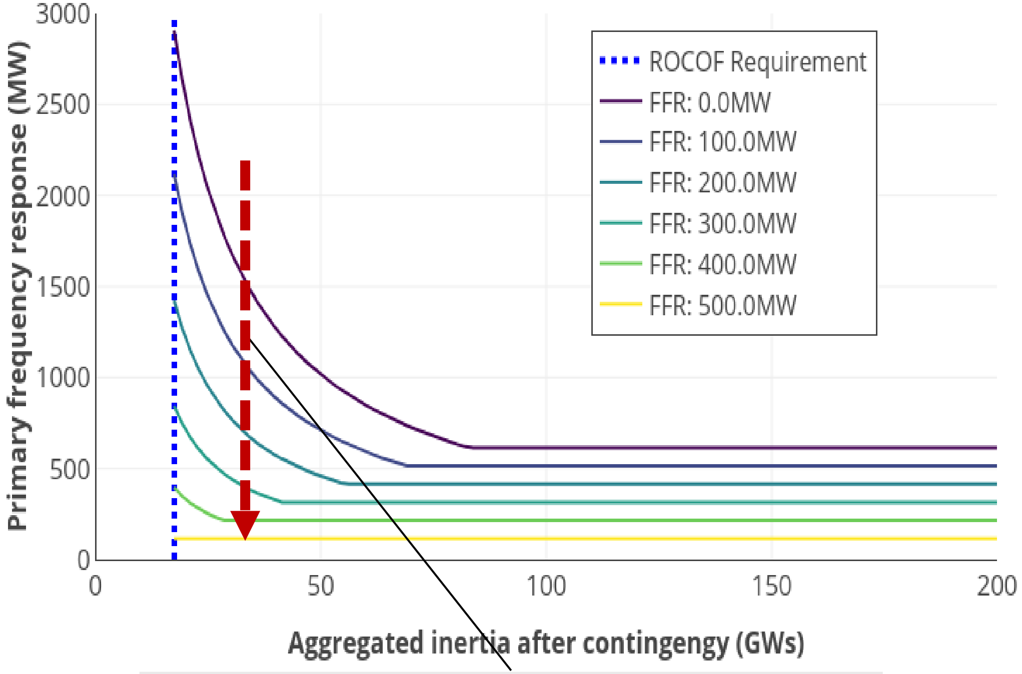
S. D. Tavakoli, *et al.*, "**Grid-Forming Services** From Hydrogen Electrolyzers", *IEEE Transactions on Sustainable Energy*, 2023

"Synchronous" vs "controlled" response

battery, electrolyser



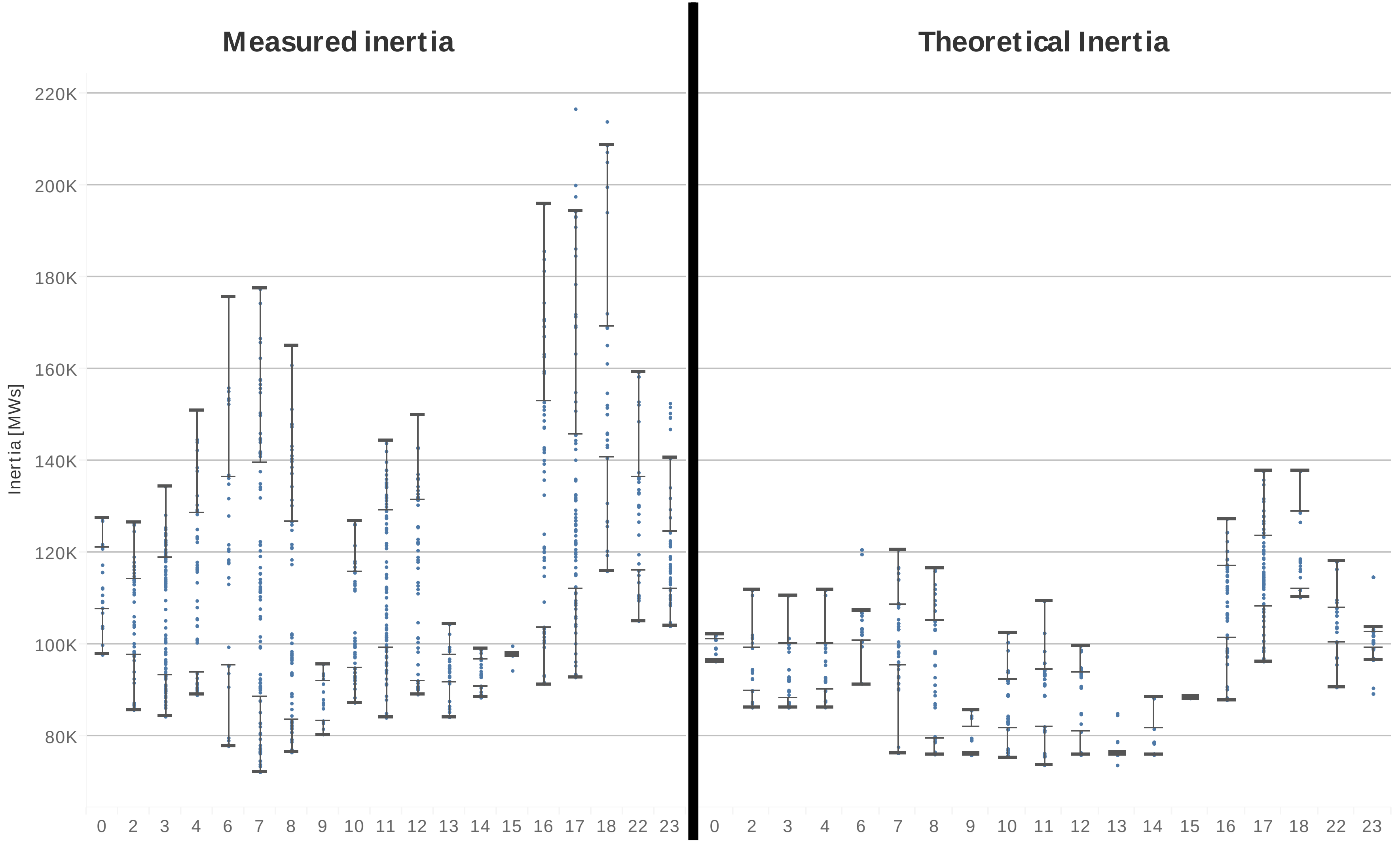




$$\frac{PFR}{INERTIA} \sim 33.3 \quad \frac{PFR}{FFR} \sim 5 \quad \frac{FFR}{INERTIA} \sim 6.\mathbf{7}$$

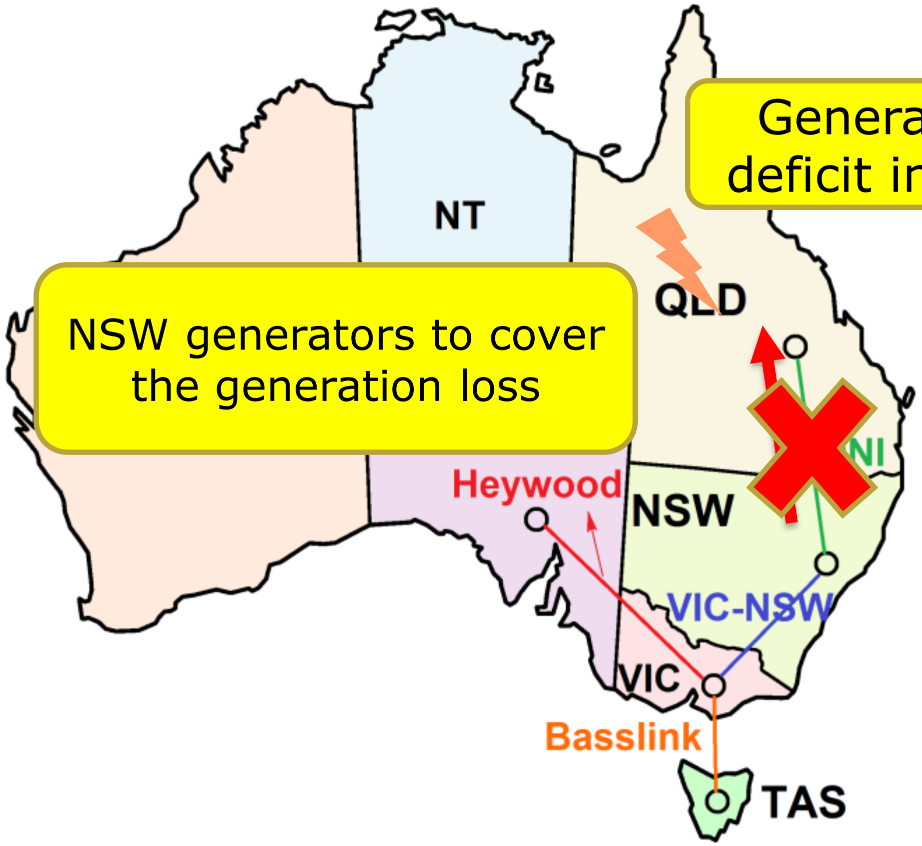
B. Moya, *et al.*, "Techno-Economic Assessment of Inertia Measurements: A Case Study for the Australian National Electricity Market", *IREP and SEGAN 2025*

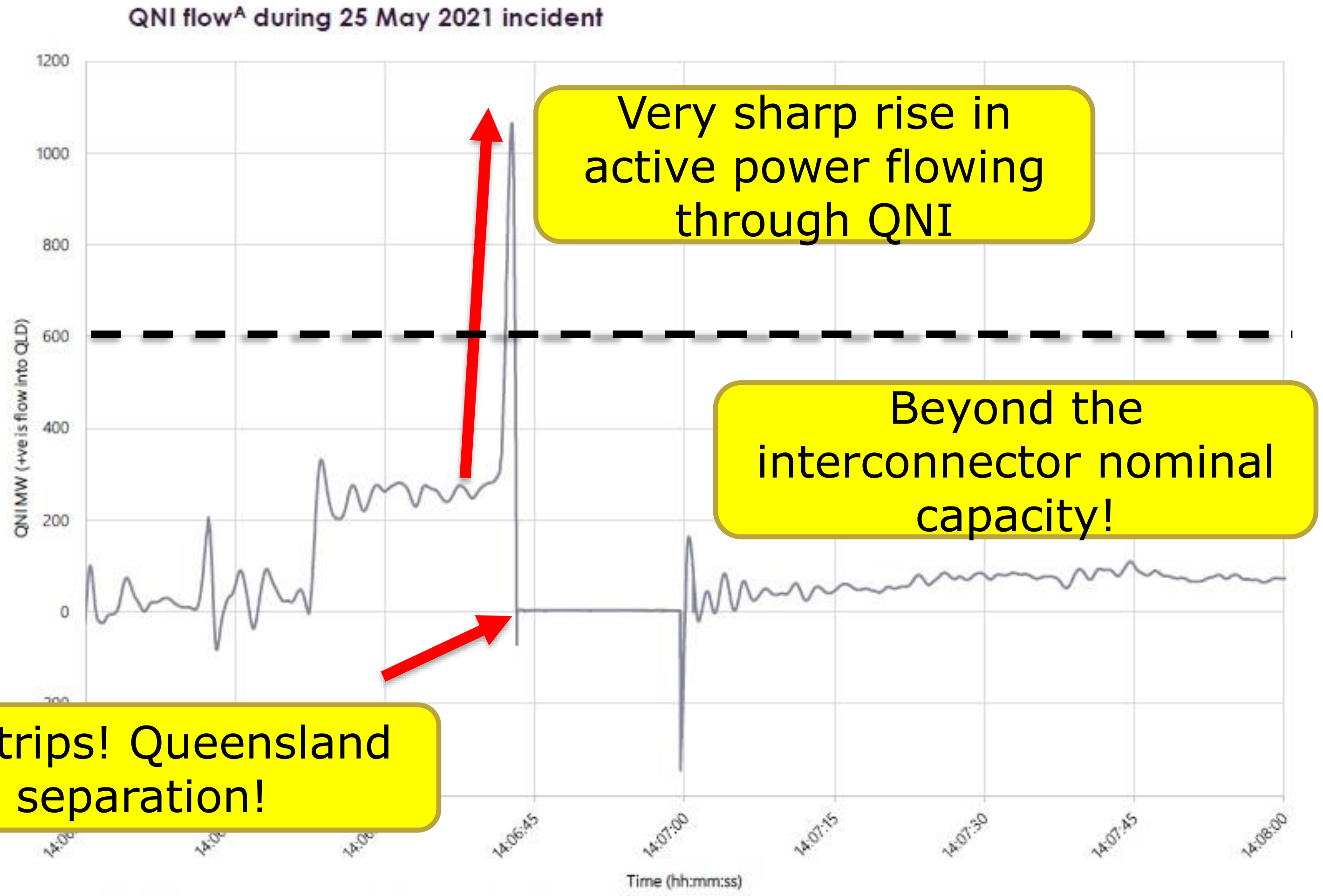
Is inertia hiding?



B. Moya, *et al.*, "Techno-Economic Assessment of Inertia Measurements: A Case Study for the Australian National Electricity Market", *IREP 2025*

Real-life example: Cascading failures in May 2021





A. Measured at Bulli Creek substation High Speed Monitoring (HSM).

AEMO, "Trip of multiple generators and lines in Queensland and associated under-frequency load shedding on 25 May 2021", October 2021

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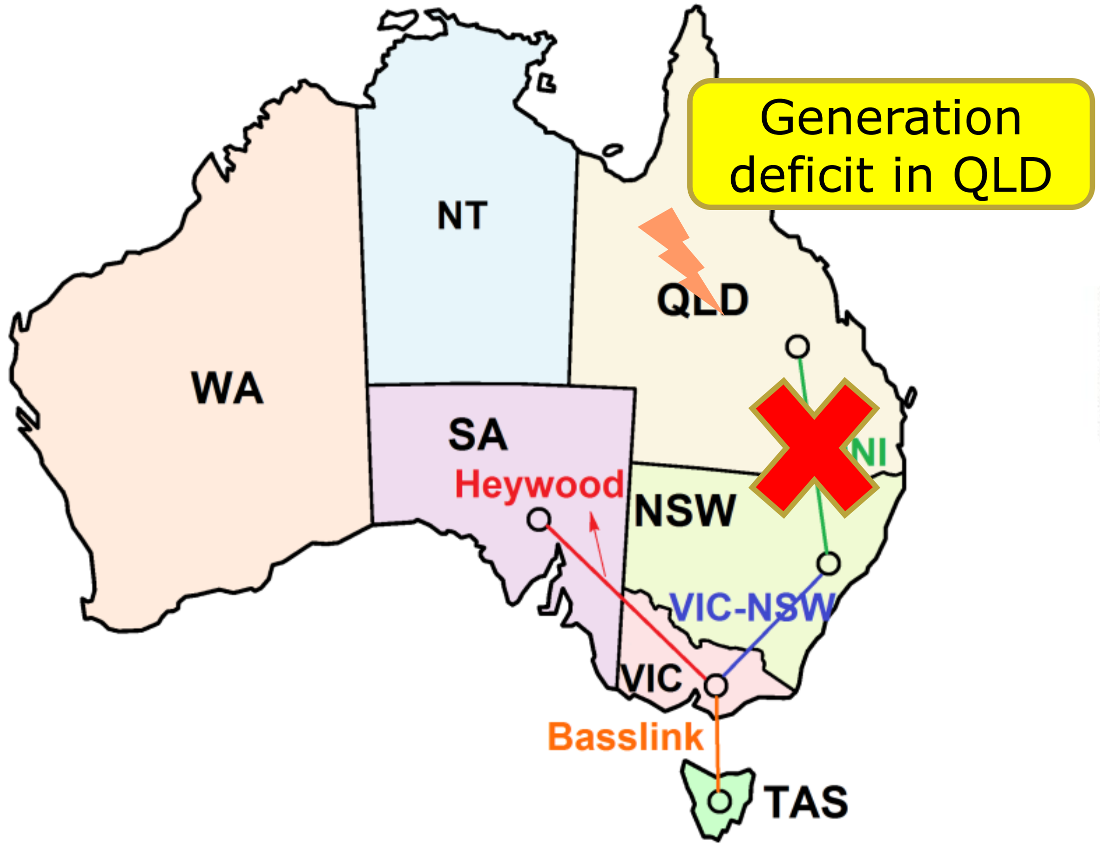
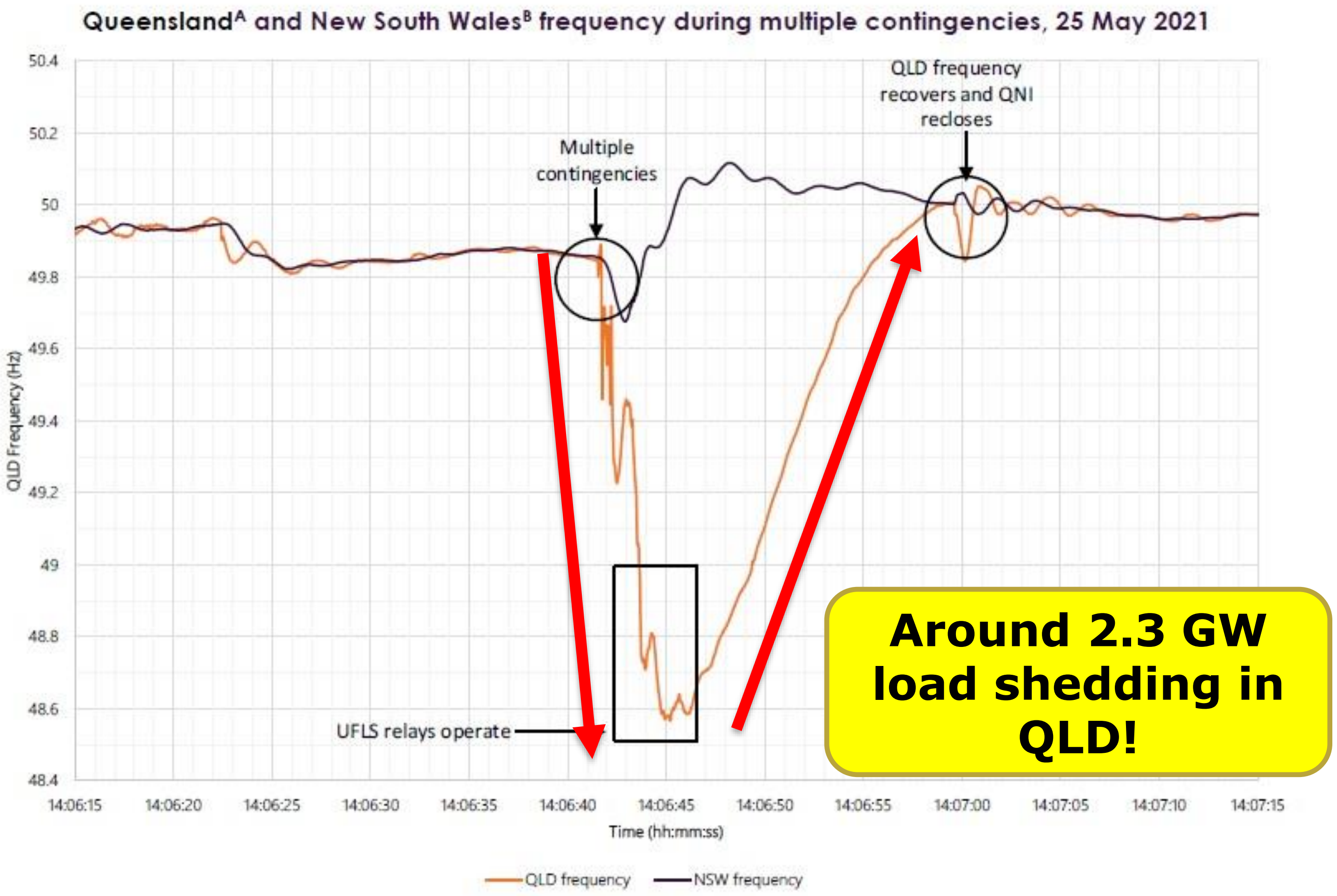
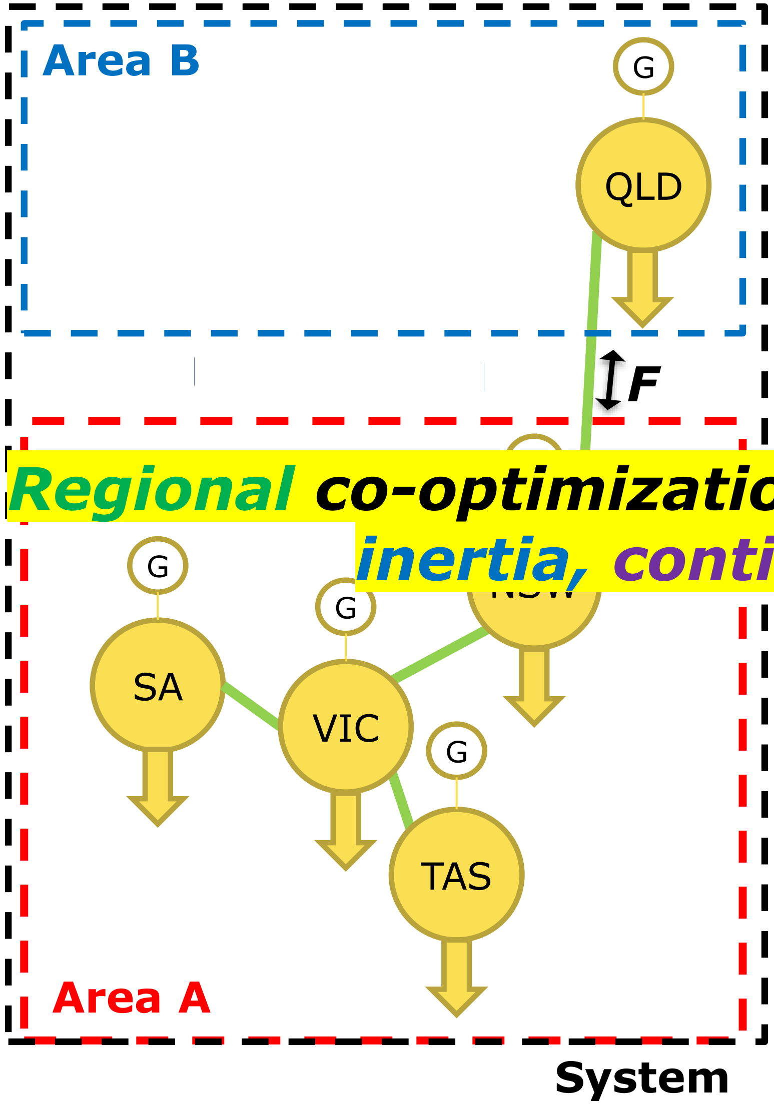


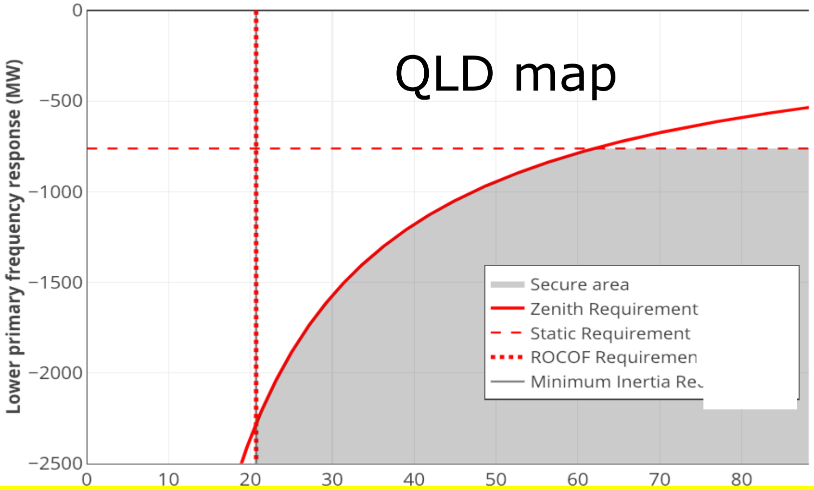


Need to protect the system against islanding: co-optimization of contingency size

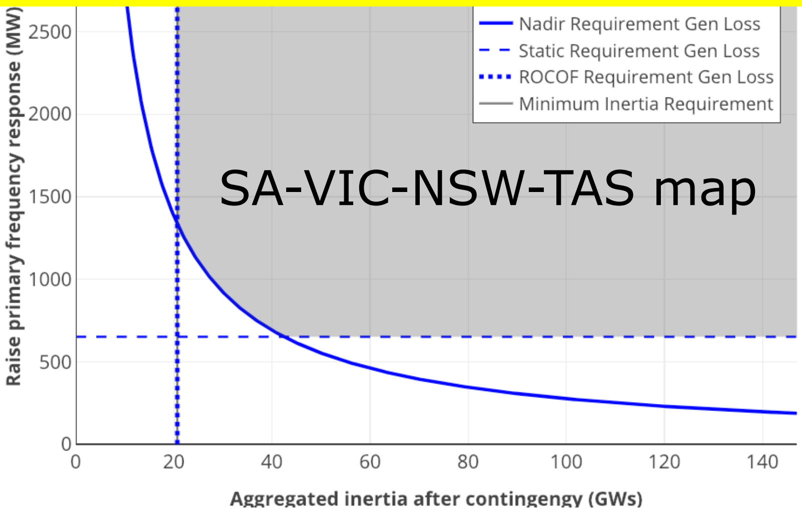
AEMO, "Trip of multiple generators and lines in Queensland and associated under-frequency load shedding on 25 May 2021", October 2021

Separation-constrained UC/OPF





Regional co-optimization of energy, frequency control ancillary services, inertia, contingency level, and interconnector flows



S. Puschel, *et al.*, "Separation event-constrained optimal power flow to enhance resilience in low-inertia power systems", *Electric Power System Research*, 2020

The "new physics"

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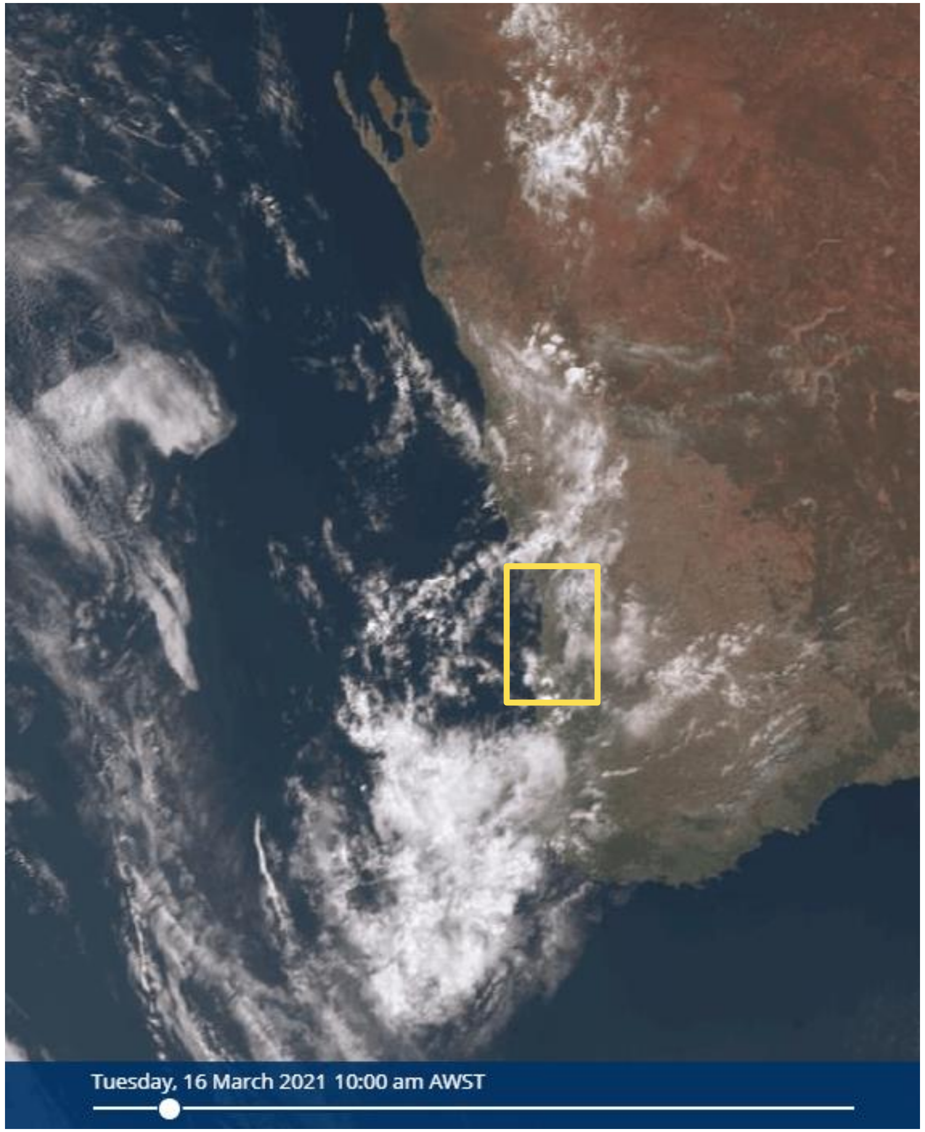
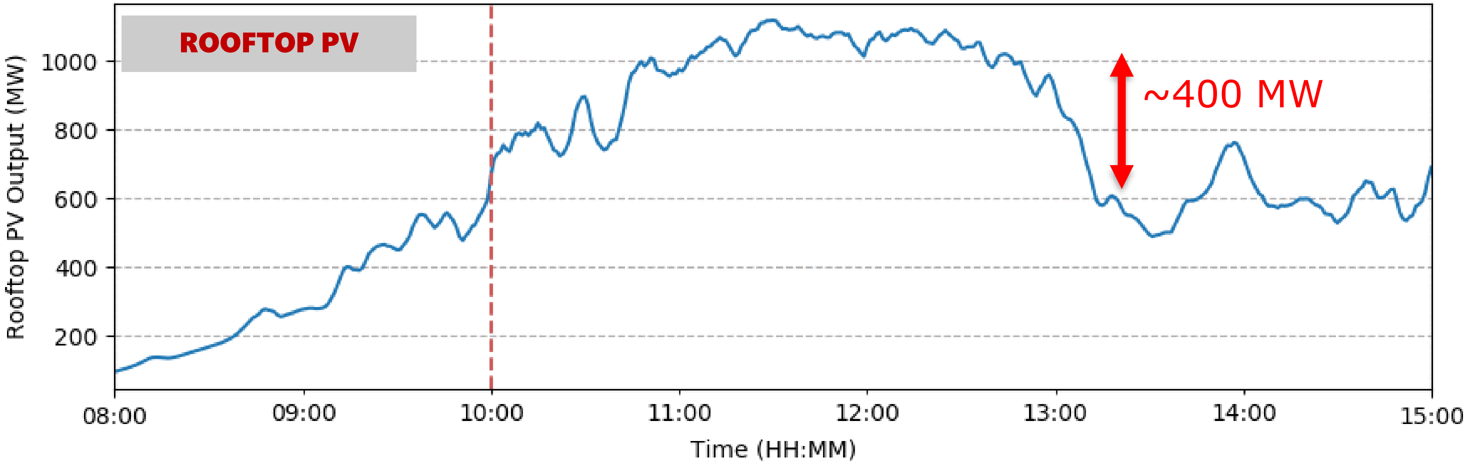
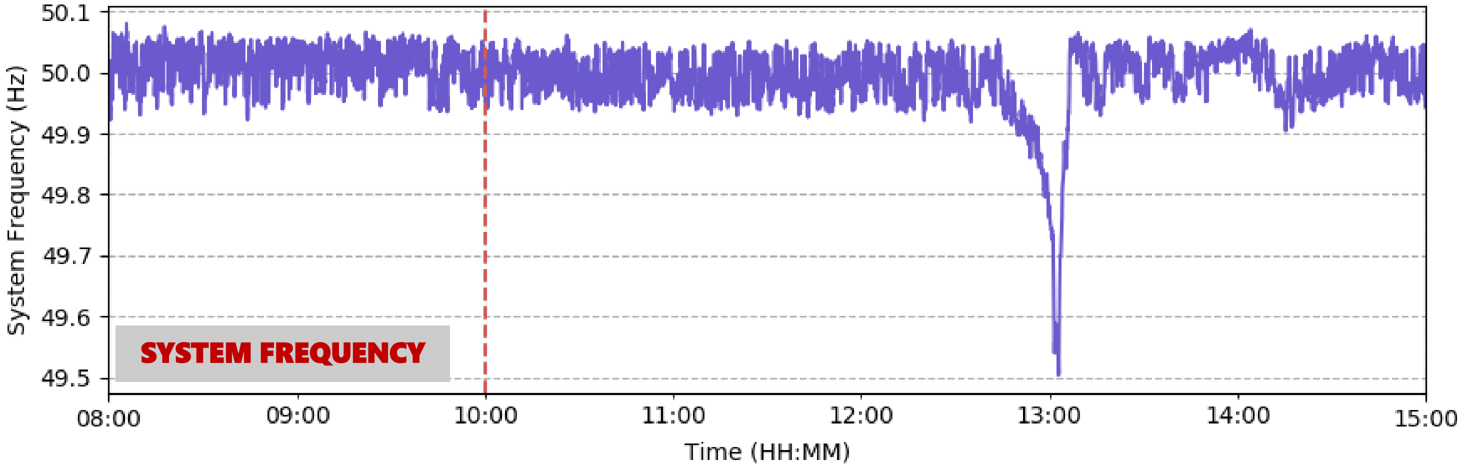
Challenges with weather-driven DER:
Rapid cloud formation in Perth, 16 March 2021







Slide courtesy of Julius Susanto, AEMO

Security in a weather-fuelled system: DER impact on reserves

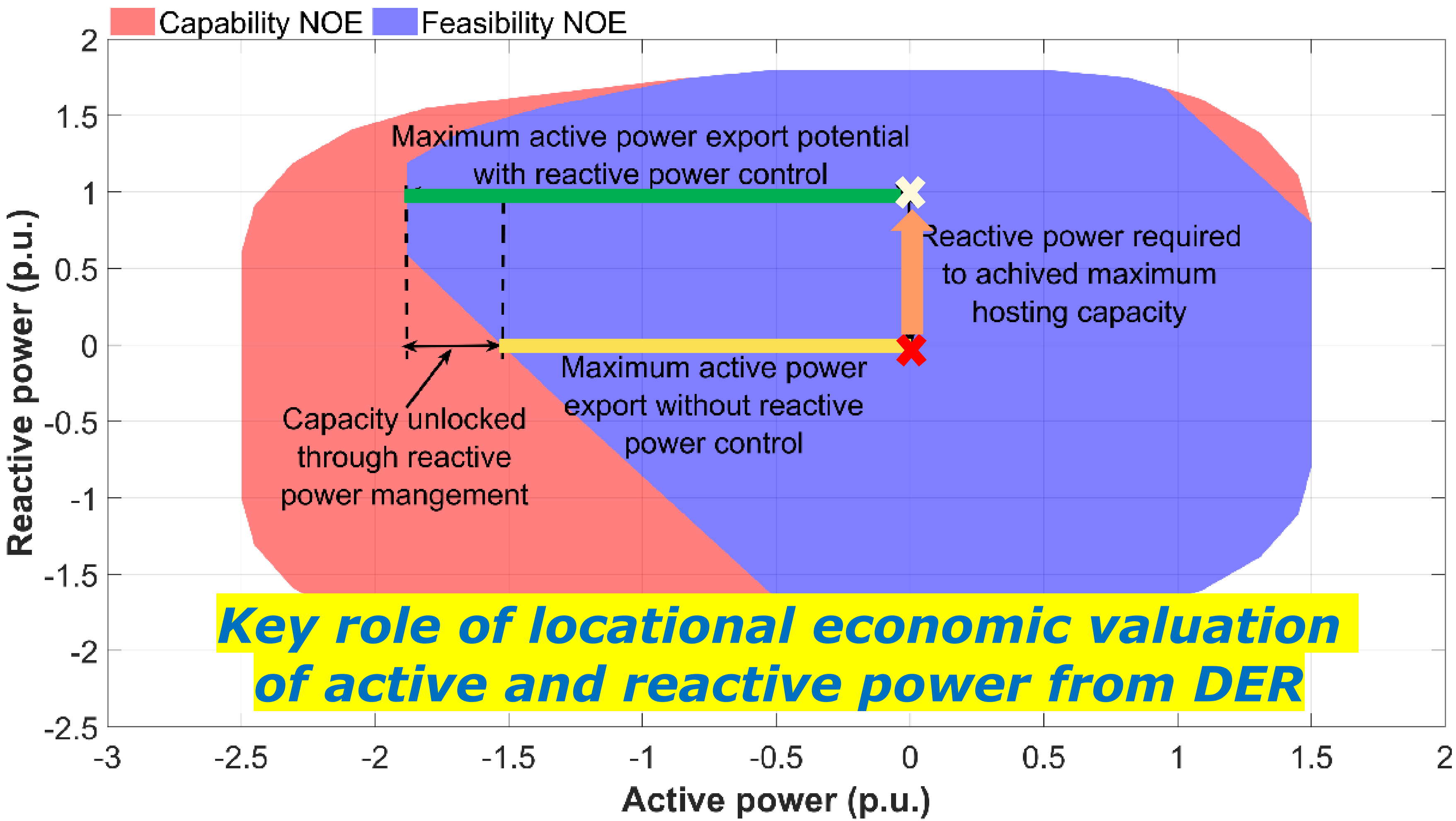
"Electricity provider authorised to switch off rooftop solar in SA in emergencies"

How would you disconnect DER for security reasons?

Source: *ABC News*, 27 August 2020

This is the consequence of DER not being visible/dispatchable/controllable!

Integrated provision of system and local services from DER



M. Liu *et al.*, "Grid and market services from the edge", *IEEE Power and Energy Magazine*, July/August 2021
S. Riaz *et al*, "Modelling and characterisation of flexibility from distributed energy resources", *IEEE Transactions on Power Systems*, July 2021
C. Bas Domenech, *et al.*, "Towards Distributed Energy Markets: Accurate and Intuitive DLMP Decomposition", *IEEE Trans. Energy Mark., Policy and Reg.*, Jan 2024

The “new physics”

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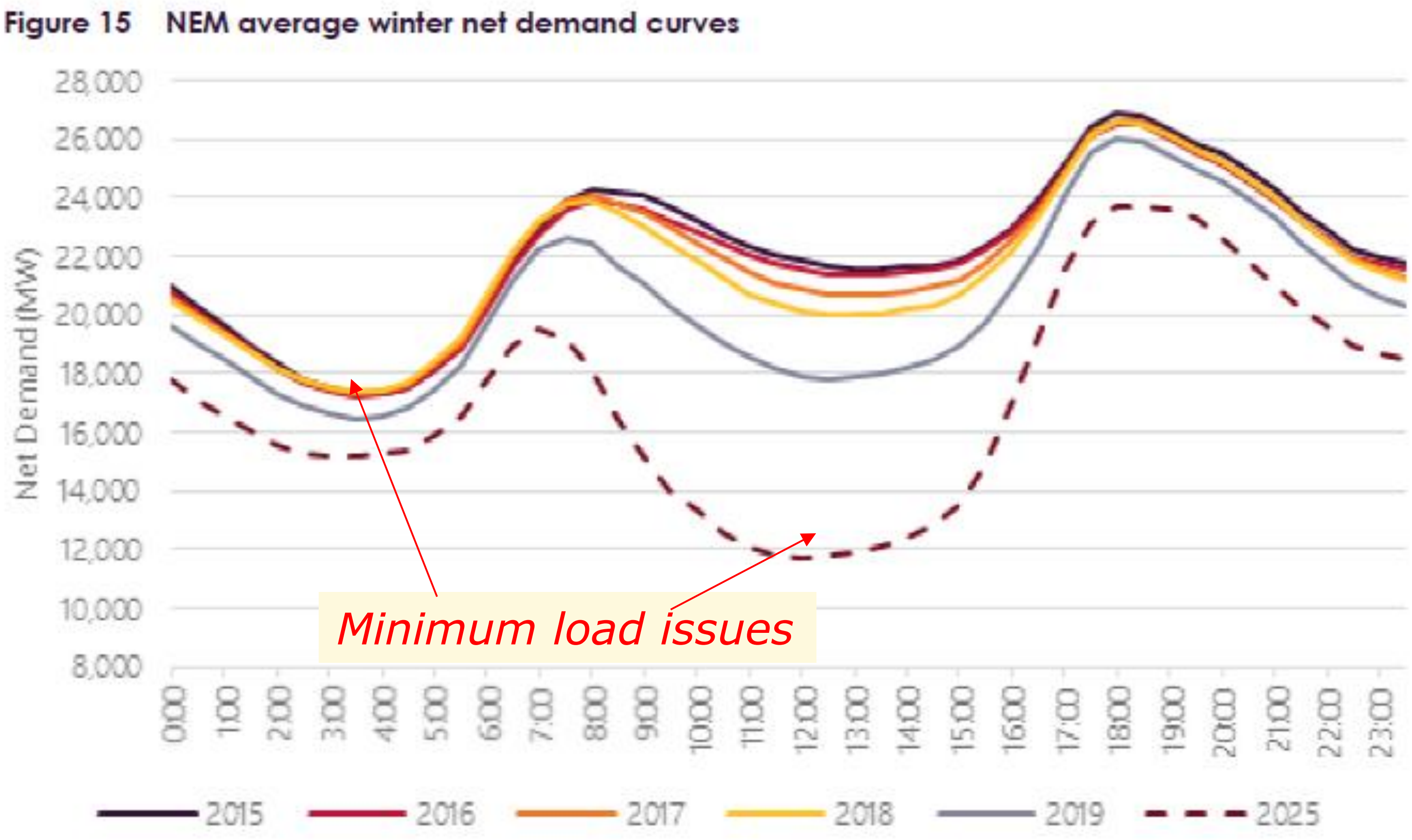
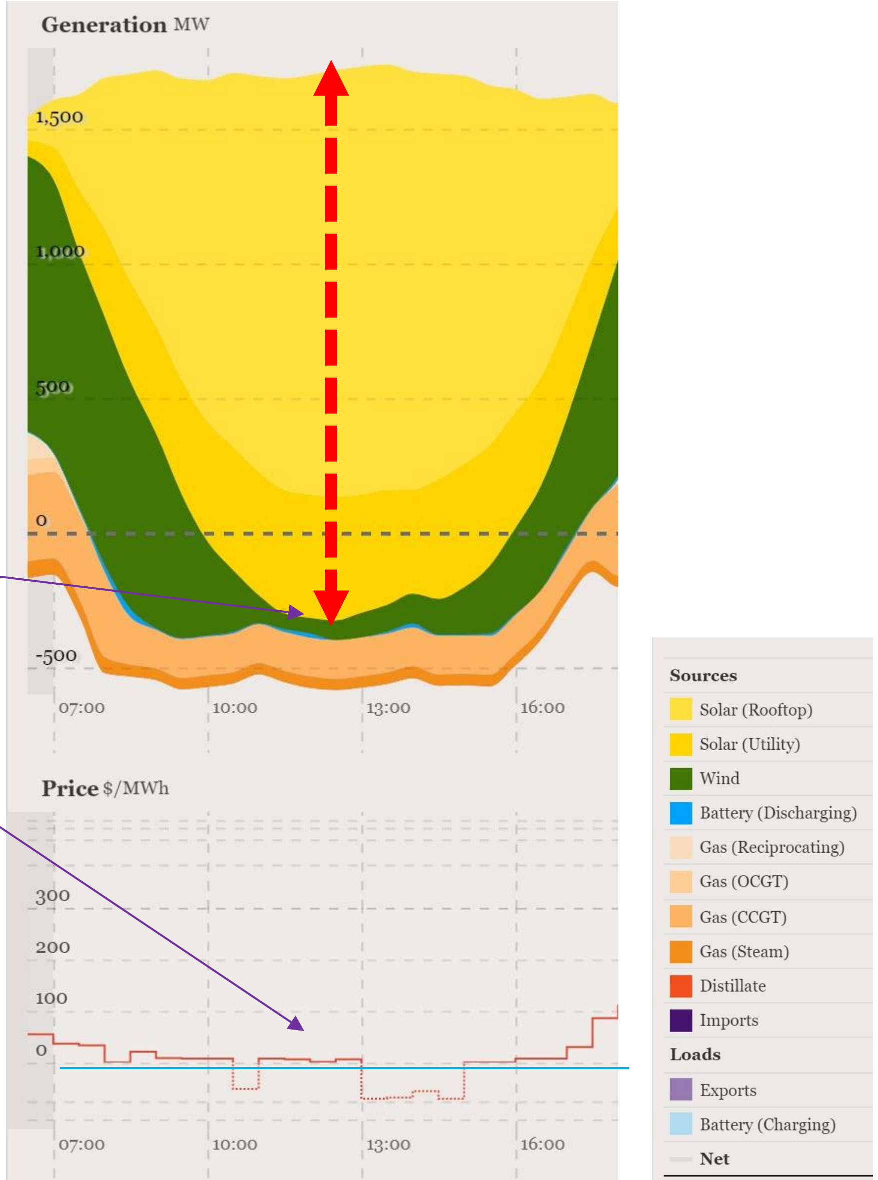
Increasing ramping requirements: The Australian duck



Source: AEMO, "Renewable Integration Study, Stage 1 - Appendix C: Managing Variability and Uncertainty", April 2020

Impact of DER on reactive power reserves

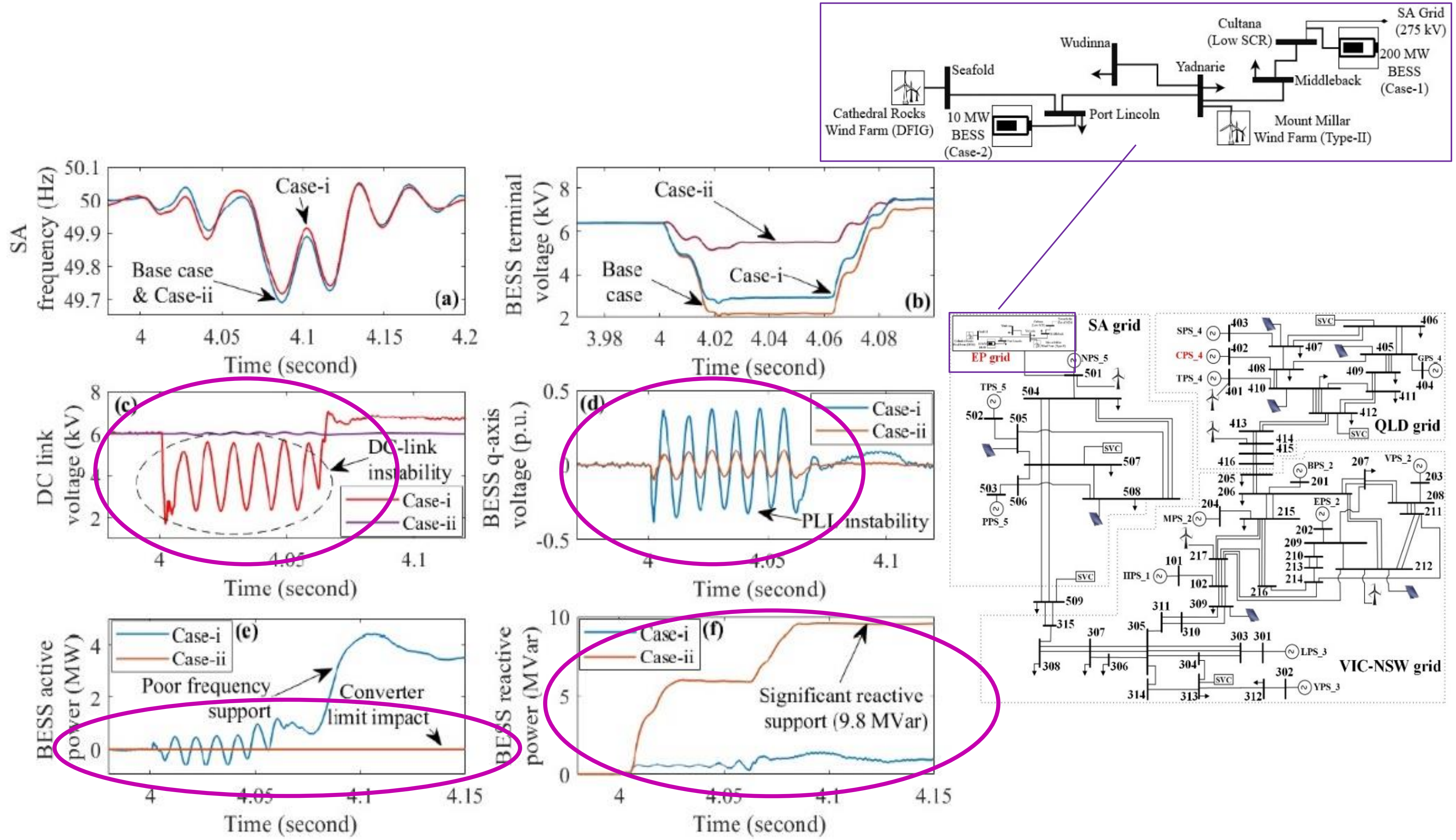
Why are these gas generators operating with these market prices?



What is the risk of operating with high voltages?

Source: AEMO and OpenNEM

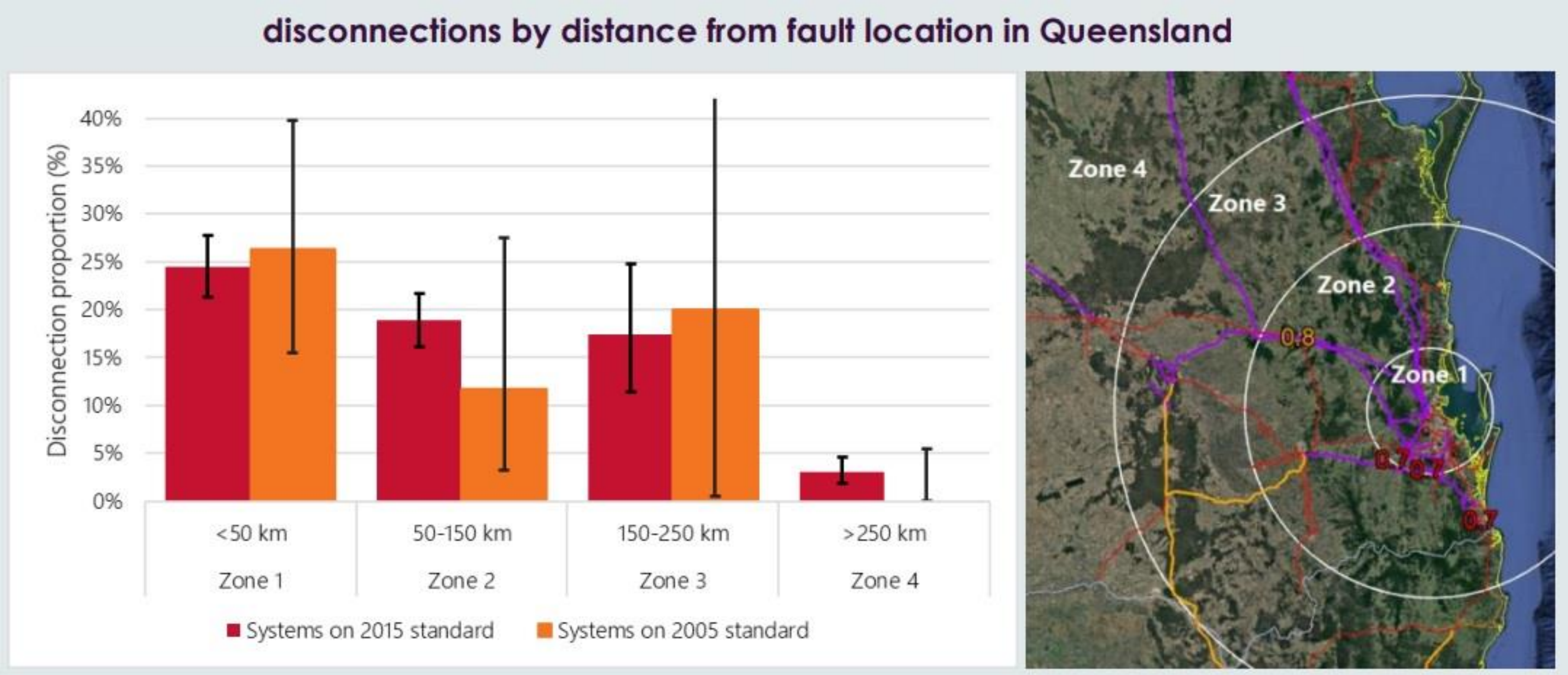
Active-reactive power interaction in weak grids



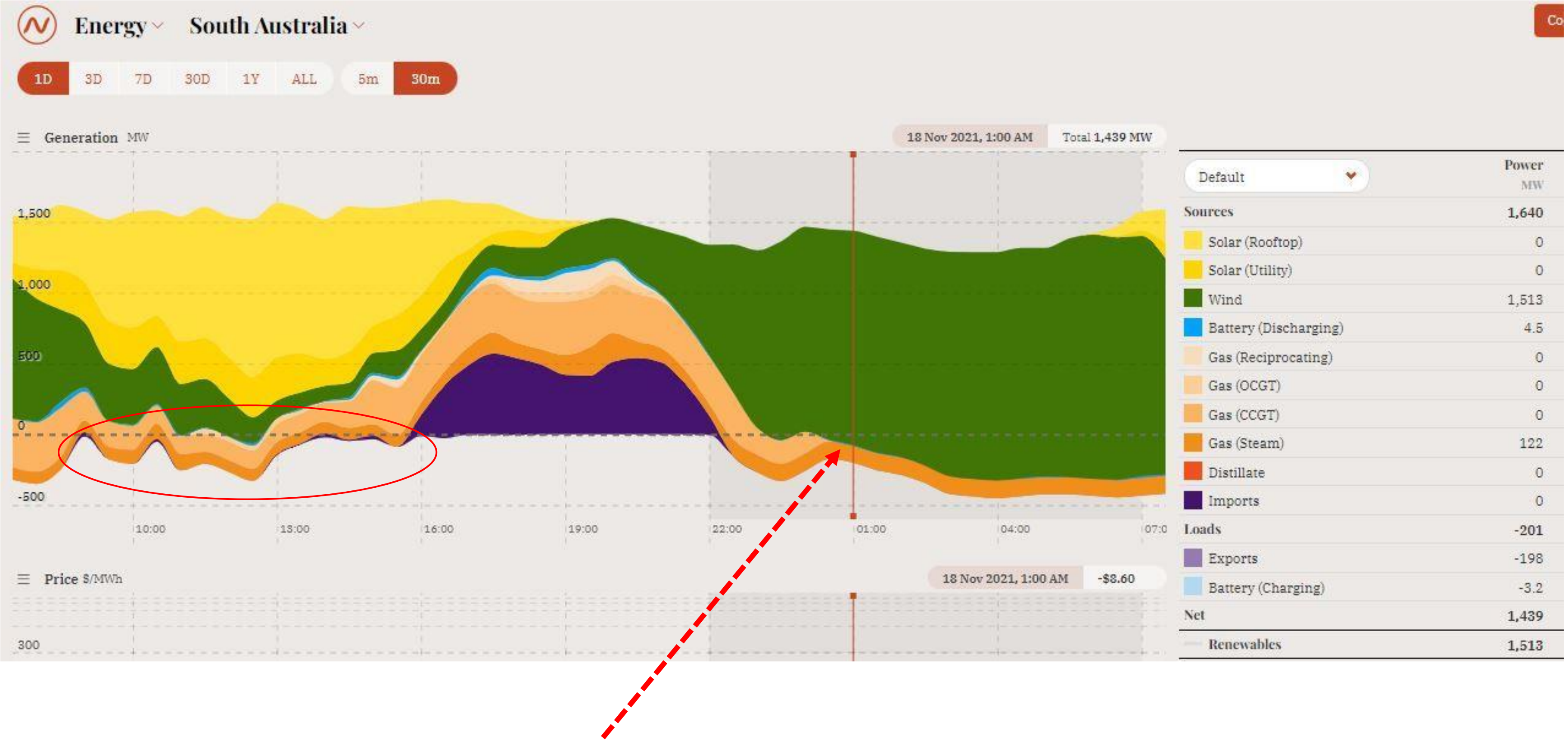
M. Ghazavi, O Gomis-Bellmunt, P. Mancarella, "Simultaneous Provision of Dynamic Active and Reactive Power Response from Utility-scale Battery Energy Storage Systems in Weak Grids", *IEEE Transactions on Power Systems, 2021*
M. Ghazavi Dozein, B. Pal, P. Mancarella, "Dynamics of Inverter-Based Resources in Weak Distribution Grids", *IEEE Transactions on Power Systems*, 2022

Sympathetic DER tripping:
November 2019 event in Queensland

180 MW-310 MW PV disconnection following a fault



Resorting to old school technologies: Effect of synchronous compensators



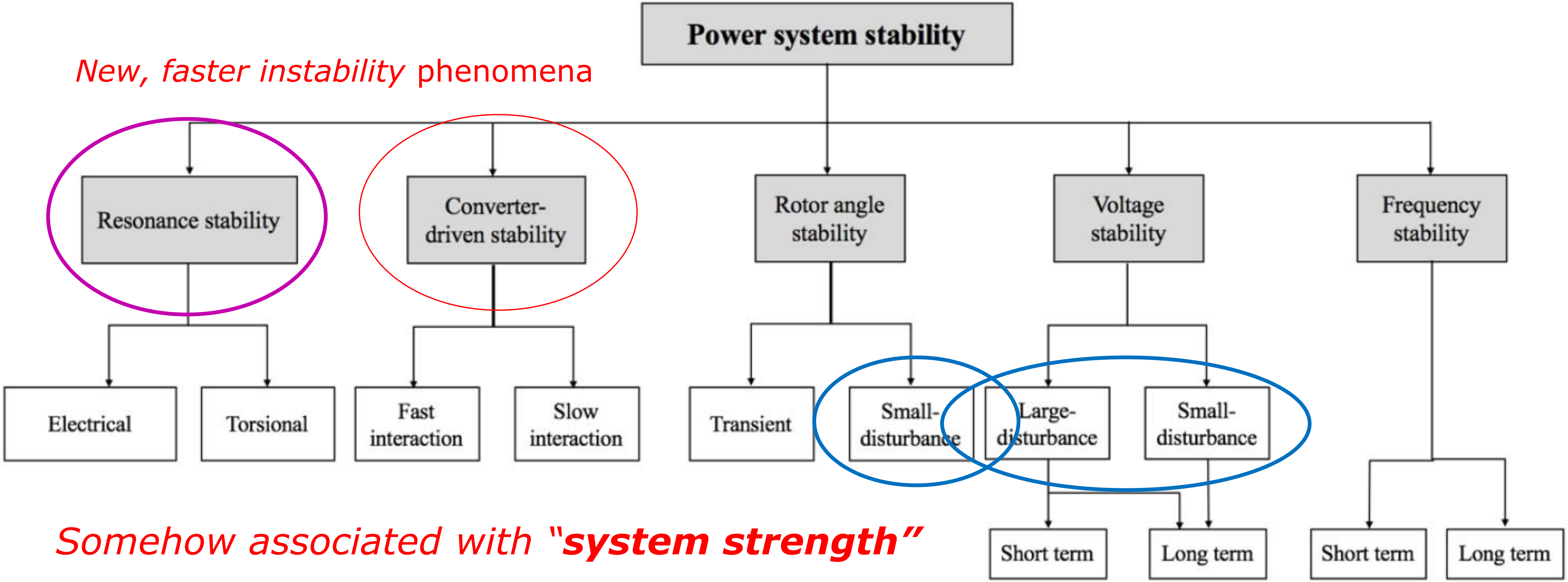
Source: https://reneweconomy.com.au/south-australia-sets-stunning-new-benchmark-as-gas-output-halved-and-wind-at-record-highs/

Henry Ford with his “horseless CAR-riage”

Pic sourced from the internet

Power system stability classification

New, *faster instability* phenomena

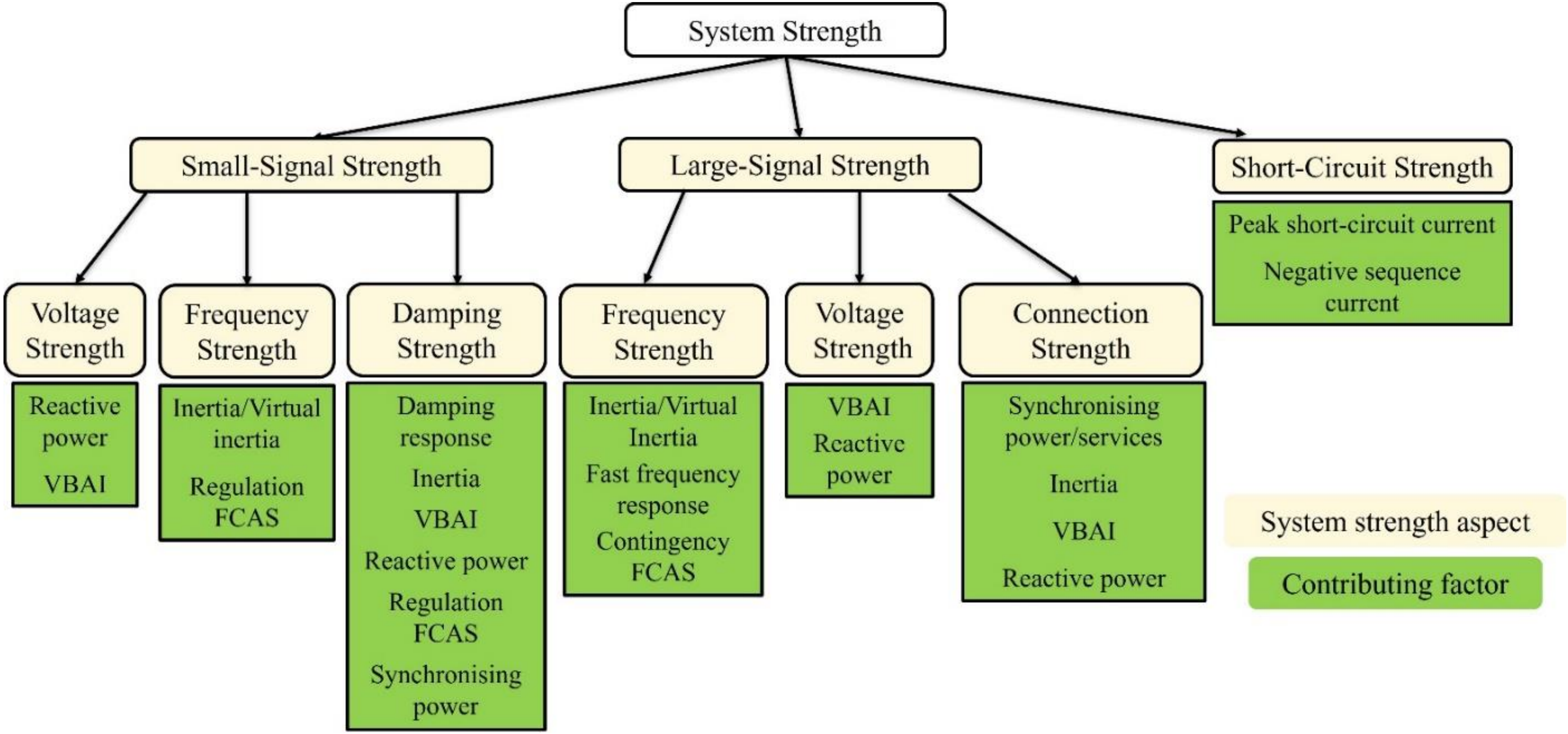


*Somehow associated with "**system strength**"*

IEEE Power System Dynamic Performance Committee, "Task Force on stability definitions and characterization of dynamic behaviour in systems with high penetration of power electronic interfaced technologies,", 2020.

Source: IEEE Power System Dynamic Performance Committee, "Stability definitions and characterization of dynamic behavior in systems with high penetration of power electronic interfaced technologies", 2020

But what is system strength?



M. Ghazavi Dozein, B. Berry, J. V. Milanović, and P. Mancarella, “System strength beyond fault level”, *IEEE Access*, 2025

New technology options to deliver system strength products

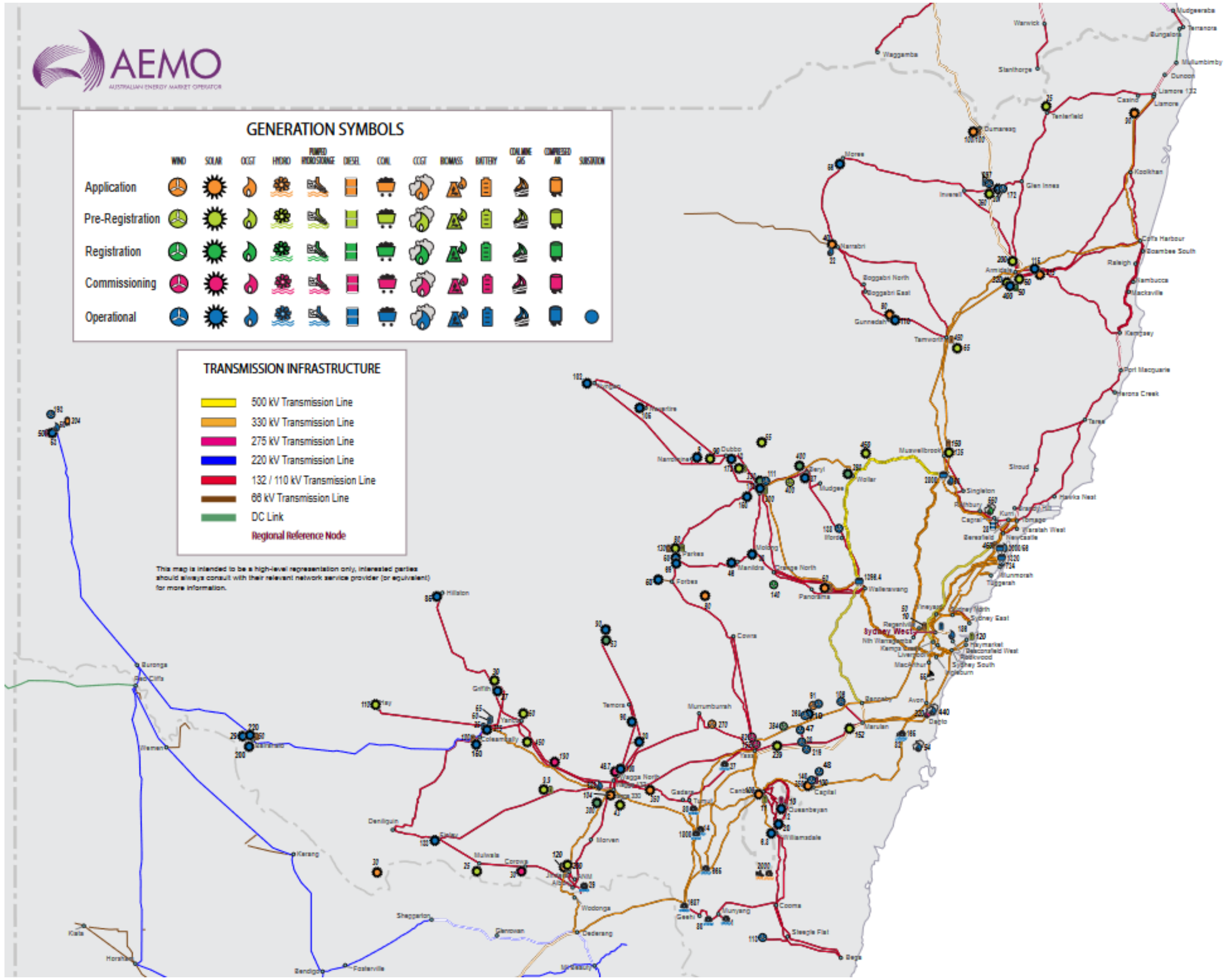
IBR Type		***Contributing Factors to System Strength***								
		Reactive power	VBAI	Virtual inertia	FFR	Cont. FCAS	Regulation FCAS	Peak current/negative component current	Damping	Synchronizing power/services
Grid following	Legacy									
	Enhanced									
Grid forming	Type 1									
	Type 2									
	Type 3									
	Type 4									

*And **network reinforcement** can enhance several forms of system strength too!*

So, it's not only about synchronous machines…

M. Ghazavi Dozein, B. Berry, J. V. Milanović, and P. Mancarella, "System strength beyond fault level", *IEEE Access*, 2025

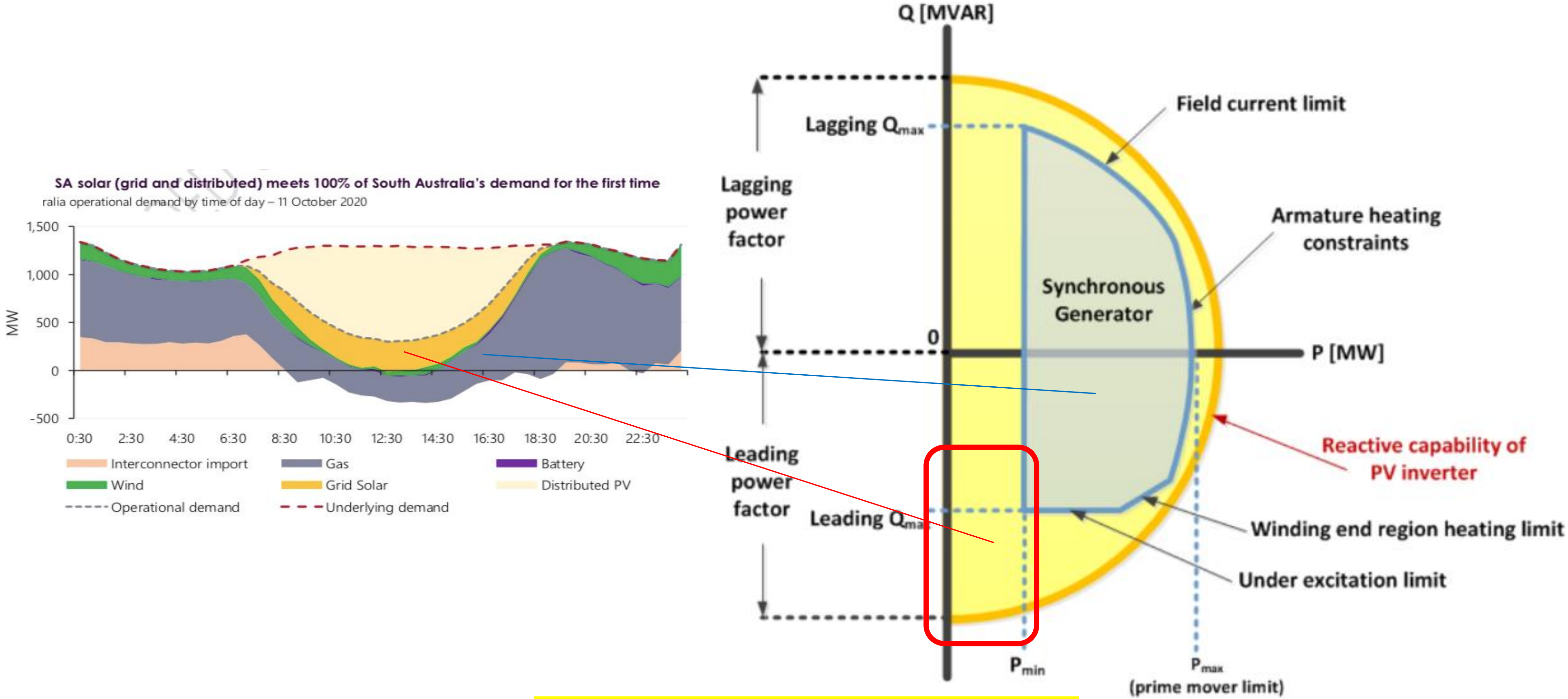
Can renewables provide voltage support?



Courtesy of Julius Susanto

NSW Generation Map [Source: AEMO]

Do we *really* need those gas plants on?



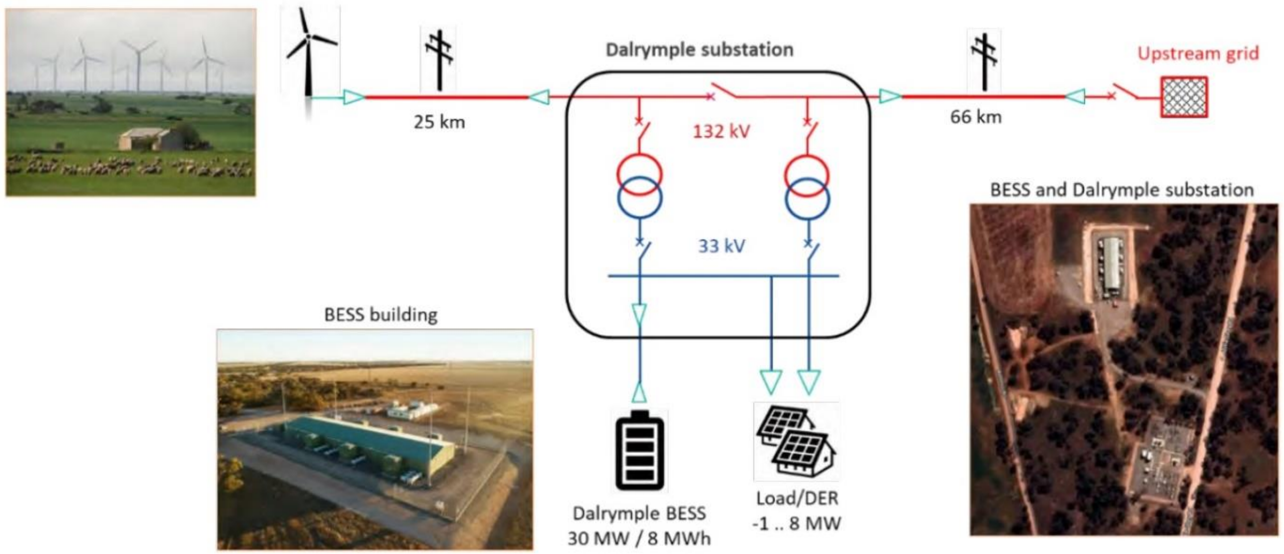
How about batteries?

Figure source: NREL, Demonstration of Essential Reliability Services by a 300-MW Solar Photovoltaic Power Plant, 2015

Example: Dalrymple battery

- **30 MW/8 MWh** BESS
- Lithium-ion technology
- Connected to the SA grid via a 33 kV/132 kV transformer
- Supplies average local demand of 3 MW, 8 MW peak
- Equipped with **virtual synchronous machine** control with converter overloading capability of 2 pu for 2 seconds

Simplified single-line diagram of the York Peninsula in South Australia

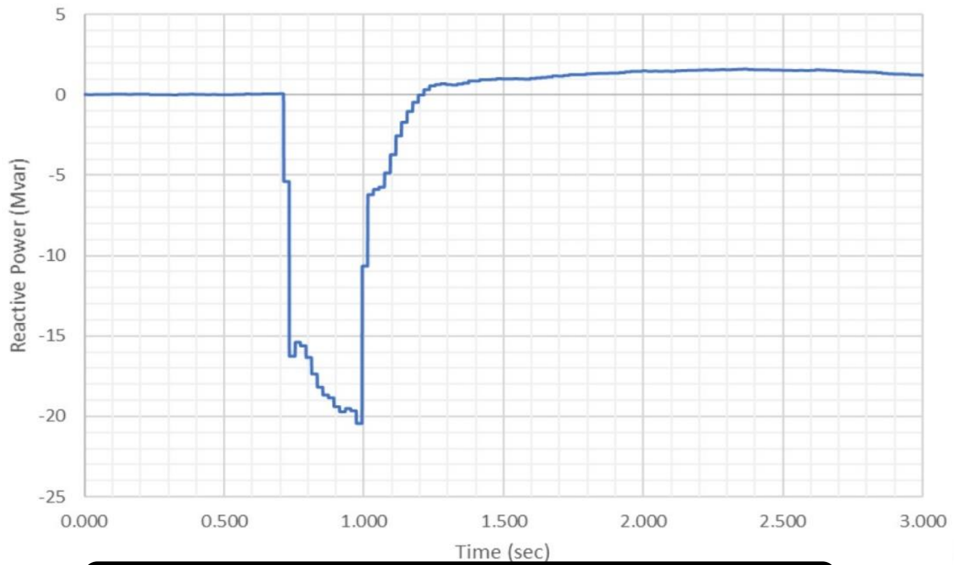


ElectraNet," ESCRI-SA battery storage project operational report#3, August 2020.

From “grid following” to “grid forming”

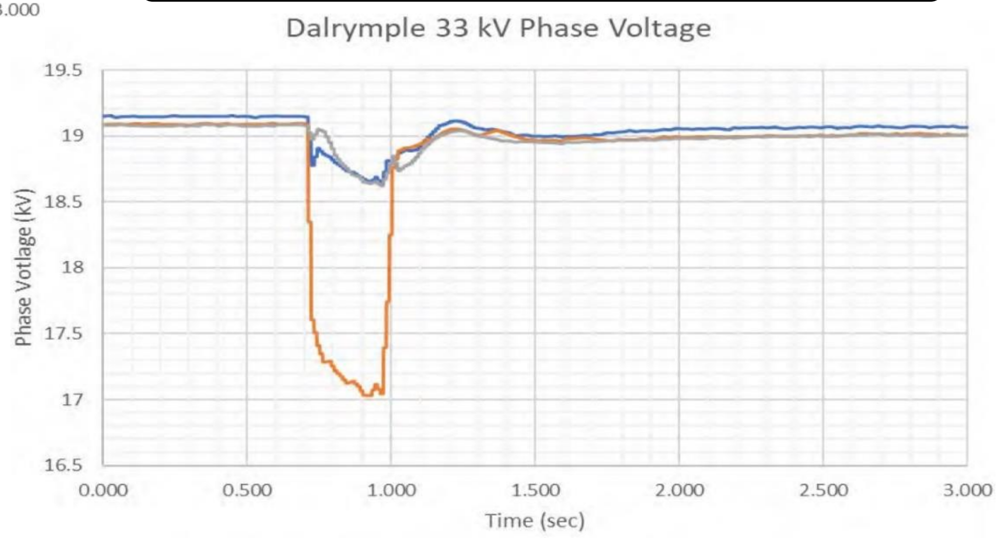
Dalrymple battery

Single-phase–to-ground fault on January 13, 2020



Battery reactive power response

Battery terminal voltage dynamics

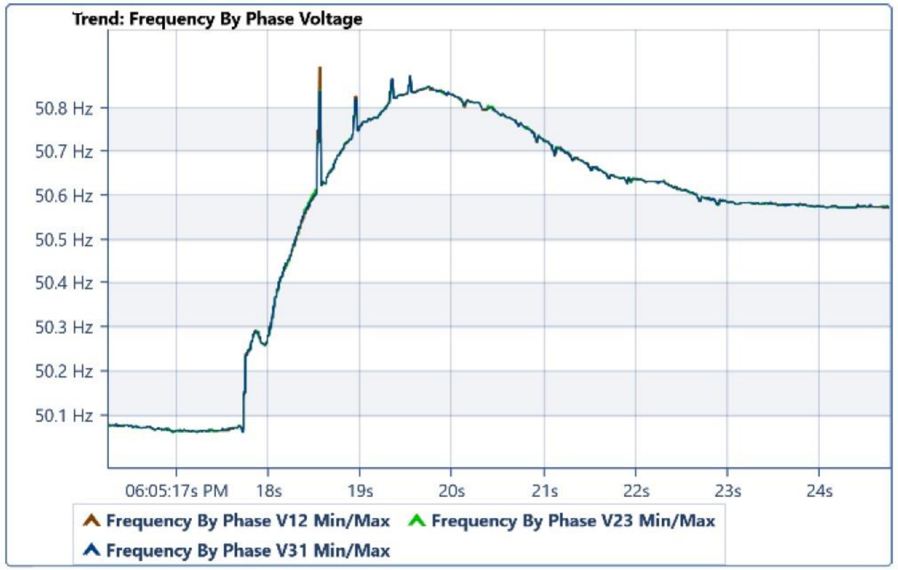


ElectraNet,” ESCRI-SA battery storage project operational report#3, August 2020.

The future emulates the past: "Virtual synchronous machine"

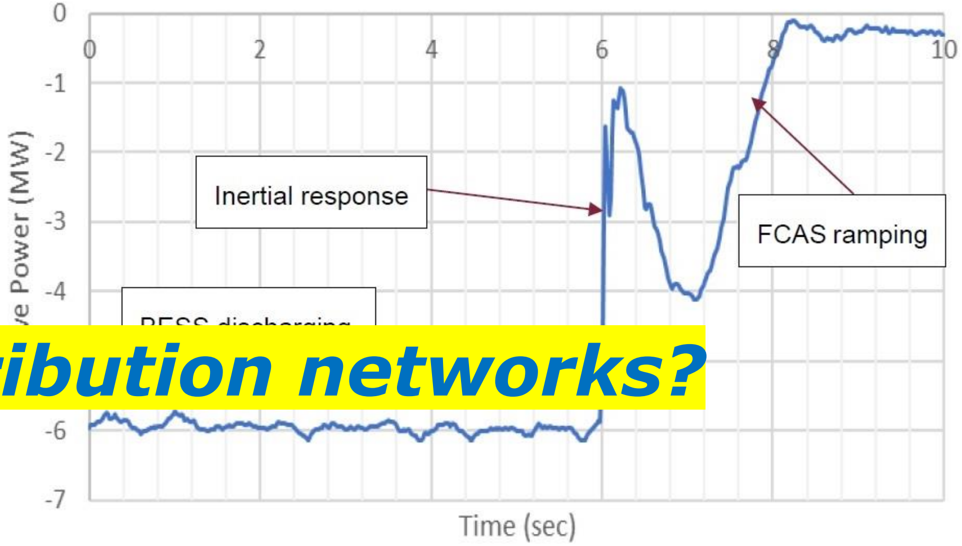
The 30 MW Dalrymple battery

SA frequency dynamics following the separation event



Virtual inertia response following the SA separation, November 16, 2019

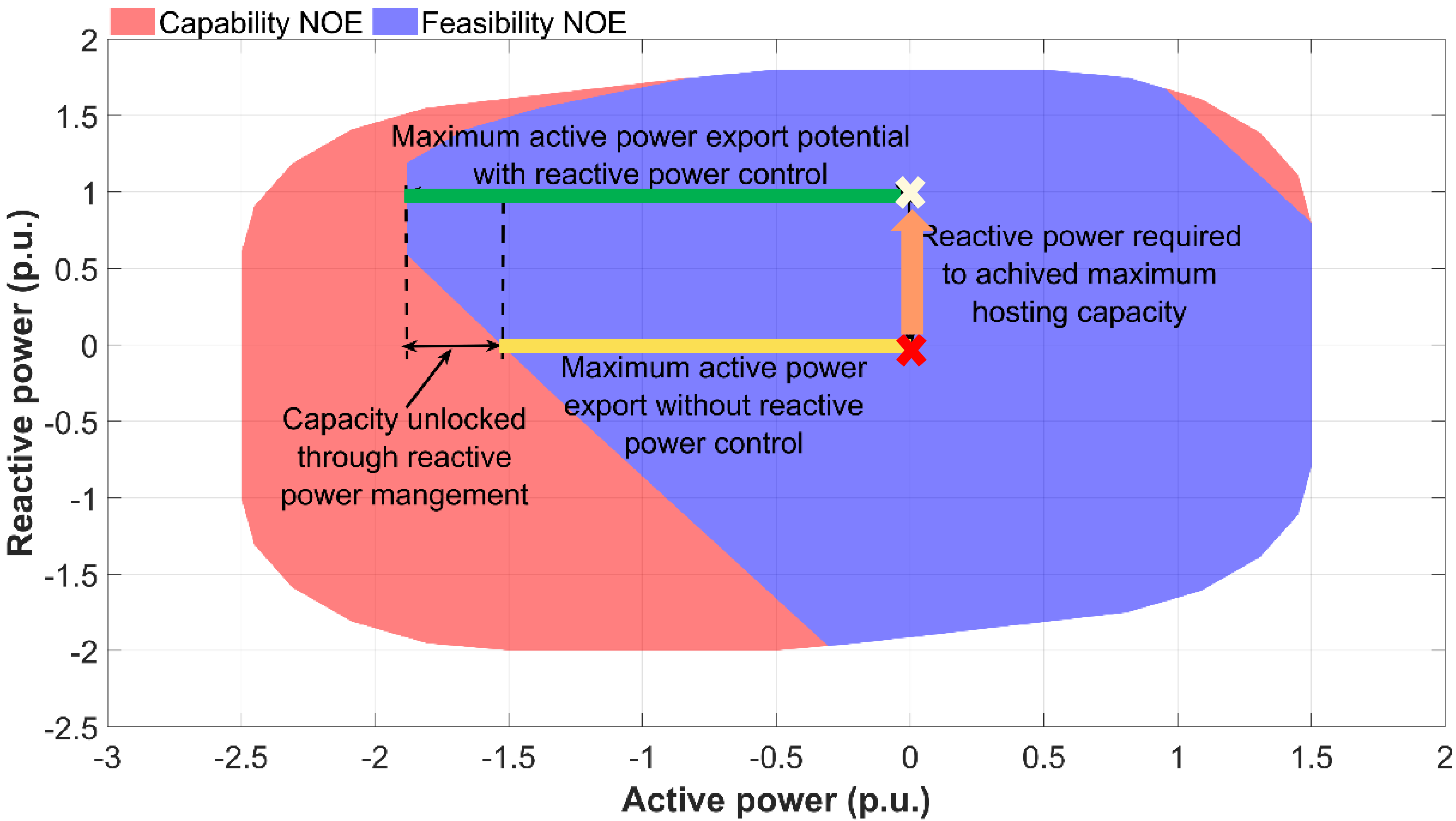
Dynamic behaviour of the Dalrymple battery during the event



How about distribution networks?

S. Cherevatsky *et. al.*, "Grid forming energy storage system addresses challenges of grids with high penetration of renewables (A case study)," 2020 CIGRE Paris session, pp. 1-13, 2020

Integrated provision of system and local services from DER



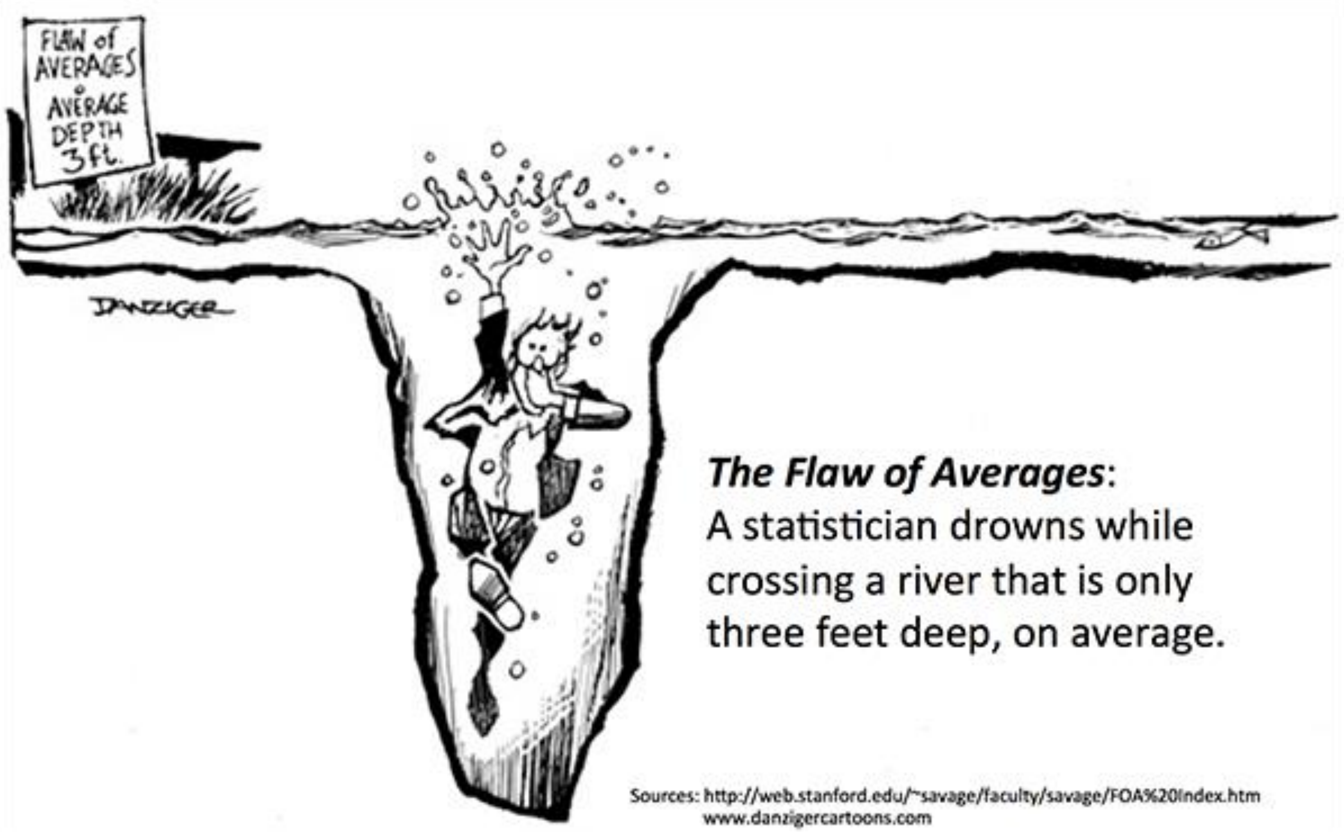
M. Liu *et al.*, "Grid and market services from the edge", *IEEE Power and Energy Magazine*, July/August 2021

S. Riaz *et al*, "Modelling and characterisation of flexibility from distributed energy resources", *IEEE Transactions on Power Systems*, July 2021

C. Bas Domenech, *et al.*, "Towards Distributed Energy Markets: Accurate and Intuitive DLMP Decomposition", *IEEE Trans. Energy Mark., Policy and Reg.*, Jan 2024

Power system resilience and grid fragility

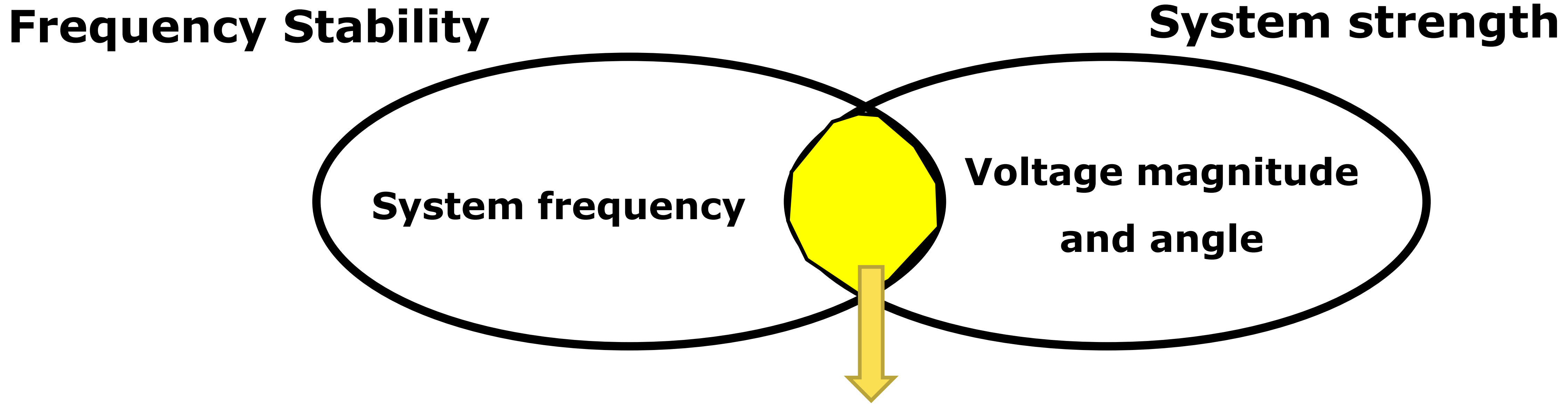
What is an extreme event in a fragile grid?



P. Mancarella, "Electricity grid fragility and resilience in a future net-zero carbon economy", *Oxford Energy Forum – Electricity Networks in a Net-Zero-Carbon Economy*, 124, pages 41-45, Sept 2020

J. Eggleston, C. Zuur, P. Mancarella, "From security to resilience: technical and regulatory options to manage extreme events in low-carbon grids", *IEEE Power & Energy Magazine*, Sept/Oct 2021

Fragility challenges in weak grids

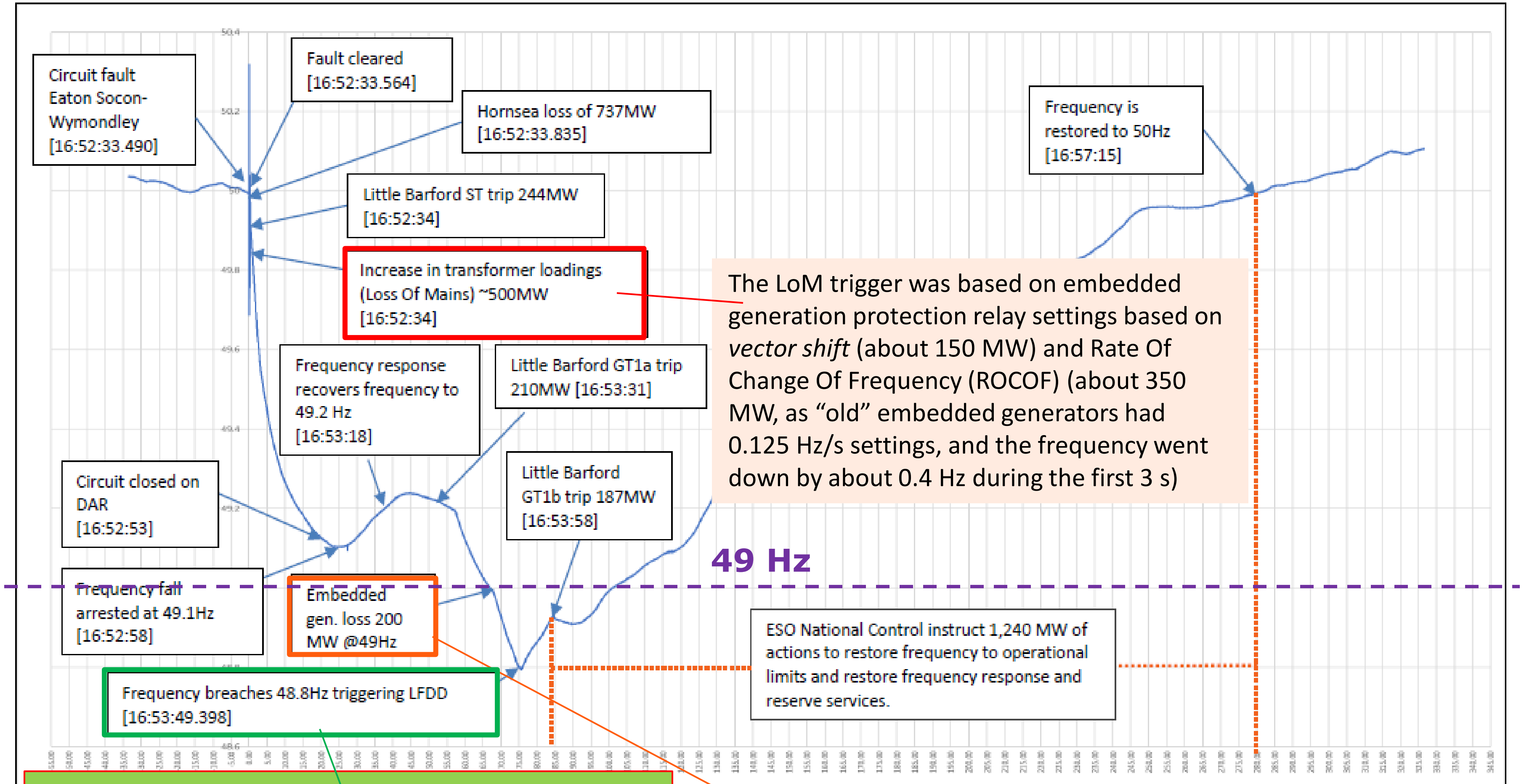


IBR control instability, small-signal instability

Lack or reactive power control, voltage instability

Cascading events (frequency and angle instability)

Grid fragility example: demand disconnection event, UK, 09/08/19



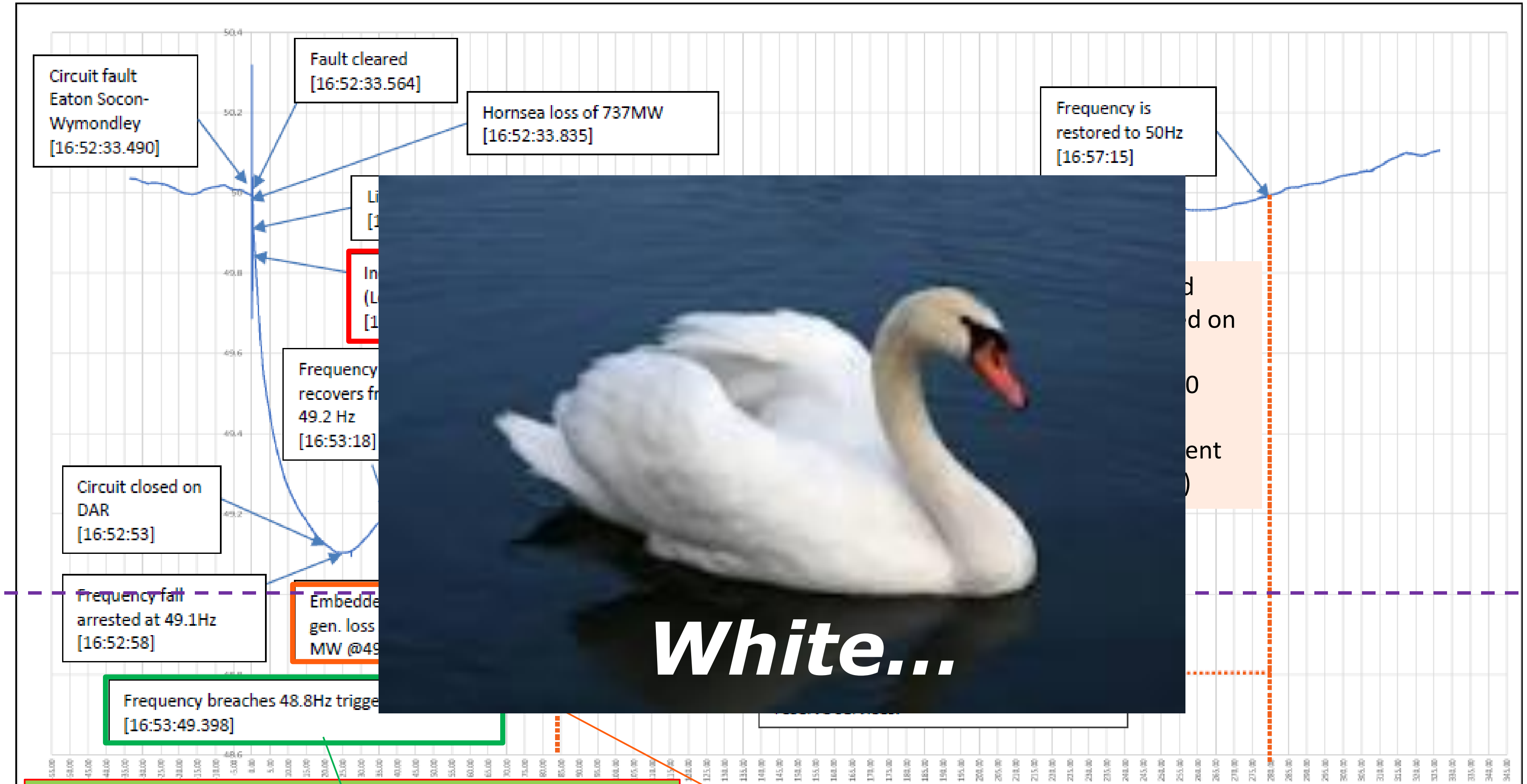
The LoM trigger was based on embedded generation protection relay settings based on *vector shift* (about 150 MW) and Rate Of Change Of Frequency (ROCOF) (about 350 MW, as "old" embedded generators had 0.125 Hz/s settings, and the frequency went down by about 0.4 Hz during the first 3 s)

The 950 MW low-frequency demand disconnection (LFDD) schemes also triggered substantial (almost 600 MW!) embedded generation disconnection, so that the net demand disconnection was actually only 350 MW

200 MW of embedded generation tripped at the frequency threshold of 49 Hz, exacerbating the cascading before demand disconnection

Source: UK National Grid ESO, "Technical report on the events of 9 August 2019", https://www.ofgem.gov.uk/system/files/docs/2019/09/eso_technical_report_-_final.pdf

Grid fragility example: demand disconnection event, UK, 09/08/19



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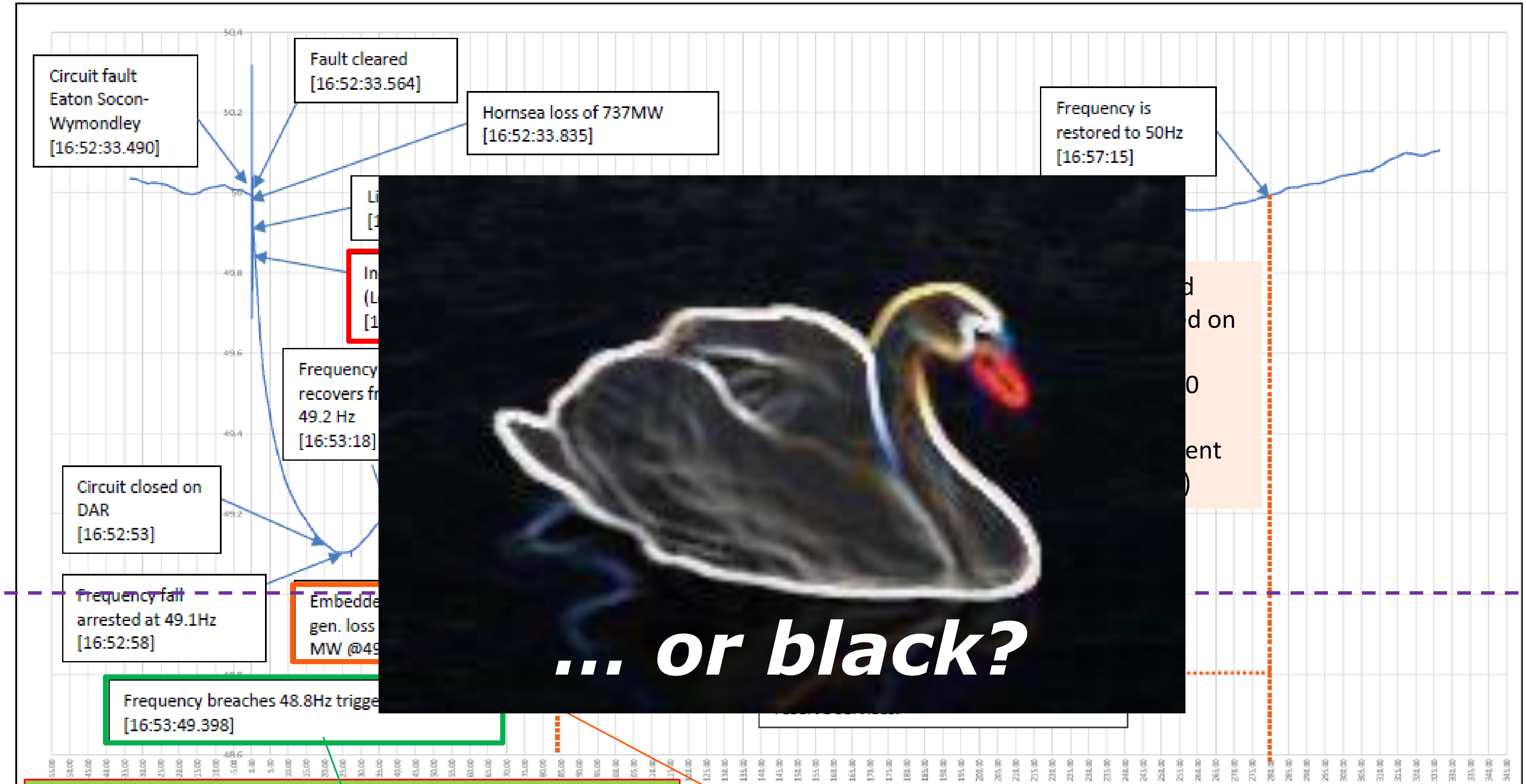
Grid fragility example: demand disconnection event, UK, 09/08/19



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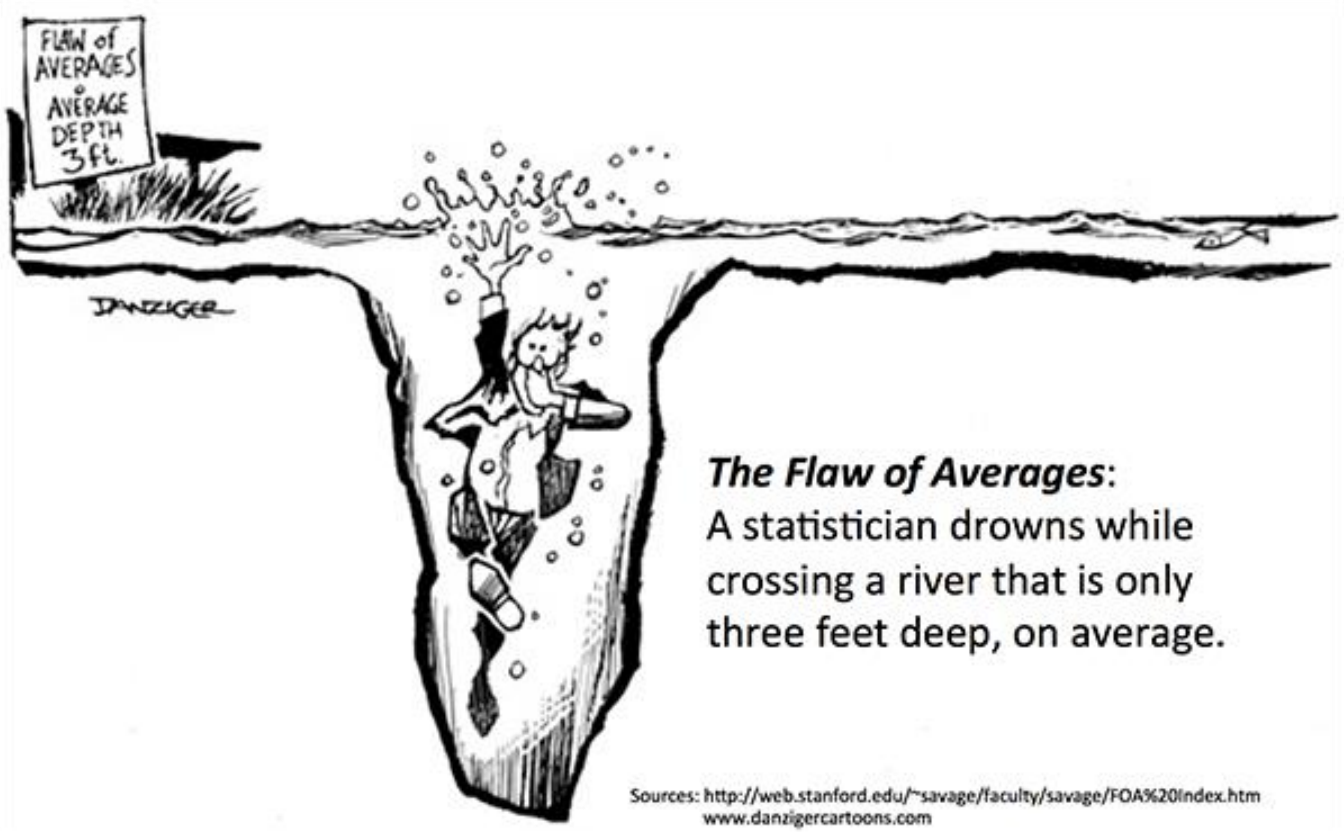
Source: UK National Grid ESO, "Technical report on the events of 9 August 2019", https://www.ofgem.gov.uk/system/files/docs/2019/09/eso_technical_report_-_final.pdf

Power system resilience and grid fragility

In a fragile grid, security and resilience merge!



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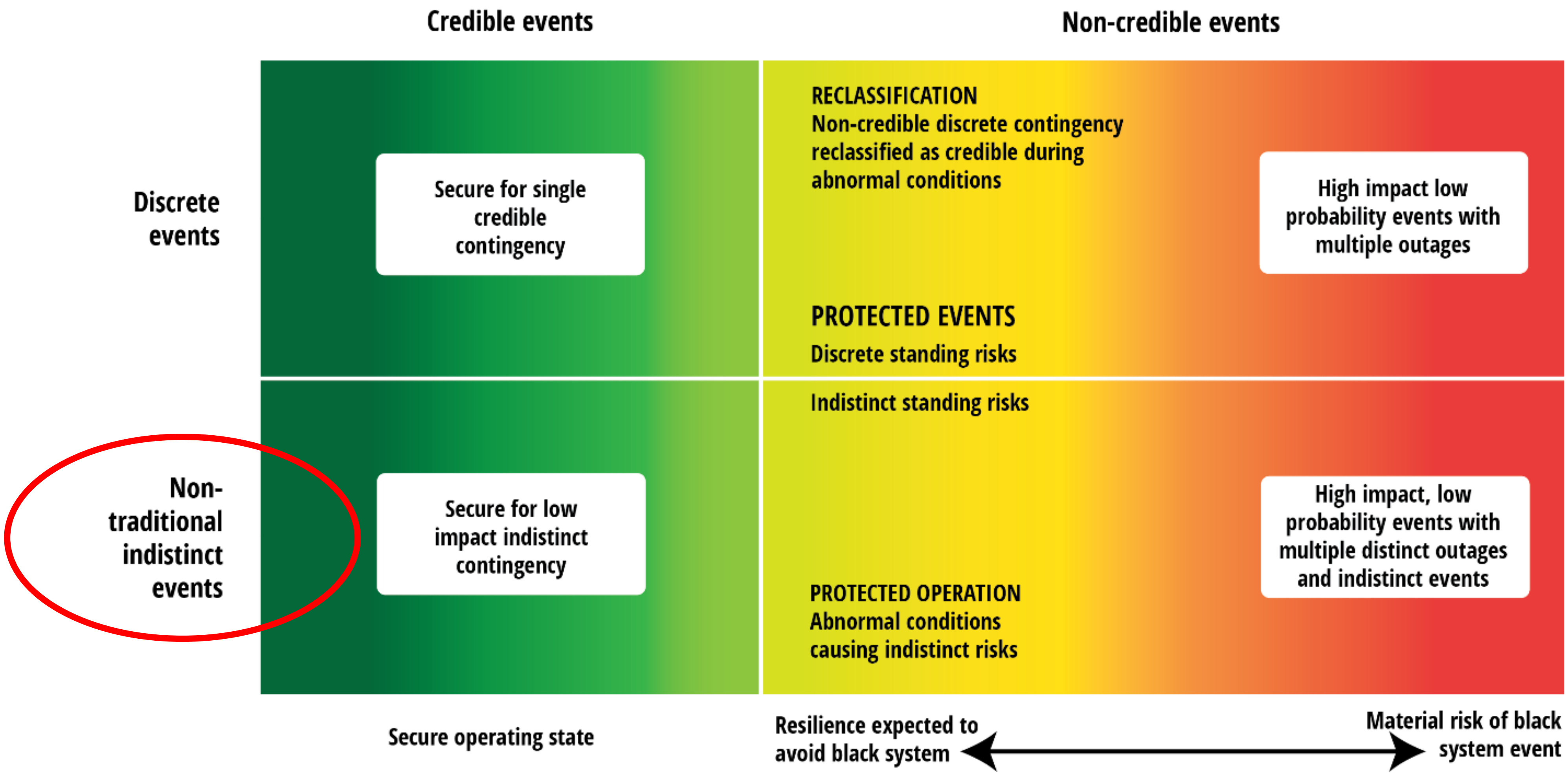
J. Eggleston, C. Zuur, P. Mancarella, "From security to resilience: technical and regulatory options to manage extreme events in low-carbon grids", *IEEE Power & Energy Magazine*, Sept/Oct 2021

Categorisation of new, “resilience” events: moving beyond *security*



J. Eggleston, C. Zuur, P. Mancarella, “From security to resilience: technical and regulatory options to manage extreme events in low-carbon grids”, *IEEE Power & Energy Magazine*, Sept/Oct 2021

Grid fragility example: Iberian peninsula blackout, 28 April 2025

What should be done moving forward?

Will more *redundancy* enhance reliability (and resilience)?

Why Investments Do Not Prevent Blackouts

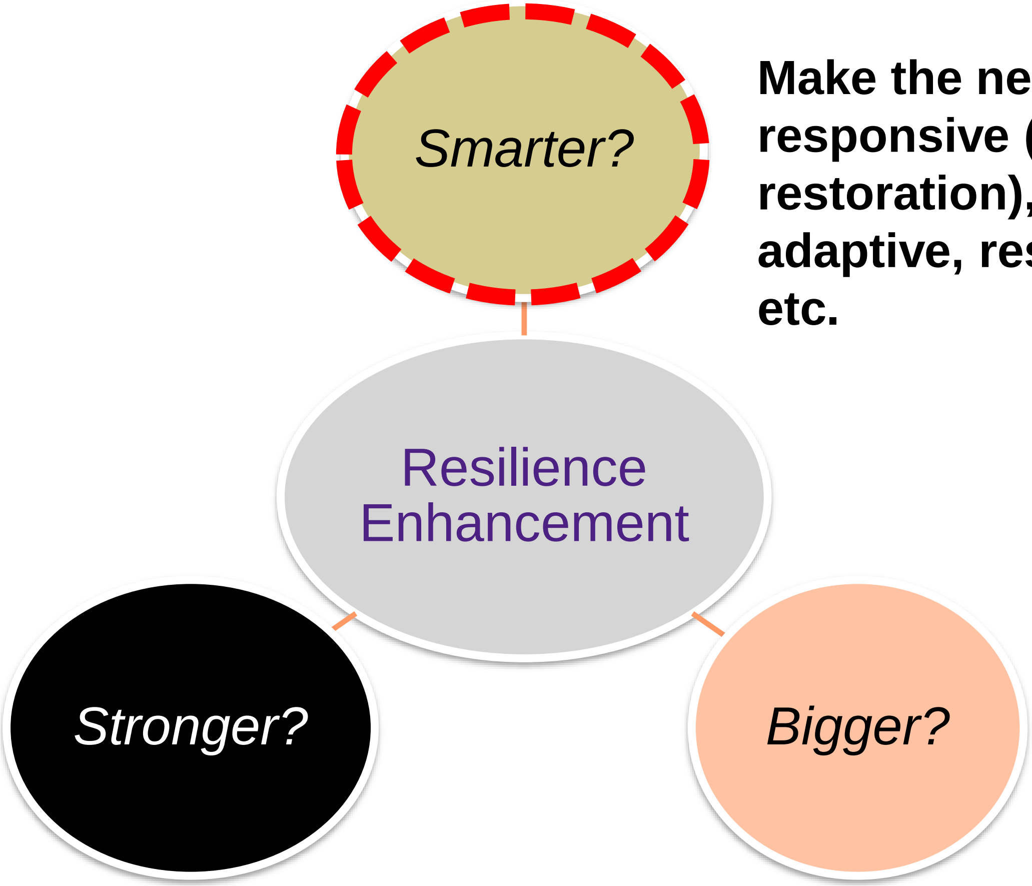
The idea that increasing the capacity of the transmission network should improve the security of the system and reduce the probability of blackouts is intuitively appealing. However, this intuition does not withstand scrutiny.

Daniel Kirschen and Goran Strbac

D. Kirschen and G. Strbac, "Why investments do not prevent blackouts", *The Electricity Journal*, March 2004

Planning for resilience: The *Resilience Trilemma*

Make the network more responsive (e.g. faster restoration), self-adaptive, resourceful, etc.



Upgrade existing infrastructure, asset life extension, etc.

Build new infrastructure, e.g. transmission lines, substations, etc.

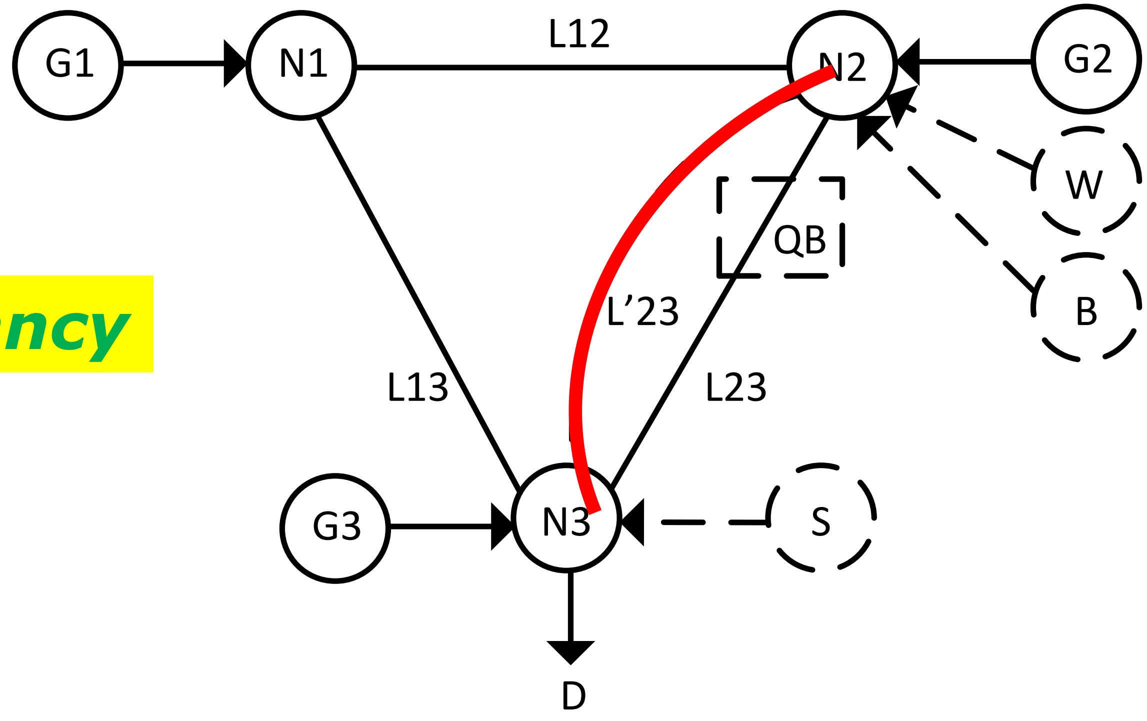
M. Panteli and P. Mancarella, The Grid: Stronger, Bigger, Smarter? Presenting a conceptual framework of power system resilience, *IEEE Power and Energy Magazine,* May/June 2015

R. Moreno, *et al.*, “From Reliability to Resilience: Planning the Grid Against the Extremes”, *IEEE Power and Energy Magazine*, *July-August 2020*

M. Panteli, *et al.*, "Power Systems Resilience Assessment: Hardening and Smart Operational Enhancement Strategies," Proceedings of the IEEE, 105, 7, pp. 1202-1213, July 2017

Planning for the new grid

Redundancy

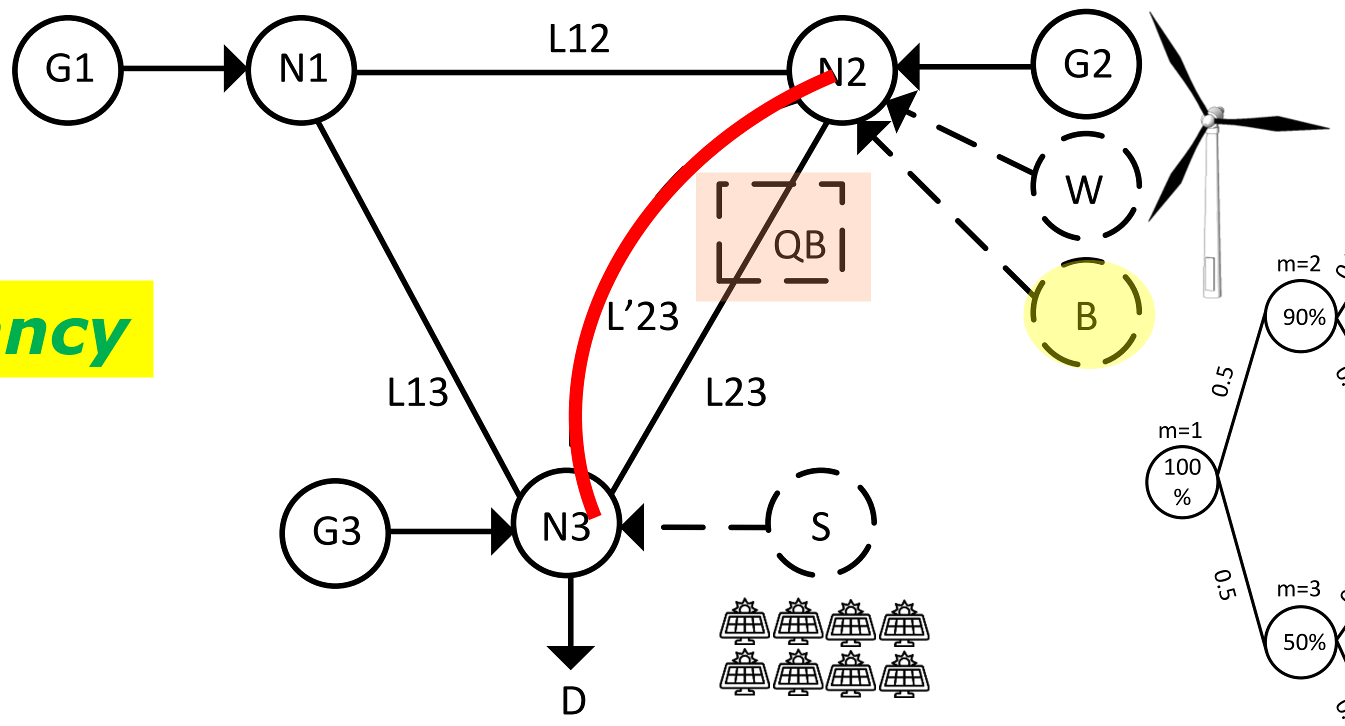


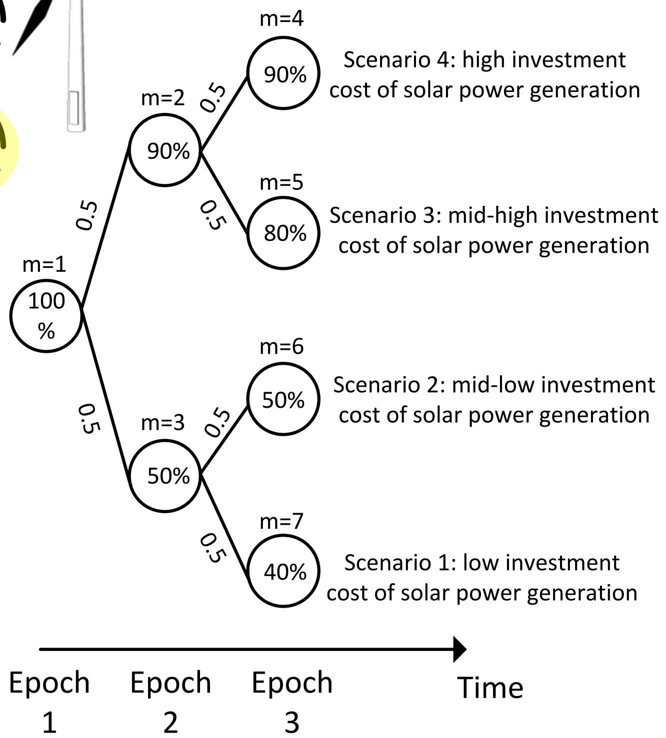
R. Moreno, A. Street, J.M. Arroyo, and P. Mancarella, "Planning Low-Carbon Electricity Systems under Uncertainty Considering Operational Flexibility and Smart Grid Technologies", *Philosophical Trans. Royal Society A*, June 2017

B. Moya, *et al.*, "Uncertainty representation in investment planning of low-carbon power systems", *Electric Power Systems Research*, Volume 212, Nov. 2022, 108470

Planning for the new grid

Redundancy





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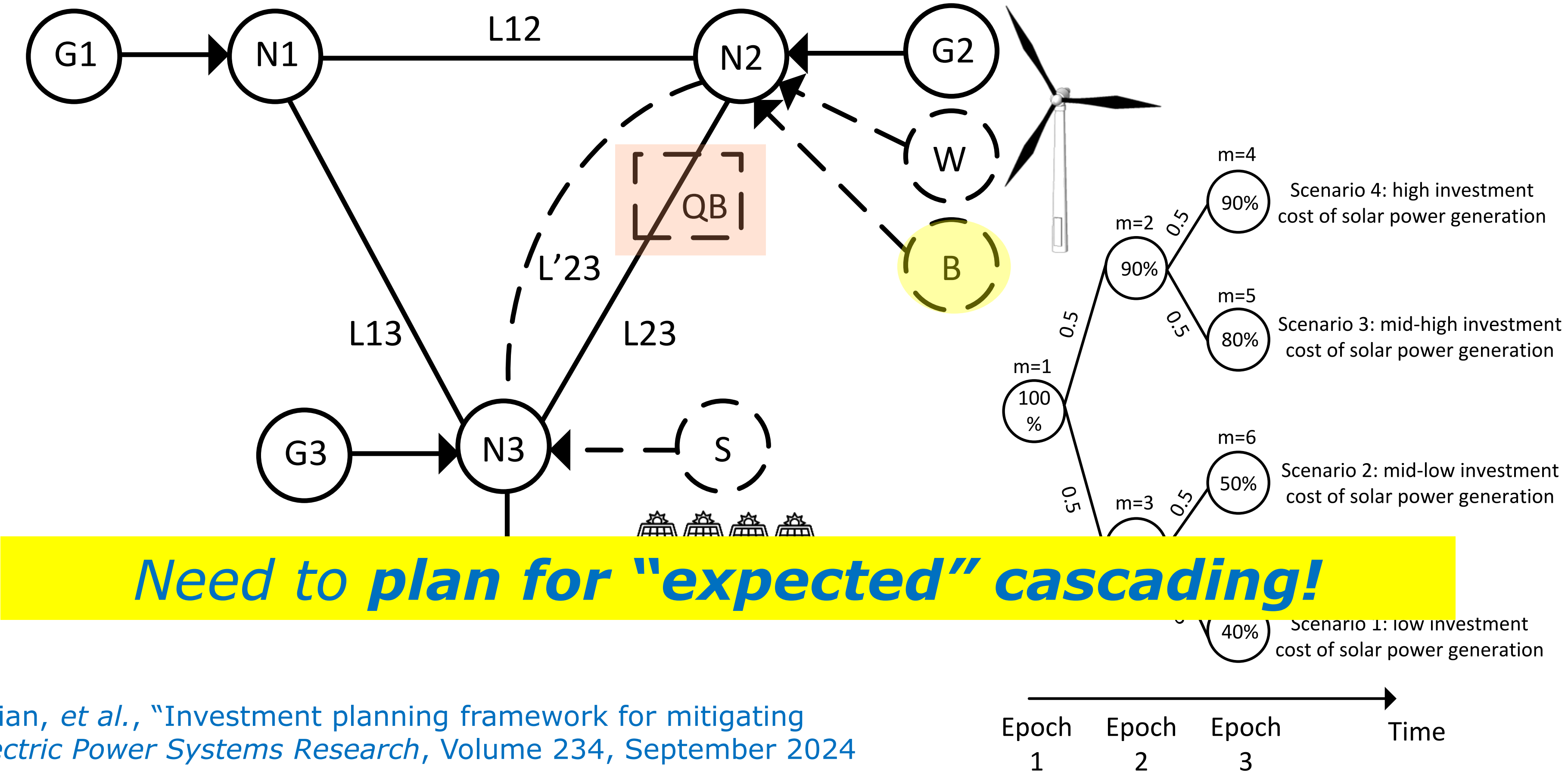
B. Moya, *et al.*, "Uncertainty representation in investment planning of low-carbon power systems", *Electric Power Systems Research*, Volume 212, Nov. 2022, 108470

Planning for the new grid

*Need to think in terms of **cost-value-risk analysis**!*



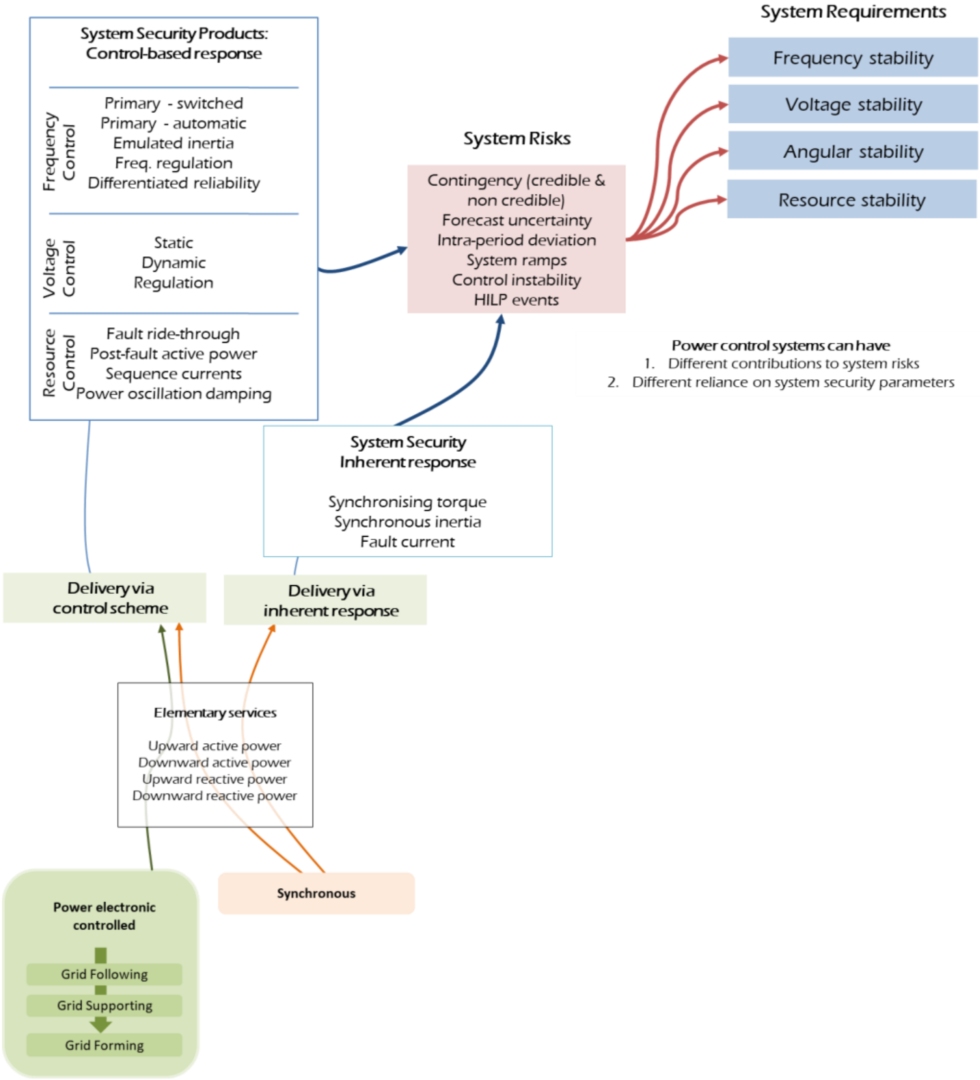
*Need to **plan for "expected" cascading!***

B.V. Venkatasubramanian, *et al.*, "Investment planning framework for mitigating cascading failures", *Electric Power Systems Research*, Volume 234, September 2024

R. Moreno, A. Street, J.M. Arroyo, and P. Mancarella, "Planning Low-Carbon Electricity Systems under Uncertainty Considering Operational Flexibility and Smart Grid Technologies", *Philosophical Trans. Royal Society A*, June 2017

B. Moya, *et al.*, "Uncertainty representation in investment planning of low-carbon power systems", *Electric Power Systems Research*, Volume 212, Nov. 2022, 108470

Key starting point: designing new markets for the new physics…



F. Billimoria *et al.*, "Market and regulatory frameworks for operational security in decarbonising electricity systems: from physics to economics", *Oxford Open Energy,* 2022

US-UK-Australia NSF Global Centre on Climate Change and Clean Energy

Electric Power Innovation for a Carbon-free Society (EPICS)

New Global Research Centre to provide EPIC clean energy boost

The new Electric Power Innovation for a Carbon-Free Society (EPICS) Centre will address challenges in clean energy production and storage.

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https://www.csiro.au/en/news/All/News/2023/September/Australian-institutes-spearhead-global-efforts-in-clean-energy-innovation

https://www.unimelb.edu.au/newsroom/news/2023/september/new-global-research-centre-to-provide-epic-clean-energy-boost

My “Vuelta a Espana”

- Barcelona (UPC), Wednesday 28th May
  - **Security, Reliability and Resilience in Low-carbon Power Systems**
- Madrid (Comillas), Tuesday 3rd June
  - **Economics, markets and regulation for new essential system services: first principles and practical experiences**
- Ciudad Real (UCLM, Thursday 5th June
  - **Integrated planning of transmission and distribution systems**
- Sevilla (USE), Monday 9th June
  - **Running a net-zero grid in 2025: experiences from the Australian “real-world lab”**
- Malaga (UM), Thursday 12th June
  - **Utility-scale and distributed batteries in renewables-dominated power systems: experiences and lessons learnt from Australia**
- Bilbao (UPV/EHU) Thursday 19th June
  - **Security, Reliability and Resilience in Low-carbon Power Systems**

Acknowledgements

- C4NET for the *"ESP-V"* project
- CSIRO and AEMO for the "*Planning*" topic as part of the GPST project stream
- My research team!

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Selected references on dynamics of low-carbon grids

- M. Ghazavi Dozein, B. Berry, J. V. Milanović, and P. Mancarella, "System strength beyond fault level", *IEEE Access*, 2025
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Thank you!
Any question?

pierluigi.mancarella@unimelb.edu.au

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Security, reliability and resilience in low-carbon power systems

Prof Pierluigi Mancarella, FIEEE

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Professor of Smart Energy Systems, The University of Manchester

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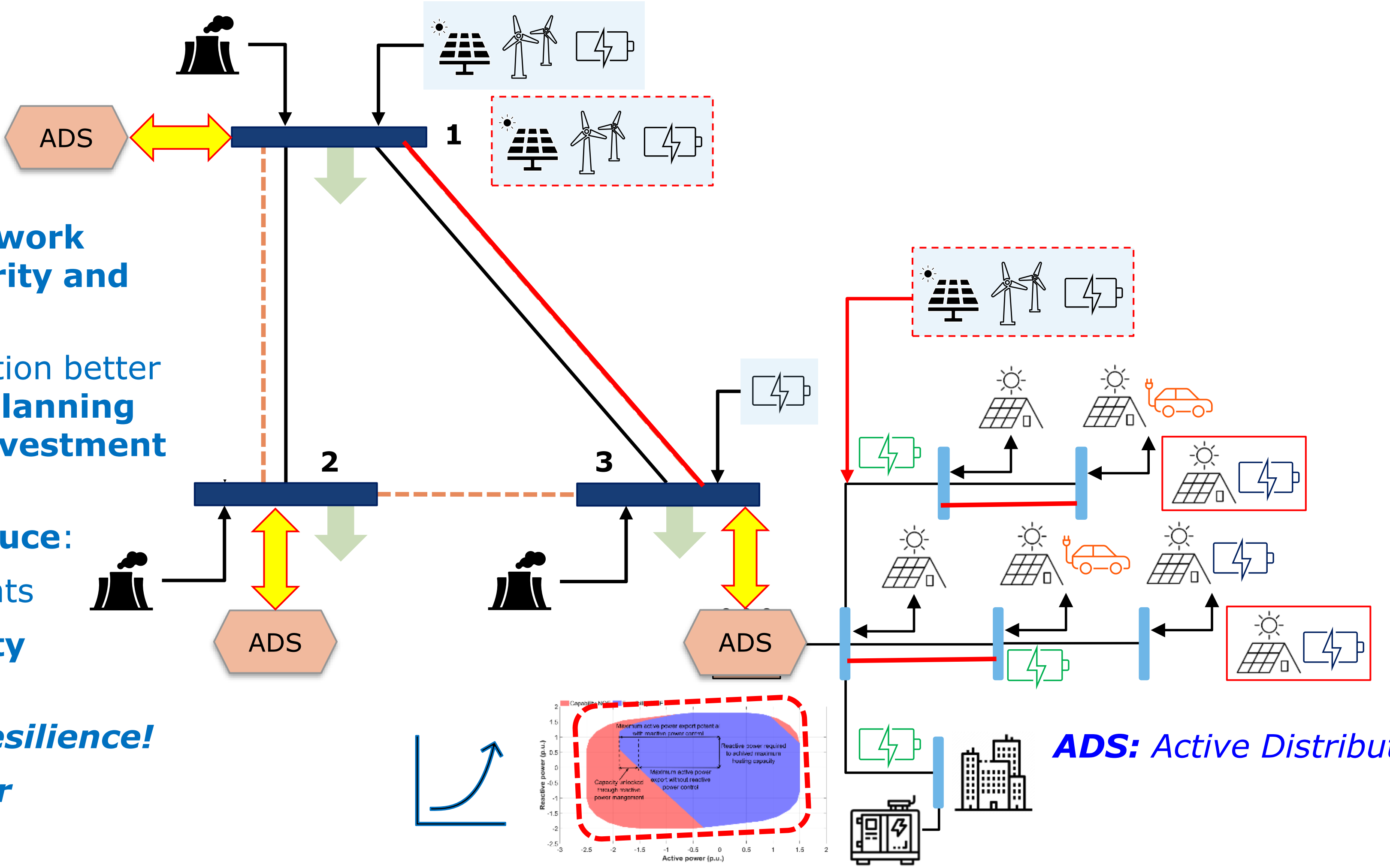
IEEE Power and Energy Society Distinguished Lecturer Program

"Vuelta a Espana" 2025

UPV/EHU School of Engineering, Bilbao, 19th June 2025

DER benefits across the whole system

- **Orchestrated DER** and **network investment complementarity and synergy**
- Benefits from DER orchestration better captured when considering **planning uncertainty** and network **investment risk**
- ***DER*** may systematically **reduce**:
  - **investment** requirements
  - **investment uncertainty** → *risk-hedge value*
- *Greatly enhanced **system resilience!***
- *Consistent with **planning for "expected" cascading***



B.V. Venkatasubramanian, *et al.*, "Investment planning framework for mitigating cascading failures", *Electric Power Systems Research*, Volume 234, September 2024

P. Apablaza *et al.*, "Valuing DER Flexibility in an Uncertain and Risk-Aware Low-Carbon Power System Planning Context", *IREP* and *SEGAN*, 2025

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P. Mancarella, "Electricity grid fragility and resilience in a future net-zero carbon economy", *Oxford Energy Forum – Electricity Networks in a Net-Zero-Carbon Economy*, 124, pages 41-45, Sept 2020

Optimal integrated system-DER design

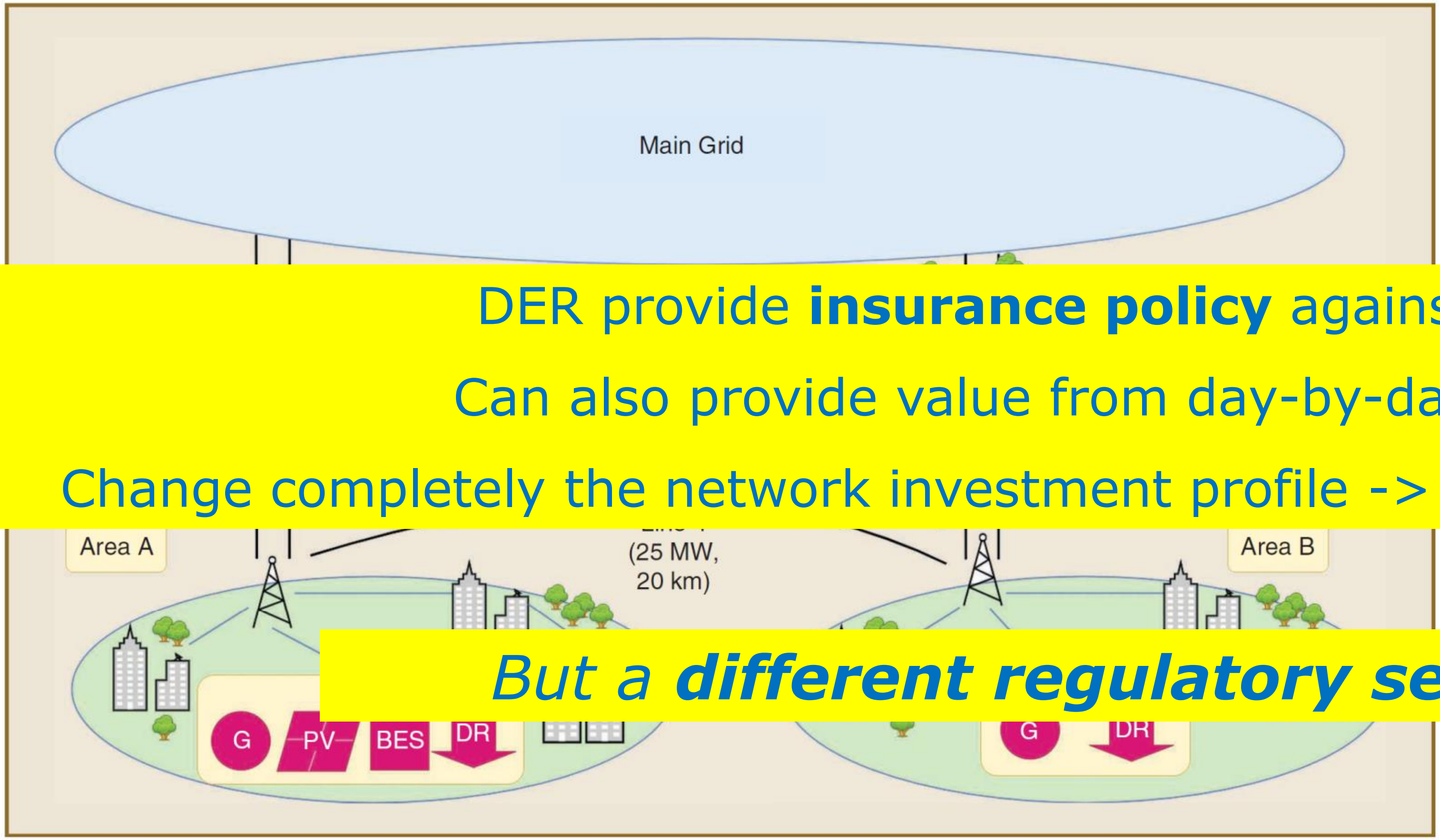


figure 8. The electricity network and DER candidates along with areas exposed to wildfires. BES: battery energy storage.

table 2. Results with costs in thousand U.S. dollars (kUS$) per year.

	Case A	Case A (Reevaluated)	Case B
Assets and measures	L1, L2, L5, L6, MG,	L1, L2, L5, L6, MG, DR	L1, L2, L3, L4, L5, PV, BES,
Operational cost	32,850	33,115	21,901
cost			
Total cost	32,990	52,893	33,558

L: line; MG: mobile generator.

DER provide **insurance policy** against extreme events!

Can also provide value from day-by-day market operation

Change completely the network investment profile -> **less redundancy, smarter grid!**

*But a **different regulatory set-up is needed!***

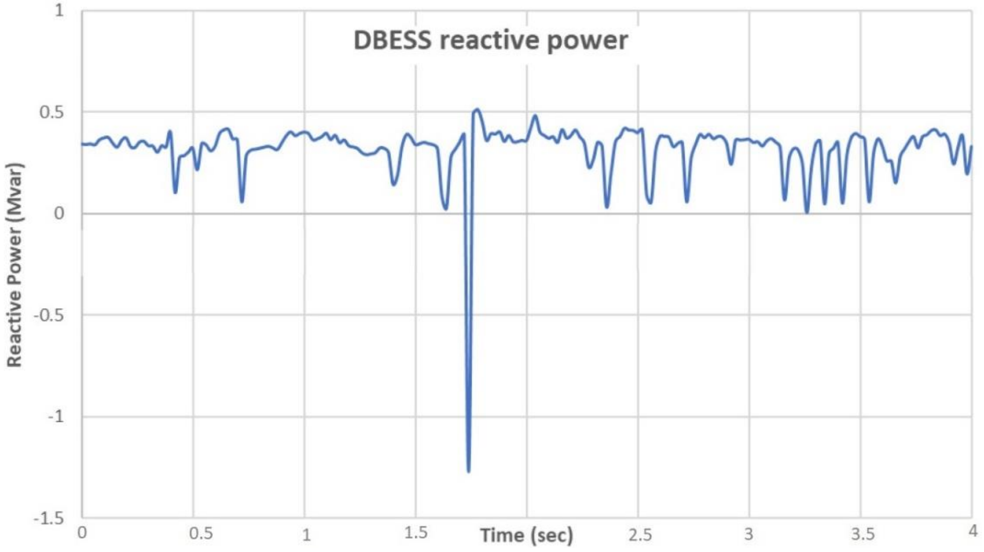
Moreno, *et al.*, "Microgrids Against Wildfires: Distributed Energy Resources Enhance System Resilience". *IEEE Power and Energy Magazine*, 20(1), 78-89, 2022.

Moreno, *et al.*, "From Reliability to Resilience: Planning the Grid Against the Extremes", *IEEE Power and Energy Magazine*, *July-August 2020*

Y. Zhou, *et al.*, "System-level assessment of reliability and resilience provision from microgrids", *Applied Energy*, Volume 230, 15 November 2018, Pages 374-392

From "grid following" to "grid forming"

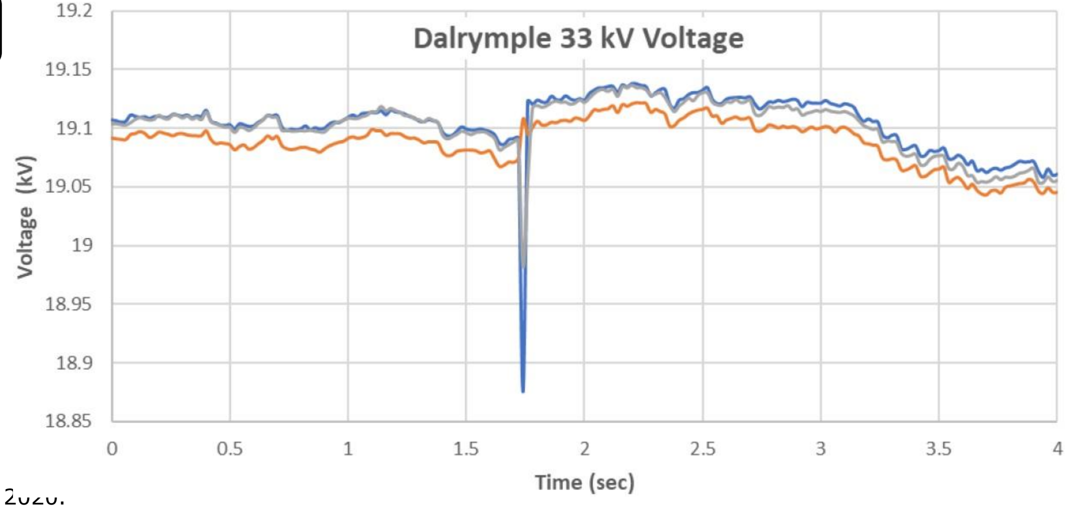
Dalrymple battery



Single-phase–to-ground fault on January 13, 2020

Battery reactive power response

Battery terminal voltage dynamics



ElectraNet," ESCRI-SA battery storage project operational report#3, August 2020.