Panel 1:
Flexibility and Resiliency in Decarbonised Energy Systems

The Fragile Grid:

Security and Resilience Challenges in Low-carbon Power Systems

Prof Pierluigi Mancarella

Chair of Electrical Power Systems, The University of Melbourne

Professor of Smart Energy Systems, The University of Manchester

veski Innovation Fellow

pierluigi.mancarella@unimelb.edu.au

8th Annual EPRI-IEA Workshop
Challenges in Decarbonisation: Building a Resilient Net-Zero Future

October 2021

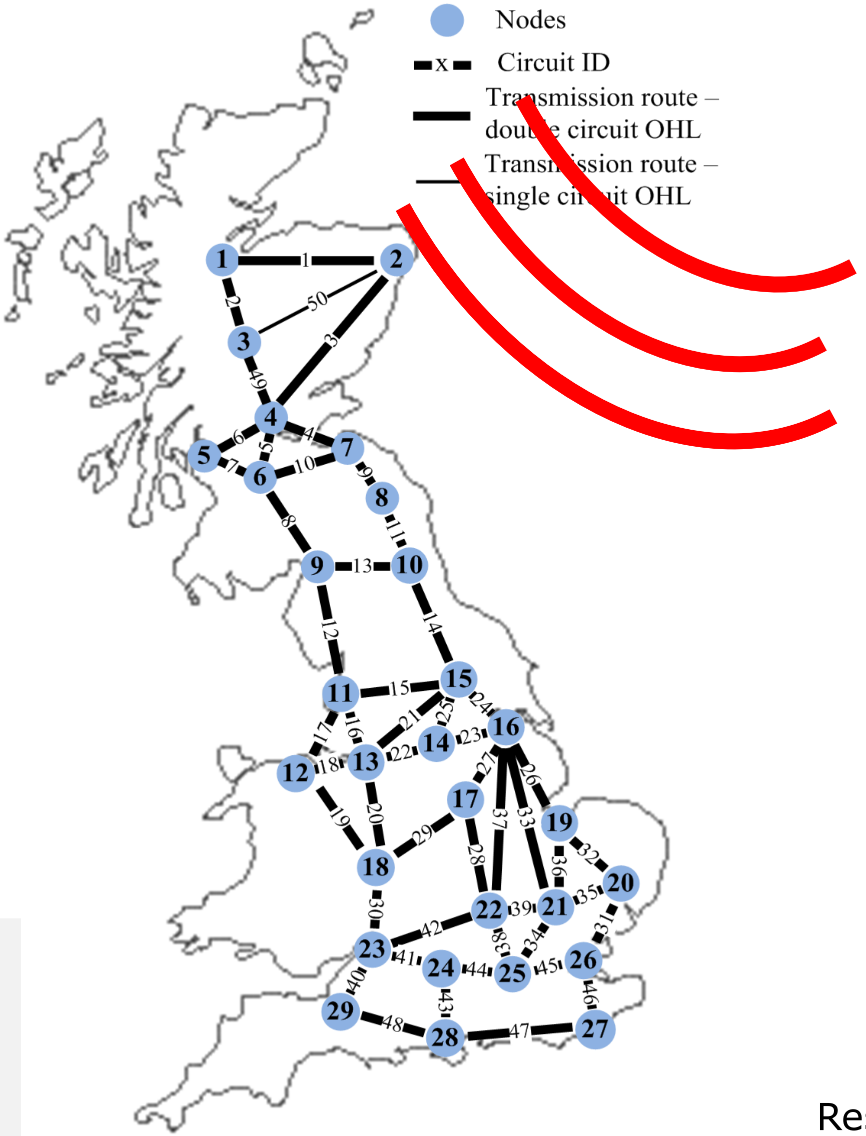
What we talk about when we talk about security and reliability

Image source: Google search

What we talk about when we talk about resilience

Image source: Google search

Example: climate change-driven windstorms



M Panteli, C Pickering, S Wilkinson, R Dawson, P Mancarella, "Power system resilience to extreme weather: Fragility modelling, probabilistic impact assessment, and adaptation measures", *IEEE Transactions on Power Systems* 32, 3747-3757, 2017

ResNet project, 2012

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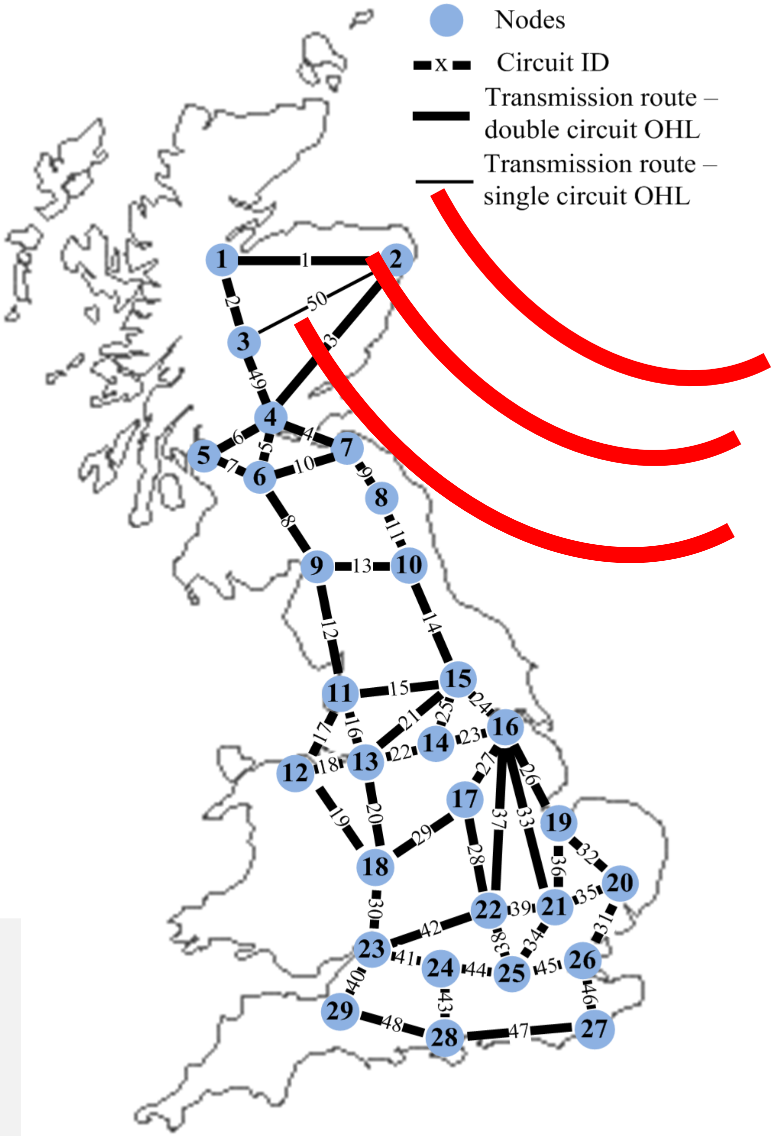

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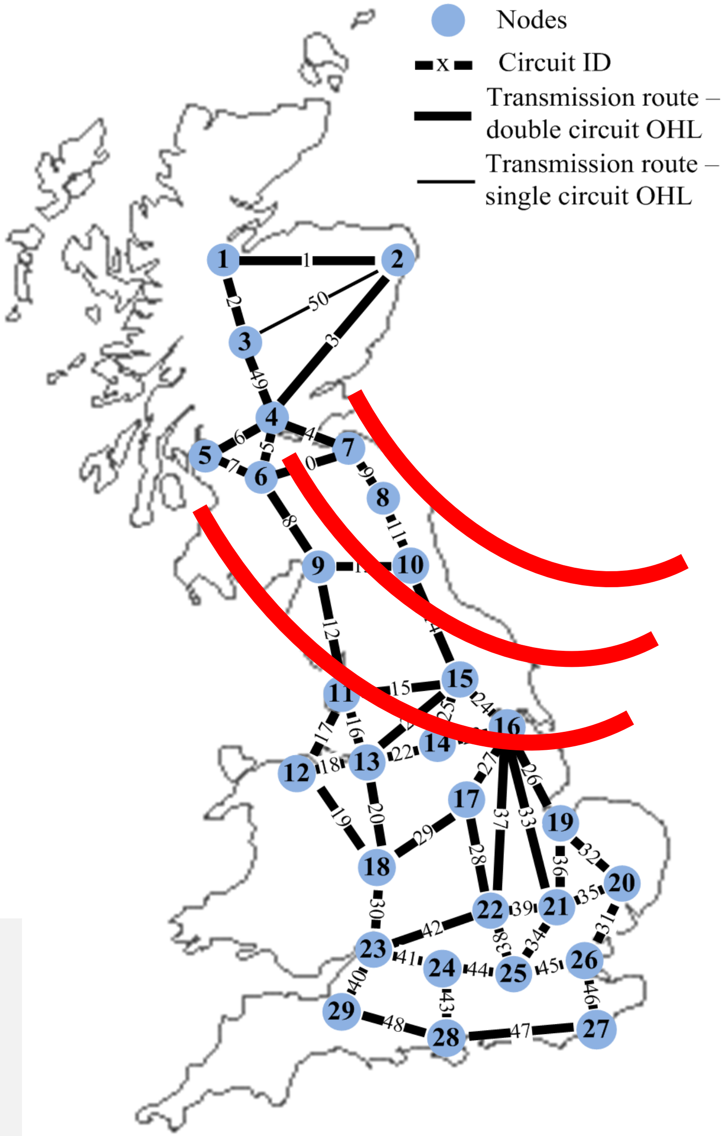

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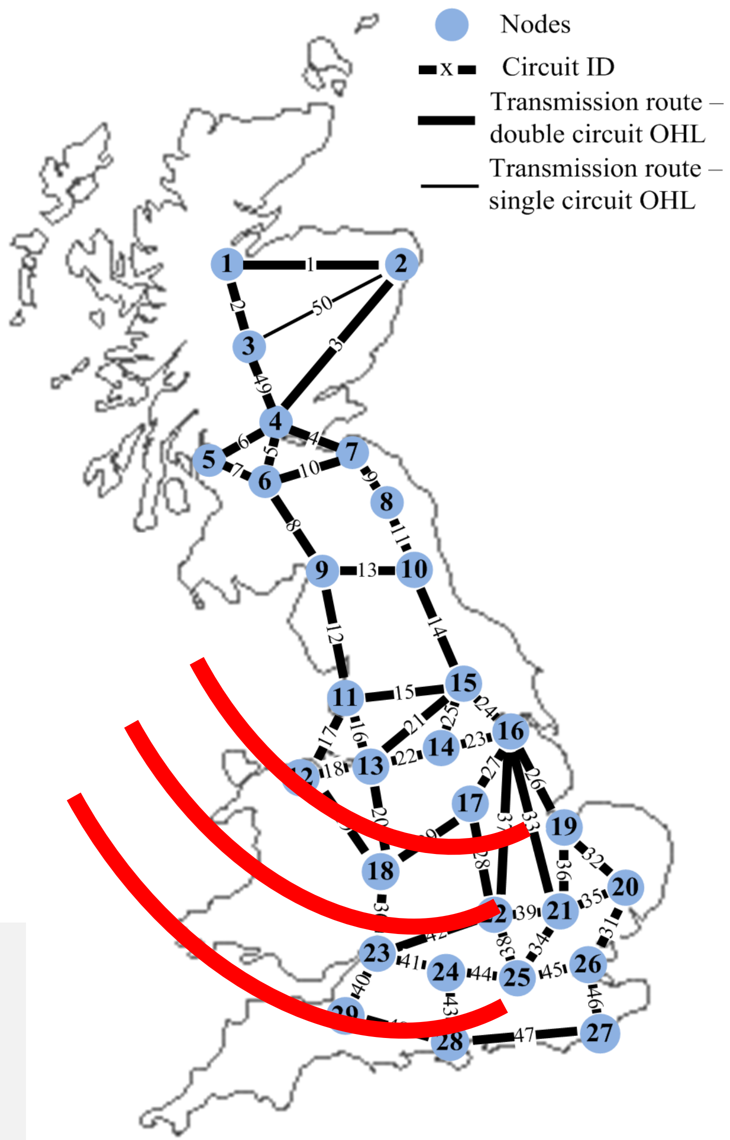

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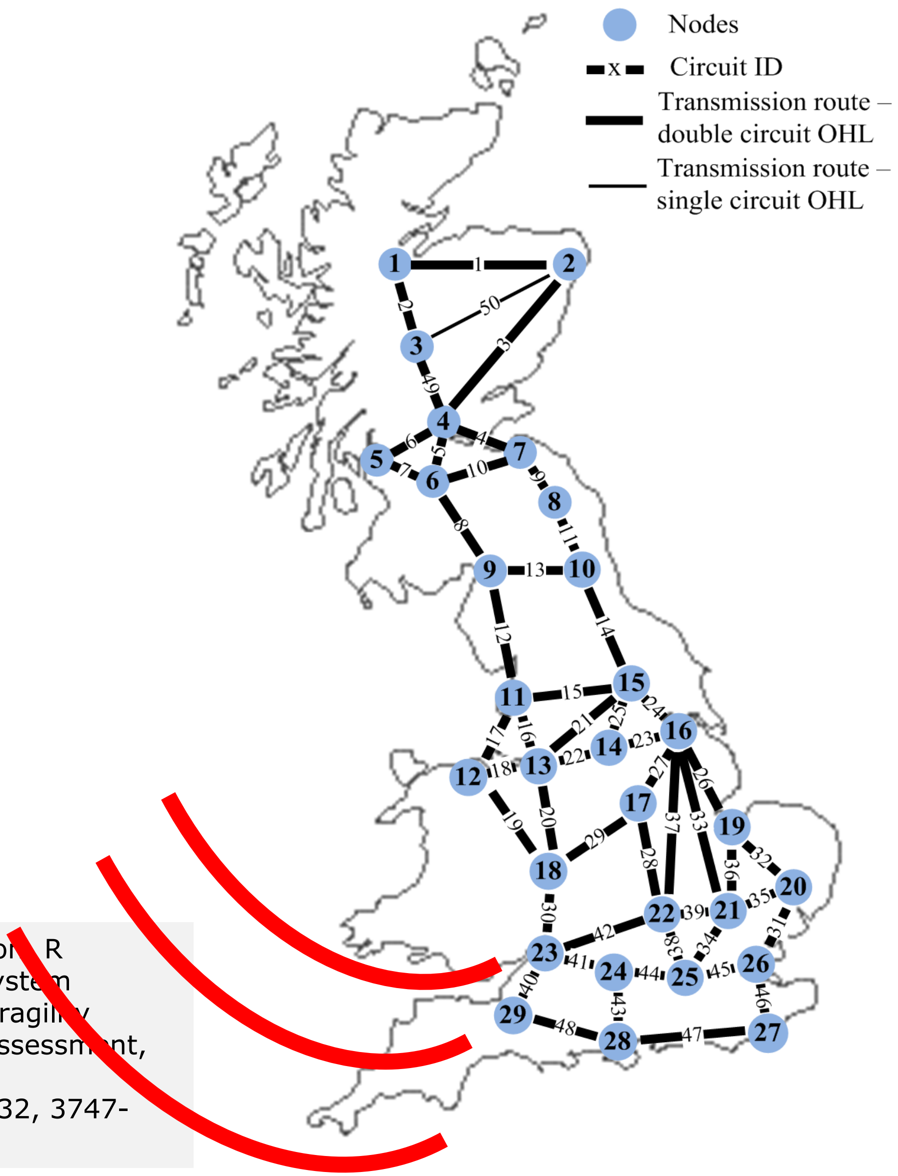

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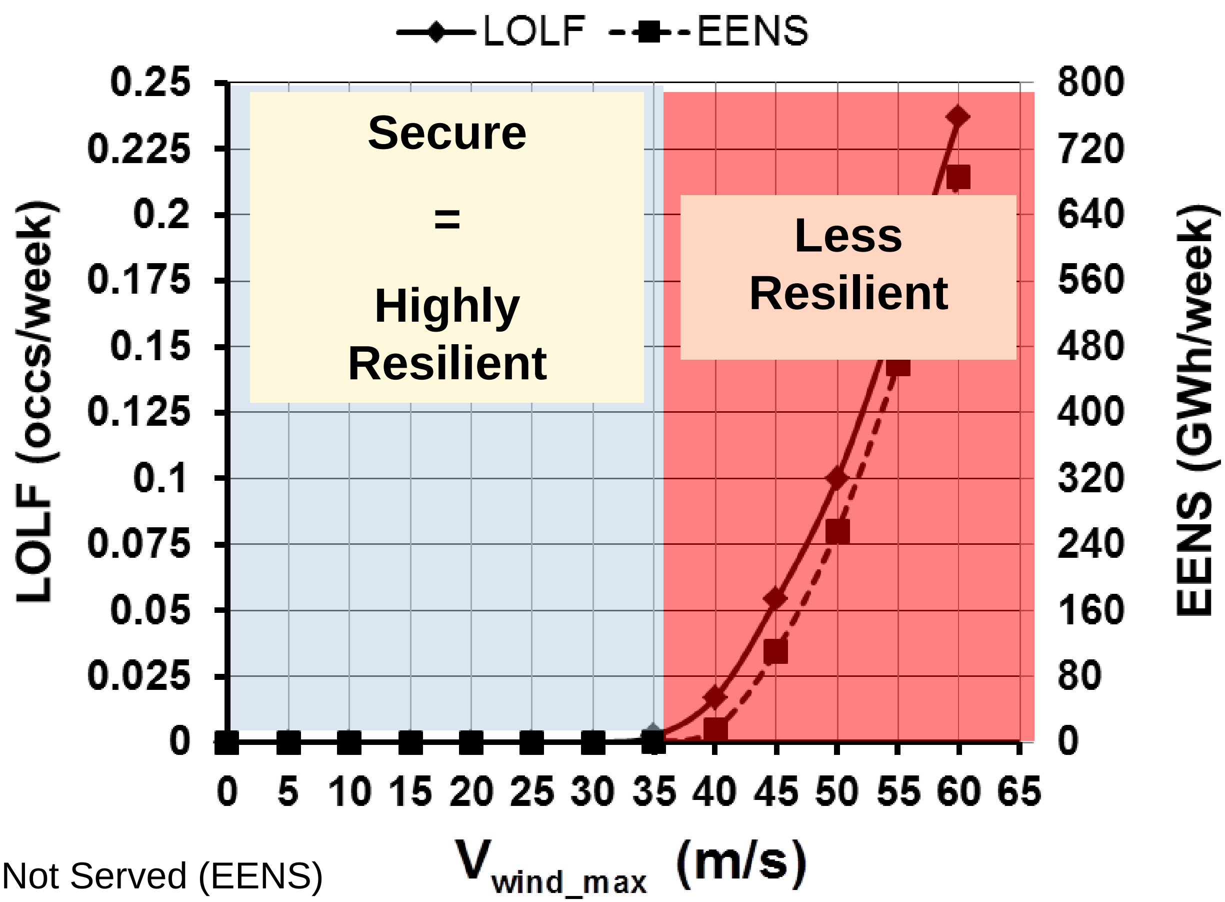
ResNet project, 2012

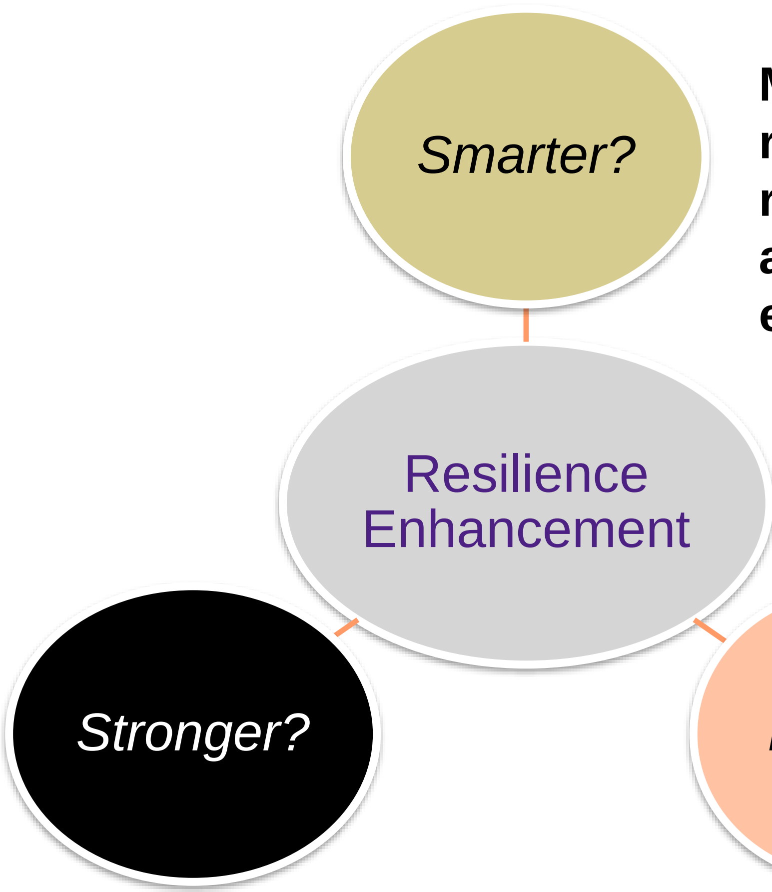
Resilience thresholds and nonlinear cascading failures



- Expected Energy Not Served (EENS)
- Loss of Load Frequency (LOLF)

M. Panteli and P. Mancarella, "Modelling and evaluating the resilience of critical power infrastructure to extreme weather events", *IEEE Systems Journal,* vol. 11, no. 3, pp. 1733-1742, Sept. 2017

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, *Invited Paper*

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

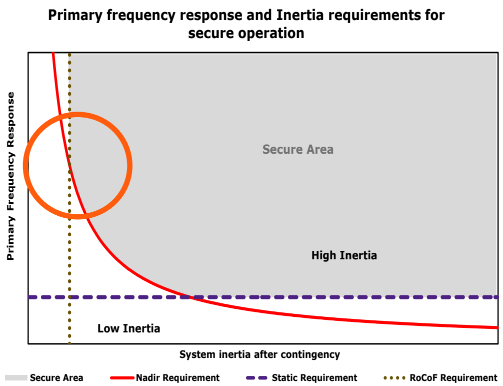
The “new physics”

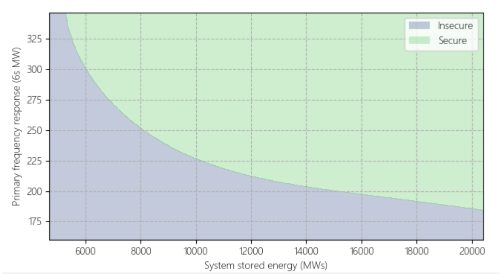
Risk	Emerging issues	Possible Mitigations
Frequency control and inertia	- Sustained frequency excursions (regulation) - High ROCOF following contingency - Insufficient regional inertia - Insufficient PFR - Risk of low-inertia and insufficient PFR after separation	- Minimum inertia levels - Compulsory 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 and uncertainty	- Large variation in net demand - Insufficient short- and medium-term and ramping reserves	- 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)
System strength	- Fault current shortage - Voltage instability - Sustained voltage oscillations after fault - Fault-ride through issues	- Minimum level of inertia and fault current (generators constrained on) - Synchronous condensers - STATCOM and SVC to improve voltage stability - Improvements of control loops (especially in solar farms) - Grid forming inverters

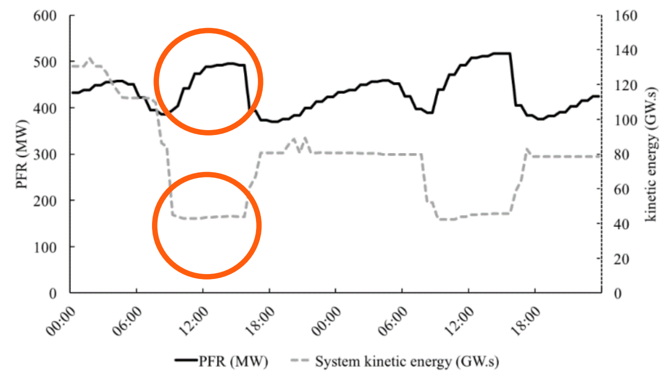
P. Mancarella and F. Billimoria, ‘The Fragile Grid – The physics and economics of security services in low-carbon power systems”, *IEEE Power and Energy Magazine*, 2021

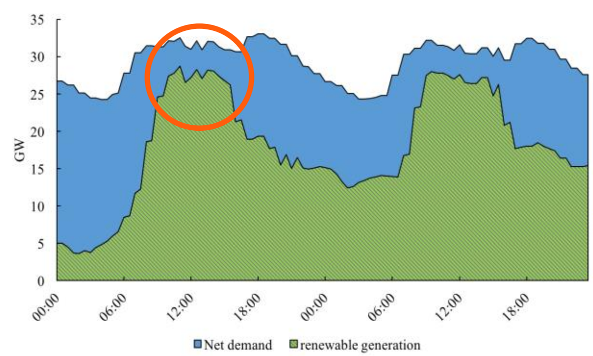
Co-optimization of energy, frequency control ancillary services, inertia and largest contingency level

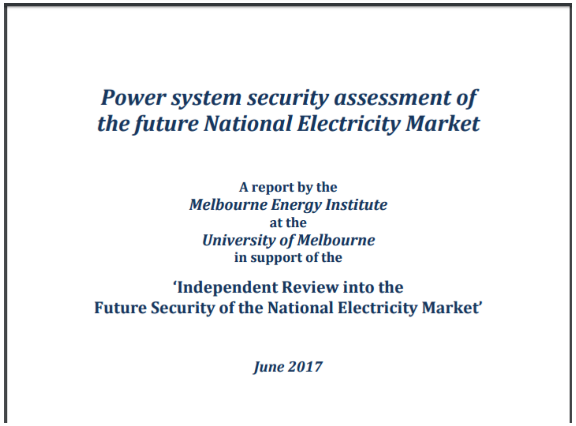
Co-optimization of energy, inertia, FR and largest contingency level










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

"Finkel Review", http://www.environment.gov.au/system/files/resources/1d6b0464-6162-4223-ac08-3395a6b1c7fa/files/power-system-security-assessment.pdf

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

How about new technologies?

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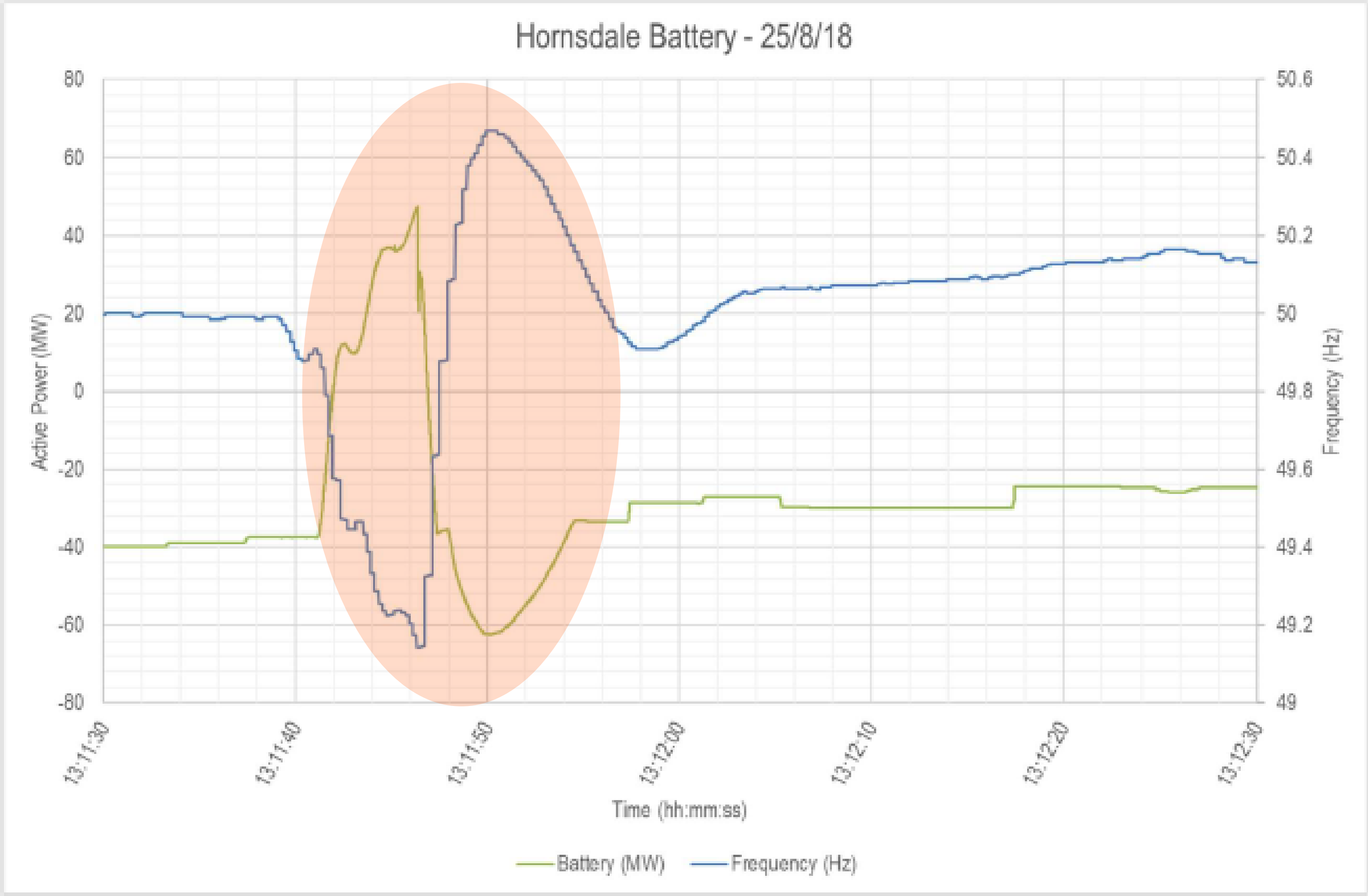
A stronger, bigger or smarter grid? Resilience from new security technology

Figure 41 SA transmission-connected battery response – short-term

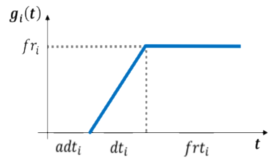


Source picture: AEMO

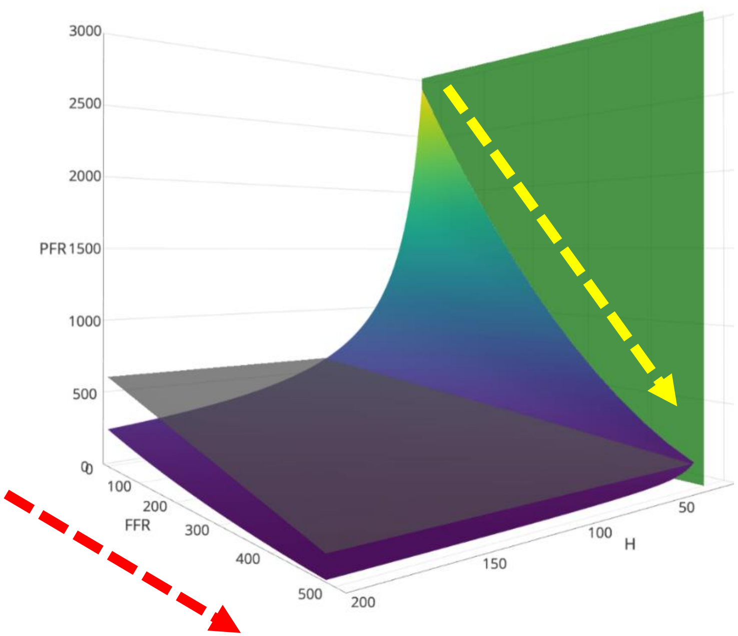
But there's a catch....

Substitutability of frequency response products: "synchronous" vs "controlled" energy injections

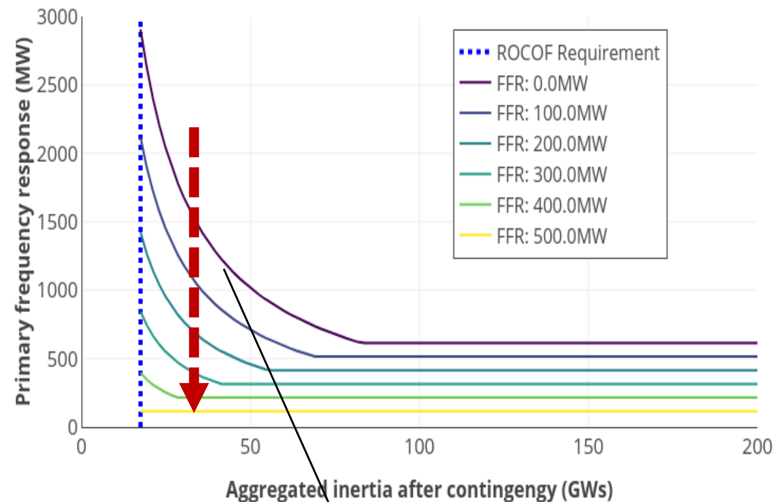
battery, electrolyser



Demand (HD) 17GW Gen Loss 700MW
Load-damping factor 1%/Hz Nadir Target 49.3Hz
FFR Resources: 0.3s Activation Time - Delivery time 0.05s "



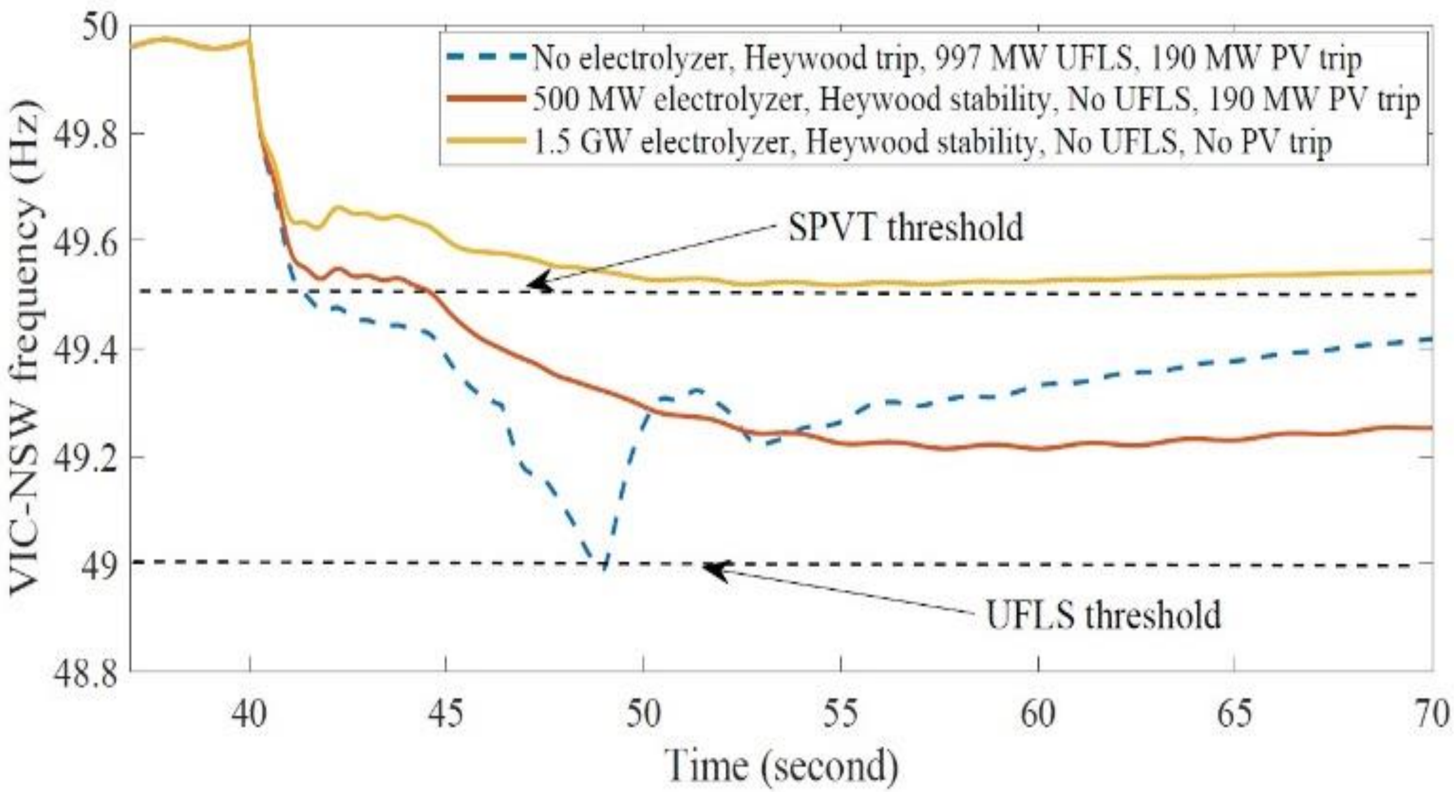
New technologies (batteries, electrolysers) can competitively provide security services



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

Adapted from: S. Puschel, M. Ghazavi, S. Low, and P. Mancarella, "Separation event-constrained optimal power flow to enhance resilience in low-inertia power systems", *Electric Power System Research*, 2020

Role of future technologies: Resilience from hydrogen electrolyzers in Victoria



M. Ghazavi, A. Jalali, P. Mancarella, "Fast Frequency Response from Utility-Scale Hydrogen Electrolysers", *IEEE Transactions on Sustainable Energy, 2021*

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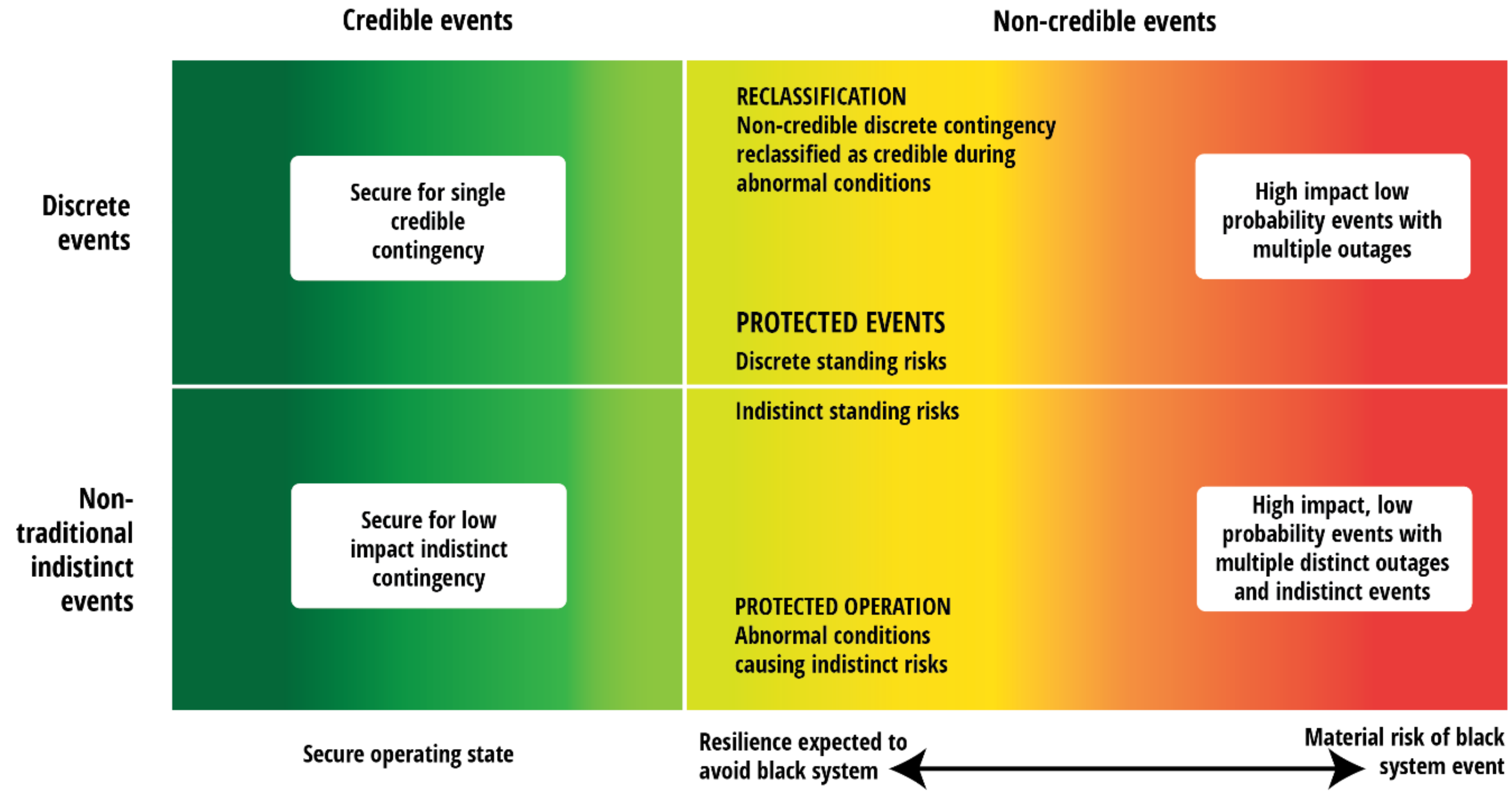
Source: P. Mancarella and F. Billimoria, ‘The Fragile Grid – The physics and economics of security services in low-carbon power systems”, *IEEE Power and Energy Magazine*, 2021

"Blurring" of security and resilience



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

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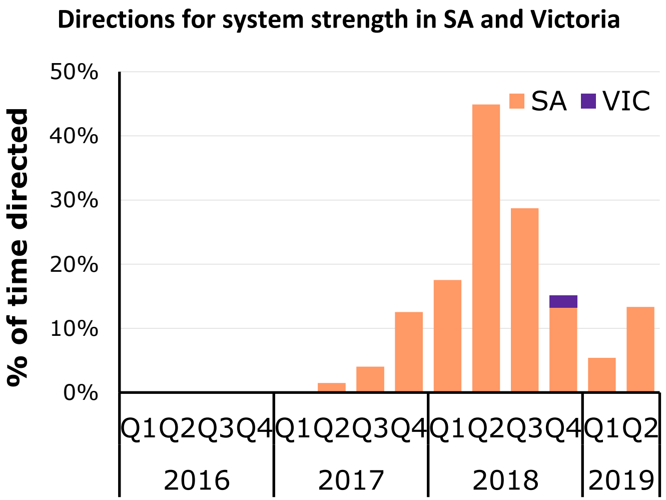
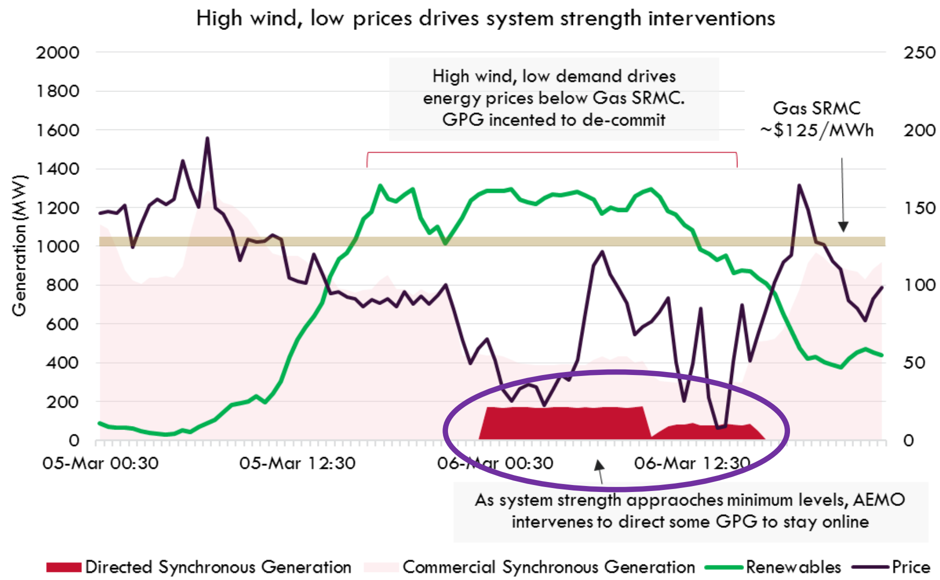
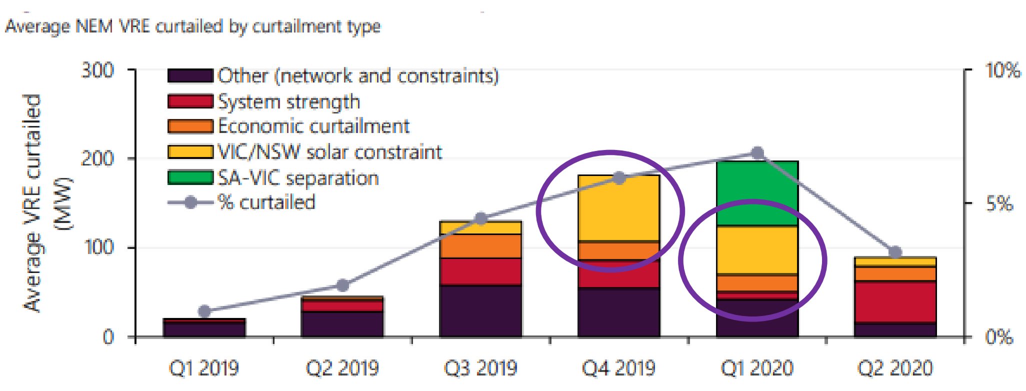
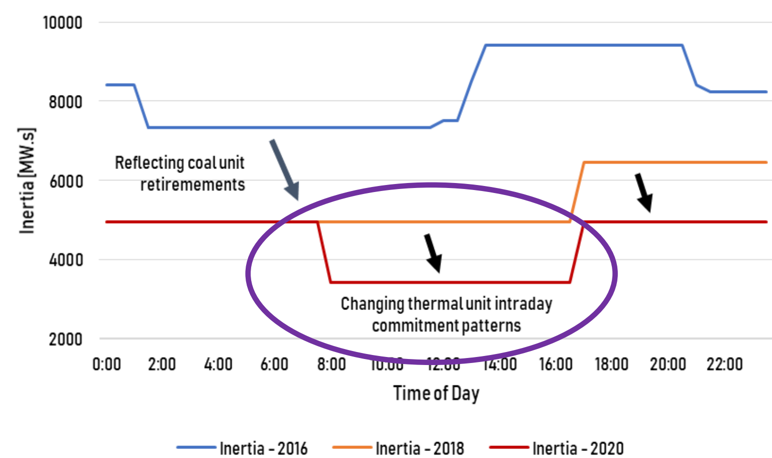
How about markets and incentives? Running an *old market* with the *new physics*…



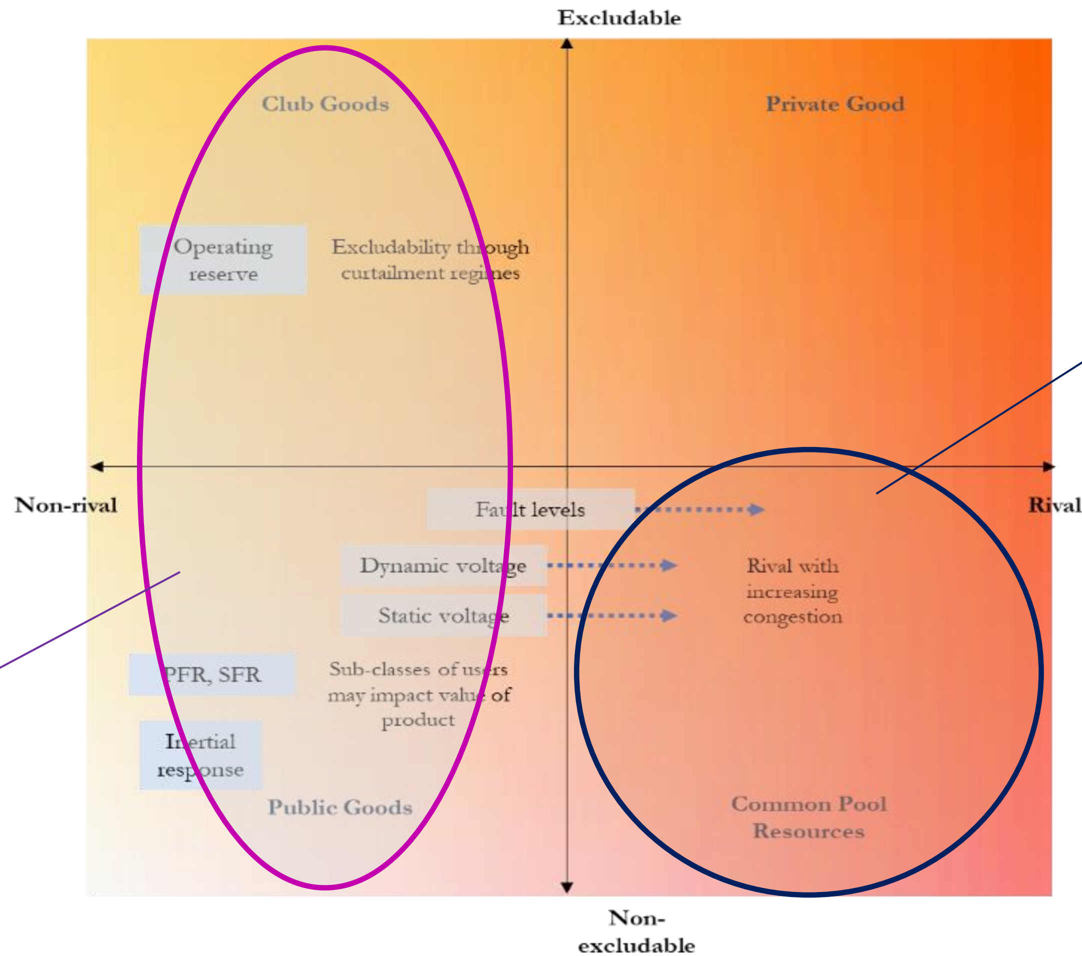






Source: AEMO

New markets and regulation: The 'basket of goods' for system security (and resilience)



Markets are easier to develop

Mix of:

- **technology requirements**
- **<u>coordinated</u> network interventions**
- **new operational measures**

F. Billimoria, P. Mancarella, R. Poudineh, "Market design for system security in low-carbon electricity grids: from the physics to the economics", *Oxford Institute for Energy Studies*, June 2020

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Concluding remarks

- Low-carbon grids are naturally **more fragile**
- In more **fragile grids**, ***security* and *resilience* concepts** become more **intertwined**
- The **"new physics"** calls for **new security and resilience services**
- Starting from physical first principle and **bottom-up** ("*from physics to economics*")
- **Technical complexity** underscores **economic nuances**
  - but economic design MUST consider the physics!
- The **economic products** of system security (and resilience) comprise a **'basket of goods'** with very different characteristics
- Market and regulatory design should reflect all the relevant economic nuances, but considering, most importantly:
  - **The physics!**
  - New operational solutions and technologies
  - **Risk-averse attitude** of system operator, regulator, and *consumers*

Further reading

- 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*, May-June 2021
- J. Eggleston, C. Zuur, P. Mancarella, "From security to resilience: technical and regulatory options to manage extreme events in low-carbon grids", IEEE Power and Energy Magazine, September/October 2021
- F. Billimoria, P. Mancarella, R. Poudineh, "Market design for system security in low-carbon electricity grids: from the physics to the economics", *Oxford Institute for Energy Studies*, June 2020
- P. Mancarella, "Electricity grid fragility and resilience in a future net-zero carbon economy", *Oxford Institute for Energy Studies Forum*, 124, pages 41-45, September 2020
- M. Ghazavi, A. Jalali, P. Mancarella, "Fast Frequency Response from Utility-Scale Hydrogen Electrolysers", *IEEE Transactions on Sustainable Energy, 2021*
- R. Moreno, *et al.*, "From Reliability to Resilience: Planning the Grid Against the Extremes", *IEEE Power and Energy Magazine*, *July-August 2020*
- S. Püschel-Løvengreen, M. Ghazavi Dozein, S. Low, P. Mancarella, "Separation event-constrained optimal power flow to enhance resilience in low-inertia power systems", *Electric Power Systems Research*, 2020, 189, 106678
- B. Skinner, P. Mancarella, M. Vrakopoulou, I. Hiskens, "Incorporating new power system security paradigms into low-carbon electricity markets", *Electricity Journal*, 2020, 33 (9), 106837

Any question?

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