Flexibility and Resilience in Future Low-Carbon Energy Systems

Dr Mathaios Panteli, University of Cyprus
Dr Rodrigo Moreno, Universidad de Chile, Chile, and Imperial College London, UK
Prof Pierluigi Mancarella, The University of Manchester, UK and The University of Melbourne, Australia
Dr. E. Alejandro Martínez Ceseña, The University of Manchester, Tyndall Centre for Climate Change Research, UK

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Aims and Objectives

- Introduce fundamentals on infrastructure planning and operation with deep levels of uncertainty and extreme but rare events
- Demonstrate state-of-the-art risk-averse and resilience-informed planning and operation models for future low-carbon energy systems, including regulatory needs
- Illustrate the application of these tools using real-world examples across the globe (including transmission networks, distribution networks, smart buildings and community multi-energy systems) and a variety of extreme events (including windstorms, earthquakes, wildfires, etc.)

Tutorial Outline

- **Background**

- **First Block:**
  - Infrastructure Planning and Operation Under Uncertainty
    - Modelling different uncertainty types
    - Decision theory, robust and flexible decisions
    - New stochastic programming and optimization approaches
  - Infrastructure planning and operation considering uncertain extreme events
    - Risk-averse and resilience-informed planning and operation
    - Resilience and risk metrics
    - Tools: Cascading modelling, probabilistic impact assessment and optimization via simulation
    - Novel probabilistic operational and planning methods

Tutorial Outline

- **Coffee Break**
- **Second Block:**
  - Infrastructure planning and operation for flexible and adaptive energy systems
    - Smart distribution networks and flexible active network management
    - Building and community multi-energy systems
  - Cascading modelling and impact quantification for resilience applications
    - Analysis and comparison of static and dynamic cascading modelling under extreme events
    - Observed acceleration of cascading events
  - Planning and operating the grid against extreme events
    - Low-carbon, “fragile” grids: the physics and economics of security services in low-carbon power systems
    - Resilient energy systems: Development of optimal portfolios considering asset and non-asset solutions for stronger and smarter, more flexible transmission and distribution networks
    - Regulatory standards for future resilient systems: standards and mandates versus market approaches to drive resilient and flexible network design

Background

Resilience is not a recent concept…

Taylor & Francis

The Philosophical Magazine

Series 1

ISSN: 1941-5796 (Print) 1941-580x (Online) Journal homepage: https://www.tandfonline.com/loi/tphm12

XXXVII. *On the transverse strength and resilience of timber*

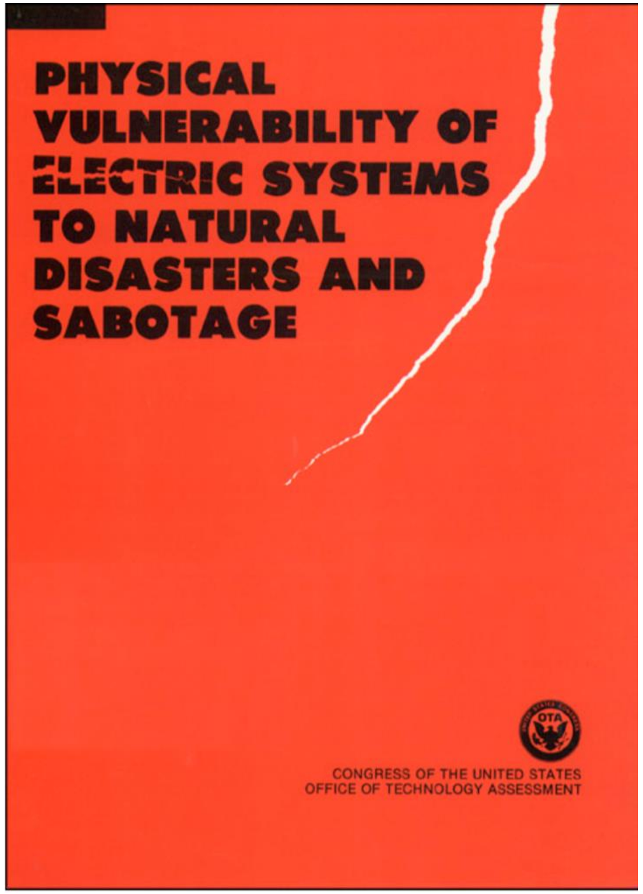
Mr. Thomas Tredgold

To cite this article: Mr. Thomas Tredgold (1818) XXXVII. *On the transverse strength and resilience of timber* , The Philosophical Magazine, 51:239, 214-216, DOI: 10.1080/14786441808637536

To link to this article: https://doi.org/10.1080/14786441808637536

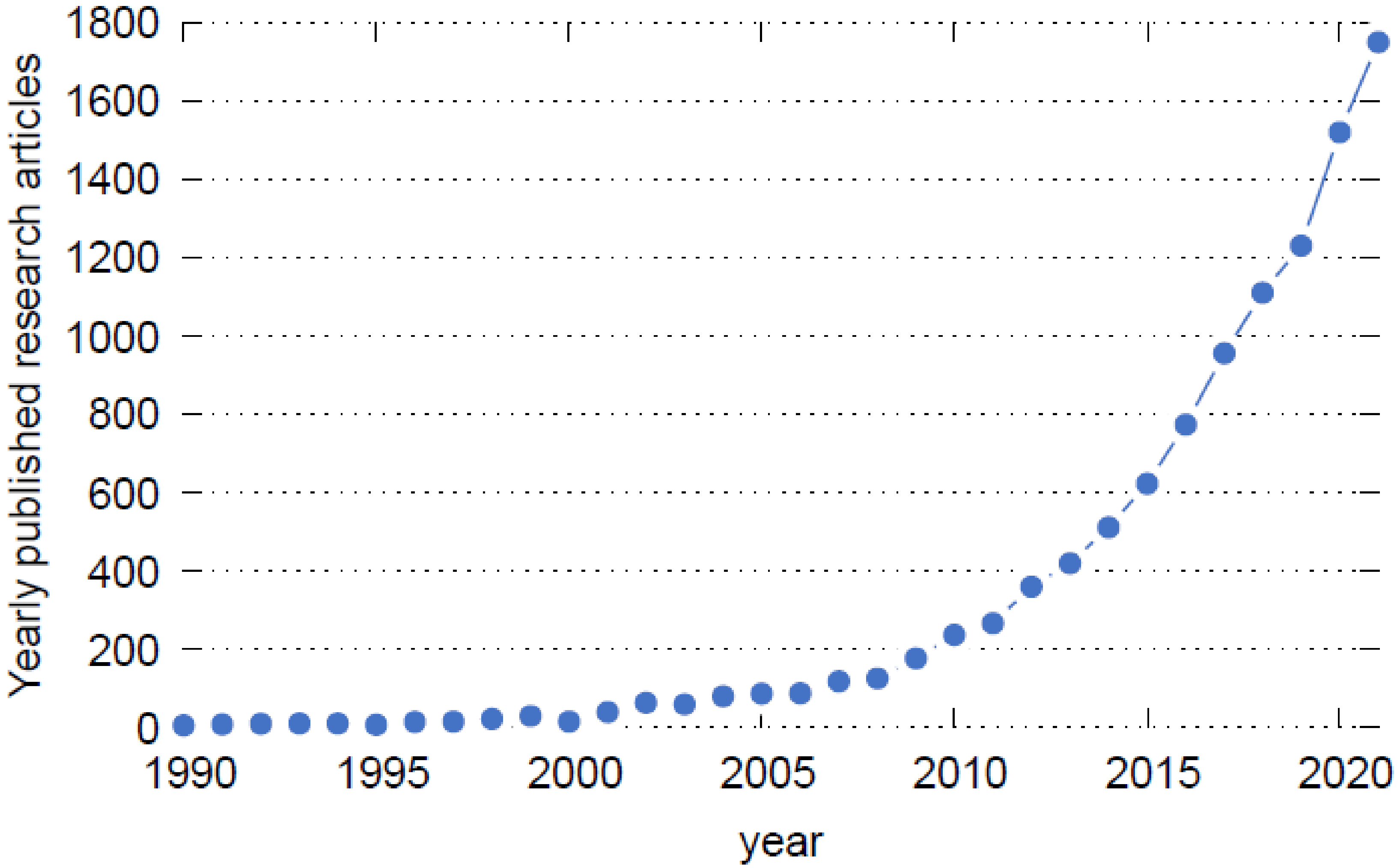
Published online: 27 Jul 2009.

First reference to resilience in 1818!!

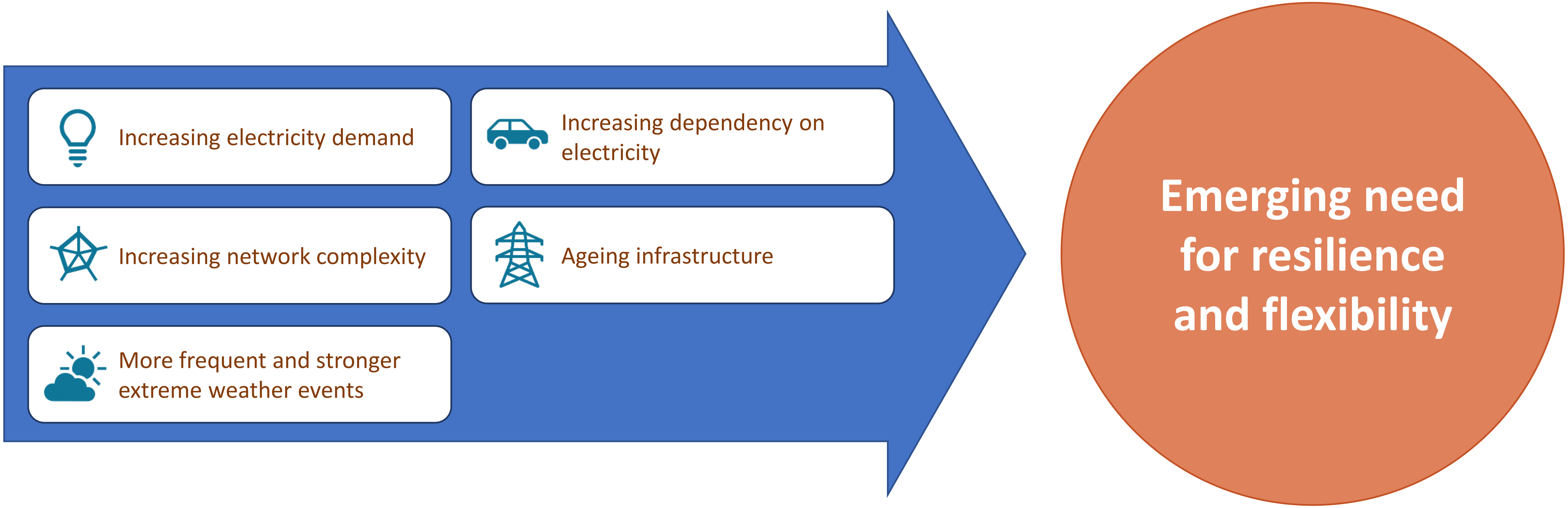


June 1990

Google Scholar Search – “Power Network/System Resilience”



Increasing Need for Flexibility and Resilience



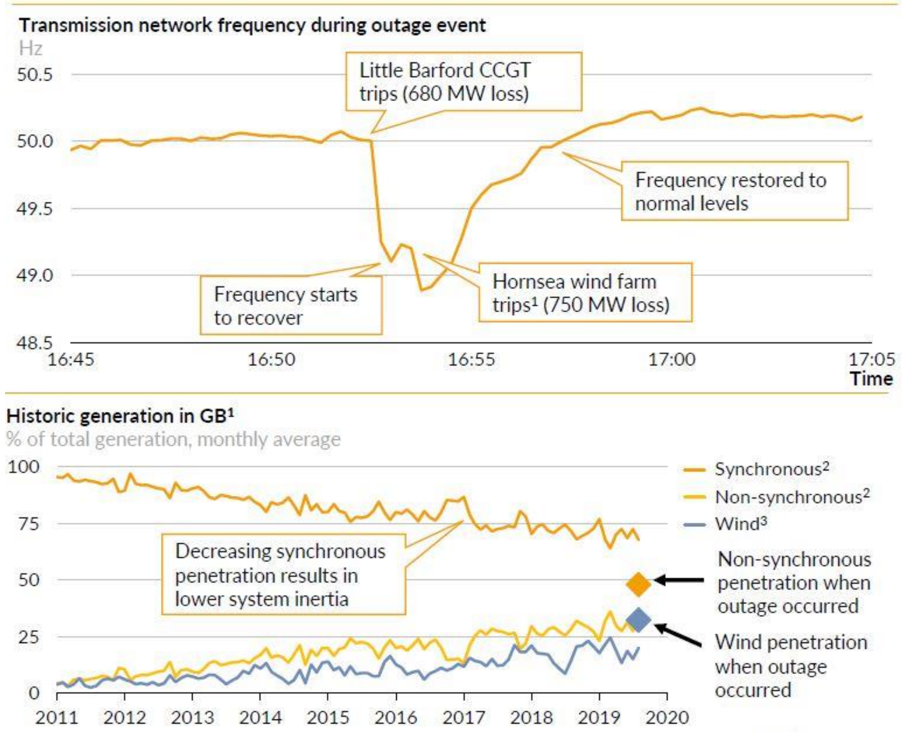
Recent Blackouts Around the World

South Australian Blackout, September 2016

"…highlights a number of challenges and valuable lessons relevant to improving power **system security** and customer supply reliability, particularly as the power system responds to **extreme circumstances**, as the NEM generation mix changes and Australia makes the transition to **high levels of renewable energy sources**"
"**Big batteries**, stabilisation urged for Australia's power system"

United Kingdom (UK) Blackout, August 2019

Around **30% of the generation was from wind**, 30% from gas and 20% from nuclear and 10% from interconnectors.
"As this generation would not be expected to trip off or de-load in response to a **weather event**, **this represents an extremely rare and unexpected event**."
"**Once-in-30-years event**", John Pettigrew, CEO National Grid

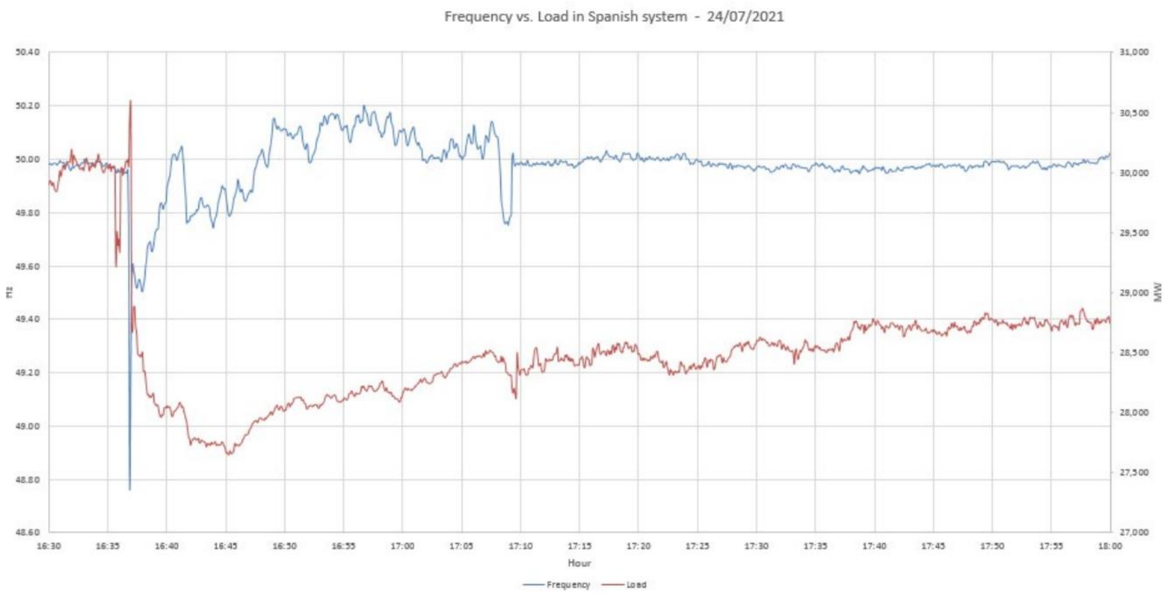


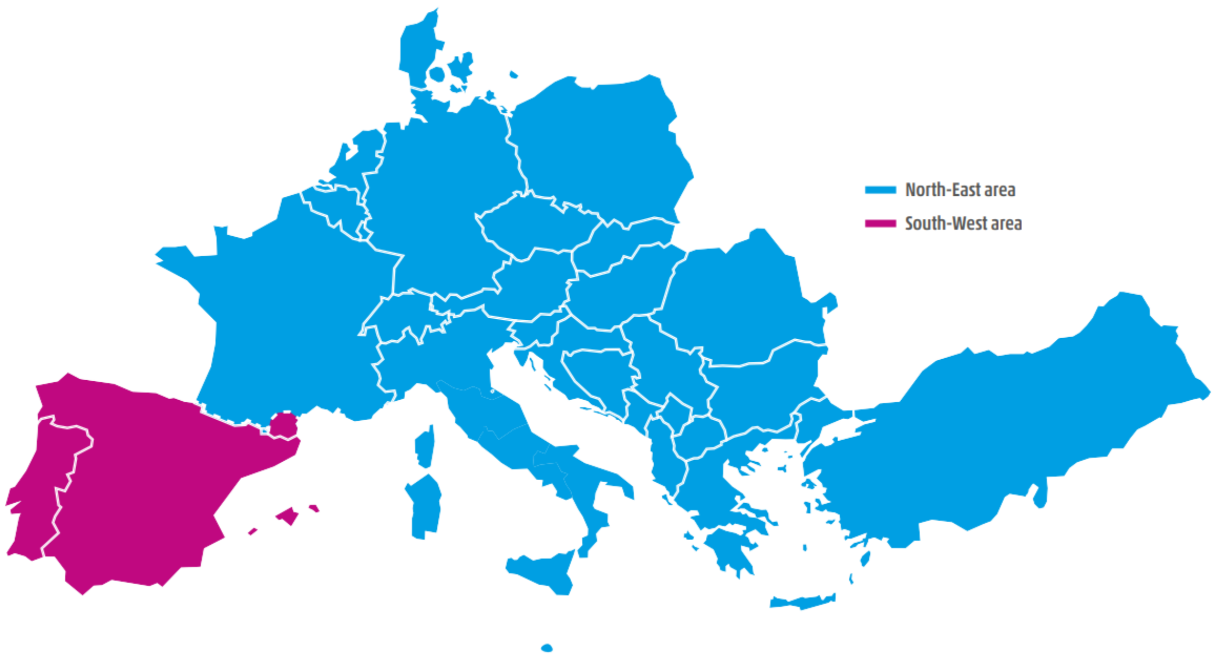
Source: https://www.energynetworks.com.au/news/energy-insider/blackout-uk-whos-to-blame/

What about near misses?

Continental Europe Synchronous Area Separation on 24 July 2021

Severe fire in the vicinity of the city Moux, Southern France

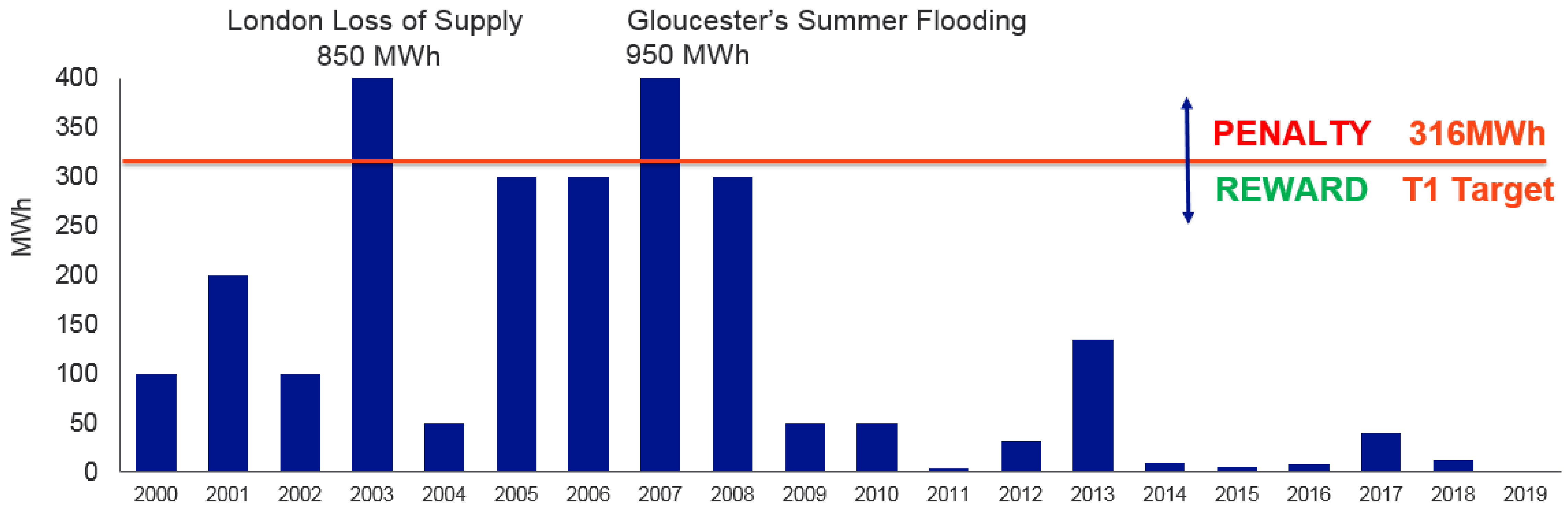




Limitations in Current Regulatory Standards

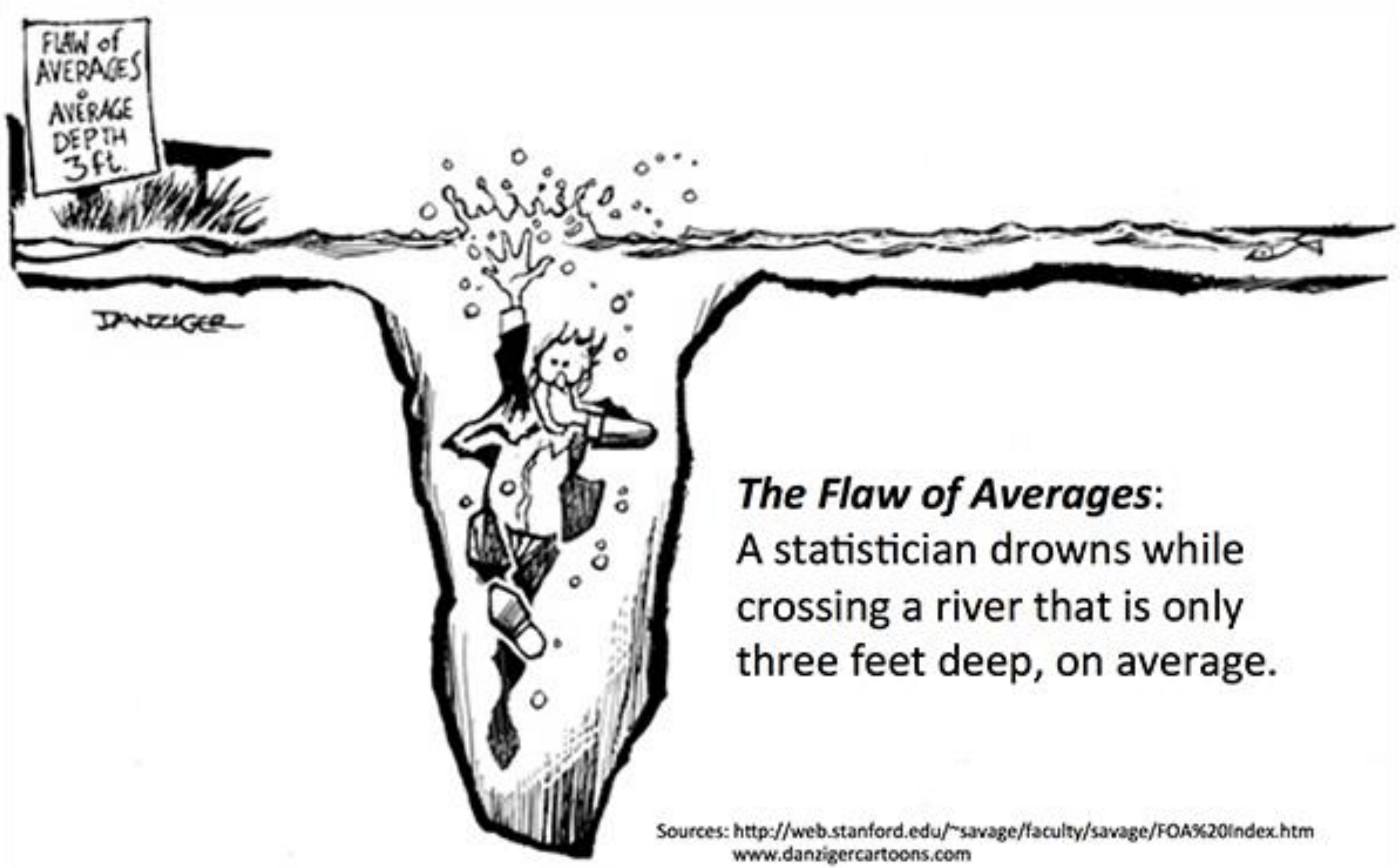
Ofgem – RIIO-2 Final Determination

- The performance target for NGET is **147MWh** (average ENS).
- This is significantly lower than the RIIO-1 target of **316MWh**



National Grid, "Annex NGET_A9.11 ENS Incentive", December 2019 (as part of the NGET Business Plan Submission) (Link)

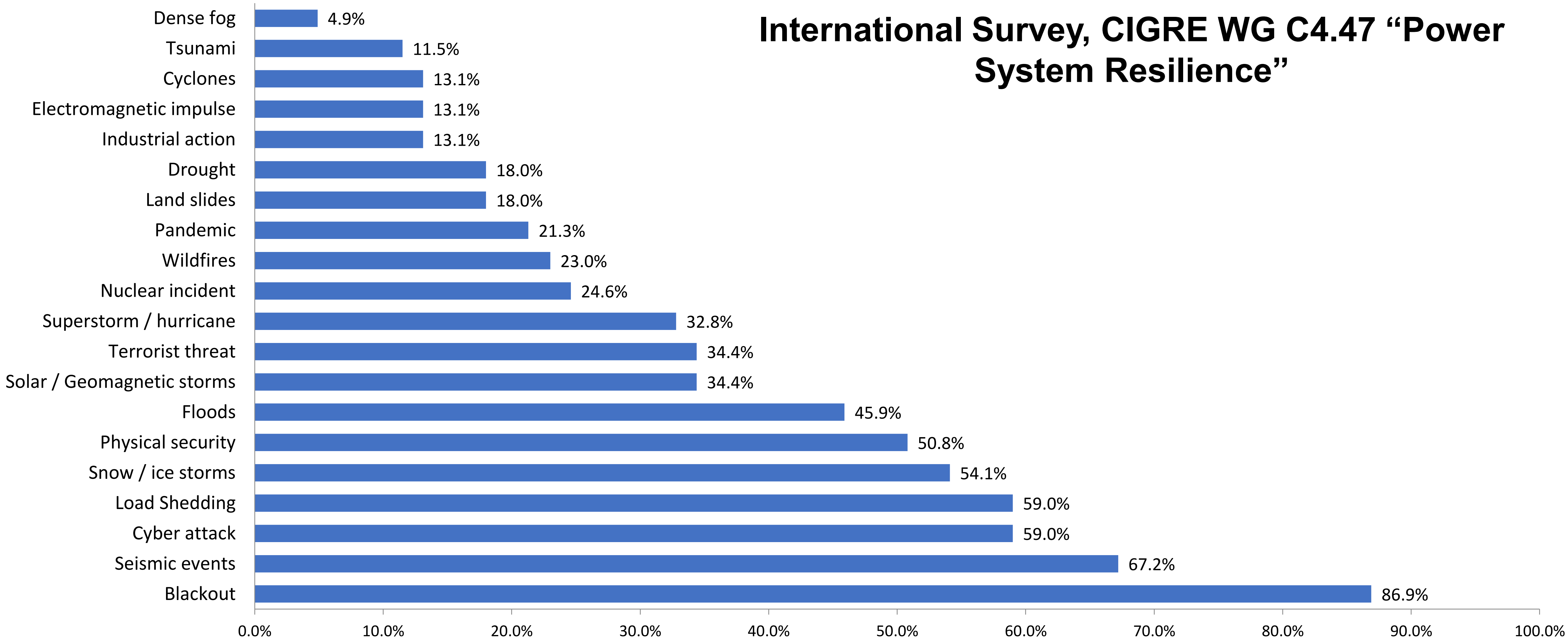
Limitations in Current Regulatory Standards



The Flaw of Averages:
A statistician drowns while crossing a river that is only three feet deep, on average.

Sources: http://web.stanford.edu/~savage/faculty/savage/FOA%20Index.htm
www.danzigercartoons.com

HILP Events in Power Systems



International Survey, CIGRE WG C4.47 "Power System Resilience"

CIGRE WG C4.47 Definition of Resilience

*the ability to limit the **extent, severity** and **duration** of **system degradation** following an **extreme event**.*

Anticipation	Preparation	Absorption	Adaptation	Rapid recovery	Sustainment of critical system operation
• the process by which newly incorporated knowledge gained is used to foresee possible crises and disasters	• the process through which grid operators establish a set of actions to be deployed in case the critical operating condition occurs	• the process through which a set of measures is deployed to limit the extent, the severity and the slope of the degradation of power system performance	• the process through which changes are carried out in the power system management procedures, on the basis of past disruptions, in order to adjust the system to undesirable situations	• the process through which the energy supply to the customers is restored and the damages to the grid infrastructure are repaired	• the process which deploys the measures allowing an impaired power system to supply a minimum system load level in order to maintain a reduced but acceptable functioning of everyday life

Key takeways from CIGRE International Survey

- **Lack of clear understanding of resilience**, and its differentiation with other well-established concepts, e.g., reliability and security

- Need for well-defined, benchmarked **metric systems and methodologies** for assessing and quantifying resilience

- What is the **role of emerging flexible solutions and integrated energy systems** in enhancing future power system resilience?

- Lack of systematic approaches for **explicitly integrating resilience in the traditional cost-benefit analysis** in order to justify resilience investments

- **Limitations in regulatory and market frameworks** to incentivize resilience reinforcement and set out clear guidelines for network stress-testing.

Infrastructure Planning and Operation Under Uncertainty

Modelling different uncertainty types

- What is the best planning approach and solution to deal with uncertainty?

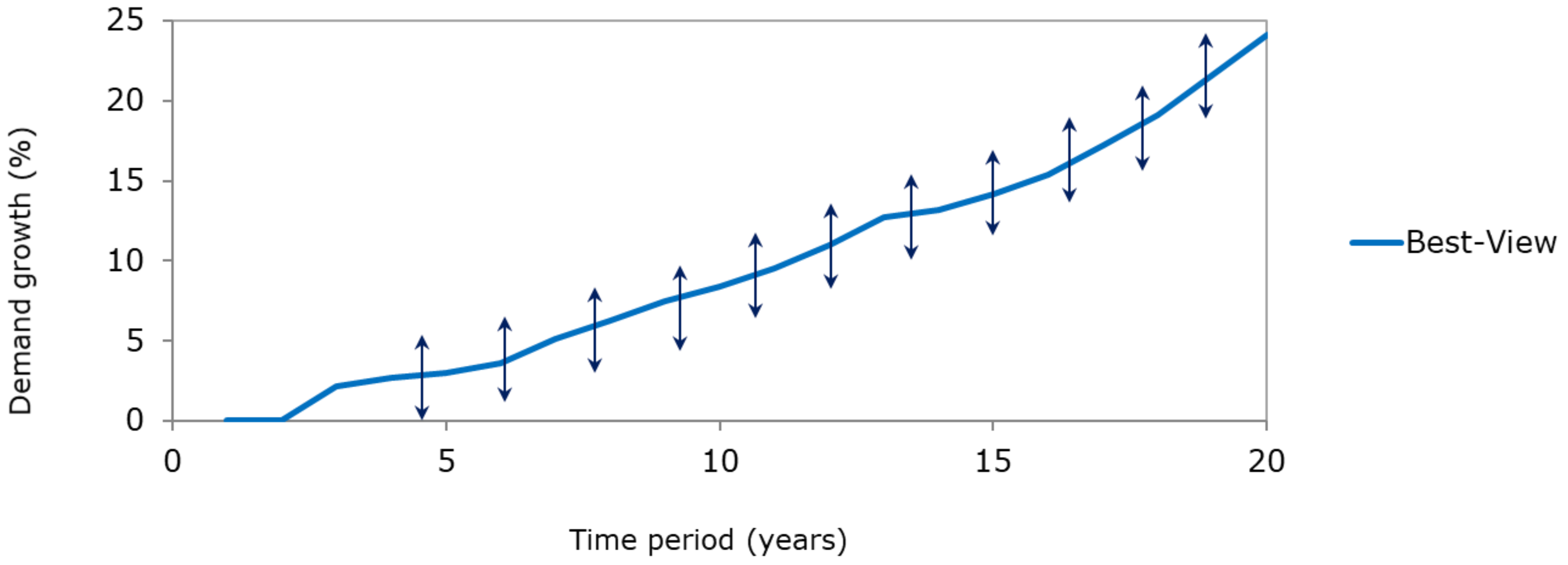
- The value of flexibility is a function of uncertainty – **Would you buy flexible flight tickets if you knew with absolute certainty the date of your flights?**

- Different approaches are needed to capture flexibility and uncertainty – **Would you use the same approach to assess a conventional and a flexible flight ticket?**

A roughly certain future

What our view about the future?

- There is a best-view future, and there can be some minor potential variations that can be captured with sensitivity studies

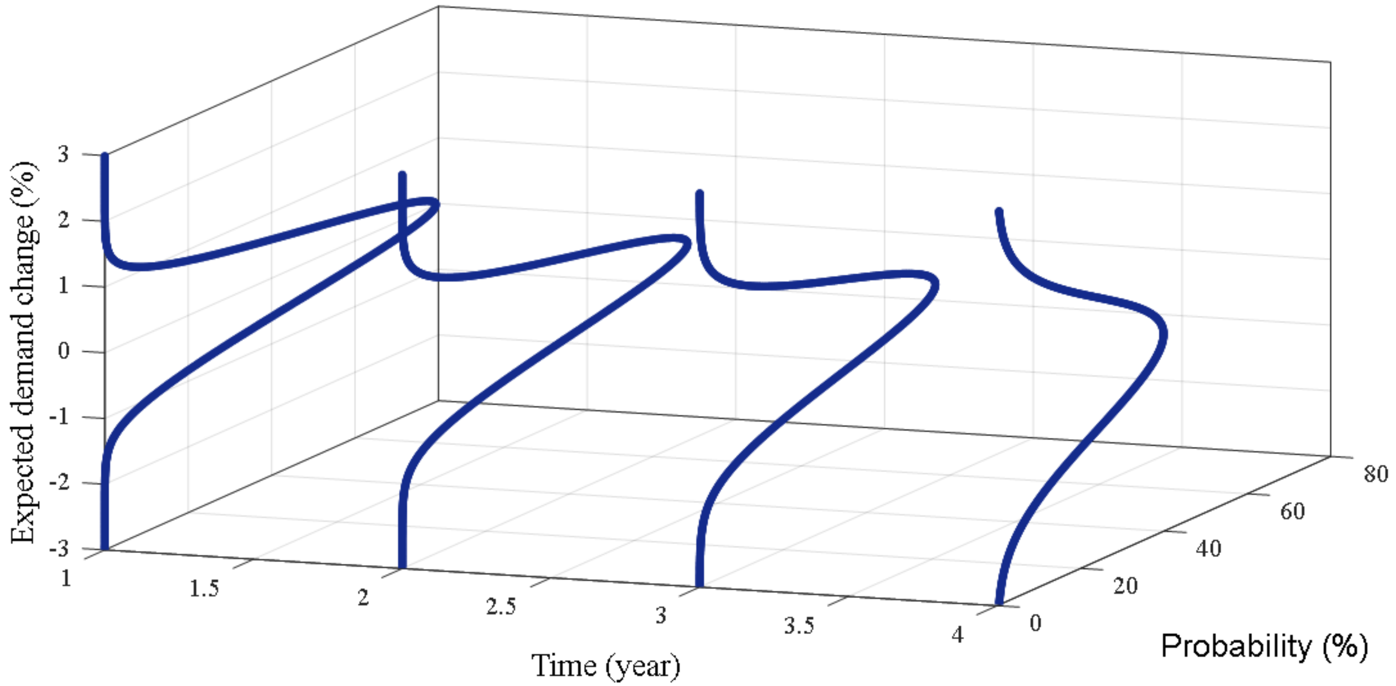


- Should we be robust?

An uncertain future

What is our view about the future?

- There are multiple futures, usually around a best-view scenario, and we can represent them with probability density functions

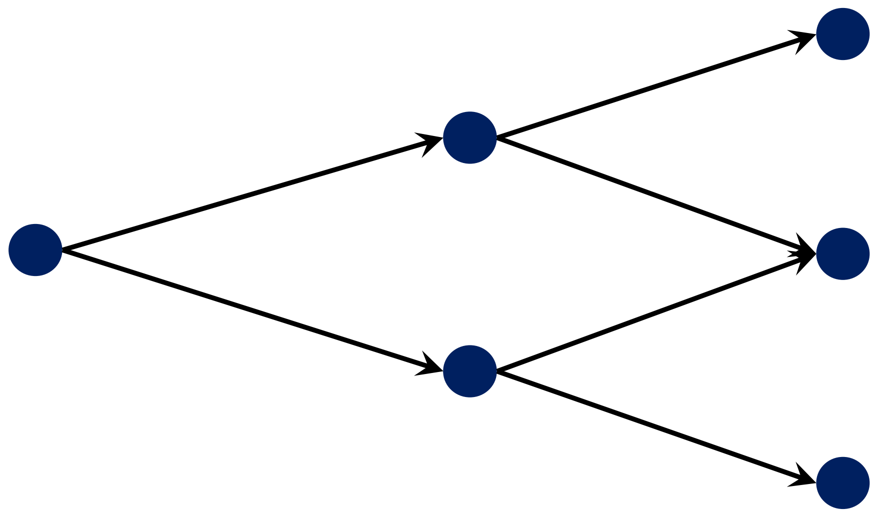


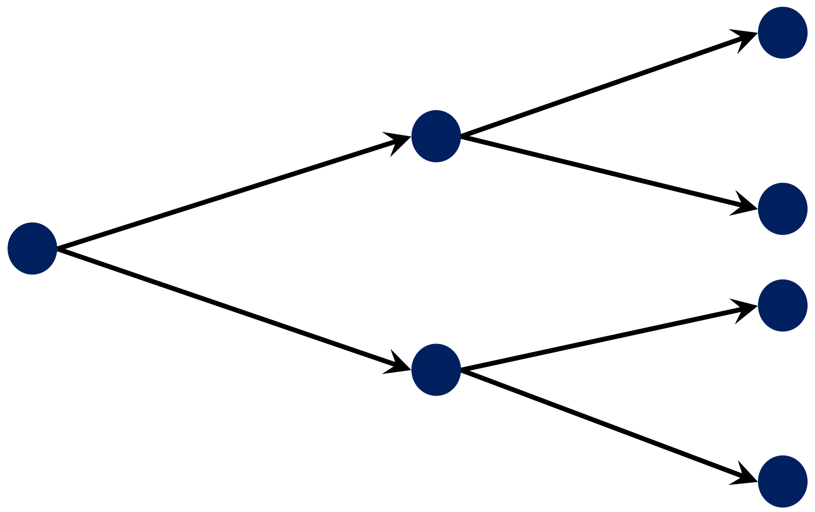
- Should we be robust or flexible?

A deeply uncertain future

What is our view about the future?

- There are multiple and widely spread futures, and our decisions may lock-in some options in the future.

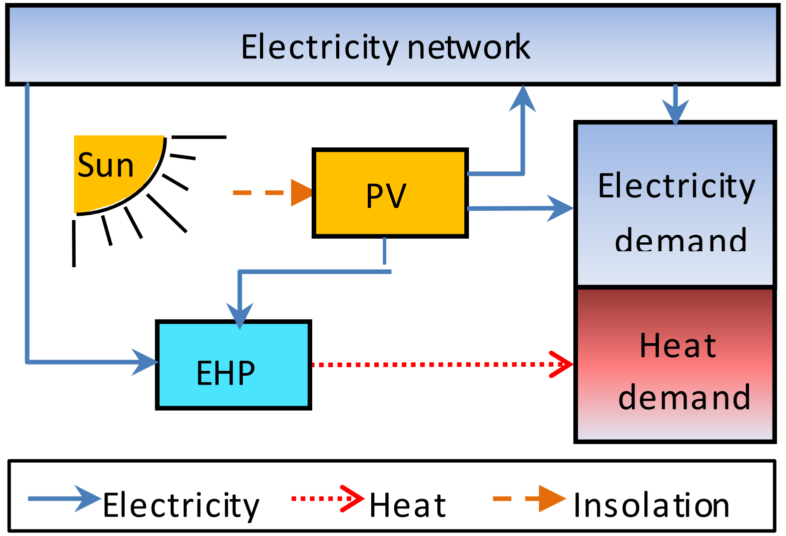


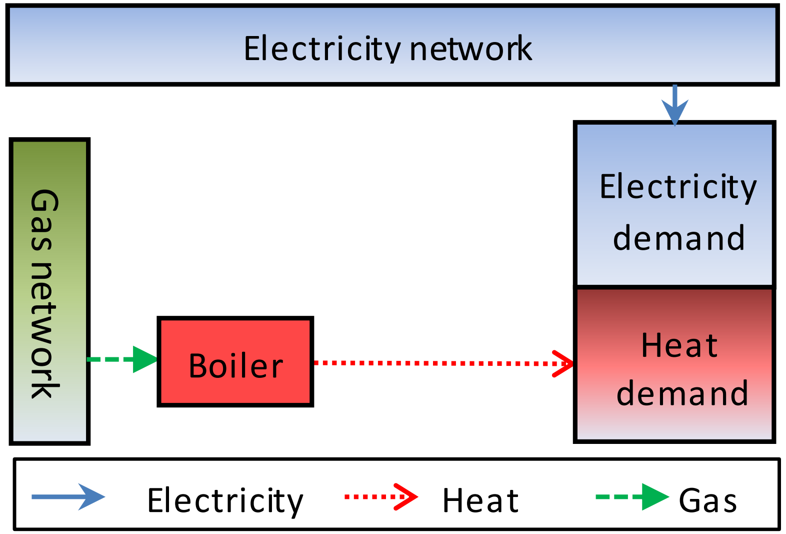


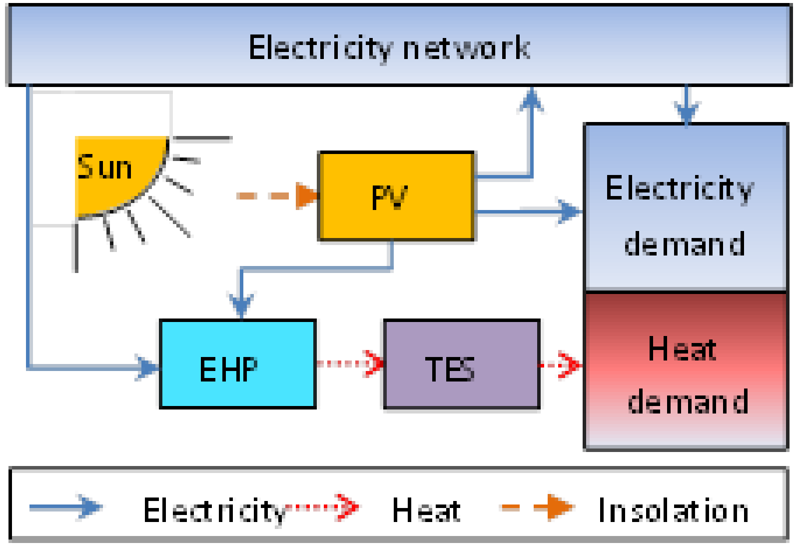
- Robust or flexible? Resistant or resilient?

Building Multi-energy systems

- Are these systems flexible?







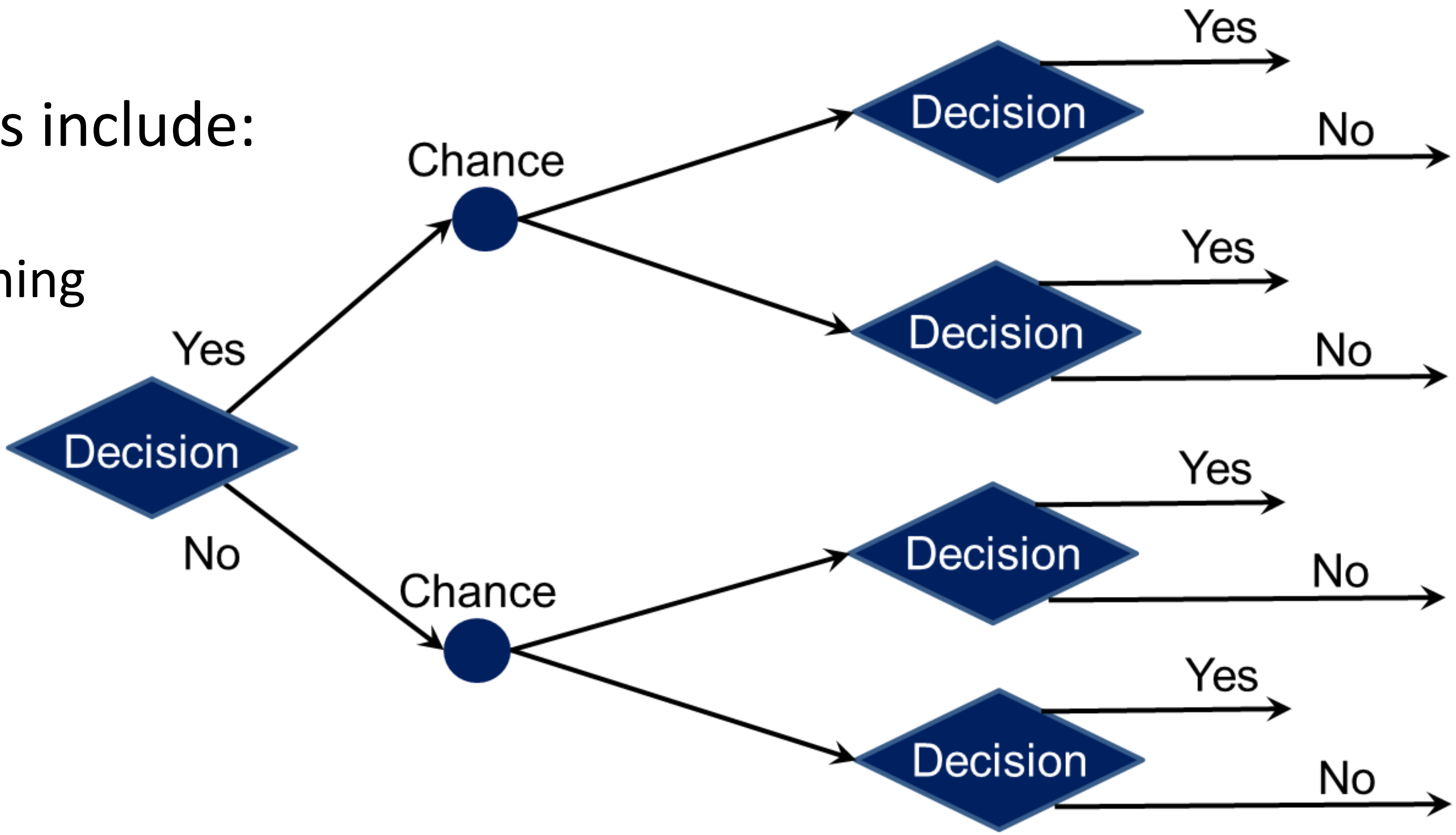
Let us explore the flexibility of these MES using live examples:

- Use this link: https://gitlab.com/cesenia/mes-tutorial-basic-concepts
- Scroll down and click on: launch binder

Planning under uncertainty

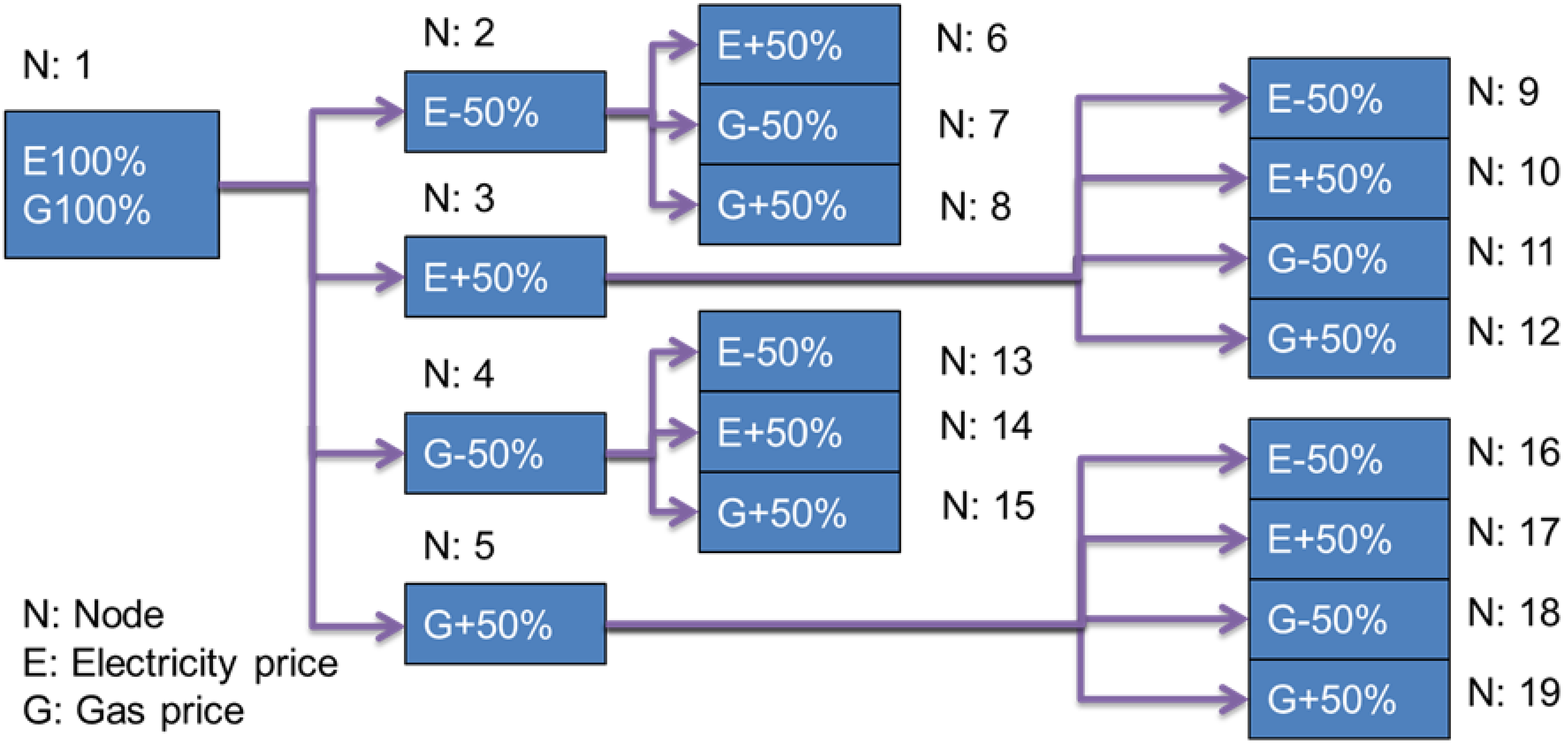
- Decision making should be based on explicit consideration of the expected, and often uncertain, futures

- Some available tools include:
  - Scenario trees
  - Dynamic programming
  - Simulations



Example – Decision tree

- Design a MES considering the following decision tree



Example – Investment approaches

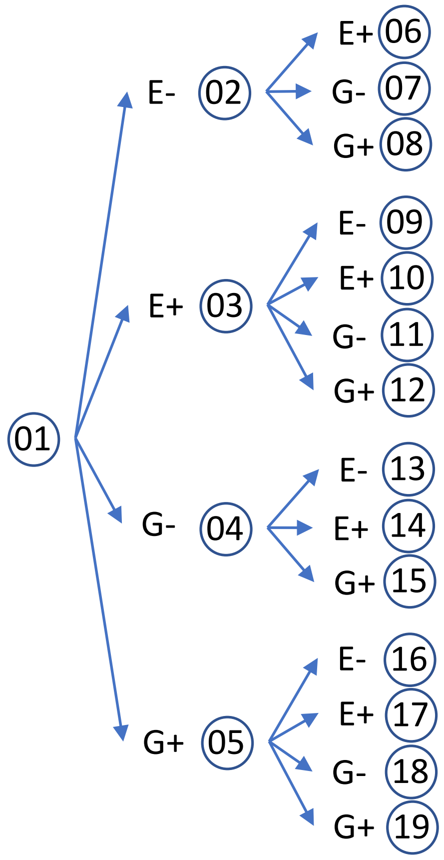
- The system design is optimised considering
  - Expected values (risk neutral)
  - Maximum loss, i.e., Regret (risk averse)

- Different planning approaches are considered
  - Do nothing: Electricity is supplied by the grid and heat with gas boilers
  - Traditional: Robust approach where decisions can only be done in the first year
  - Multi-Stage: Robust approach where new decisions are optimised every time period
  - Options based: Adaptive planning strategy

Example – Costs and risks

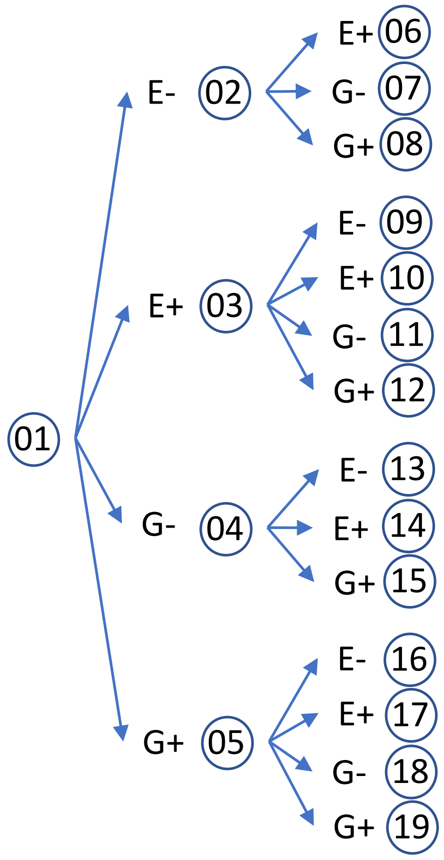
Investment scheme	Expected discounted cost	Regret
Do nothing	£10.496M	£14.935M
Traditional (risk averse)	£10.496M	£14.935M
Traditional (risk neutral)	£9.080M	£15.261M
Traditional (staged) (risk averse)	£7.749M	£11.027M
Traditional (staged) (risk neutral)	£7.740M	£15.321M
Options based	£6.500M	£9.055M

Example – Decisions (part 1)



N	**Traditional (risk neutral)**			**Traditional (risk averse)**			**Options based**		
	EHP	CHP	TES	EHP	CHP	TES	EHP	CHP	TES
1	**2500**	**1500**	0	0	0	0	**1500**	**1000**	0
2	2500	1500	0	0	**500**	0	**2500**	**1000**	0
3	2500	1500	0	**1500**	**1500**	0	**1500**	**1500**	**200**
4	2500	1500	0	**1500**	**1500**	0	**1500**	**1500**	**150**
5	**3500**	1500	**300**	0	**500**	**50**	**3000**	**1000**	**250**
6	2500	1500	**250**	**2500**	**1000**	**250**	2500	1000	**250**
7	2500	1500	**100**	**2000**	500	**50**	2500	1000	**100**
8	**3500**	1500	**450**	**3500**	500	**450**	**3500**	1000	**450**

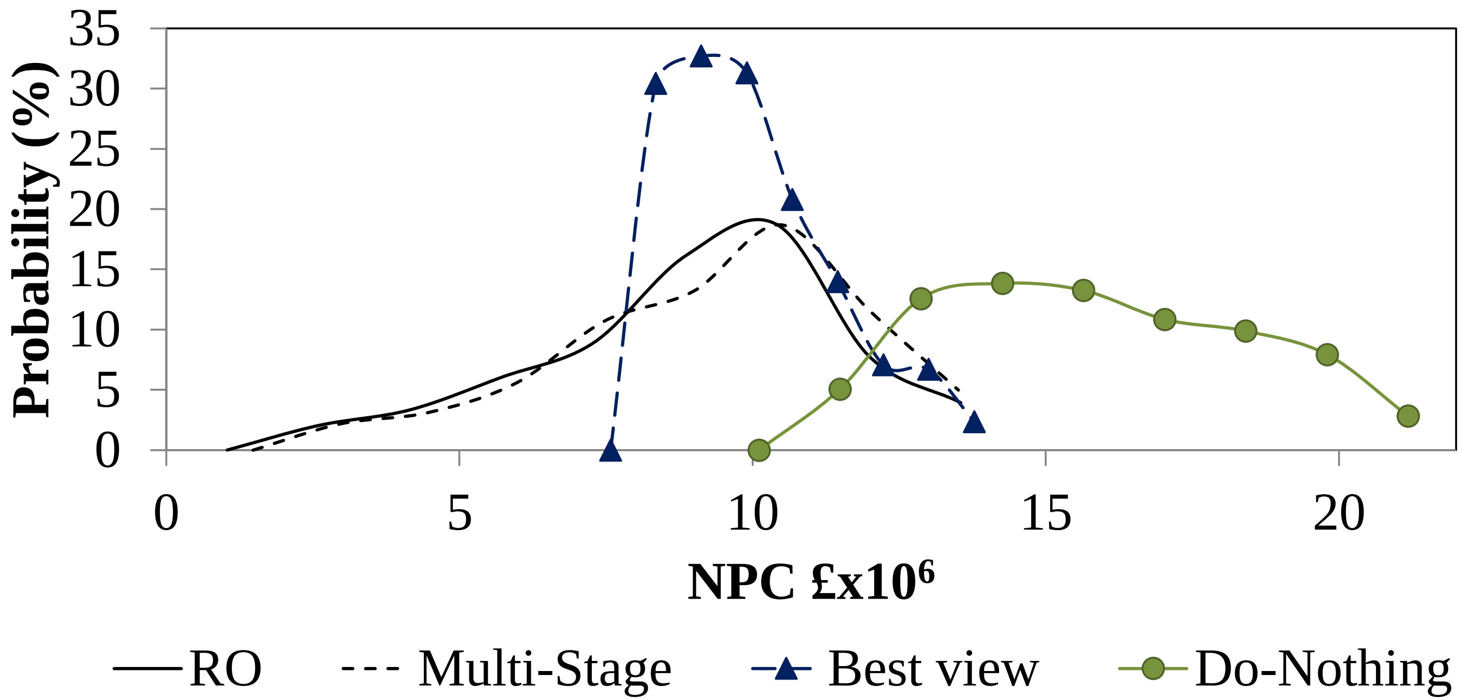
Example – Decisions (part 2)



N	Traditional (risk neutral)			Traditional (risk averse)			Options based		
	EHP	CHP	TES	EHP	CHP	TES	EHP	CHP	TES
9	2500	1500	**250**	**2500**	1500	**200**	**2500**	1500	**250**
10	2500	1500	0	1500	**4000**	**600**	1500	**4000**	**600**
11	2500	**3000**	0	1500	**3500**	**450**	1500	**3500**	**450**
12	2500	1500	**300**	**2500**	1500	**300**	**2500**	1500	**300**
13	2500	1500	**100**	**2000**	1500	**100**	**2000**	1500	**150**
14	2500	**3000**	0	1500	**3500**	**450**	1500	**3500**	**450**
15	2500	1500	**250**	**2500**	1500	**250**	**2500**	1500	**250**
16	3500	1500	**450**	**3500**	500	**450**	**3500**	1000	**450**
17	3500	1500	300	**2500**	**1500**	**300**	3000	**1500**	**300**
18	3500	1500	300	**2500**	**1000**	**250**	3000	1000	250
19	3500	1500	300	**3000**	**1000**	**300**	**3500**	1000	**300**

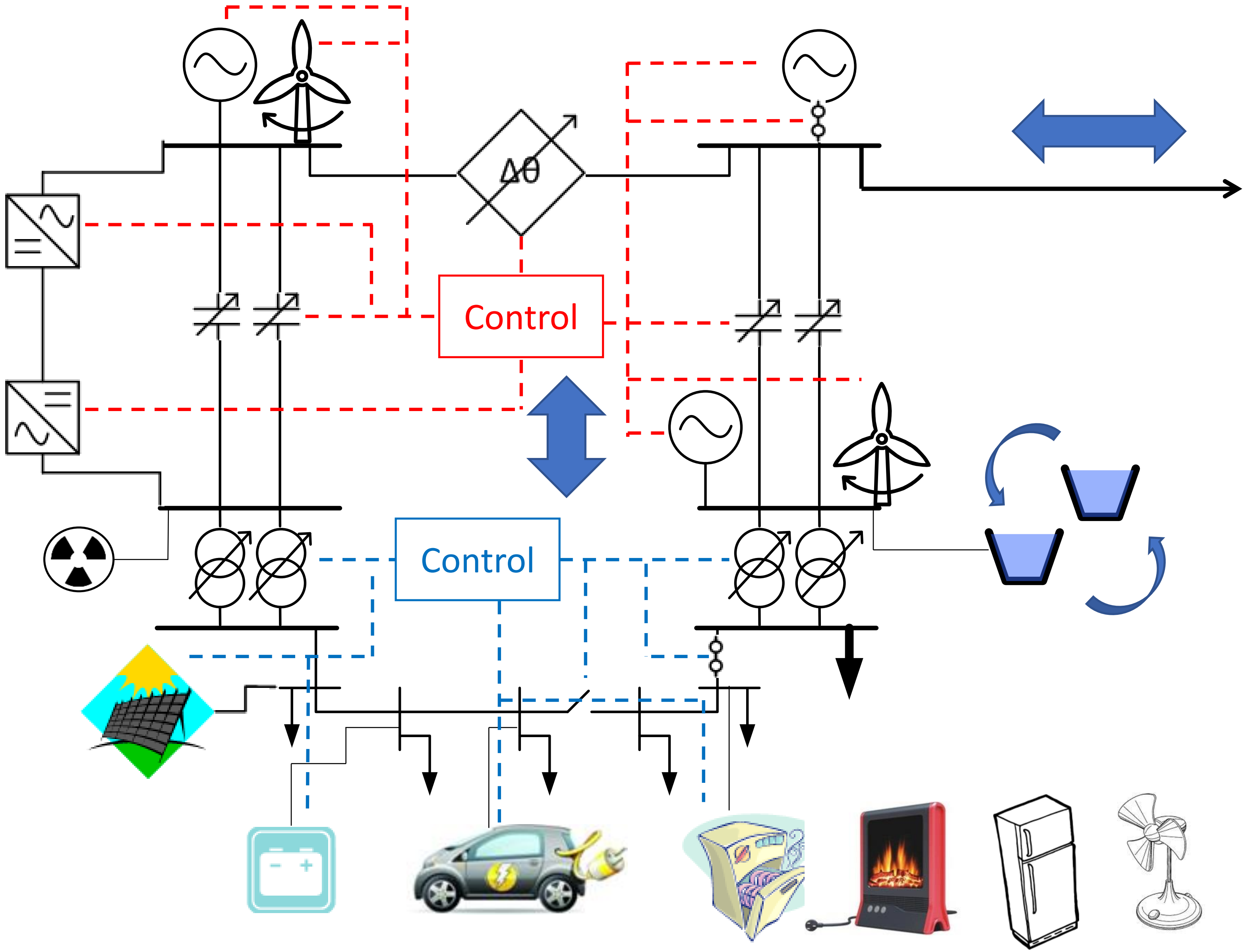
Example – Probability density functions

- The value of flexibility skews and shifts the economic performance of the MES



E. A. Martinez Cesena, T. Capuder and P. Mancarella, “Flexible distributed multi-energy generation system expansion planning under uncertainty,” IEEE Transactions on Smart Grid, 2016,

Moving from conventional to smart grids



New complexity in network planning

From	To
Peak demand	Load curve (time coupling, higher time resolution, distributed generation)
Energy-only	Coordinated multiple services (e.g. reserves)
Asset-heavy	Smart solutions (DSR, storage/EV, SPS, FACTS/HVDC, line switching, etc.)
Preventive security	Real time, corrective control security
Steady state, DC power flow	Full AC power flow and dynamic/stability
Single scenario	Multiple scenarios (various sources of uncertainty in short and long term)
Deterministic optimisation	Stochastic/robust decision making (including risk measures)

Models must remain tractable!

About uncertainty in long- and short-term

- Unknown generation investment patterns.
- Changing commercial and regulatory frameworks aimed to foster low-carbon technologies.
- Evolving availability of market information on feasibility and costs of various technologies.
- Availability of renewable generation outputs.
- Equipment availability, system failures.
- Natural hazards, attacks, etc.

The general framework: One layer of uncertainty

Chosen utility function (e.g. expectation, max)

Investment decisions

Operational decisions

$$\min_{x(\cdot),y(\cdot)} f_\varepsilon\{C^I(x(\varepsilon),\varepsilon) + C^O(y(\varepsilon),\varepsilon)\}$$

s.t.:

$$x(\varepsilon) \in X(\varepsilon);\ \forall\varepsilon \in E$$

$$y(\varepsilon) \in Y(x(\varepsilon),\varepsilon);\ \forall\varepsilon \in E$$

Moreno, R., Street, A., Arroyo, J.M., Mancarella, P. 2017. Planning low-carbon electricity systems under uncertainty considering operational flexibility and smart grid technologies. Phil. Trans. R. Soc. A 375:20160305.

The general framework: Two layers of uncertainty

Chosen utility function (e.g. expectation, max)

Investment decisions

Scheduled/planned operation

$$\min_{x(\cdot),y(\cdot),z(\cdot,\cdot)} f_{\varepsilon,\xi}\{C^I(x(\varepsilon),\varepsilon) + C^O(y(\varepsilon), z(\varepsilon,\xi), \varepsilon, \xi)\}$$

Real-time operation

s.t.:

$$x(\varepsilon) \in X(\varepsilon);\ \forall \varepsilon \in E$$

$$y(\varepsilon) \in Y(x(\varepsilon), \varepsilon, \xi);\ \forall \varepsilon \in E, \forall \xi \in \Xi$$

$$z(\varepsilon,\xi) \in Z(x(\varepsilon), y(\varepsilon), \varepsilon, \xi);\quad \forall \varepsilon \in E, \forall \xi \in \Xi$$

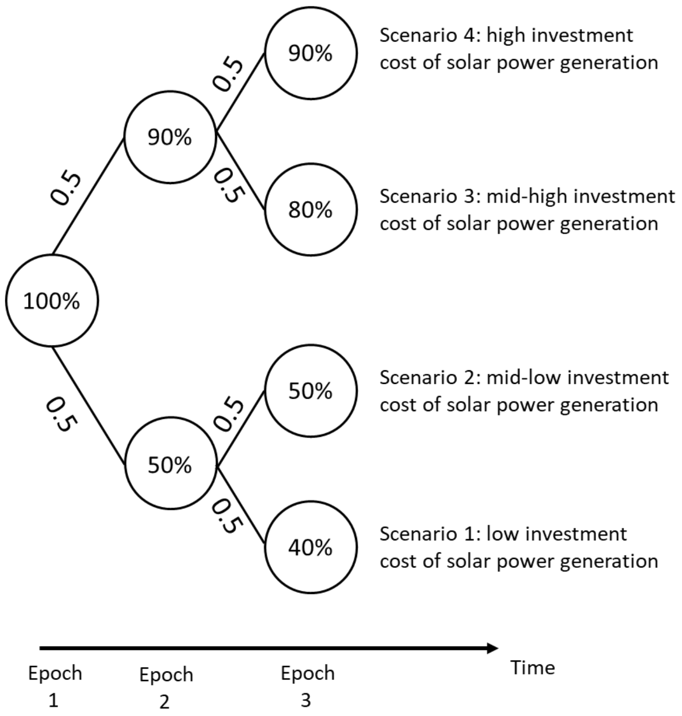
Moreno, R., Street, A., Arroyo, J.M., Mancarella, P. 2017. Planning low-carbon electricity systems under uncertainty considering operational flexibility and smart grid technologies. Phil. Trans. R. Soc. A 375:20160305.

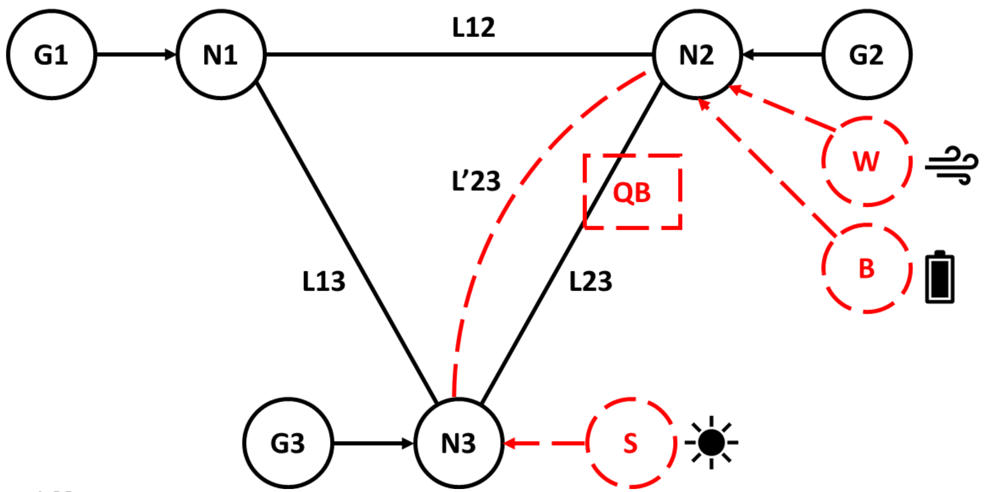
The planning problem: Illustrative example

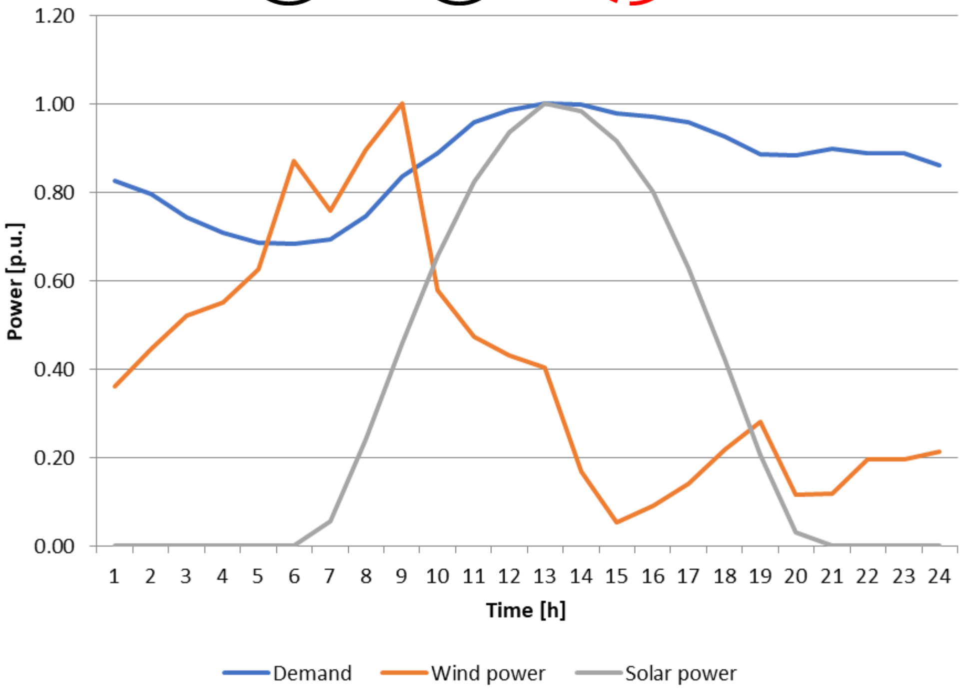
Minimise expected cost of *investment and operation*

considering:

- Long-term uncertainty
- Operational details and constraints







Lag of 1 epoch for conventional infrastructure
No lag for "flexible" infrastructure

The optimisation problem

Min. cost of Investment + operation

$$min\left\{\sum_{m\in M}\rho_m r_m(\tau^I I_m + \tau^O O_m)\right\}$$

$$I_m = \sum_{g\in\hat{G}} \pi_g^{IG}\,\bar{P}_{g,m}^G + \sum_{l\in\hat{L}} \pi_l^{IL}\,\mu_{l,m}^L + \sum_{b\in\hat{B}} \pi_b^{IB}\,\bar{P}_{b,m}^B + \sum_{l\in\hat{L}^Q} \pi_l^{IQ}\,\mu_{l,m}^Q\,; \quad \forall m \in M$$

$$O_m = \sum_{t\in T}\sum_{g\in G} \pi_g^{OG}\,P_{g,m,t}^G\,; \quad \forall m \in M$$

s.t.

- Nodal power balance
- Power flows (including FACTS)
- Line capacity (including big-M)
- Generation capacity (min and max)
- Generation availability (especially for renewables)
- Ramp rate limits
- UC constraints (including minimum running/shutdown times)
- Storage constraints
- Non-anticipativity constraints

Moreno, R., Street, A., Arroyo, J.M., Mancarella, P. 2017. Planning low-carbon electricity systems under uncertainty considering operational flexibility and smart grid technologies. Phil. Trans. R. Soc. A 375:20160305.

The importance of uncertainty

Stochastic solution

	scenario 1 low	scenario 2 mid-low	scenario 3 mid-high	scenario 4 high
expansion plan per epoch and scenario				
epoch 1	W⟨16⟩			
epoch 2	S⟨39⟩		W⟨10⟩, QB	
epoch 3	S⟨18⟩	S⟨5⟩, W⟨2⟩	B⟨1⟩	B⟨1⟩

Deterministic (perfect information) solution

	scenario 1 low	scenario 2 mid-low	scenario 3 mid-high	scenario 4 high
expansion plan per epoch and scenario				
epoch 1	W⟨16⟩	W⟨16⟩	W⟨19⟩	W⟨19⟩
epoch 2	S⟨39⟩	S⟨39⟩	W⟨7⟩, L'23	W⟨7⟩, L'23
epoch 3	S⟨18⟩	S⟨5⟩, W⟨2⟩	W⟨1⟩	W⟨1⟩

Moreno, R., Street, A., Arroyo, J.M., Mancarella, P. 2017. Planning low-carbon electricity systems under uncertainty considering operational flexibility and smart grid technologies. Phil. Trans. R. Soc. A 375:20160305.

The importance of the operational details

Stochastic solution

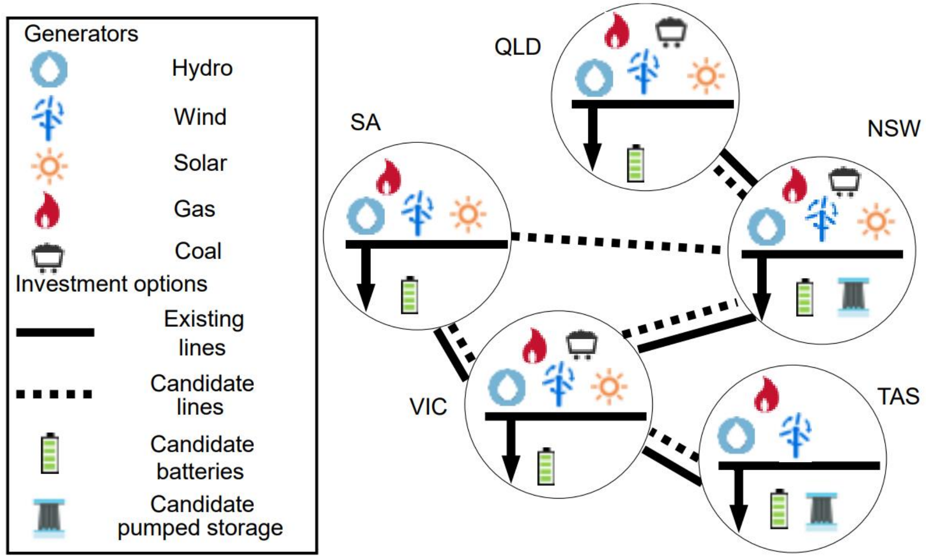
	scenario 1 low	scenario 2 mid-low	scenario 3 mid-high	scenario 4 high
expansion plan per epoch and scenario				
epoch 1	W⟨16⟩			
epoch 2	S⟨39⟩		W⟨10⟩, QB	
epoch 3	S⟨18⟩	S⟨5⟩, W⟨2⟩	B⟨1⟩	B⟨1⟩

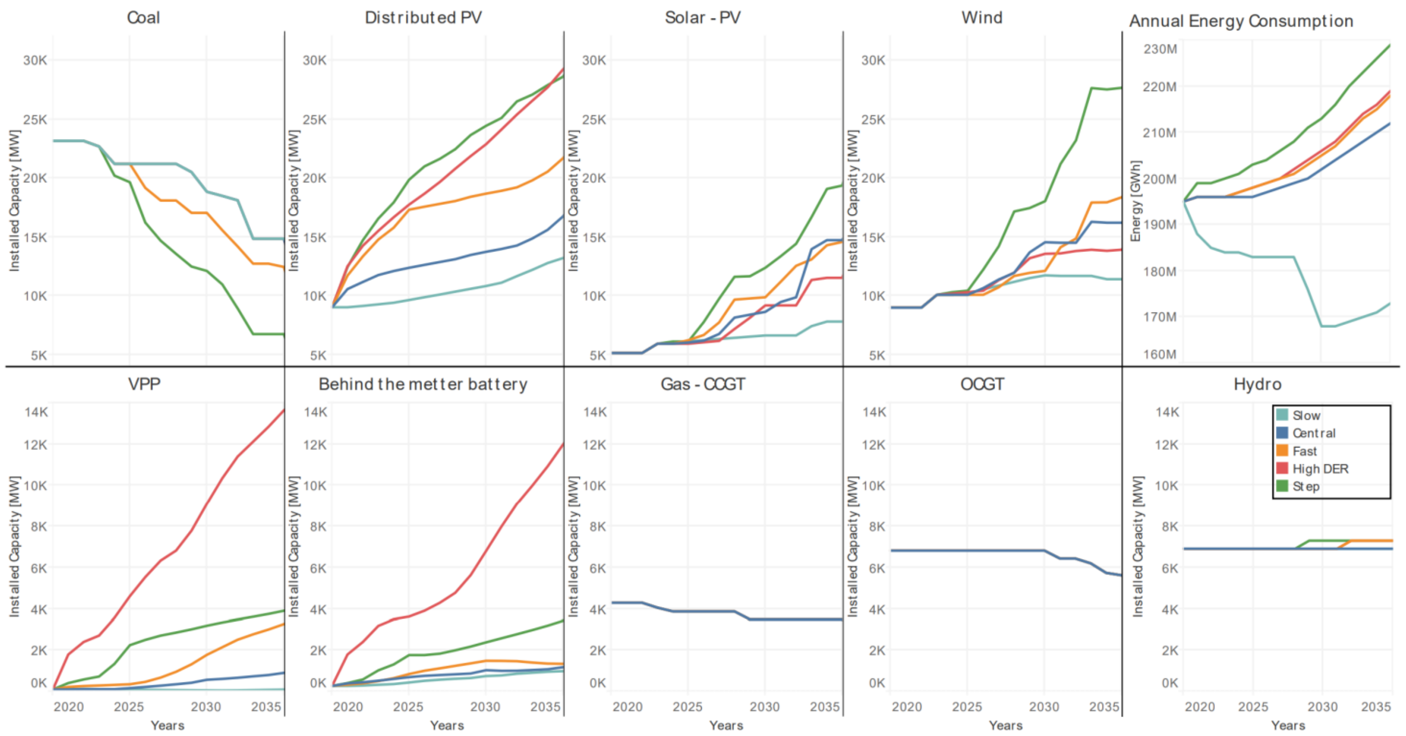
Stochastic solution (no ramp rate constraints)

	scenario 1 low	scenario 2 mid-low	scenario 3 mid-high	scenario 4 high
expansion plan per epoch and scenario				
epoch 1	W⟨16⟩			
epoch 2	S⟨39⟩		W⟨10⟩, QB	
epoch 3	S⟨18⟩	S⟨5⟩, W⟨2⟩	N/I	N/I

Moreno, R., Street, A., Arroyo, J.M., Mancarella, P. 2017. Planning low-carbon electricity systems under uncertainty considering operational flexibility and smart grid technologies. Phil. Trans. R. Soc. A 375:20160305.

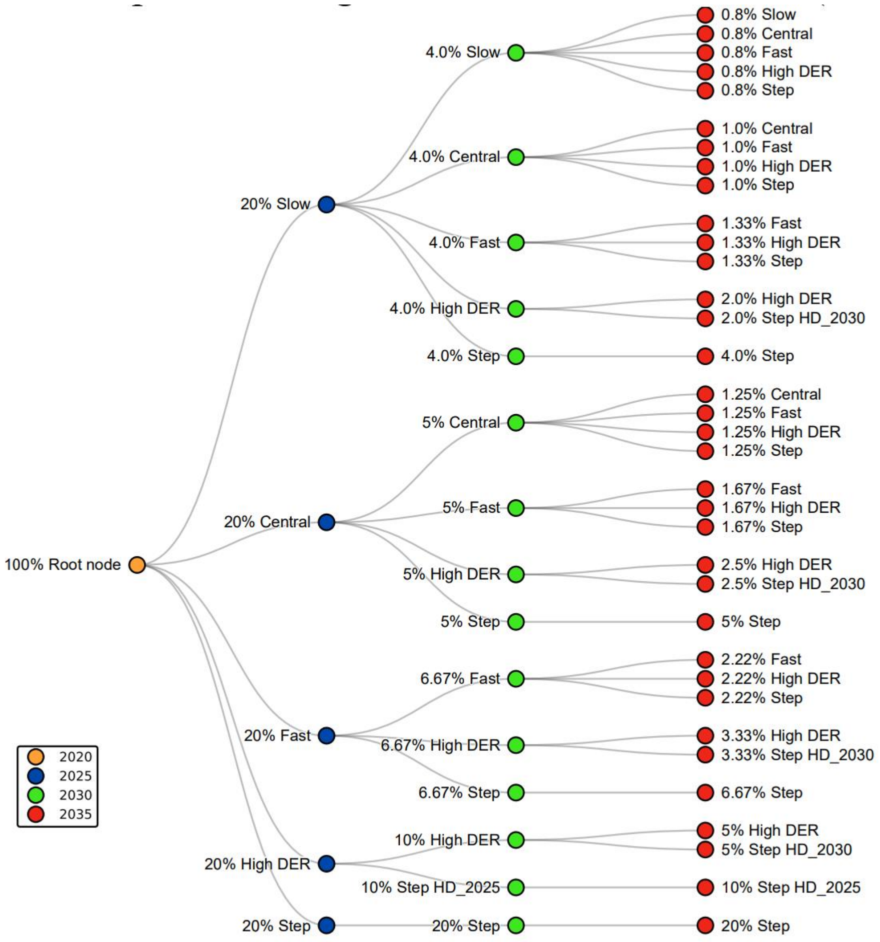
Co-optimising network and storage infrastructure: Australia

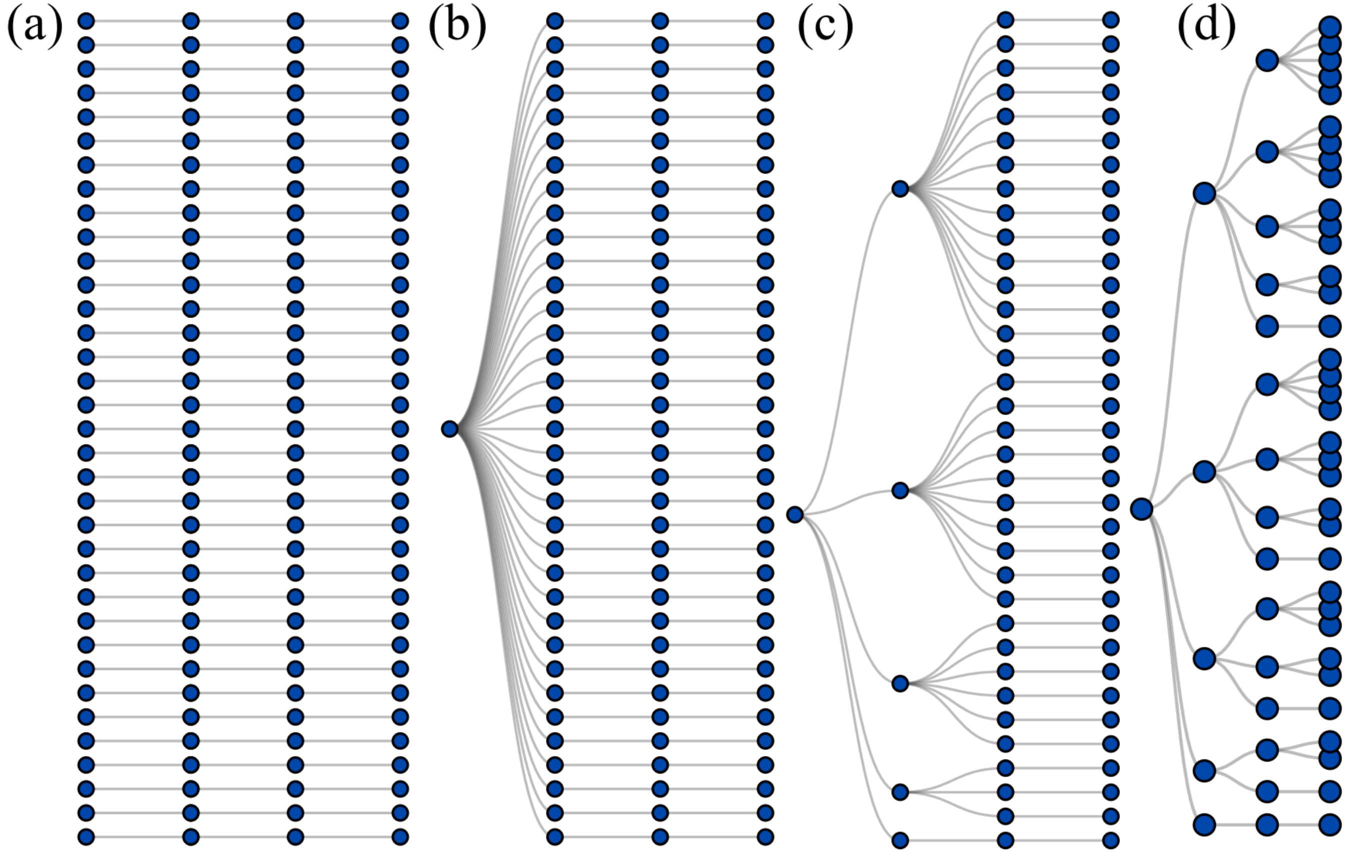




Moya, B., Moreno, R., Püschel-Løvengreen, Costa, A.M., Mancarella, P. Uncertainty representation in investment planning of low-carbon power systems. Electric Power System Research / PSCC, 2022.

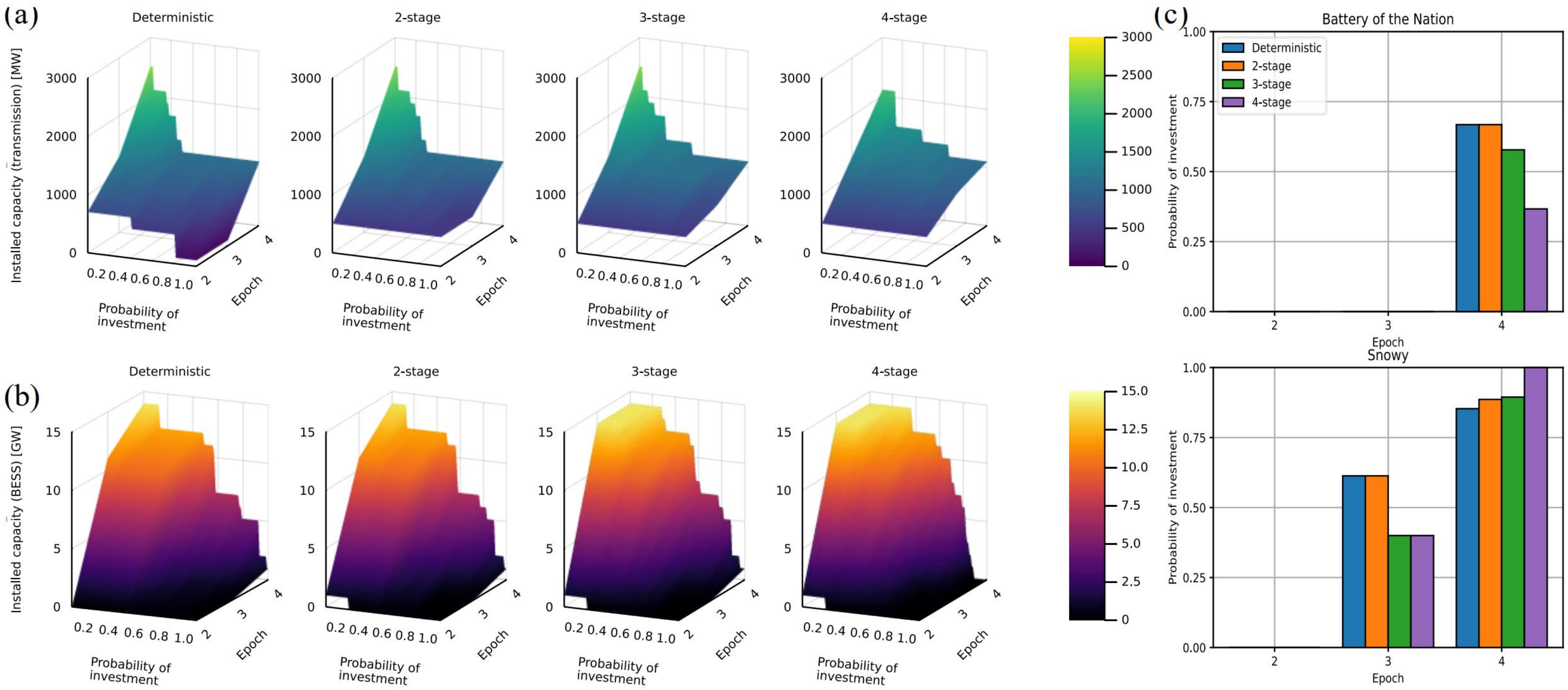
Uncertainty representation/simplifications





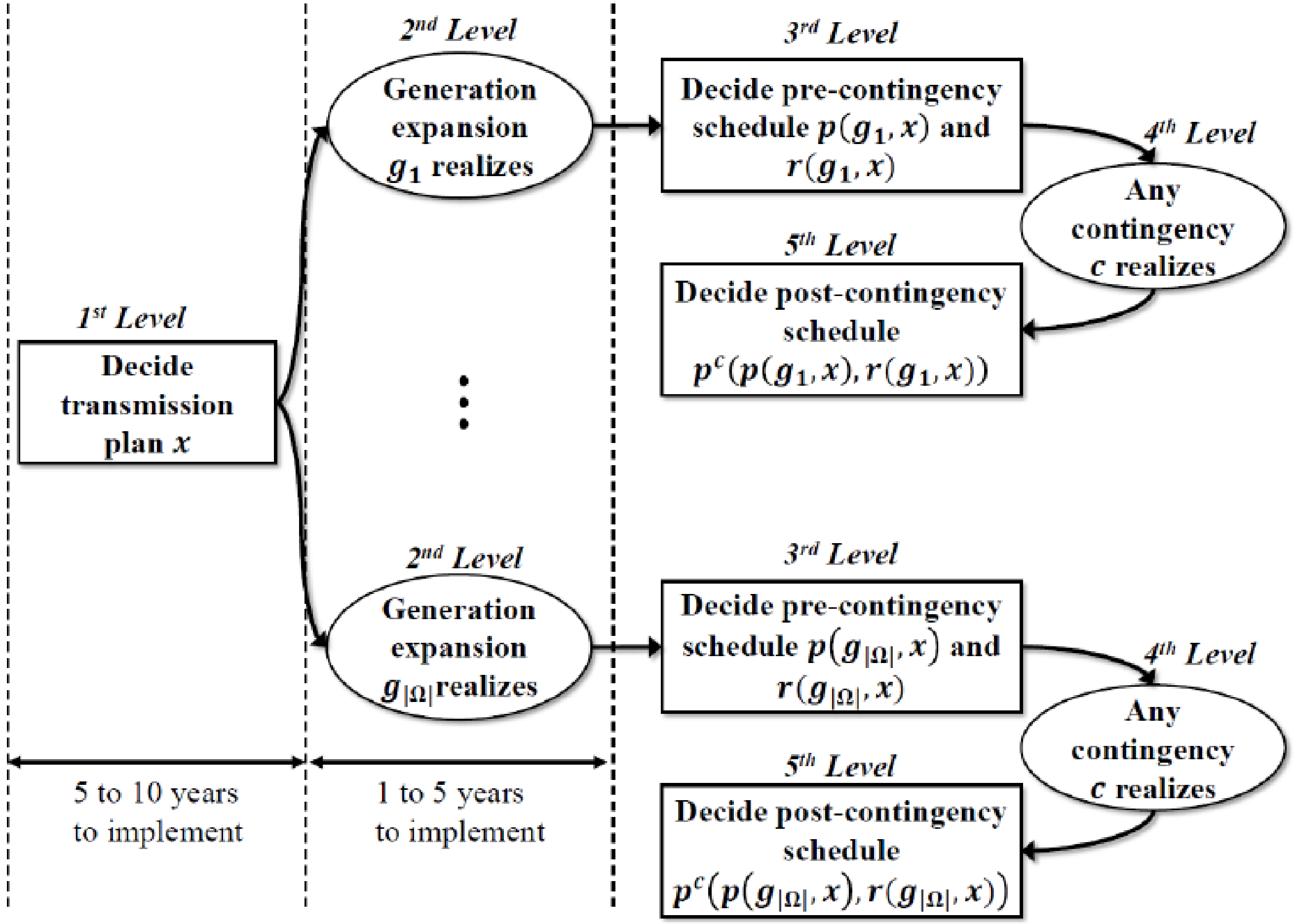
Moya, B., Moreno, R., Püschel-Løvengreen, Costa, A.M., Mancarella, P. Uncertainty representation in investment planning of low-carbon power systems. Electric Power System Research / PSCC, 2022.

Results: More batteries with more detailed uncertainty representation



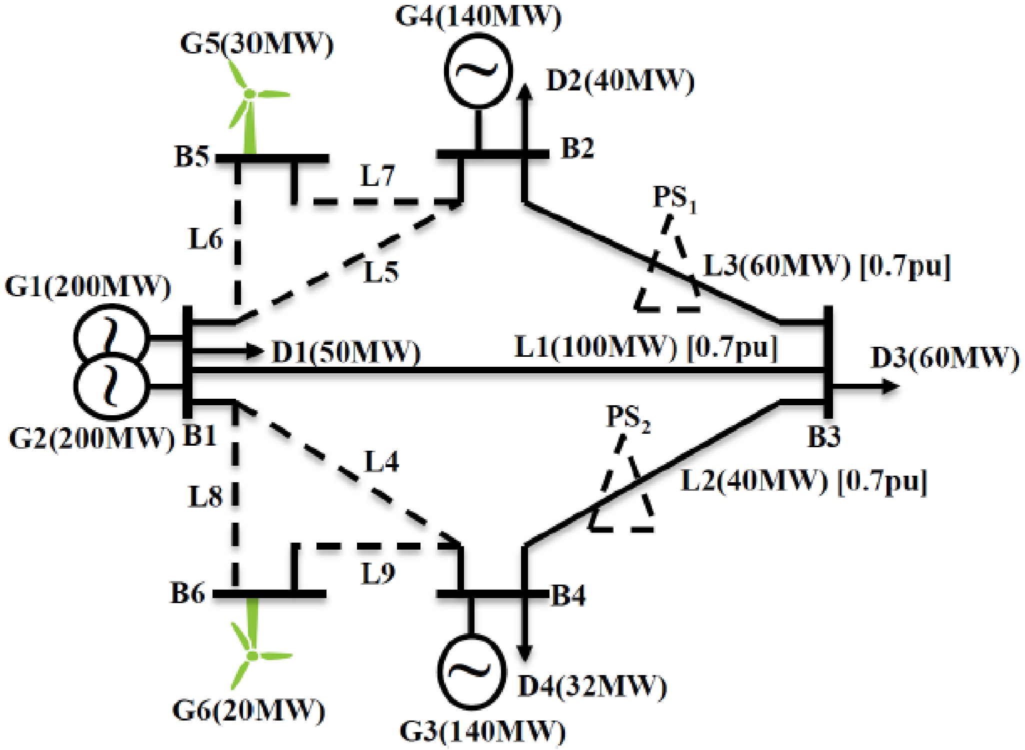
Moya, B., Moreno, R., Püschel-Løvengreen, Costa, A.M., Mancarella, P. Uncertainty representation in investment planning of low-carbon power systems. Electric Power System Research / PSCC, 2022.

Two layers of uncertainty through robust optimisation: A 5-Level MILP Model (min-max-min-max-min)



Moreira, A., Strbac, G., Moreno, R., Street, A., Konstantelos, I., "A Five-Level MILP Model for Flexible Transmission Network Planning under Uncertainty: A Min-Max Regret Approach", IEEE Transactions on Power Systems, Vol 33, Issue 1, pp 486 - 501, Jan 2018.

Results: Phase shifters become more attractive if short (faults) and long-term uncertainty is modelled

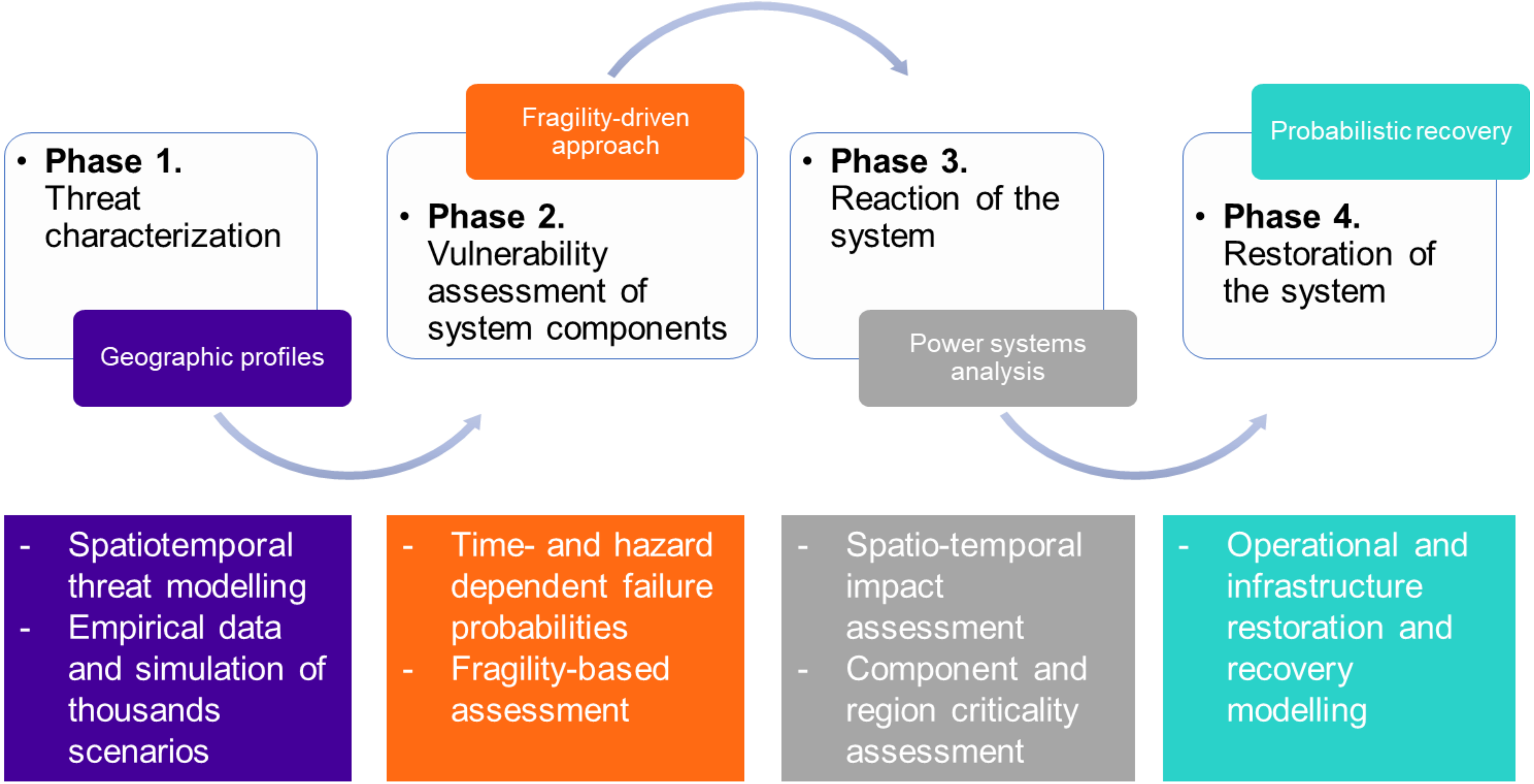


Assumption	Case	Decision
$n-0$ with candidate PS	S1	L4(48MW)
	S2	L7(30MW)
	S3	L8(20MW), L9(40MW)
	S4	L7(30MW), L9(20MW)
	MMR	L6(35MW), L7(43MW), L9(15MW)
$n-1$ with candidate PS	S1	L3(PS), L4(42MW), L5(90MW)
	S2	L3(PS), L4(32MW), L5(70MW), L7(30MW)
	S3	L4(50MW), L5(62MW), L9(20MW)
	S4	L4(41MW), L5(41MW), L7(30MW), L9(20MW)
	MMR	L2(PS), L3(PS), L6(96MW), L7(96MW), L8(36MW), L9(36MW)

Moreira, A., Strbac, G., Moreno, R., Street, A., Konstantelos, I., "A Five-Level MILP Model for Flexible Transmission Network Planning under Uncertainty: A Min-Max Regret Approach", IEEE Transactions on Power Systems, Vol 33, Issue 1, pp 486 - 501, Jan 2018.

Infrastructure planning and operation considering uncertain extreme events

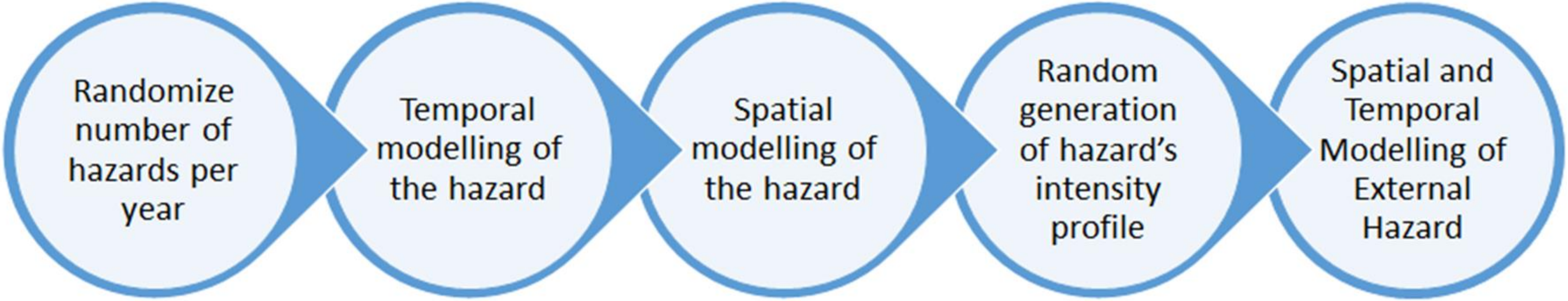
Multi-Phase Resilience Assessment



M. Panteli, D. N. Trakas, P. Mancarella, and N. D. Hatziargyriou, "Power Systems Resilience Assessment: Hardening and Smart Operational Enhancement Strategies", Proceedings of the IEEE, vol. 105, no. 7, pp. 1202-1213, July 2017.

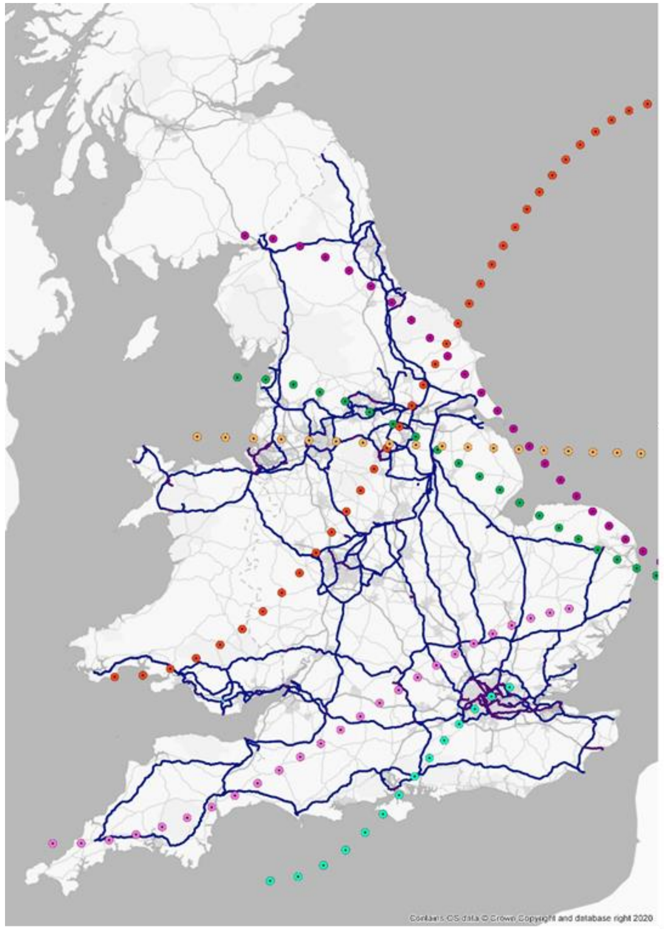
M. Panteli, P. Mancarella, C. Pickering, S. Wilkinson, and R. Dawson, "Power System Resilience to Extreme Weather: Fragility Modelling, Probabilistic Impact Assessment, and Adaptation Measures", IEEE Transactions on Power Systems, vol. 32, no. 5, September 2017.

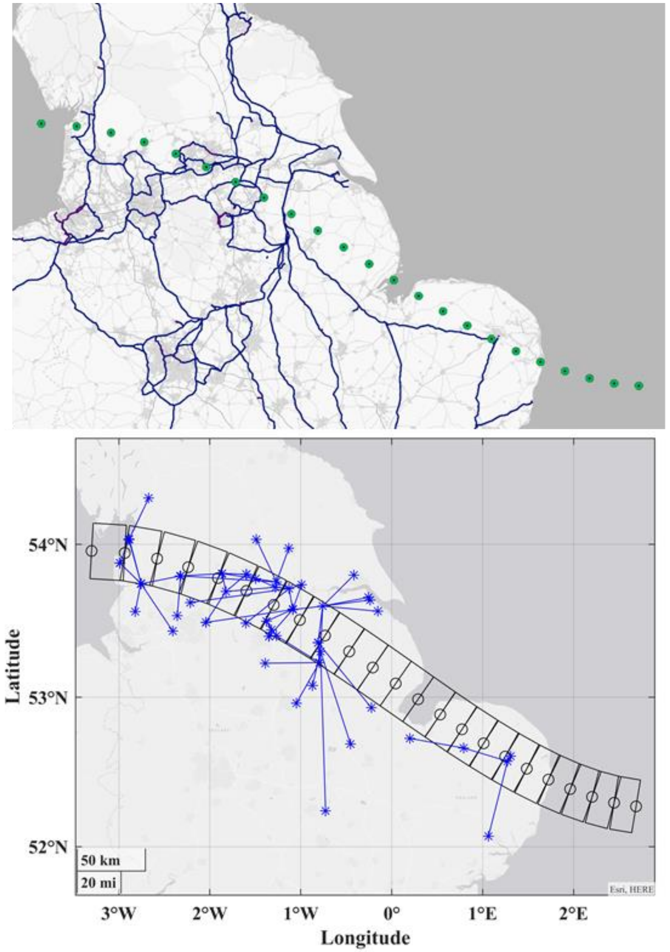
Spatial and Temporal Hazard Simulator

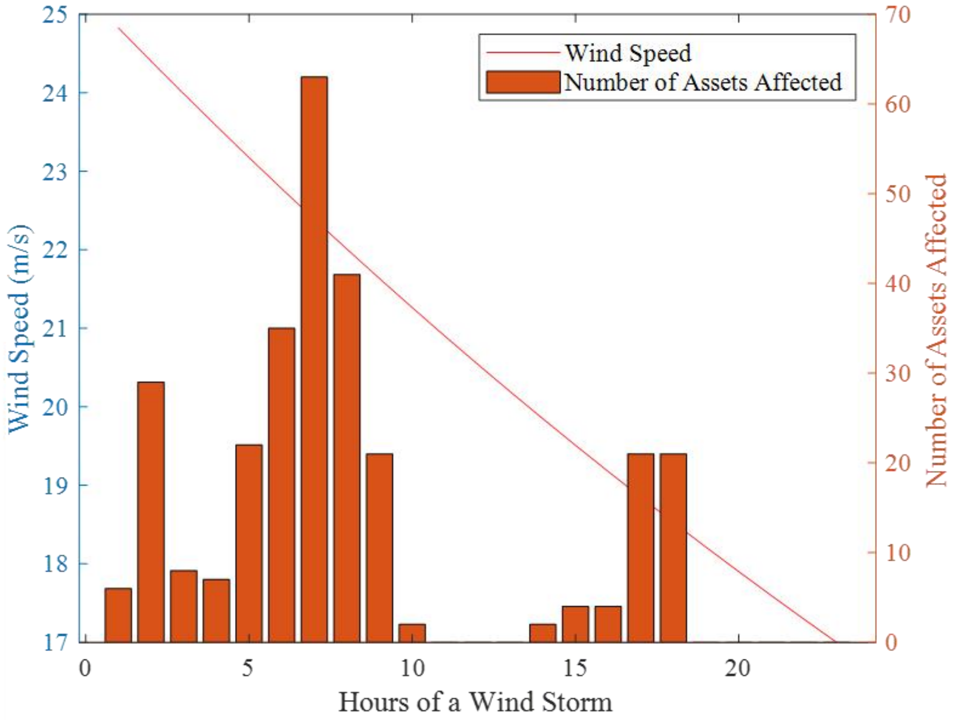


- Fully flexible and modular simulator of extreme weather events
- Enables the user to define several critical features, and simulate random events as well as historical ones.
- Examples of events: windstorms, earthquakes, wildfires, etc.

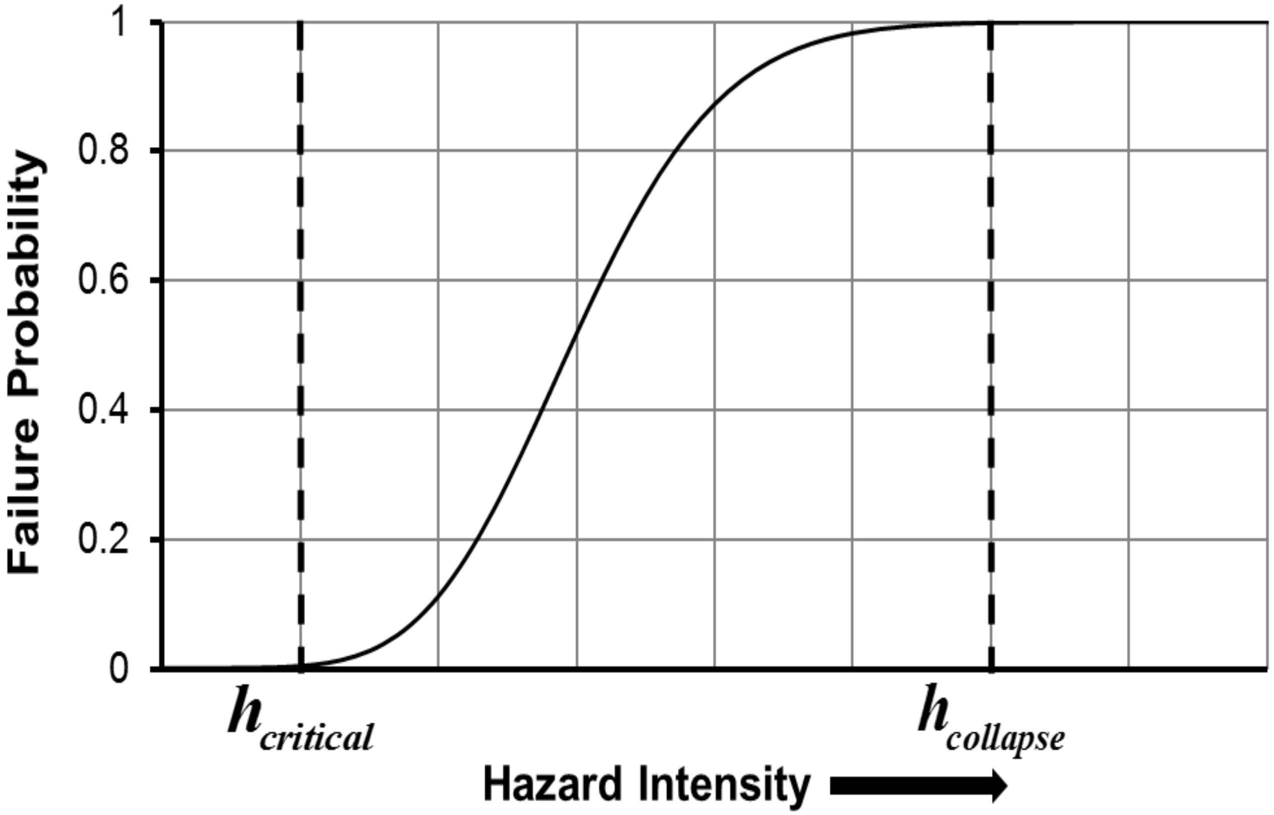
Example of Windstorm Modelling





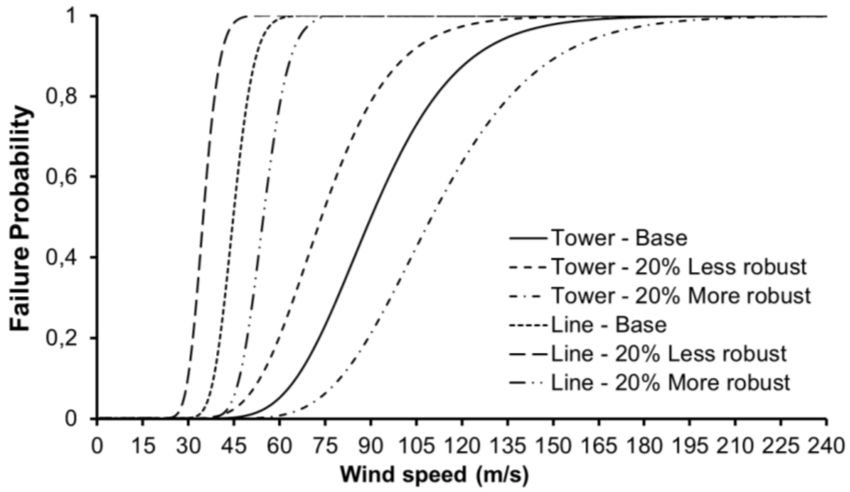


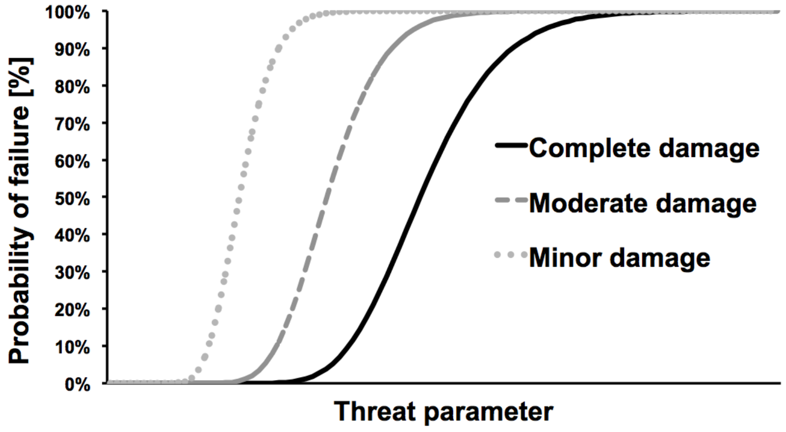
Asset Vulnerability and Fragility Modelling

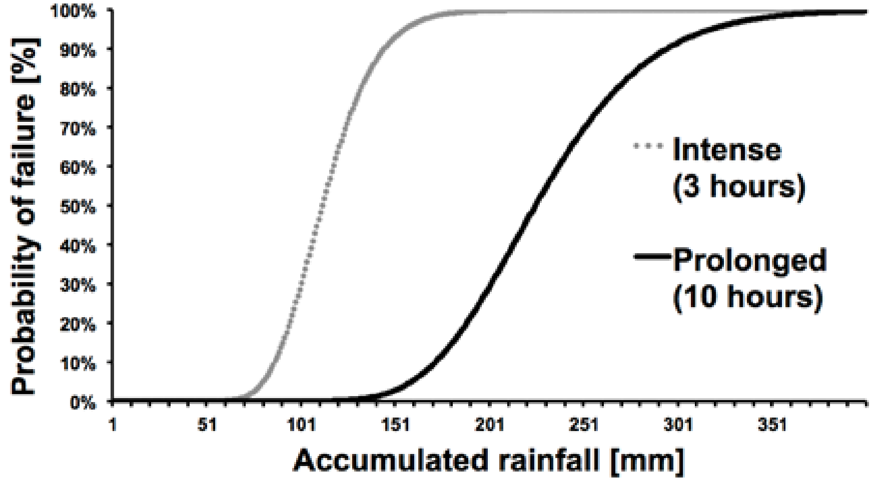


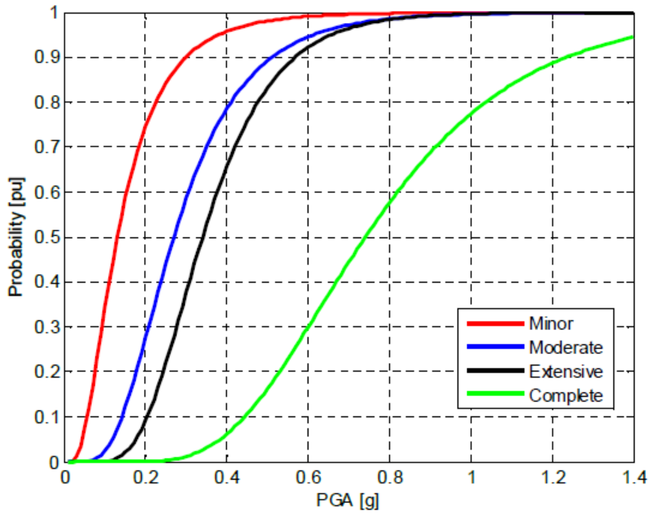
$$P_i(h) = \begin{cases} 0, & \text{if } h < h_{critical} \\ P(h), & \text{if } h_{critical} \le h < h_{collapse} \\ 1, & \text{if } h \ge h_{collapse} \end{cases}$$

Examples of Fragility Curves – Investing in more robust assets?



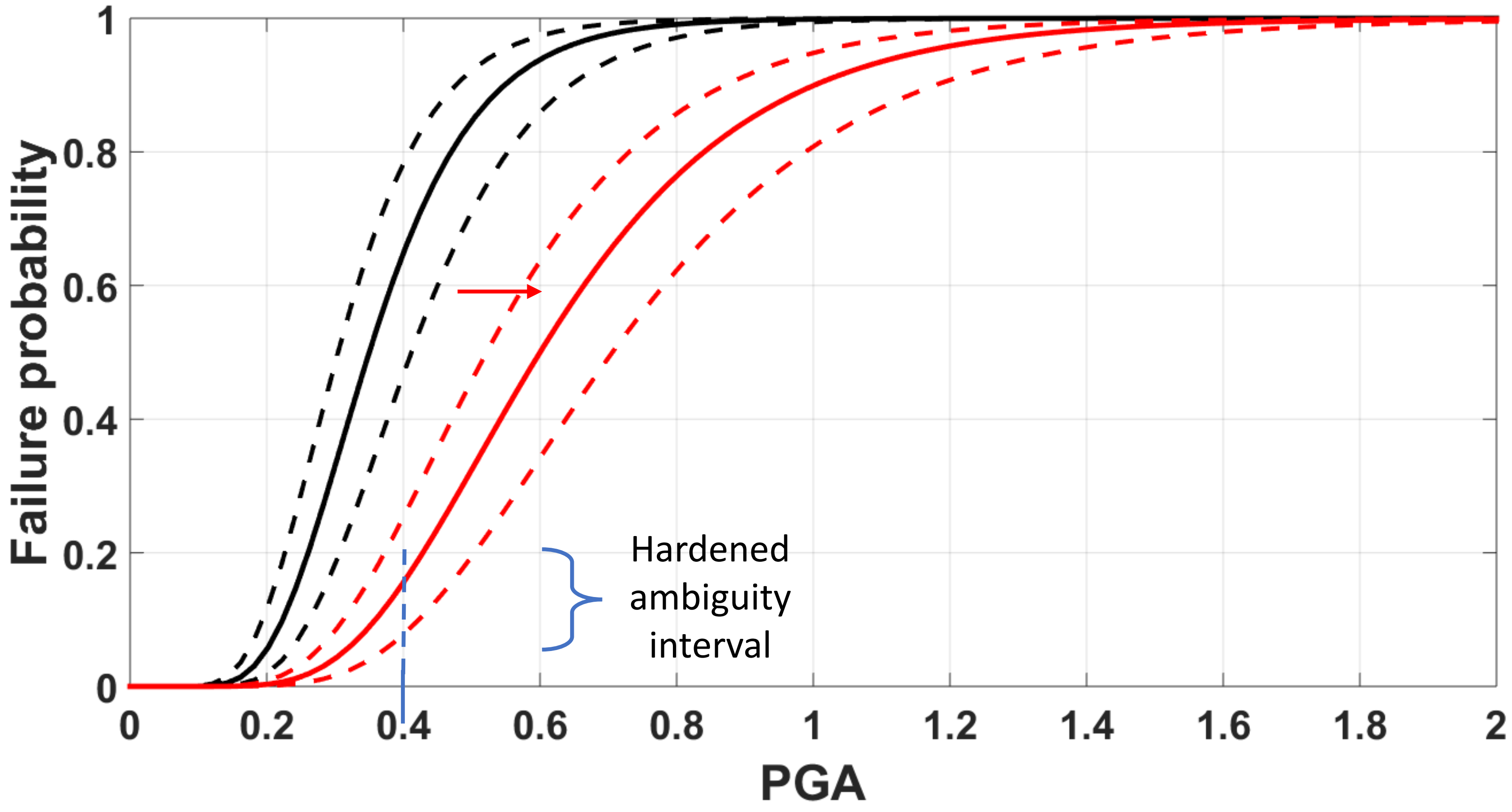




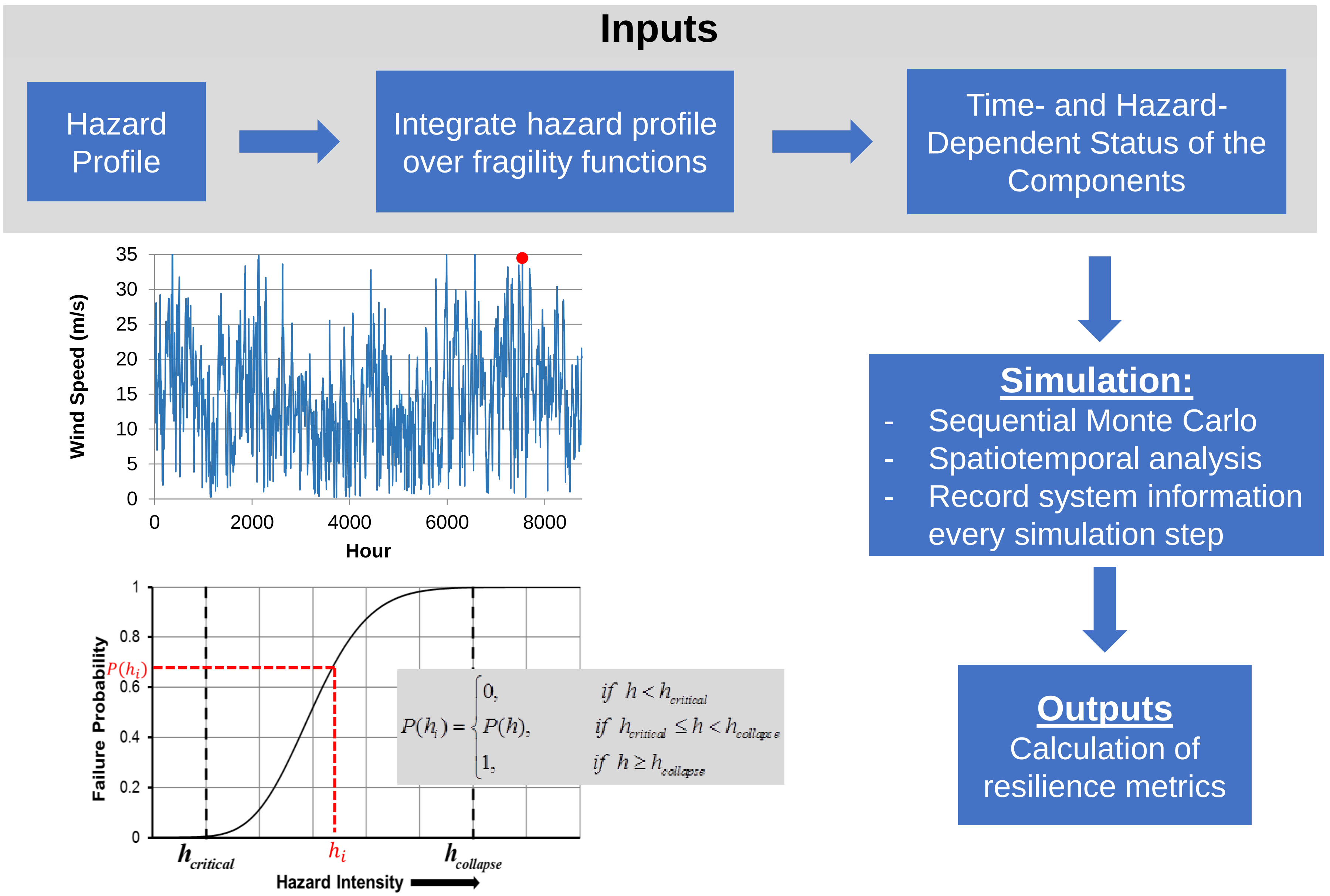


Decision-dependent ambiguity sets

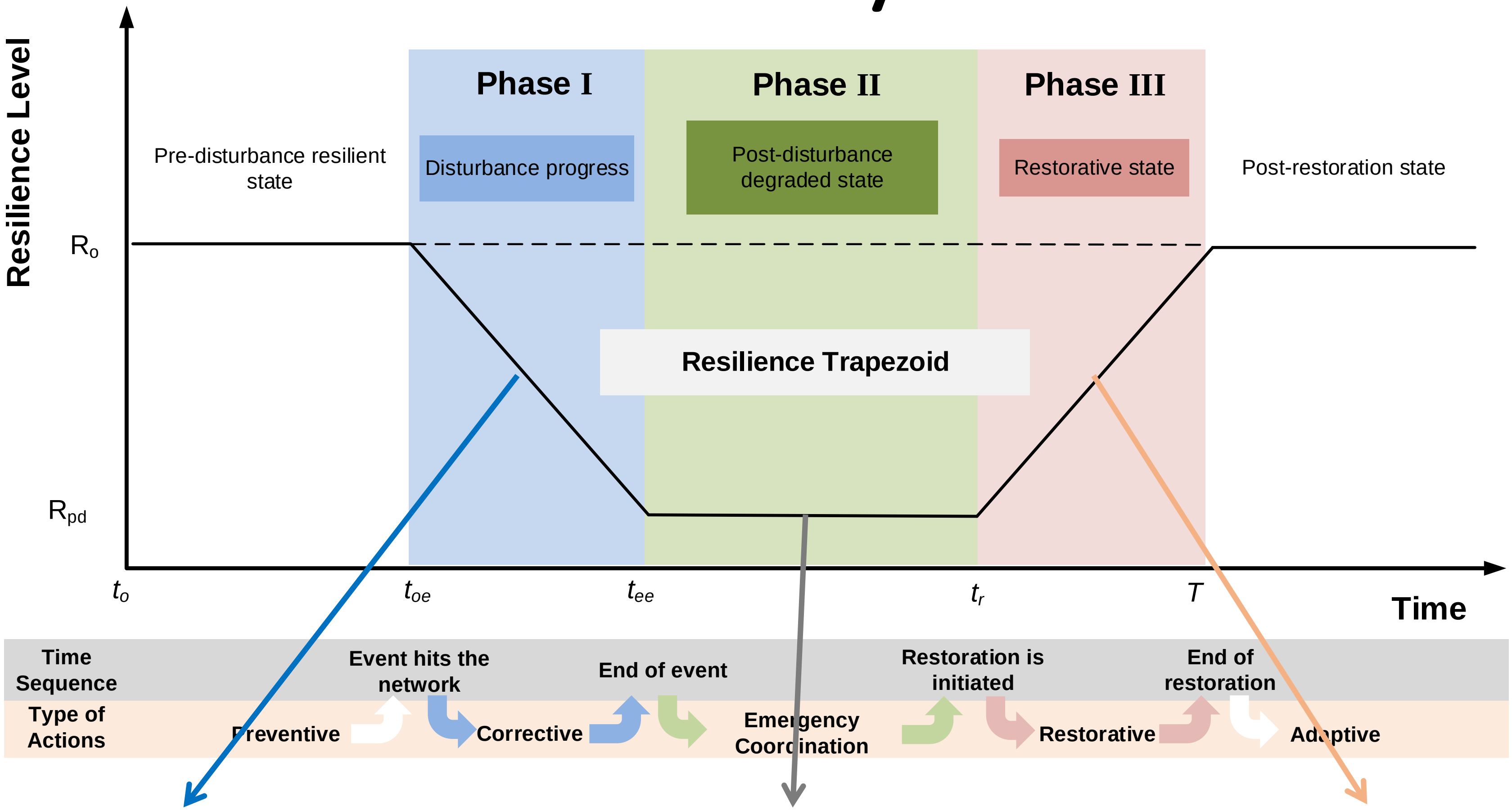
- Fragility curves / failure probabilities are decision dependent
- Ambiguity intervals can be used utilizing lower- and upper-bound fragility curves



D. Alvarado, R. Moreno, A. Street. M. Panteli, P. Mancarella, and G. Strbac, "Co-Optimizing Substation Hardening and Transmission Expansion Against Earthquakes: A Decision-Dependent Probability Approach", Accepted to Appear in *IEEE Transactions on Power Systems*


Inputs
Hazard Profile
Integrate hazard profile over fragility functions
Time- and Hazard-Dependent Status of the Components
Wind Speed (m/s)
Hour
35
30
25
20
15
10
5
0
0
2000
4000
6000
8000
Failure Probability
1
0.8
0.6
0.4
0.2
0
$P(h_i)$
$h_{critical}$
h_i
$h_{collapse}$
Hazard Intensity
$P(h_i) = \begin{cases} 0, & \text{if } h < h_{critical} \\ P(h), & \text{if } h_{critical} \le h < h_{collapse} \\ 1, & \text{if } h \ge h_{collapse} \end{cases}$
Simulation:
- Sequential Monte Carlo
- Spatiotemporal analysis
- Record system information every simulation step
Outputs
Calculation of resilience metrics

Resilience Trapezoid and FLEP Resilience Metric System



how **f**ast resilience declines?
how **l**ow resilience drops?

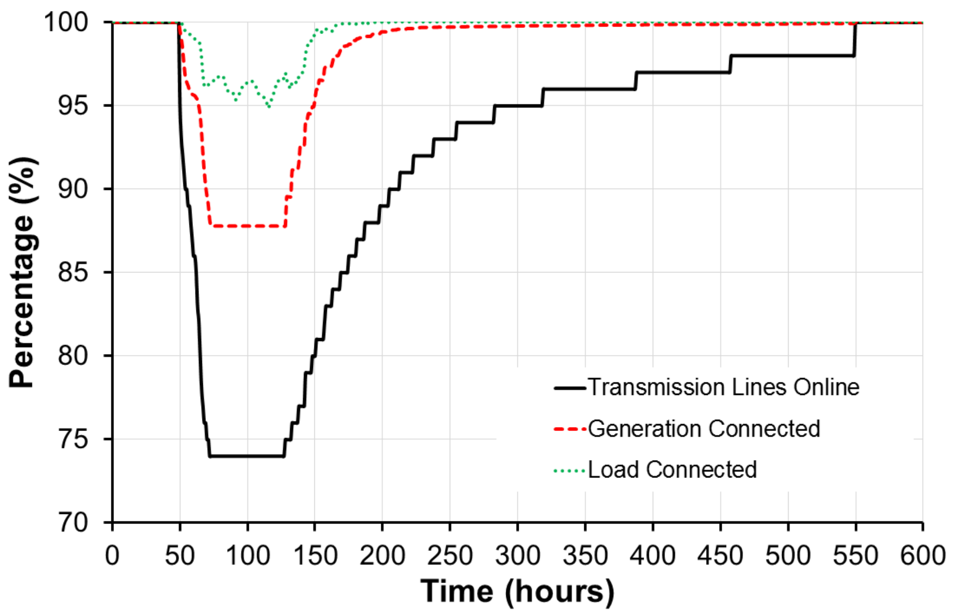
how **e**xtensive is this state?

how **p**romptly does the network recover?

M. Panteli, P. Mancarella, D. N. Trakas, E. Kyriakides, and N. D. Hatziargyriou, "Metrics and Quantification of Operational and Infrastructure Resilience in Power Systems", IEEE Transactions on Power Systems, vol. 32, no. 6, November 2017

Illustrative Example

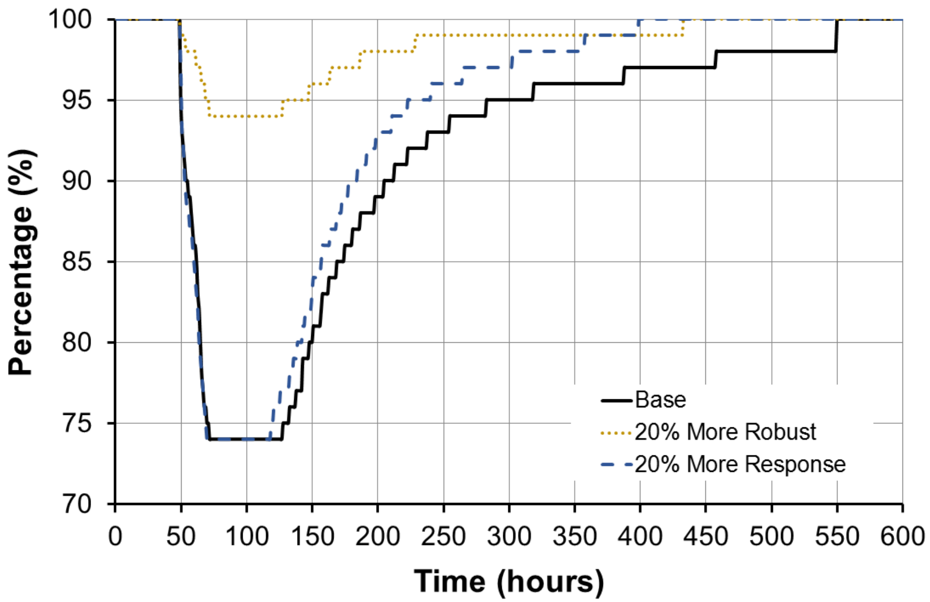
Time-dependent resilience indicators (base case study)



Resilience Metric	Resilience Indicator		
	Transmission Lines	Generation Connected	Load Connected
F	-1.083 (% of Lines tripped/h)	-0.521 (% of MW lost/h)	-0.249 (% of MW lost/h)
L	26 (% of Lines tripped)	12.5 (% of MW lost)	5.99 (% of MW lost)
E	53 (hrs)	54 (hrs)	57 (hrs)
P	0.058 (% of Lines restored/h)	0.033 (MW restored/h)	0.072 (MW restored/h)

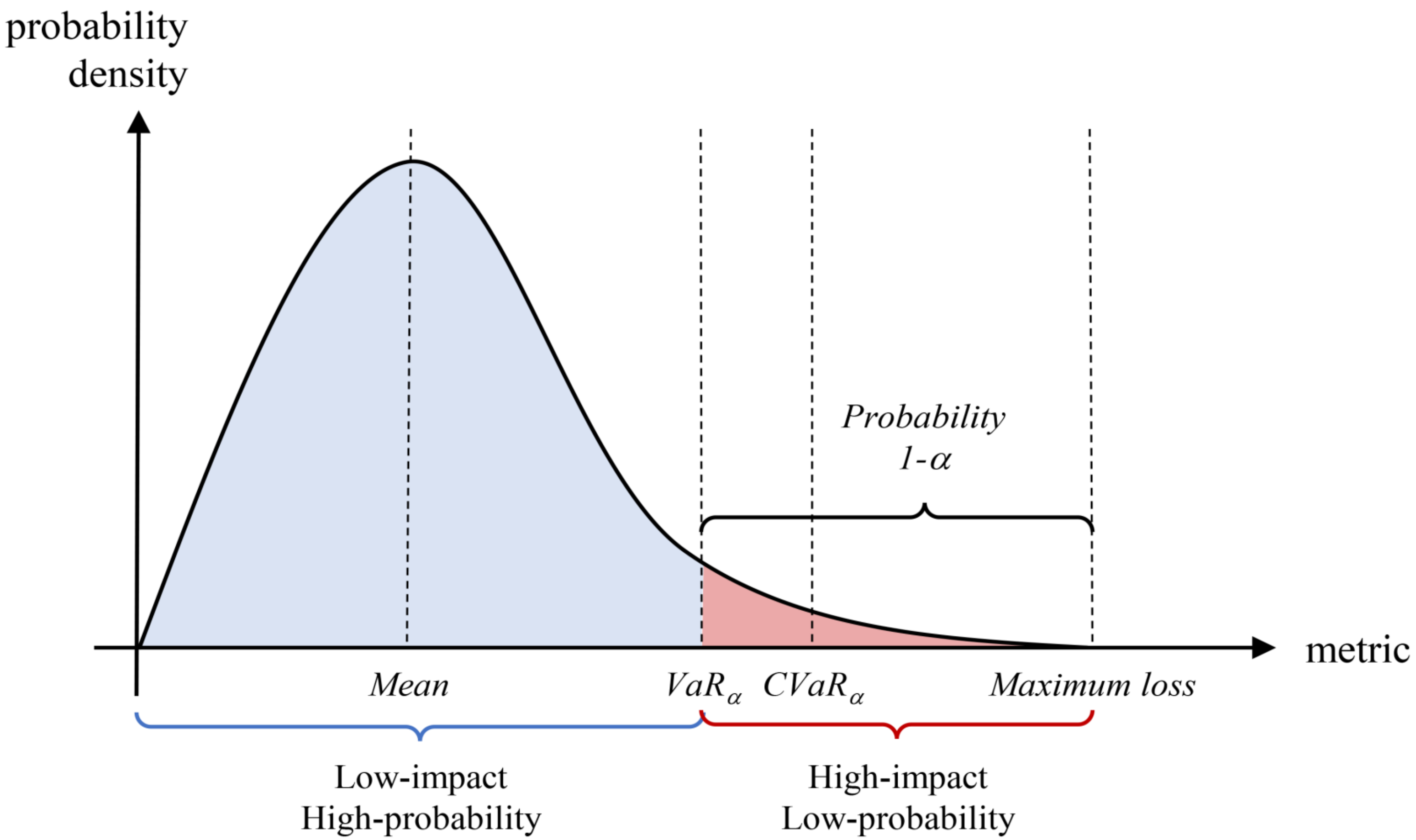
Illustrative Example – Varying Robustness and Responsiveness

Transmission lines online (base, robust and responsive case studies)



Resilience Metric	Resilience Indicator		
	Base	20% More Robust	20% More Response
F	-1.083 (% of Lines tripped/hr)	-0.25 (% of Lines tripped/hr)	-1.083 (% of Lines tripped/hr)
L	26 (% of Lines tripped)	6 (% of Lines tripped)	26 (% of Lines tripped)
E	53 (hrs)	53 (hrs)	44 (hrs)
P	0.058 (% of Lines restored/hr)	0.019 (% of Lines restored/hr)	0.092 (% of Lines restored/hr)

Average Vs Conditional Values



Value at Risk

$$VaR_\alpha(x) = min\{x \mid f_x(z) \geq \alpha\}$$

Conditional Value at Risk

$$\mathrm{CVaR}_\alpha(x) = E[x \mid x \geq VaR_\alpha(x)]$$

Challenges in Cascading Analysis for Resilience Purposes

- Resilience analysis to extreme events requires cascading fault models that reliably converge and thus provide meaningful results even for large contingencies.
- Models often have to be applied to large datasets and networks, and therefore need to be computationally fast.
- DC-based models are hence frequently used in resilience studies.
- However, past outages have shown the significant role of voltage deviations and reactive power flows, such as during the 2003 blackout in the United States and Canada or the 2009 blackout in Brazil.

Challenges in Cascading Analysis for Resilience Purposes

A further issue with current cascading fault models is a lack of a standardized validation procedure, which has been recognized by the IEEE PES working group on cascading failures.

AC Cascading Failure Model (AC-CFM)

- Specifically designed for resilience analysis by integrating seamlessly into established resilience metric frameworks
- Stable for very large contingencies or extreme conditions by efficiently addressing convergence issues
- Validated following the approaches by the IEEE PES working group on cascading failures
- Compared to other AC-based models, explicitly incorporating dynamic phenomena such as voltage and frequency protection mechanisms in a static representation
- Computationally faster than dynamic cascading models

M. Noebels, R. Preece and M. Panteli, "AC Cascading Failure Model for Resilience Analysis in Power Networks," in IEEE Systems Journal, Early Access, December 2020

AC Cascading Failure Model (AC-CFM)

Inputs

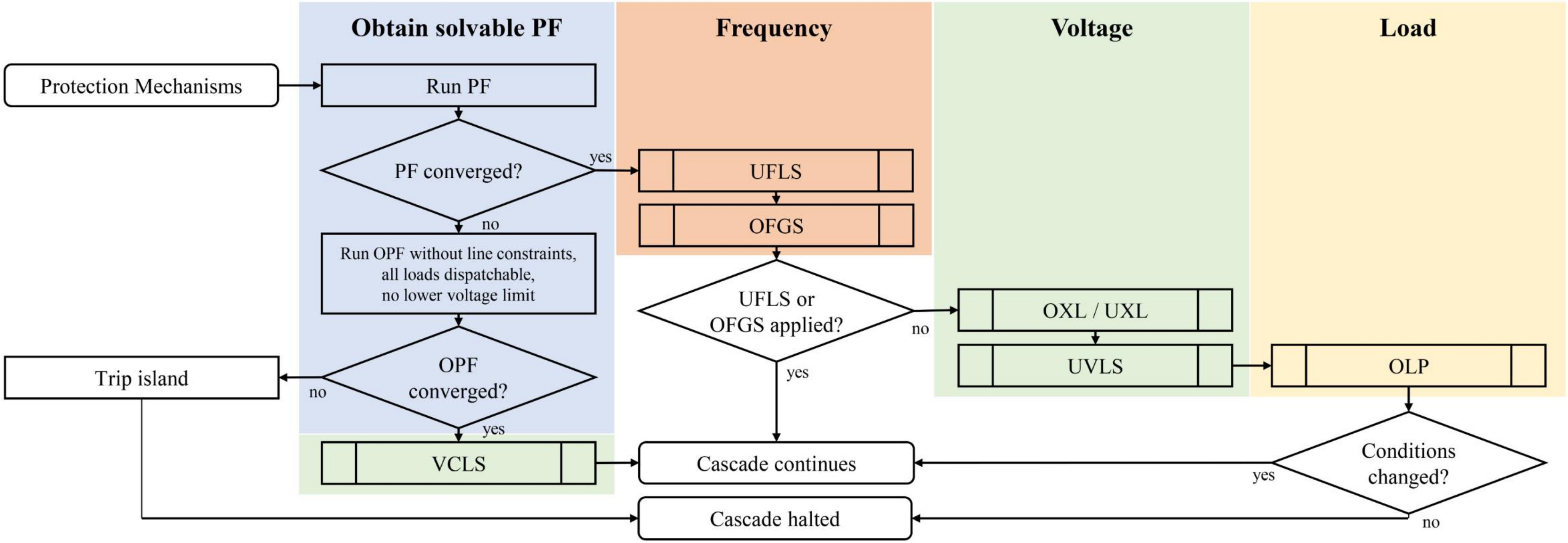
- Network topology (as Matpower case struct)
  - Buses
  - Lines
  - Generators
  - Loads
  - Transformers
  - Shunt devices
- Initial contingency
  - Event-based
  - Probability-based

AC-CFM

Outputs

- Network topology after cascade
- Cascade propagation
  - Over generation
  - Over time (using external utility data)
- Protection mechanisms
- Causalities and component failure rates
- Can be easily linked with FLEP metric framework

Protection Mechanisms in AC-CFM



VCLS = Voltage Collapse Load Shedding
UFLS = Under-Frequency Load shedding
OFGS = Over-Frequency Generation Shedding

OXL = Over Excitation Limiters
UXL = Under Excitation Limiters
OLP = Over-Load Protection

Model Validation

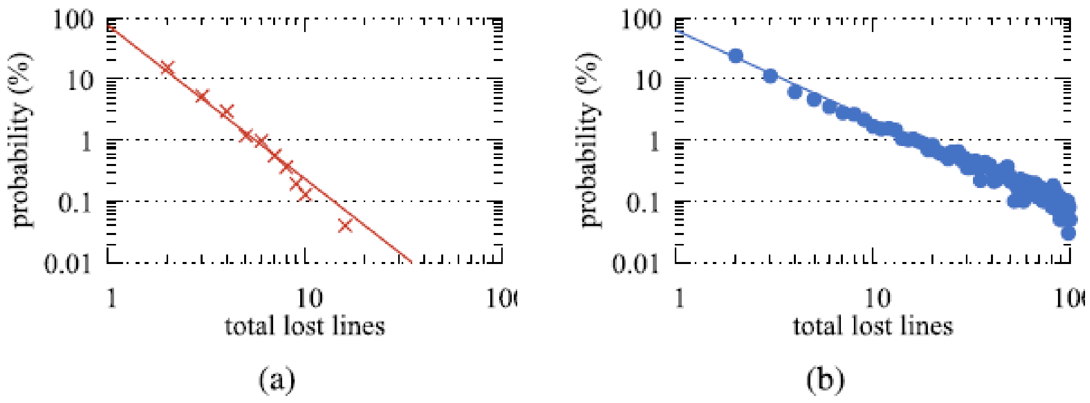


Fig. 10. Probability distribution of total lost lines. Dashed and solid lines show the Zipf distributions obtained from fitting. (a) Historical [12]. (b) AC-CFM.

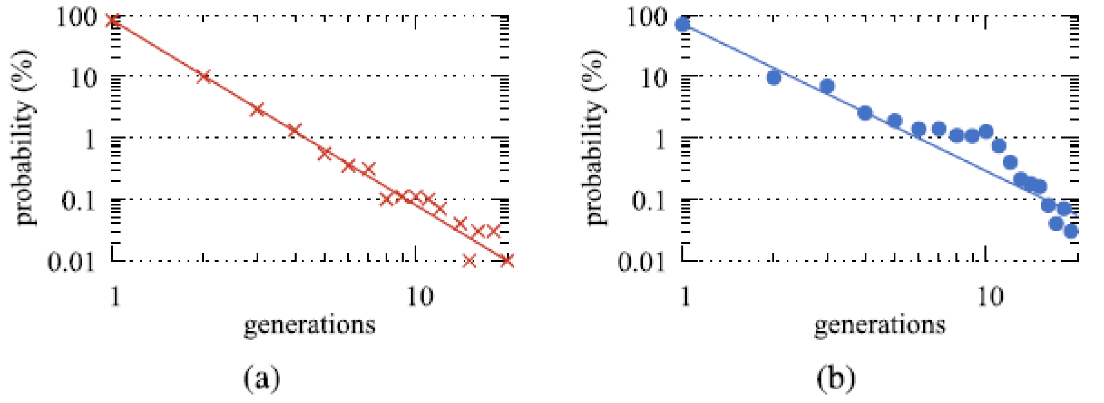


Fig. 11. Probability distribution of generations. Dashed and solid lines show the Zipf distributions obtained from fitting. (a) Historical [45]. (b) AC-CFM.

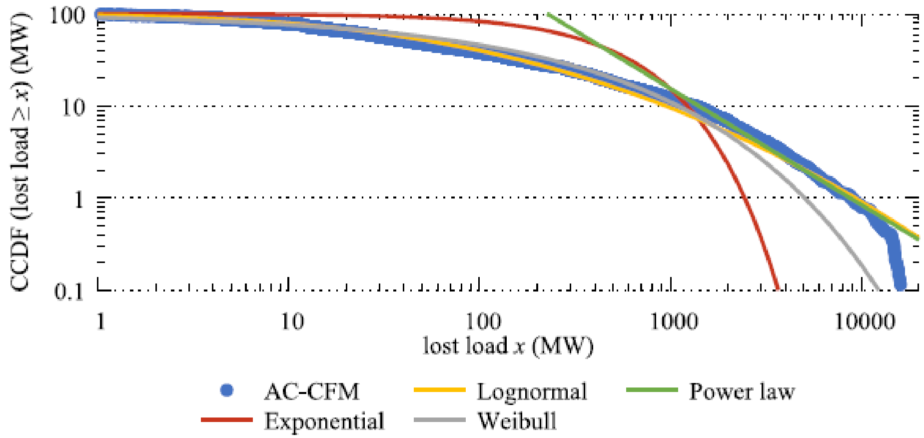


Fig. 14. CCDF of lost load as calculated by AC-CFM, including only contingencies that led to outages, and fitted probability distributions.

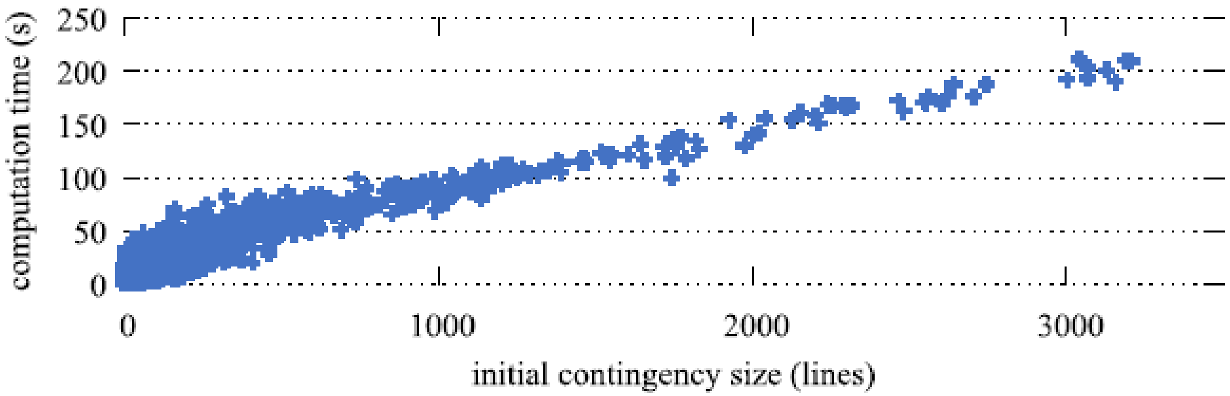
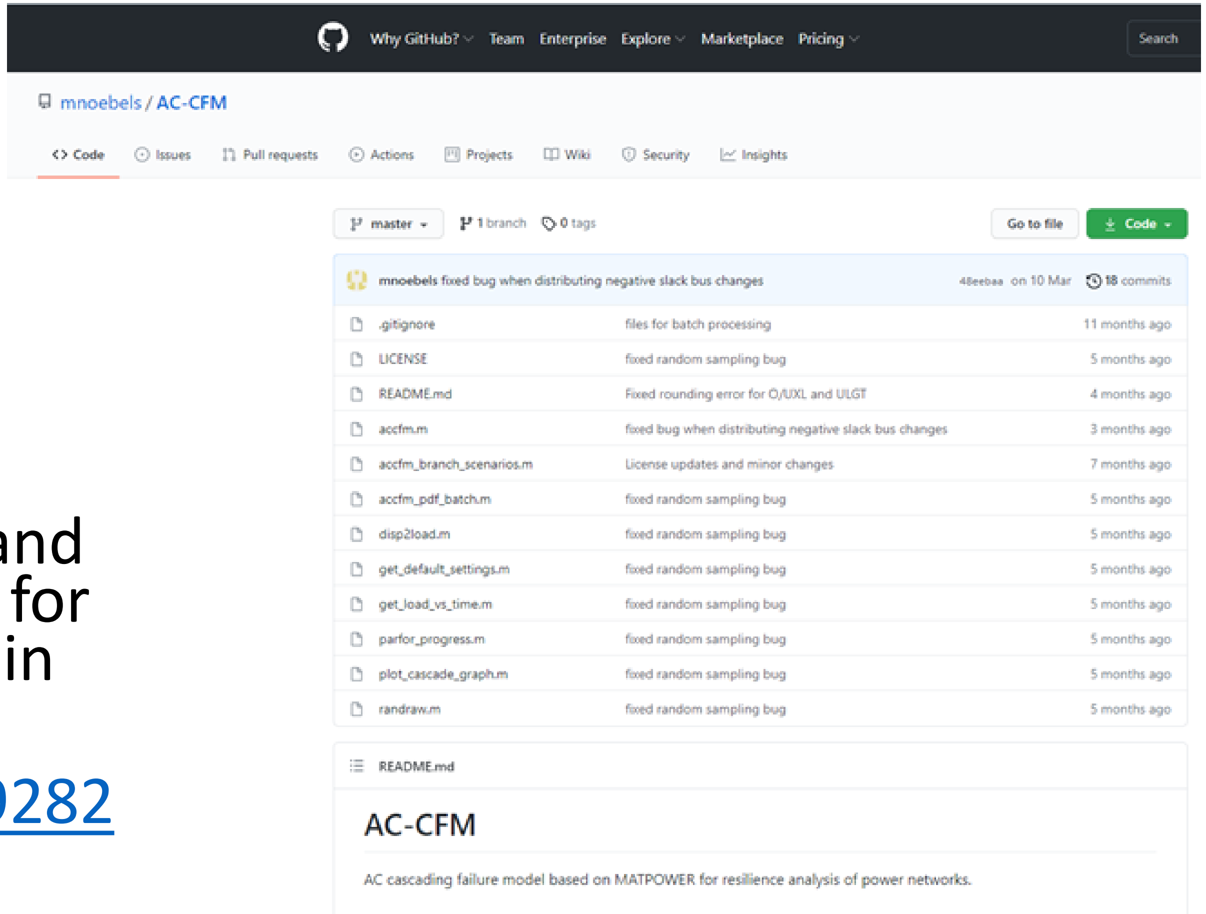


Fig. 15. Computation time analysis.

Code available via Github:

https://github.com/mnoebels/AC-CFM

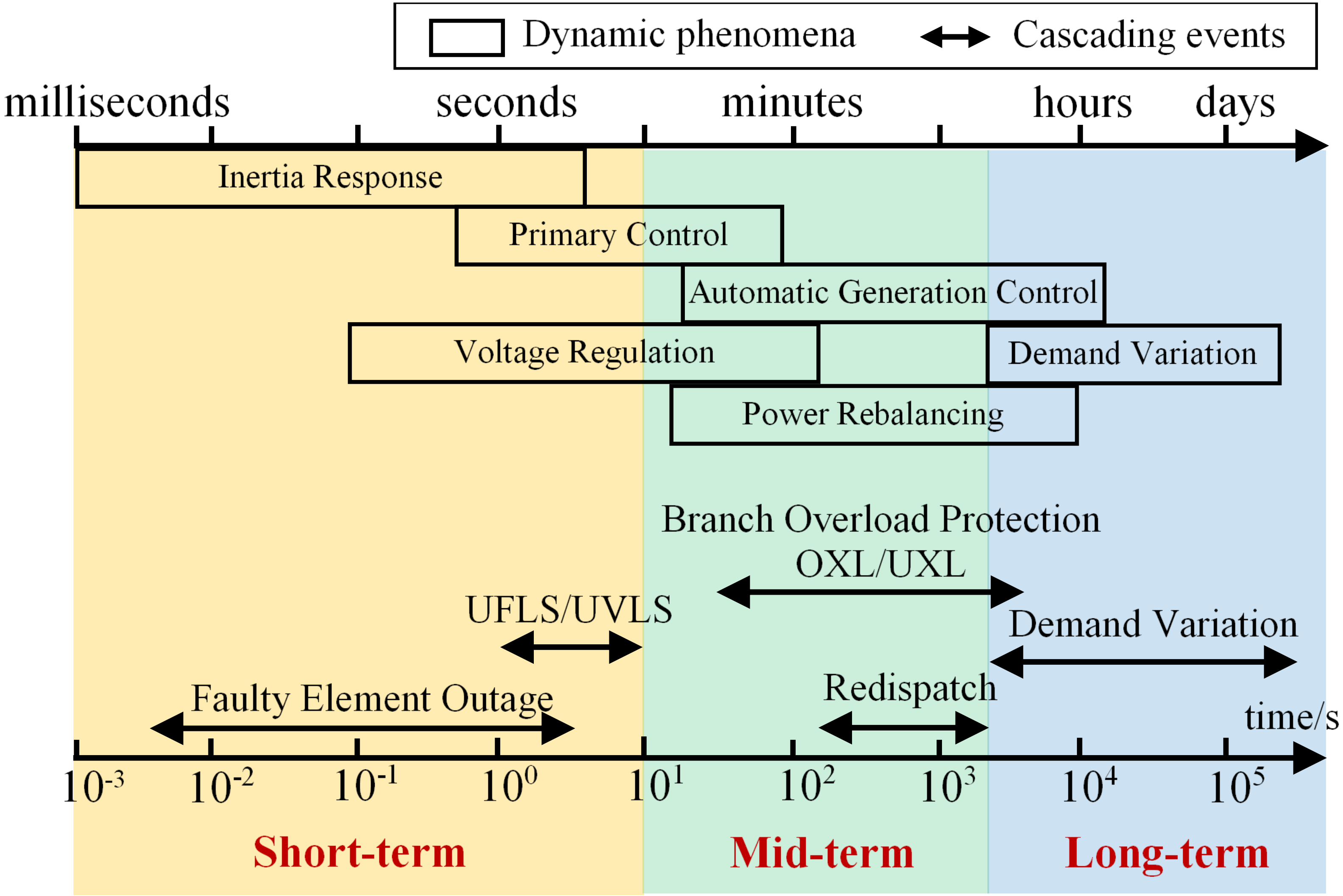
- Full, documented source code
- Getting started
- Installation prerequisites
- Usage example
- Troubleshooting



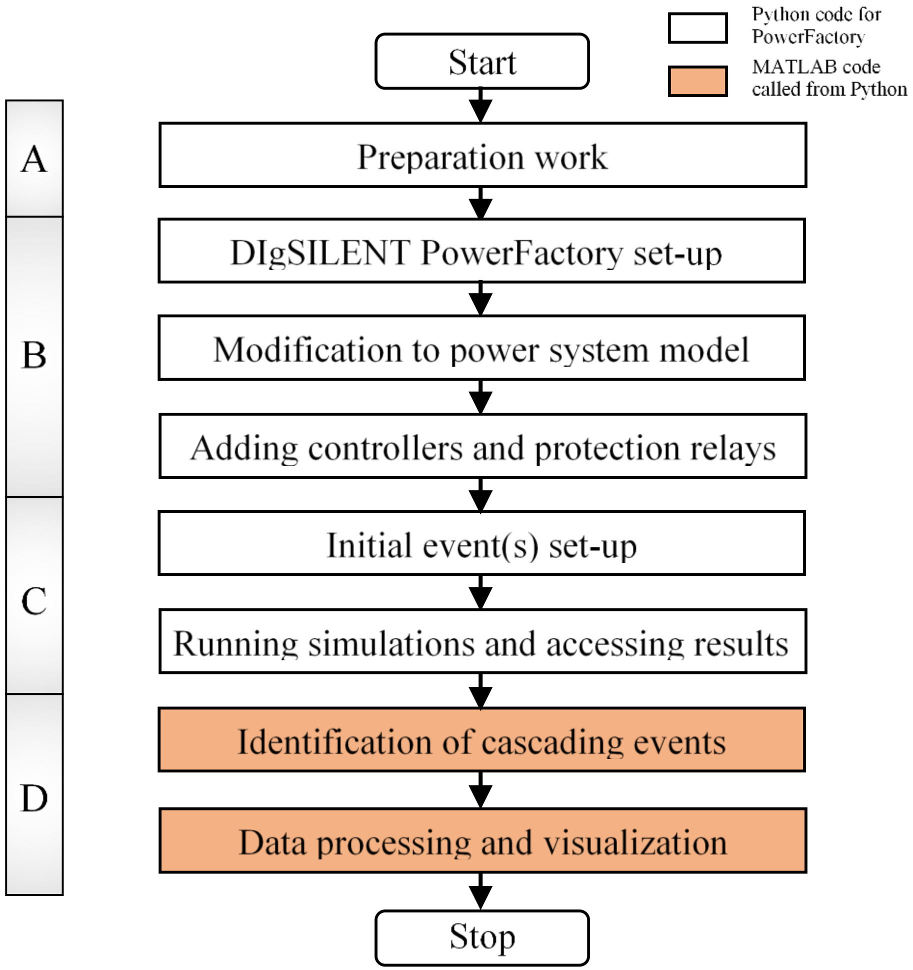
Further reading: M. Noebels, R. Preece and M. Panteli, "AC Cascading Failure Model for Resilience Analysis in Power Networks," in IEEE Systems Journal (open access)

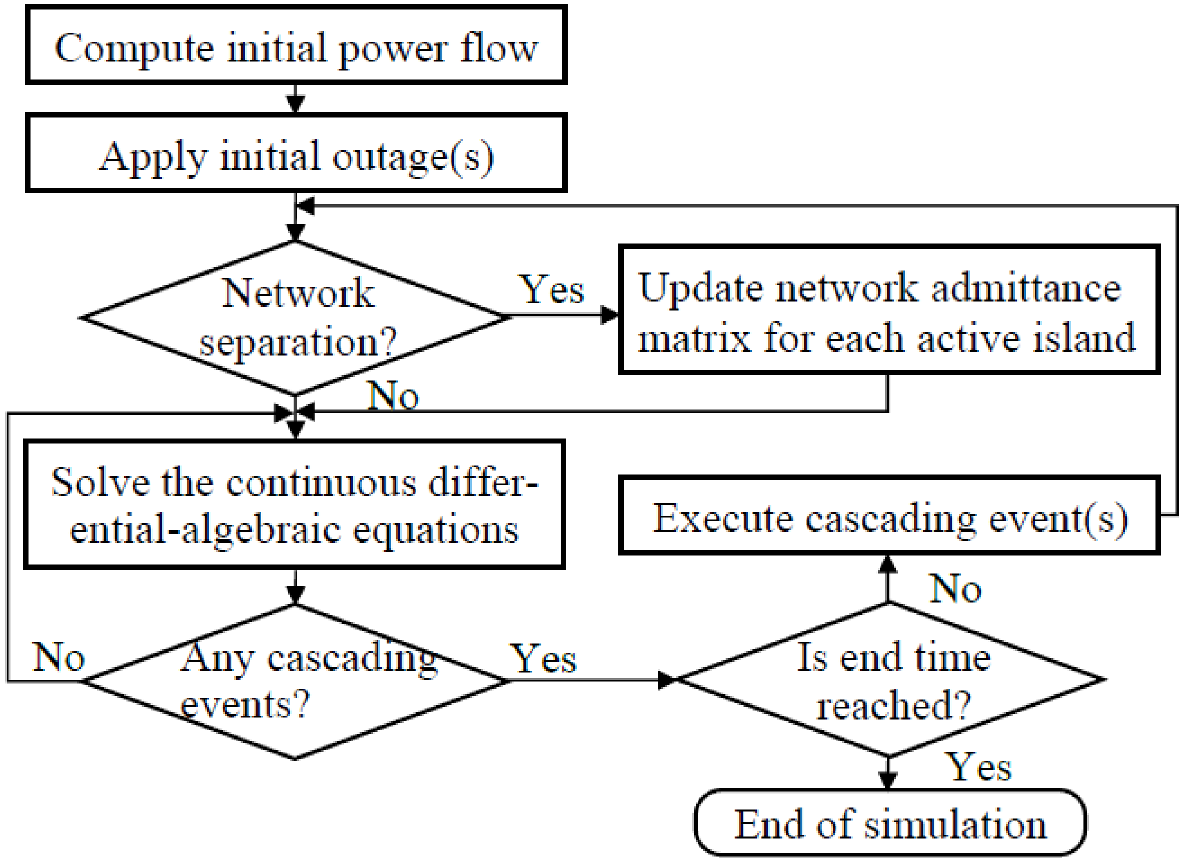
https://ieeexplore.ieee.org/document/9282067

Dynamic Cascading Modelling



Dynamic Cascading Modelling

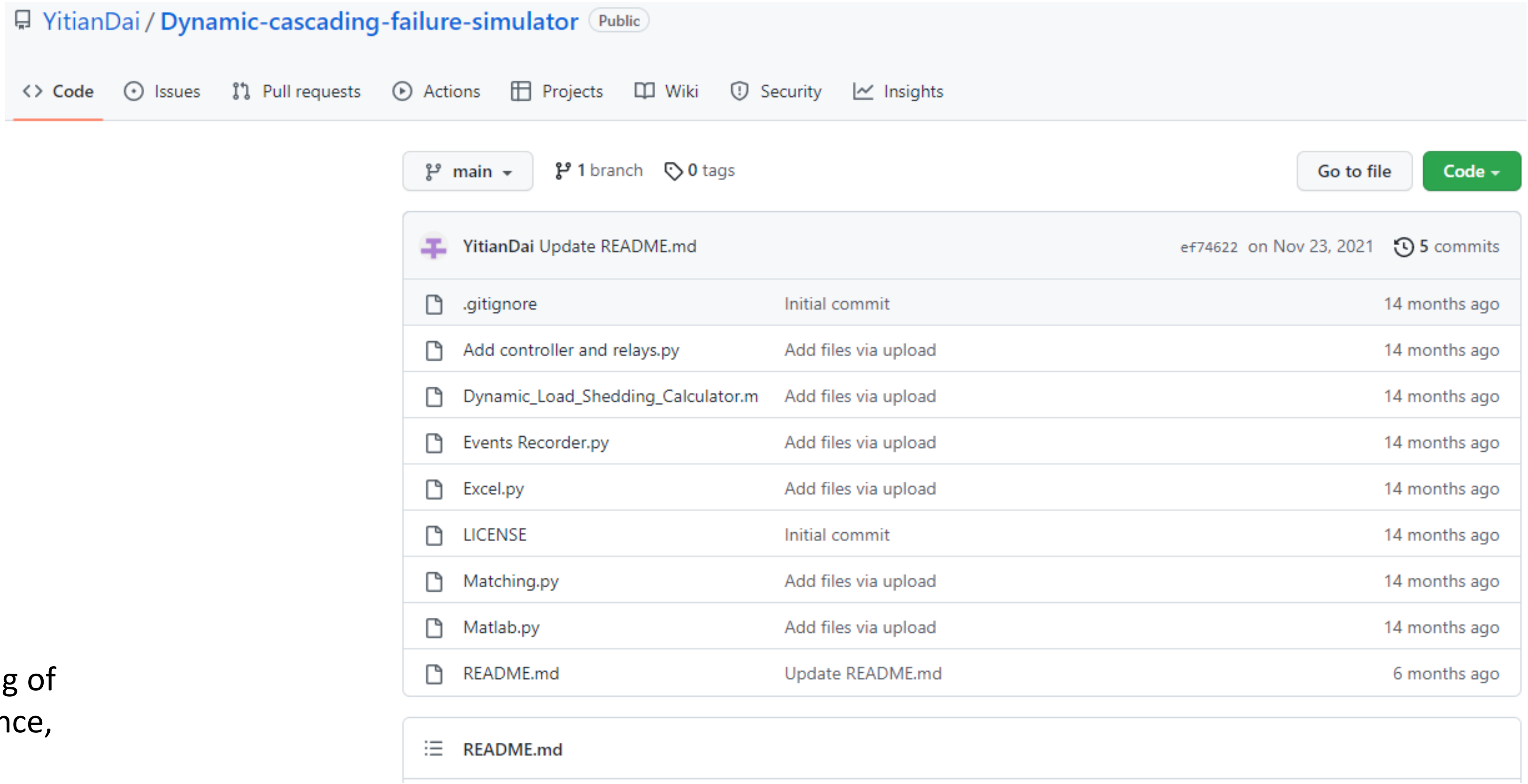




Code available via Github:

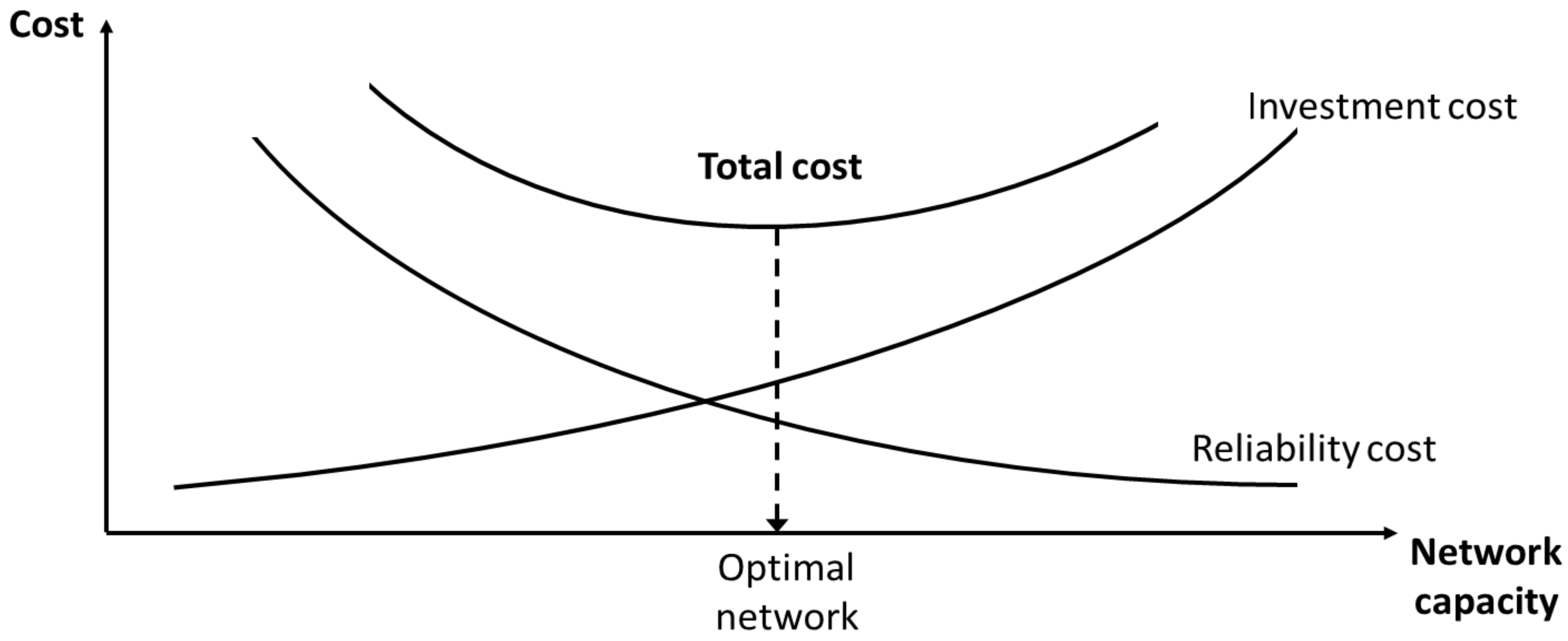
https://github.com/YitianDai/Dynamic-cascading-failure-simulator

- Full, documented source code
- Getting started
- Installation prerequisites
- Usage example
- Troubleshooting



Y. Dai, M. Panteli, and R. Preece, “Python Scripting for DIgSILENT PowerFactory: Enhancing Dynamic Modelling of Cascading Failures”, 2021 IEEE PES PowerTech Conference, June 2021

Problem of the risk-neutral approach



Problem of the risk-neutral approach

Option 1: a consumer pays **$90** for an electricity service that hardly ever fails and, when it does, small amounts of ENS are curtailed, totalizing an associated expected cost of ENS equal to **$10**

Option 2: a consumer pays **$50** for an electricity service that fails more often and with larger amounts of ENS each time, totalizing an associated expected cost of ENS equal to **$50**

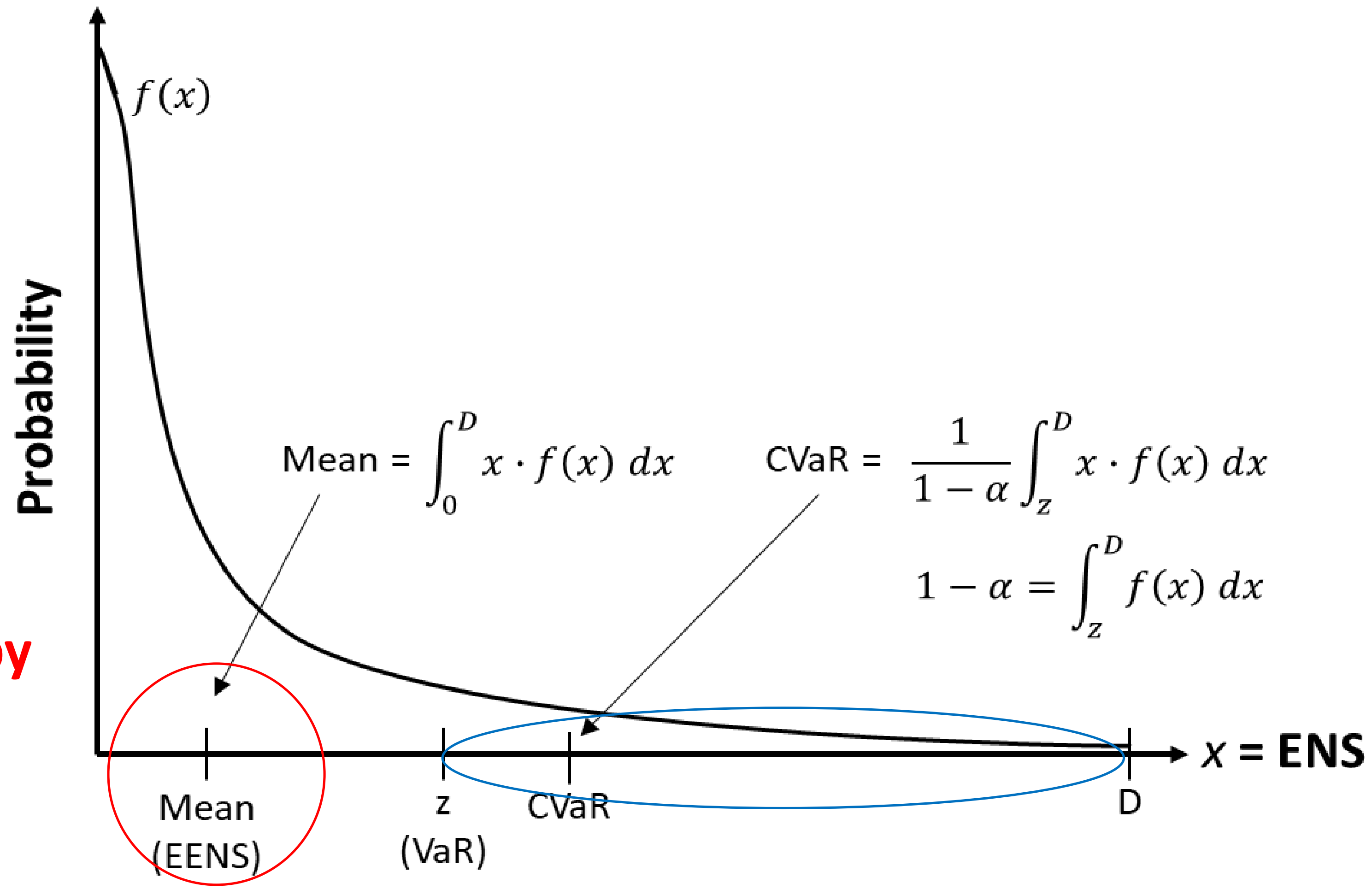
The consumer is said to be:

- Risk neutral: if he is indifferent between these two options
- Risk averse: if he prefers the first option over the second one
- Risk seeking: if he prefers the second option over the first one

Empirical evidence suggest we prefer option 1!

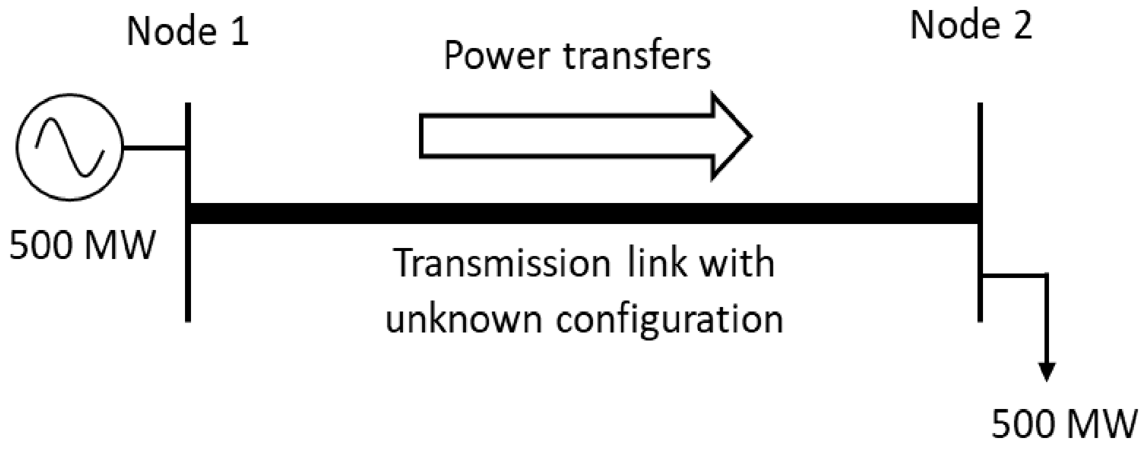
Moving from average to risk indicators:
Risk-averse approach

Mainly affected by credible outages



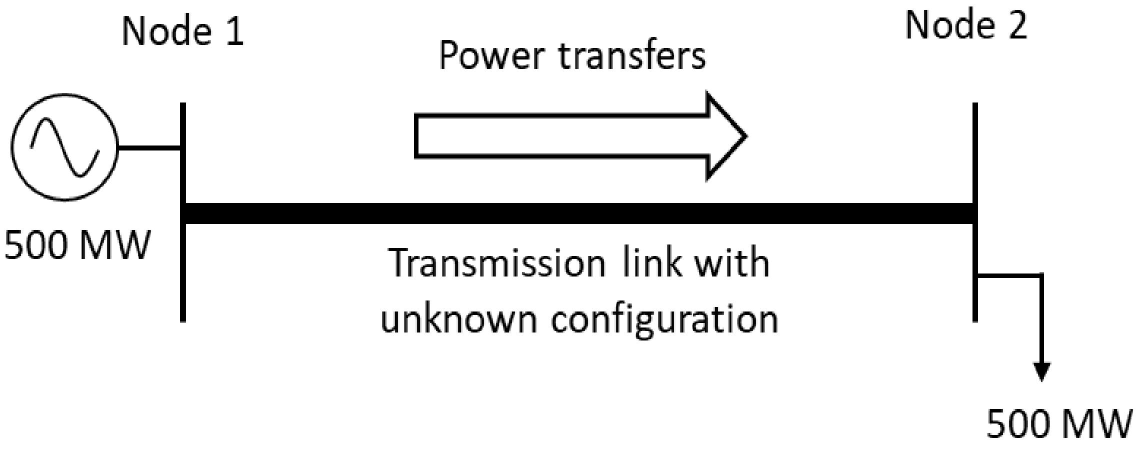
-Natural hazards
-Catastrophic events
-Common mode failures

An illustrative example



Metric	N-0 base case	N-1	N-0 shorter repair time	N-0 underground

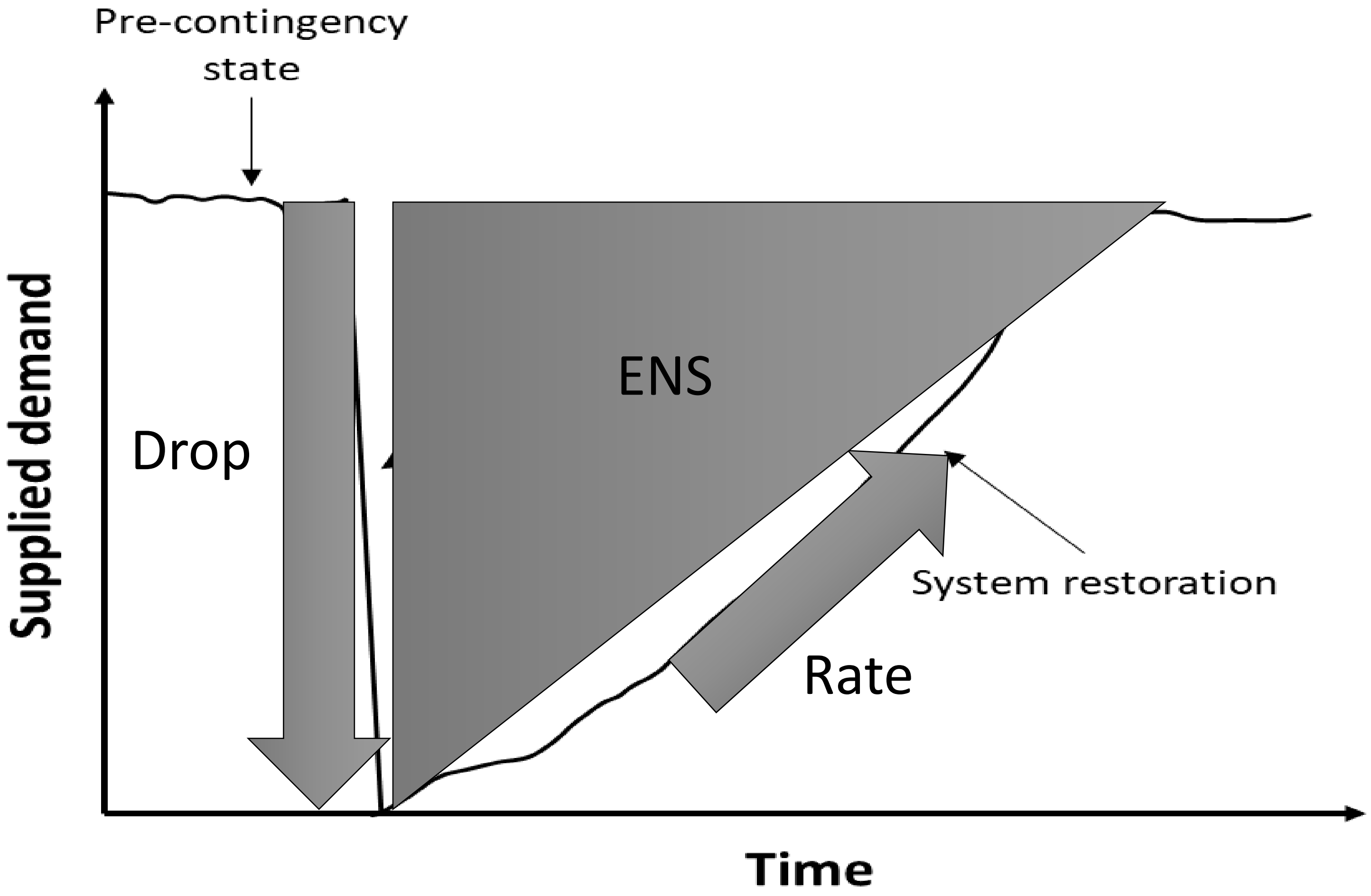
An illustrative example



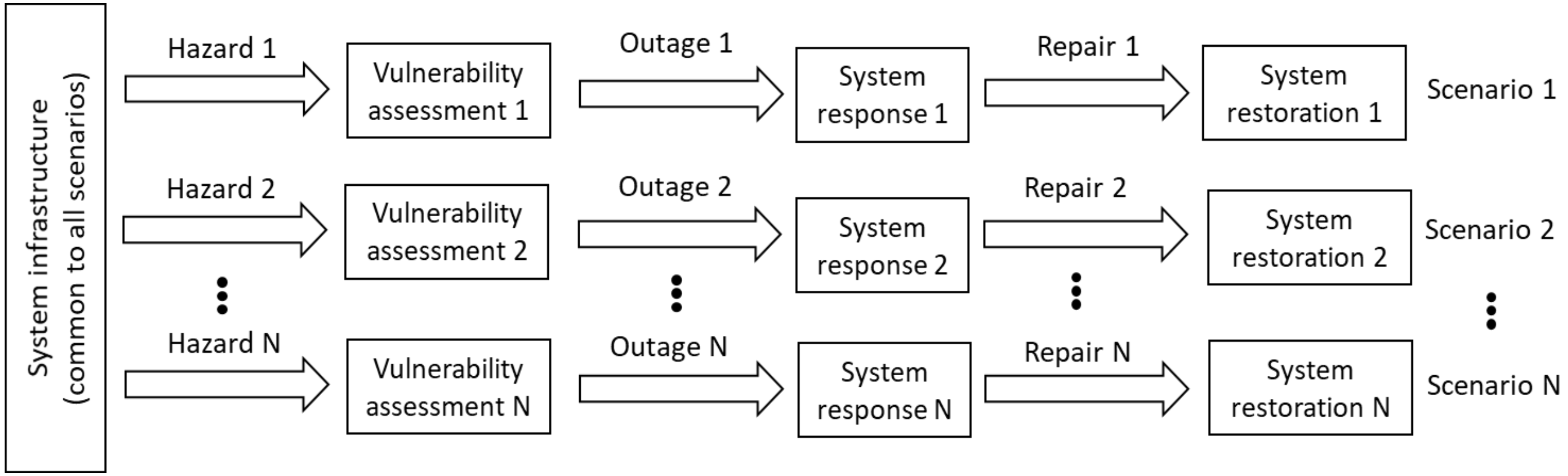
Metric	N-0 base case	N-1	N-0 shorter repair time	N-0 underground
VoLL x EENS [$]	538,532	38,464	470,506	280,428
VoLL x CVaR [$]	4,113,206,199	3,846,412,398	2,690,095,838	2,837,833,988

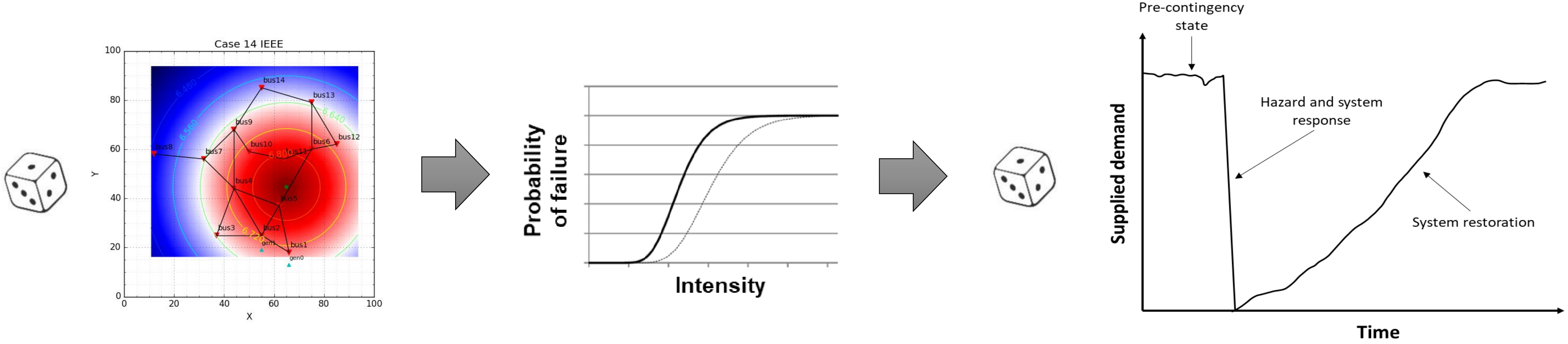
Reliable | Resilient | Compromise

From static to time domain modeling



Stochastic simulations





Mathematical program

Formulation:

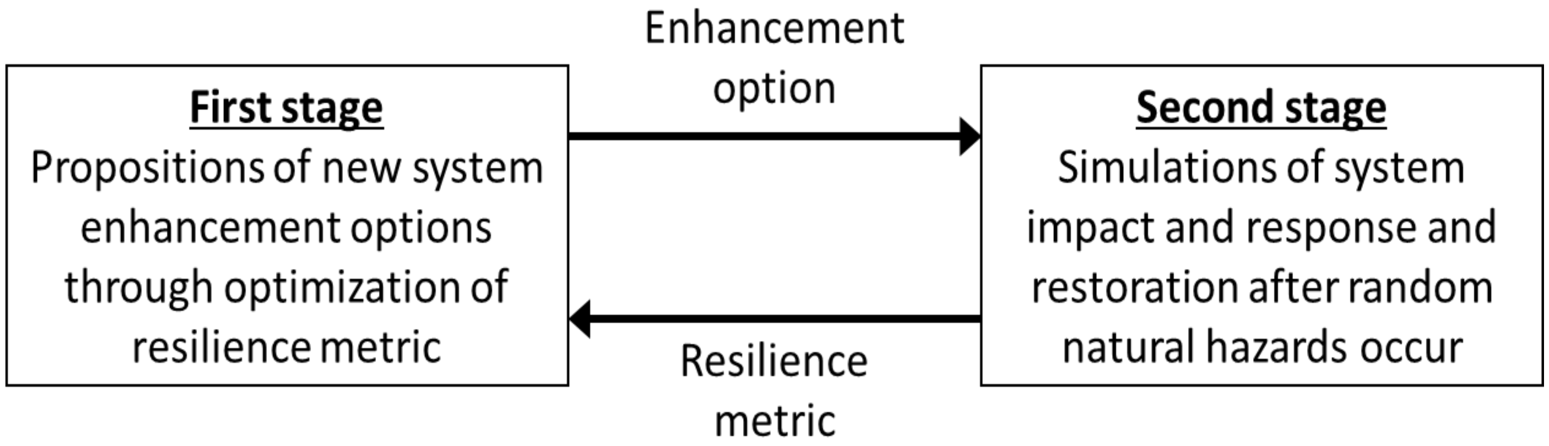
$$Min_x \left\{RiskMeasure\left(ResilienceMetric_s(x)\right)\right\}$$

$$s.t.$$

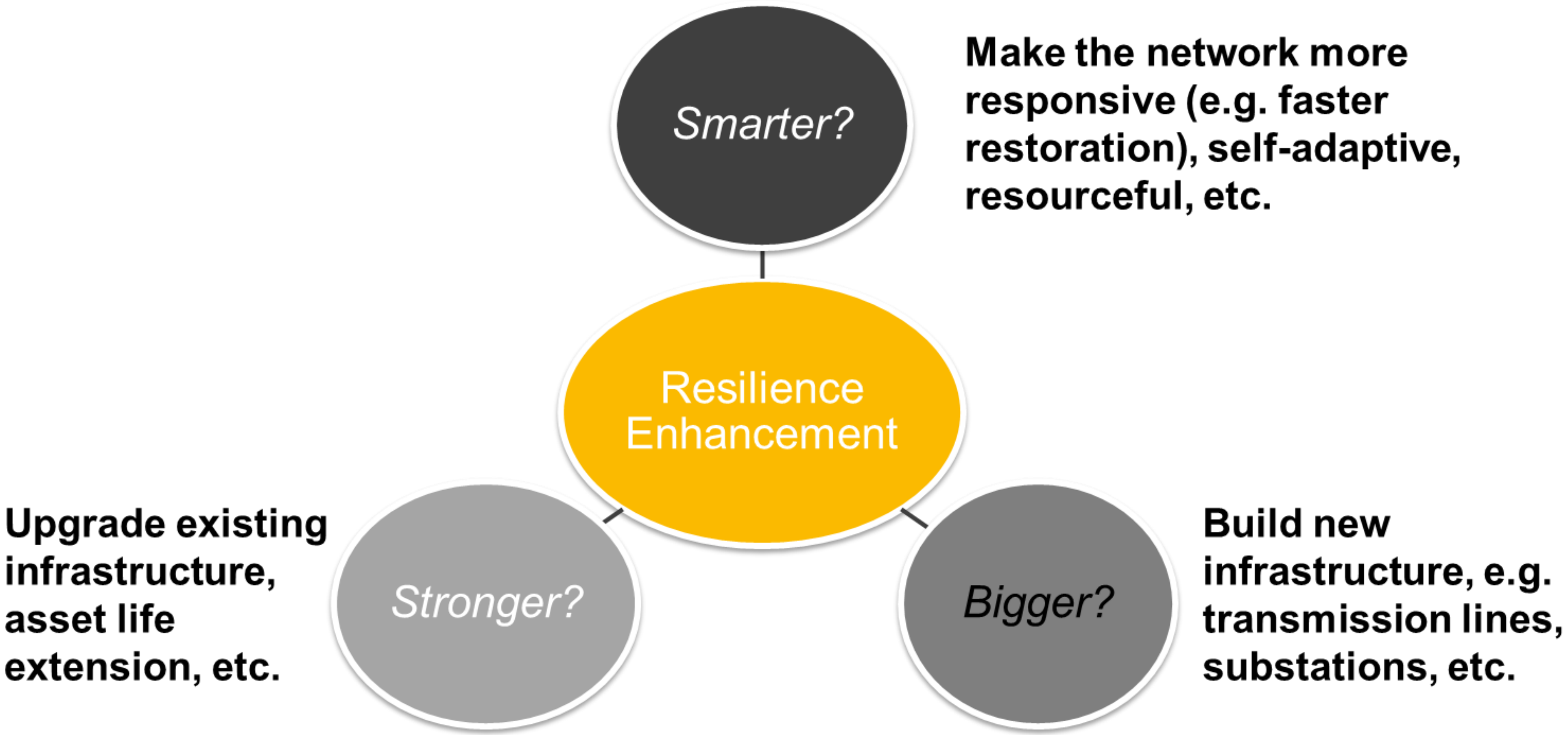
$$\sum_{i \in I} c_i \cdot x_i \leq budget$$

$$x_i \in \{0,1\} \quad \forall i \in I$$

OvS:



Resilience trilemma tackled through optimisation



Q&A

Coffee Break

Infrastructure planning and operation for flexible and adaptive energy systems

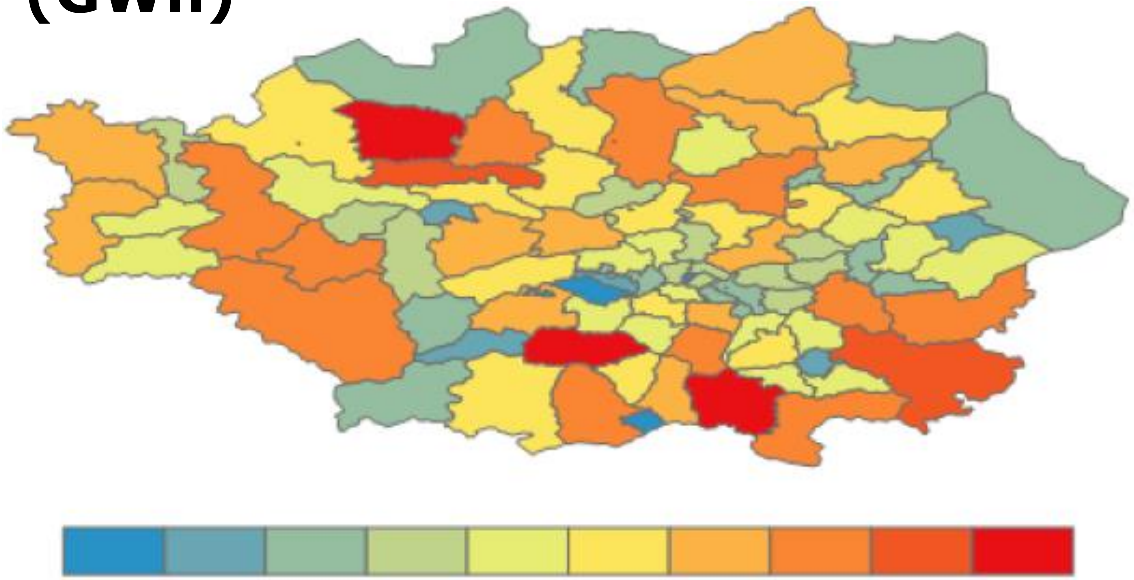
Uncertain Future Energy Scenarios

- The peak and shape of the future demand profiles will change based on improvements in energy efficiency and the adoption of low carbon technologies
- Demand models with high temporal and spatial resolution are required to inform studies that involve power network simulations
- The demand models should capture synergies between electrified heating and transports, multiple forms of storage and other technologies

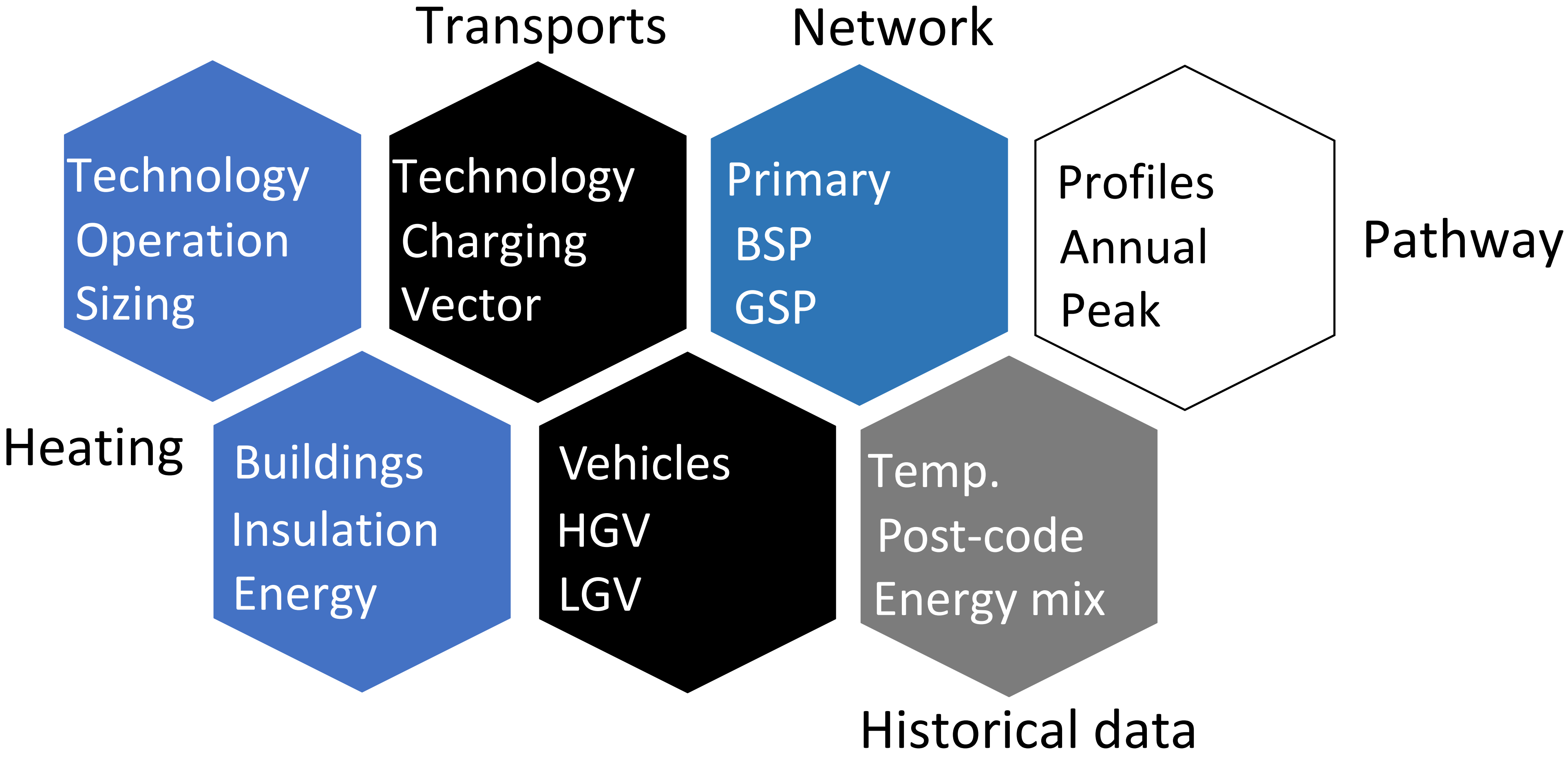
Collecting data with high spatial resolution

- Strong ongoing efforts to plan for a zero carbon future
- It is not only about electricity, we need a whole system perspective
- It is not enough to invest in low carbon technologies
  - The networks must have the capacity to integrate the technologies
  - Energy data with high spatial and temporal resolution is needed

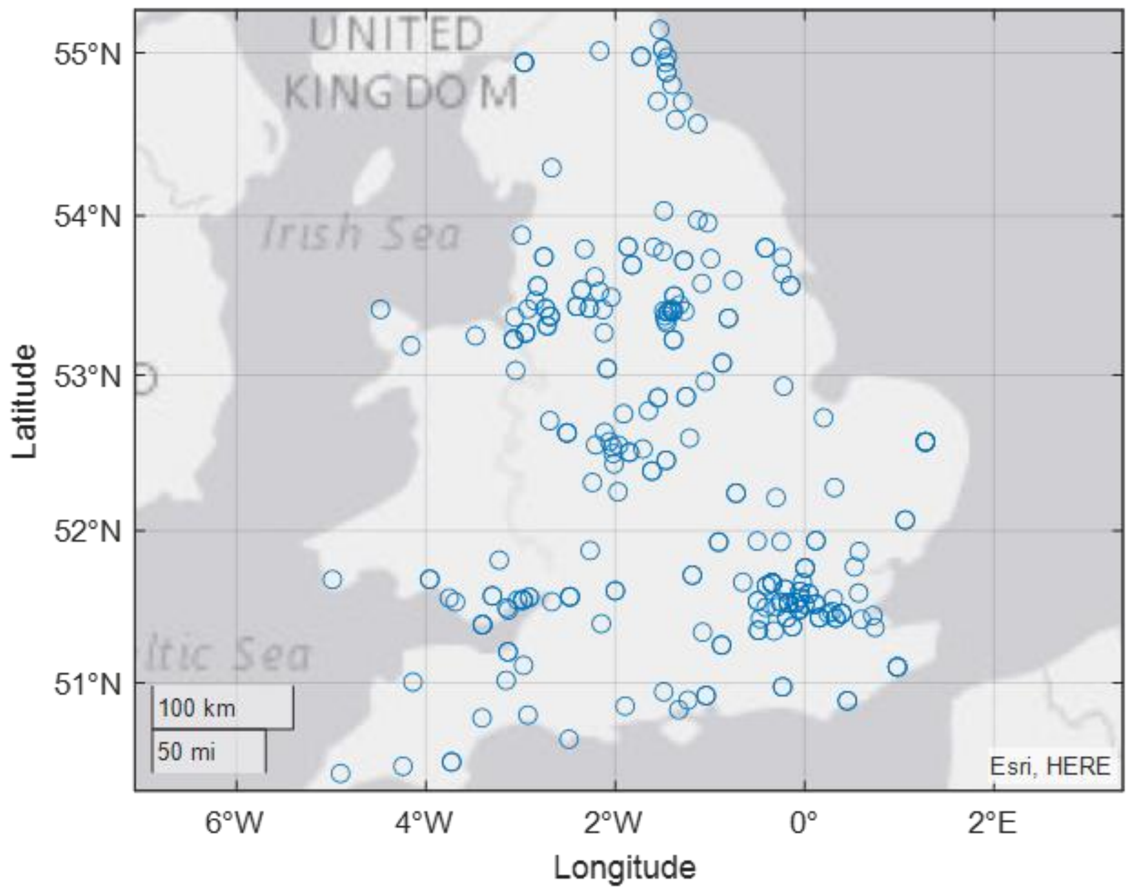
Domestic electricity consumption (GWh)

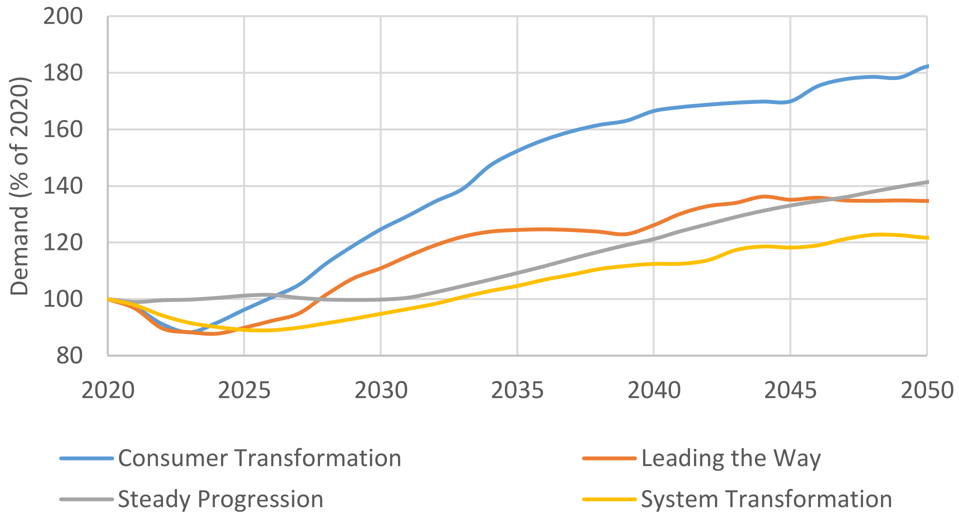


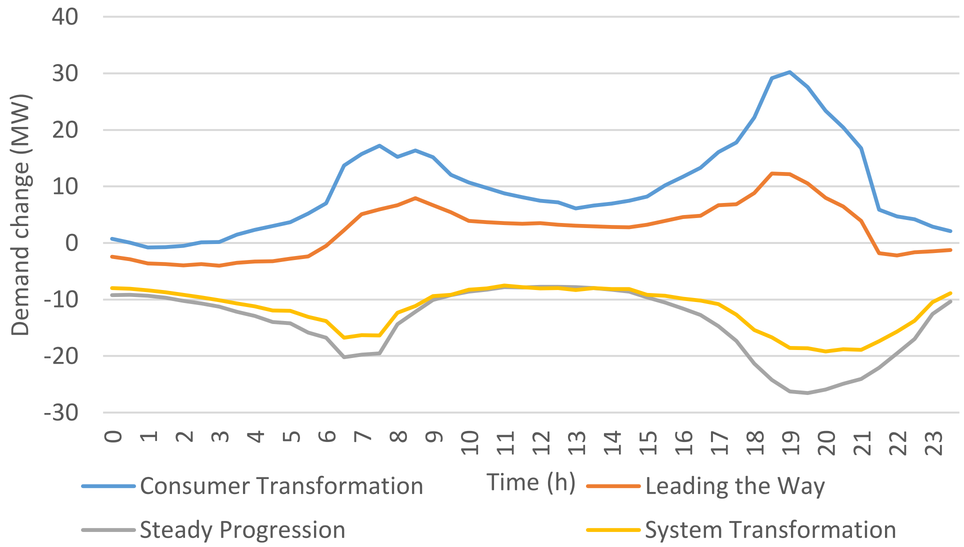
Methodology



Application to the GB system







Application – Bringing the Demand/MES and network models together

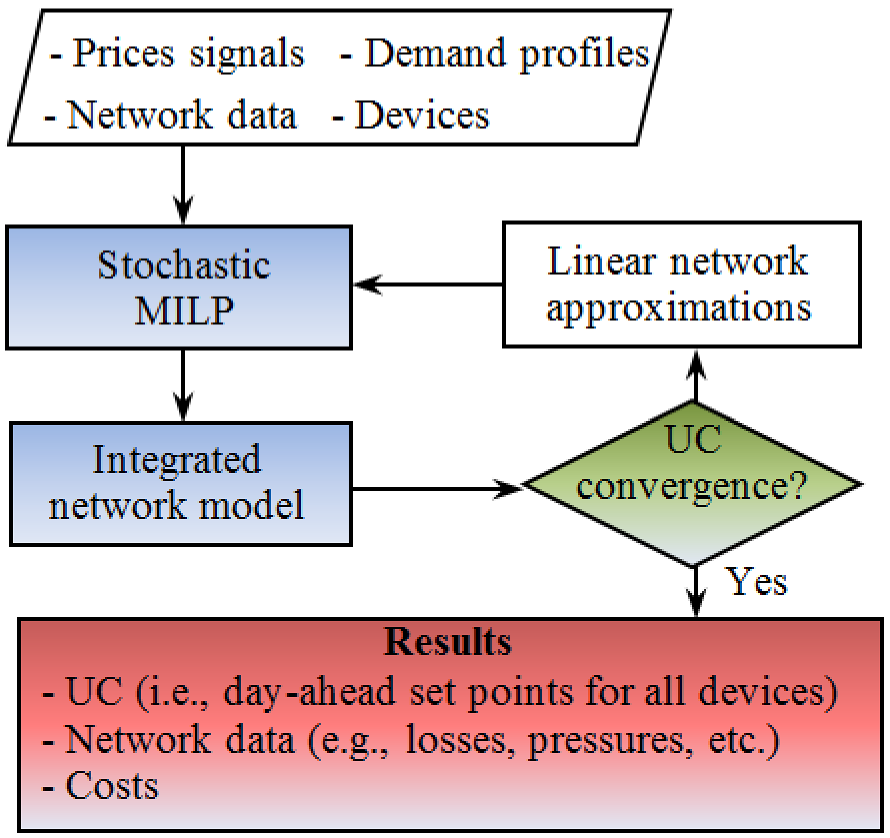
Modelling groups of coordinated/competitive building multi-energy systems alongside complex integrated electricity distribution, district heating and gas networks is not trivial:

- Simply trying to solve all these systems in a single model would lead to very large and computationally expensive optimisation
- Even if computationally feasible, the problem would become stochastic, mixed integer and non-linear, making it challenging to find a "good" solution
- The models could be simplified and linearized, but this may lead to solutions that do not work under real conditions

Modelling integrated networks and multi-energy systems

To model smart communities, we developed new techno-economic tools that iteratively bring together:

- Stochastic optimisation techniques considering time dependence (storage) applied to multi-energy systems
- Non linear integrated electricity, heat and gas network models
- Sparse matrix approximation and root finding (Newton) algorithms

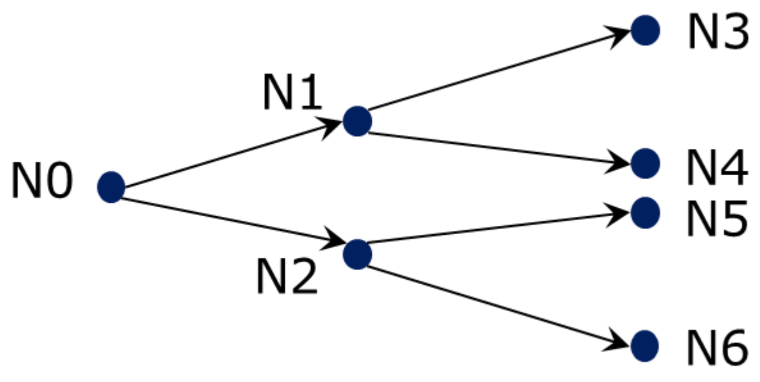


Dealing with modelling complexity

Matrices can be used to model:

- Scenario trees and robustness constraints (stochastic programming)
- Availability of different technologies in each building and the connections to the integrated network
- This approach uses many **‘unnecessary’ variables and constraints** (e.g., nonanticipativity constraints)

	N0	N1	N2	N3	N4	N5	N6
N0	1	1	1				
N1		1		1	1		
N2			1			1	1
N3		1		1			
N4		1			1		
N5			1			1	
N6			1				1



Linked Lists

- Linked Lists (LL) can minimise the number of variables and constraints
  - From nonanticipativity to nodal stochastic formulation
  - Flexible constraints allow consideration of any combinations of energy technologies per building
  - Customisable robustness constraints and scenario trees (e.g., asymmetric)
- For this purpose, LL converts sparse matrix to vectors with only non-zero blocks of information, each providing a link to the next block

$$\begin{bmatrix} A & 0 & B \\ 0 & C & 0 \\ 0 & 0 & D \end{bmatrix} \rightarrow \underset{Head\ (Row)}{\begin{vmatrix} 1 \\ 3 \\ 4 \end{vmatrix}}$$

$Index$	$Data\ (Value)$	$Data\ (Column)$	$Next$	
1	$[A]$	$[1]$	2	Block 1
2	$[B]$	$[3]$	0	Block 2
3	$[C]$	$[2]$	0	Block 3
4	$[D]$	$[3]$	0	Block 4

Linearizing the network model

- The integrated network model takes the outputs of the stochastic MILP (energy inputs and outputs per building) to simulate the conditions of the network

The methodology concludes if there are no network violations…

- Otherwise, linear approximations of each active constraint are produced by differentiating them with respect to the energy flows of each building:

$$Network\_Flow = K + \sum \frac{\partial Active\_Constraint}{\partial Building\_Export_x} \times Building\_Export_x$$

The equation represents the contributions of each smart building to network constraint violations…

Case study – Manchester University

Electricity:

- 17 buildings
- 13 nodes

Gas:

- 27 buildings
- 37 nodes

Heat:

- 30 buildings
- 36 nodes

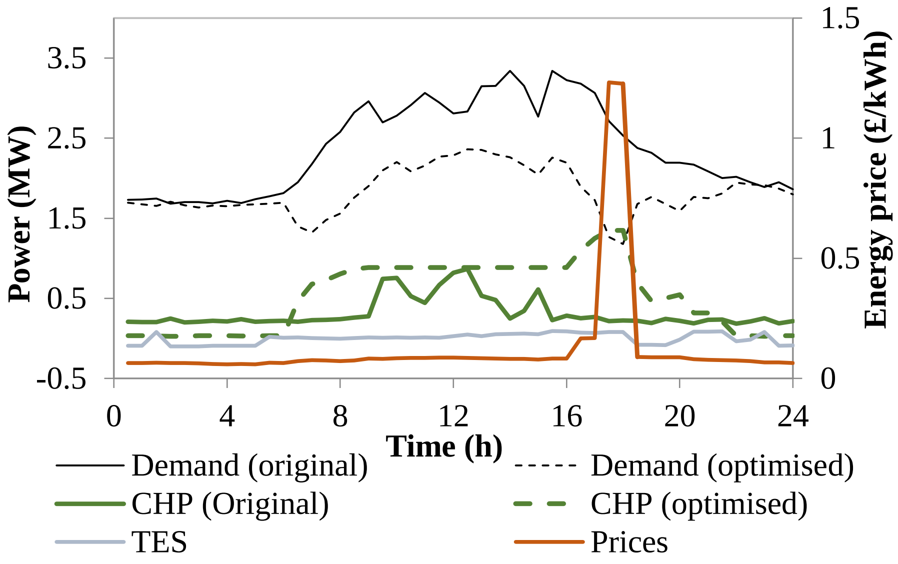
Case study – Manchester University

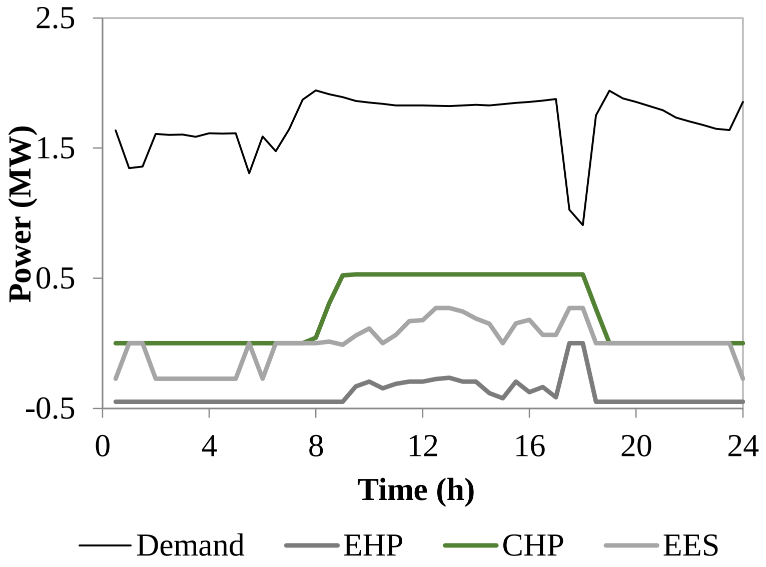
- The smart district has 60 different devices distributed in different buildings; i.e., 2.7 MW (CHP), 2.6 MW (EHP), 3.4 MW (PV) and 24 MW (Boilers)

- The day ahead (24h) operation of the district is optimised considering:
  - Addition of 1kW and $1m^3$, or 10 kW and 10 m^3 of EES and TES capacity per building
  - Reduced electricity distribution, network heating and gas network capacities
  - Deterministic (best view) and uncertain (decision tree) scenarios
  - LP (using linear CHP models) and full MILP formulations (using MILP EHP models)

District operation considering network constraints

- Even when faced with network constraints, the district can meet customer needs without sacrificing customer comfort
- However, the district has to dedicate part of its flexibility (mainly from CHP) to manage network constraints, i.e., customers perceive lower energy savings





Impacts of constraints and uncertainty

- Systems with greater flexibility cope better with network constraints and uncertainty

Installed capacity		Network constraints		
EES	TES	Electricity	Heat	Gas
0	0	25.5 k£	26.9 k£	25.9 k£
1kW	$1m^3$	25.4 k£	26.8 k£	25.8 k£
10 kW	$10\ m^3$	25.1 k£	26.3 k£	25.5 k£

Installed capacity		Deterministic (One scenario)	Stochastic (Five scenarios)	
EES	TES		Cost	VPI
0	0	25.5 k£	28.2 k£	3.51 k£
1kW	$1m^3$	25.4 k£	27.8 k£	3.24 k£
10 kW	$10\ m^3$	25.1 k£	25.4 k£	0.65 k£

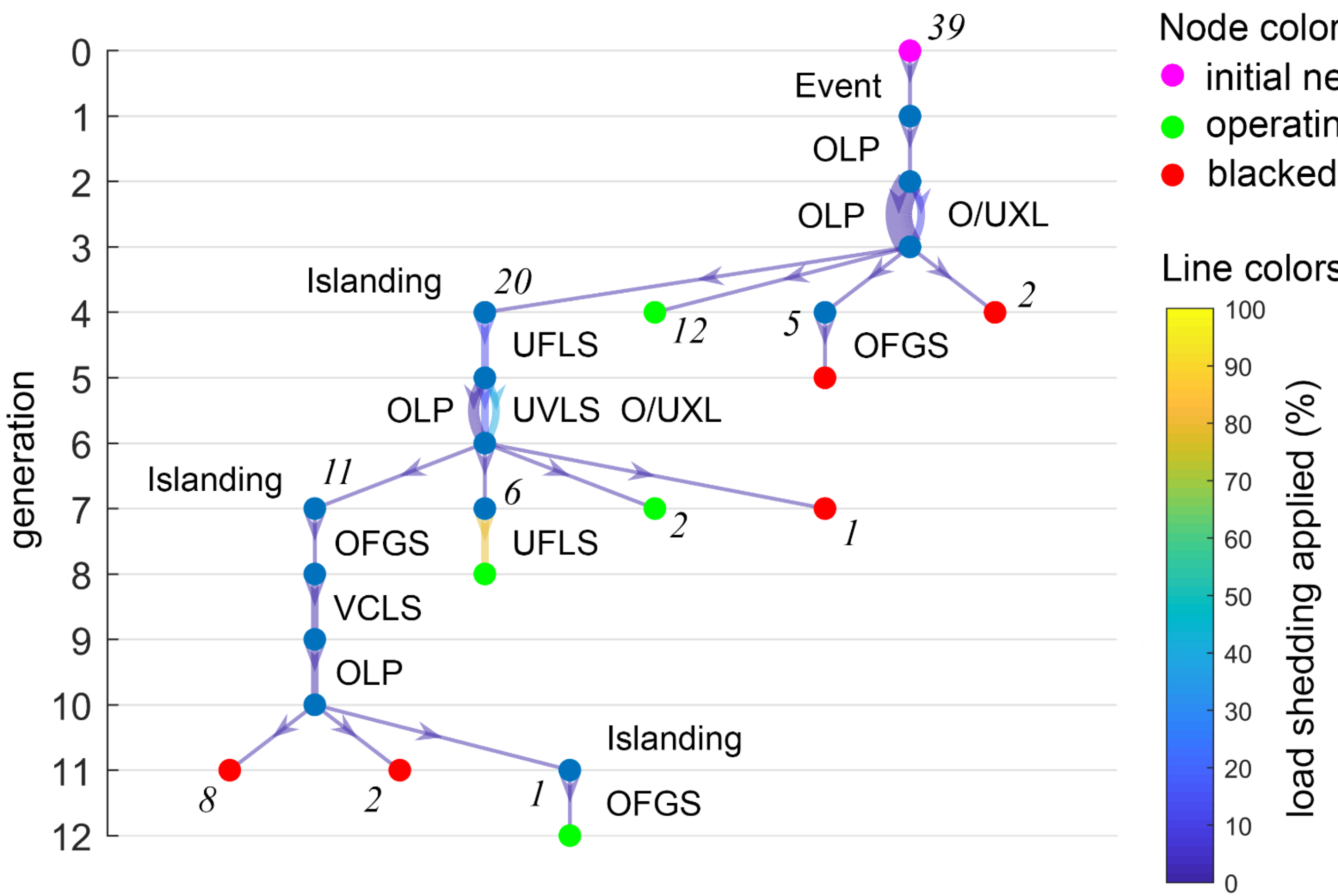
District Multi-energy systems

Live examples of the smart district model are available online:

- Use this link: https://gitlab.com/cesenia/mes-tutorial-basic-concepts
- Scroll down and click on: launch binder

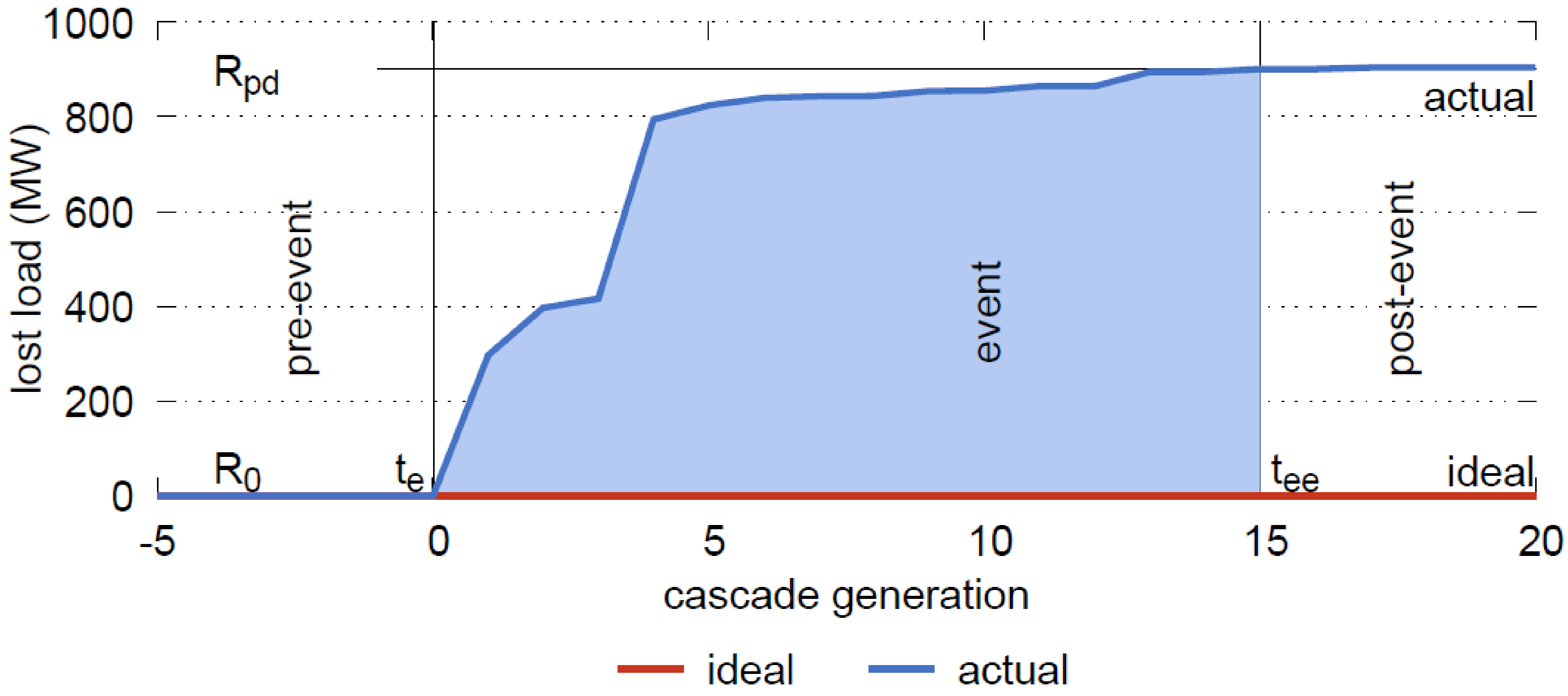
Cascading modelling and impact quantification for resilience applications

AC-CFM: Illustrative Results

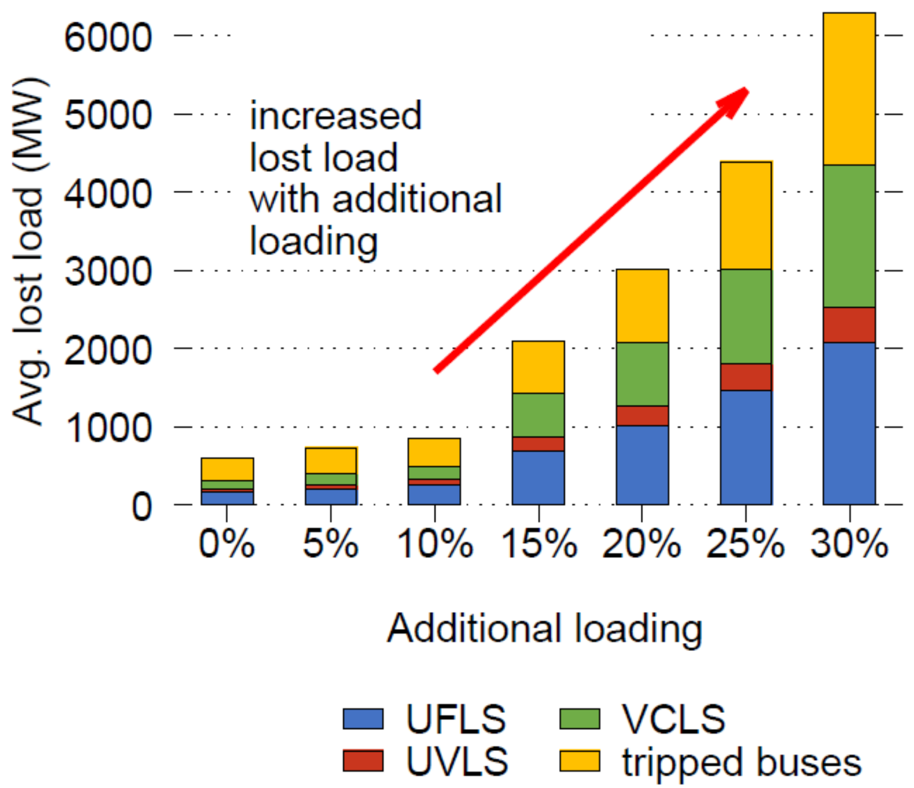


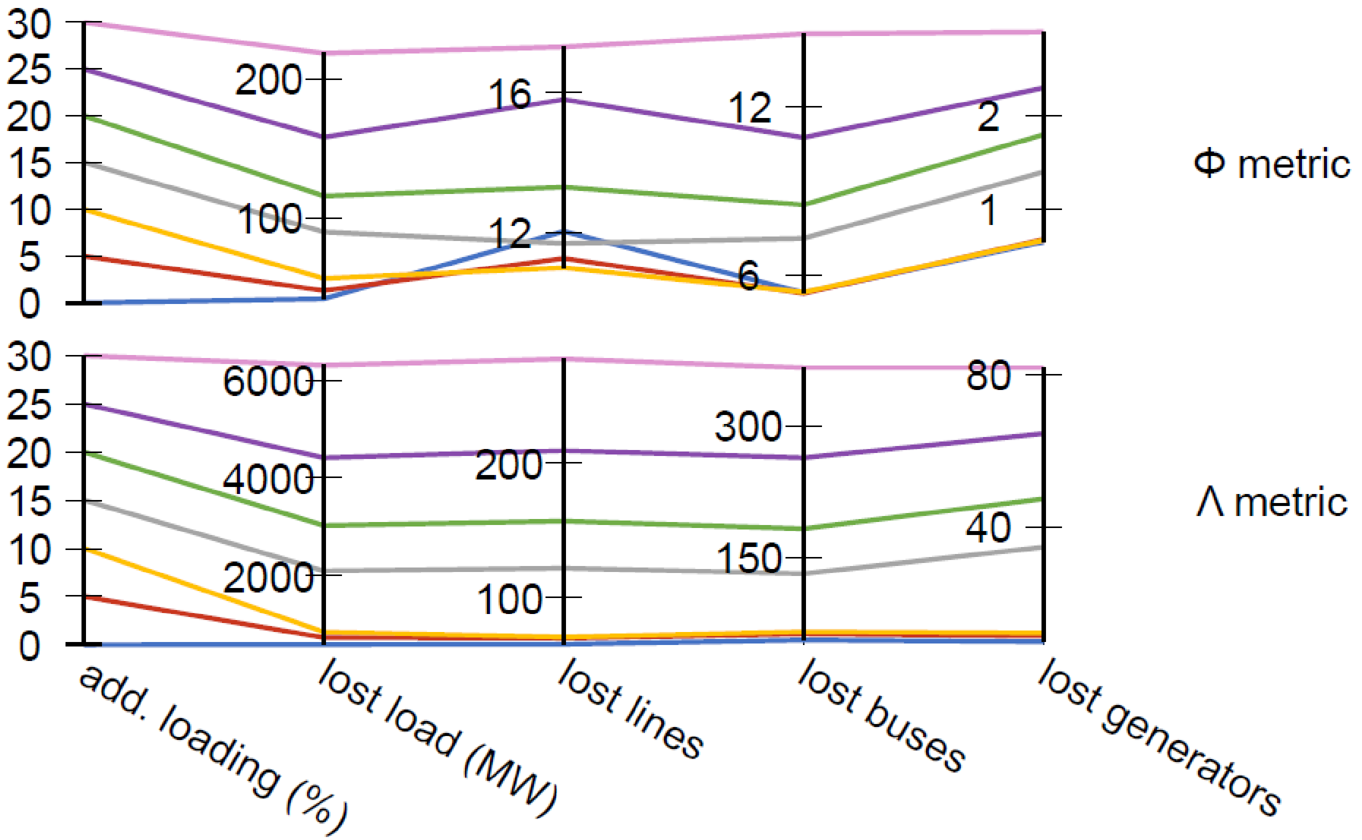
M. Noebels, R. Preece and M. Panteli, "AC Cascading Failure Model for Resilience Analysis in Power Networks," in IEEE Systems Journal, Early Access, December 2020

AC-CFM: Illustrative Results

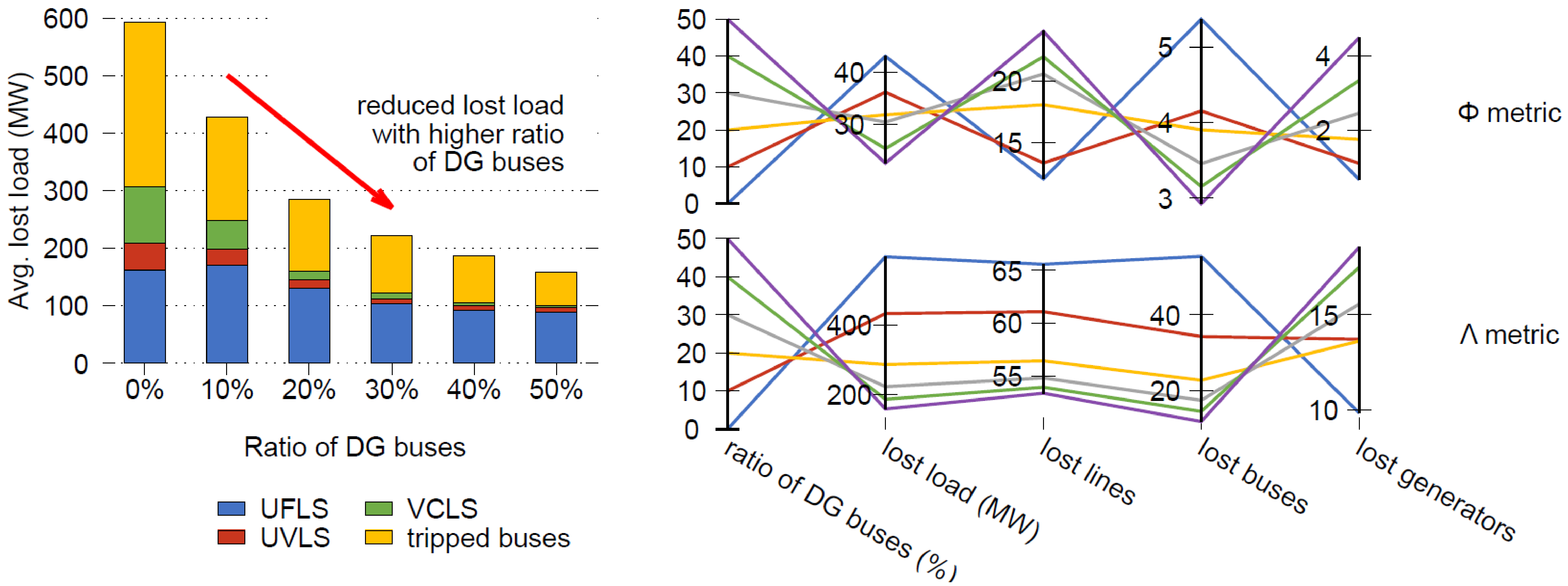


AC-CFM: Illustrative Results





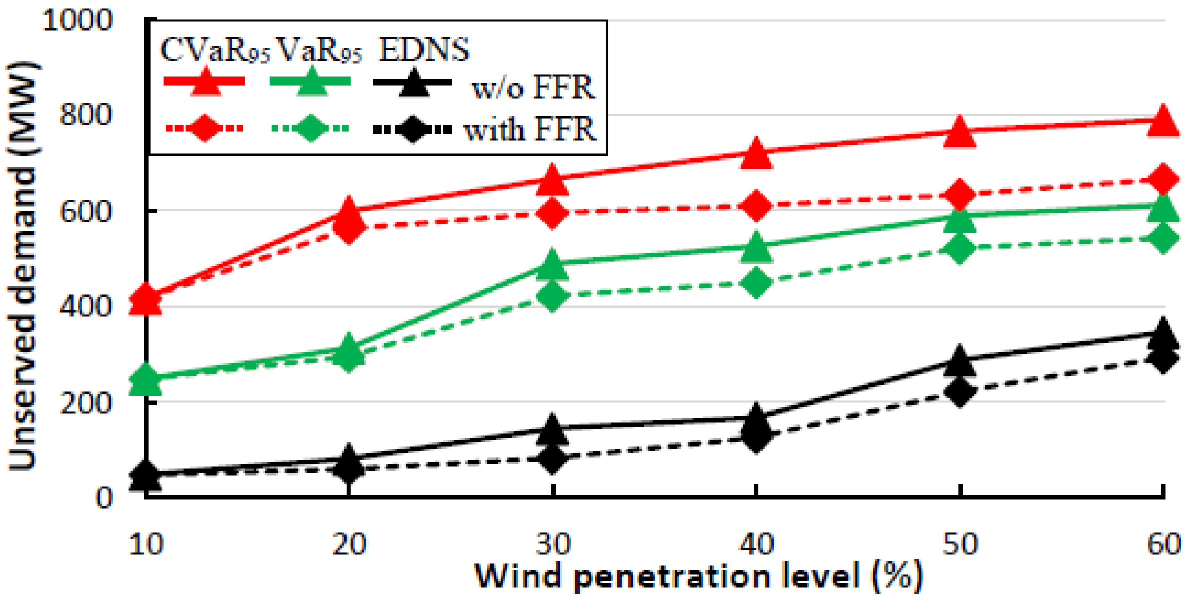
AC-CFM: Illustrative Results



Dynamic Risk Metrics with Increased Wind Penetration

Application to ACTIVSg200 Network

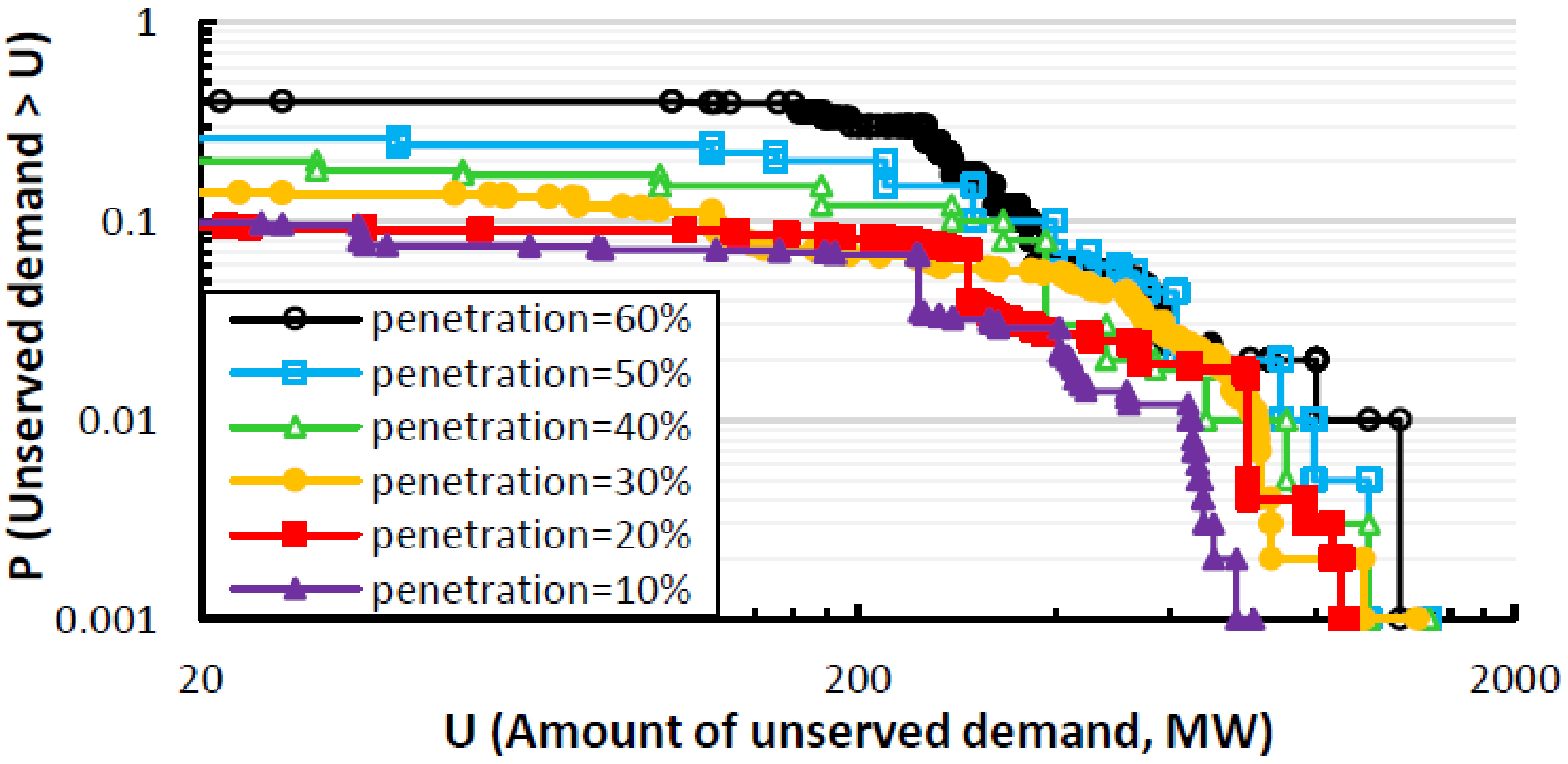
RES Penetration level (%)		10	20	30	40	50	60
Inertia level (GVA·s)		17.01	16.33	14.38	13.57	12.88	9.05
COI frequency nadir without FFR (p.u.)		0.991	0.987	0.985	0.981	0.977	0.976
Required BESS capacity (MW)	Near RES	0	12	36	60	132	192
	Near demand	0	12	30	66	132	186



Y. Dai, R. Preece, and M. Panteli, "Risk Assessment of Cascading Failures in Power Systems with Increasing Wind Penetration", Accepted for presentation in 2022 Power System Computation Conference (PSCC), Porto, Portugal, June 2022

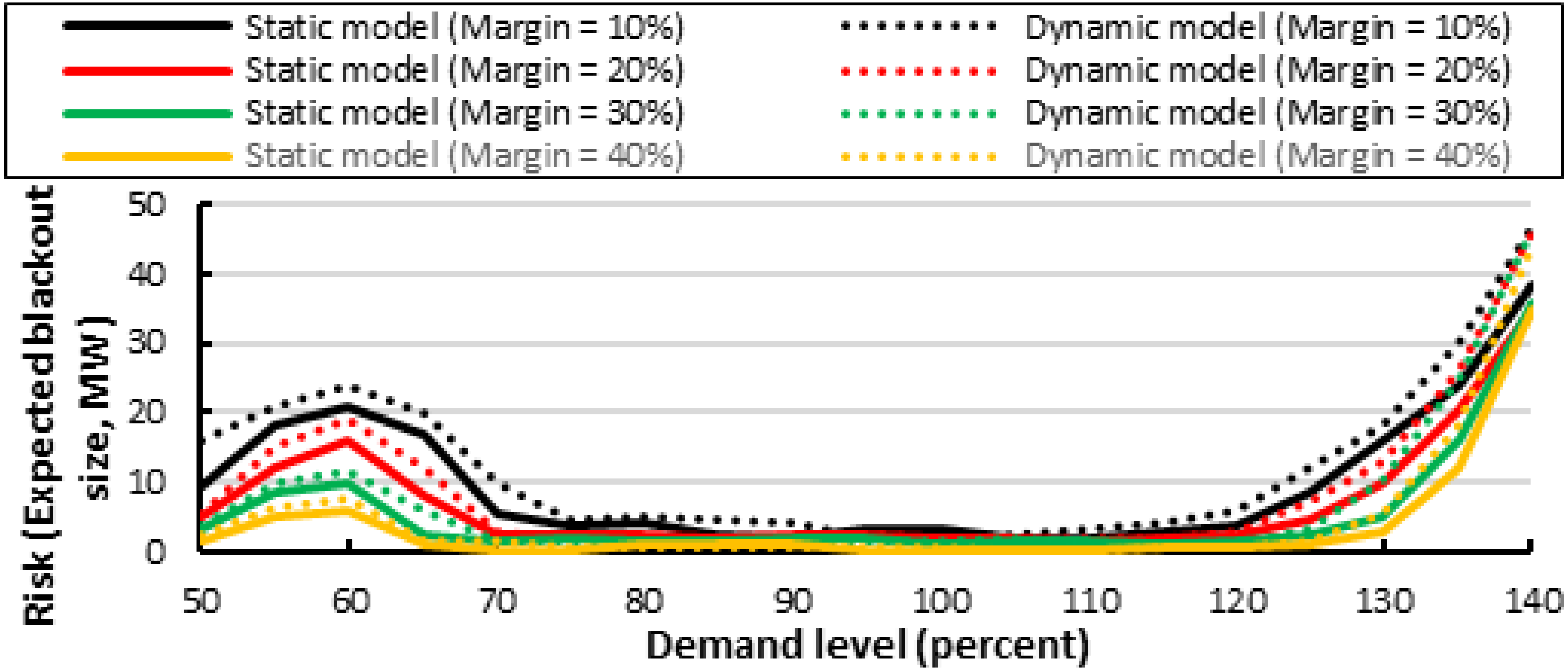
Dynamic Risk Metrics with Increased Wind Penetration

Application to ACTIVSg200 Network

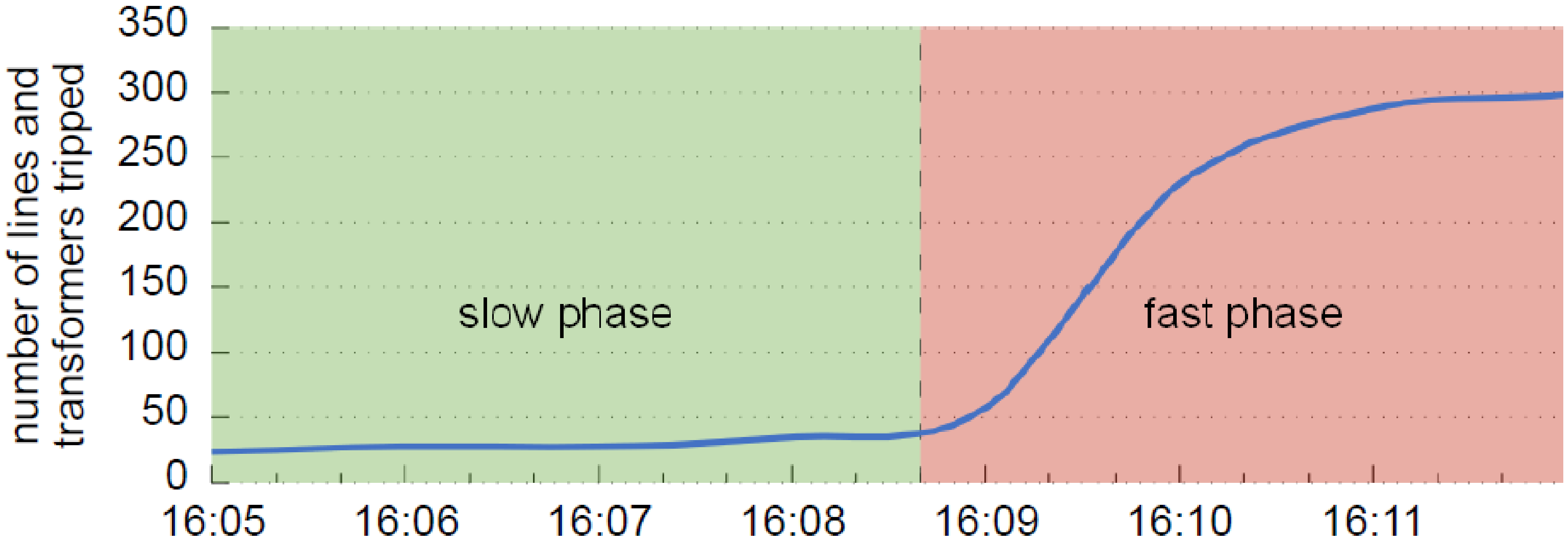


Static Vs Dynamic Cascading Modelling

Application to ACTIVSg200 Network



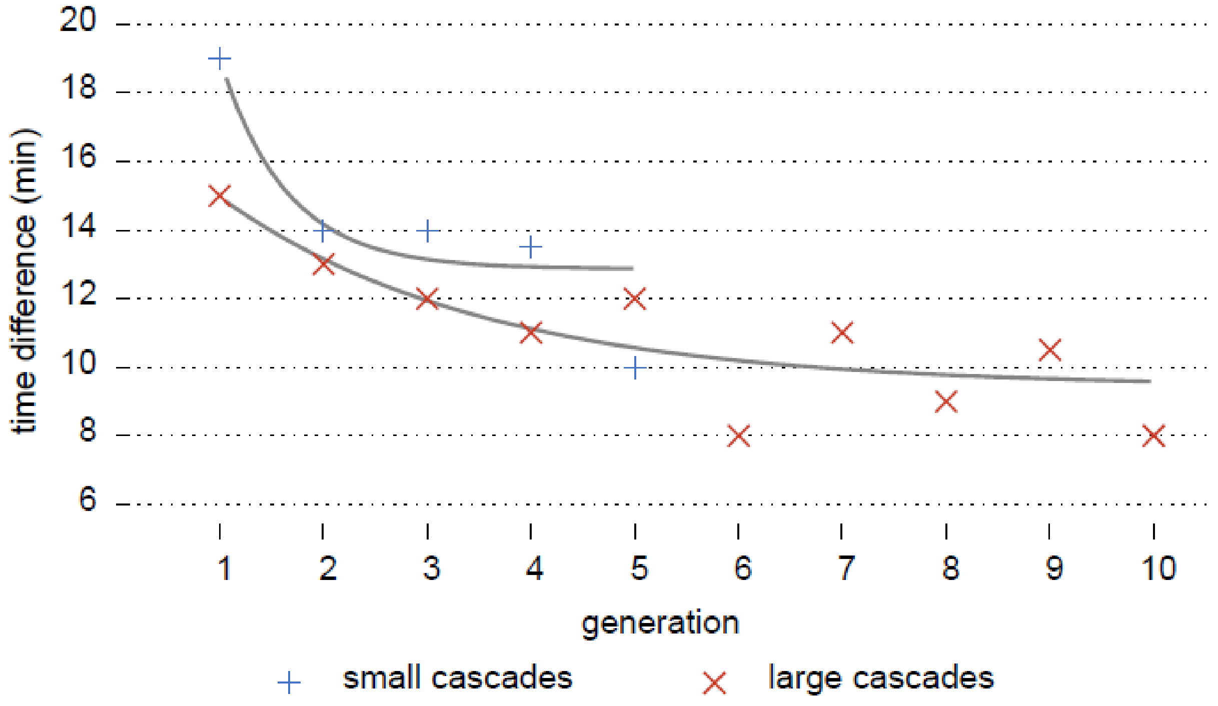
Observed Acceleration of Cascading Outages

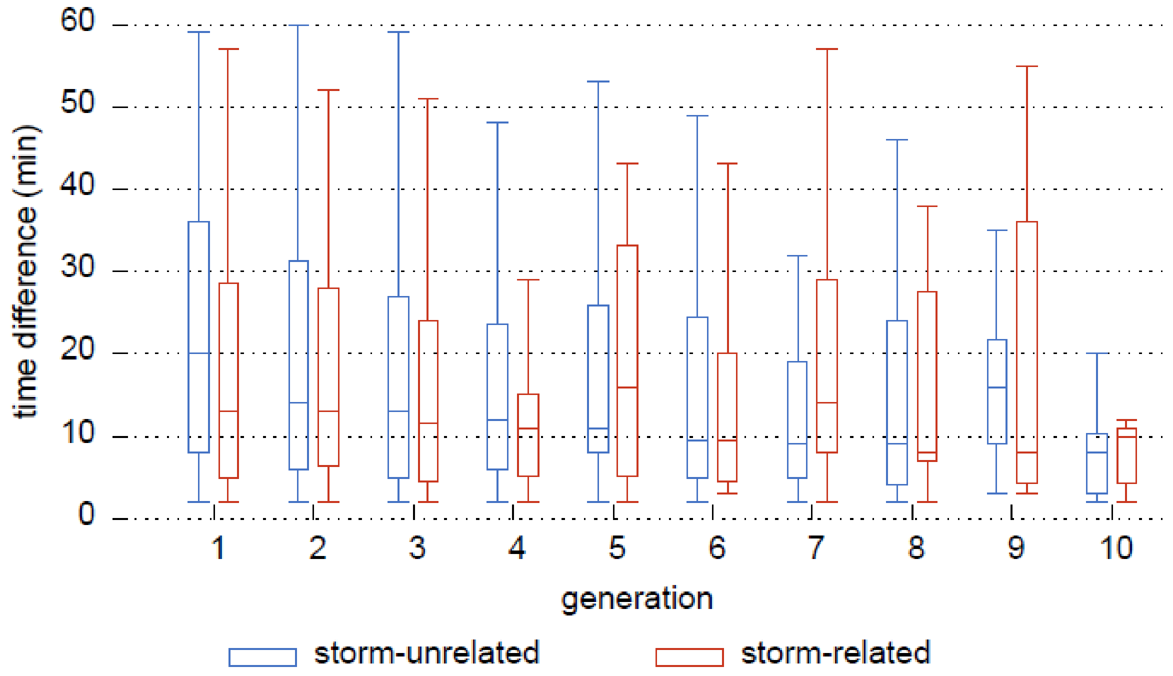


Cumulative line and transformer trips in August 2003 blackout

Illustrative results – Data-driven analysis

Data Analysis of Publicly Available Data by Bonneville Power Administration (BPA) Transmission





Data source: https://transmission.bpa.gov/business/operations/outages/

M. Noebels, I. Dobson and M. Panteli, "Observed Acceleration of Cascading Outages," IEEE Transactions on Power Systems, vol. 36, no. 4, pp. 3821-3824, July 2021

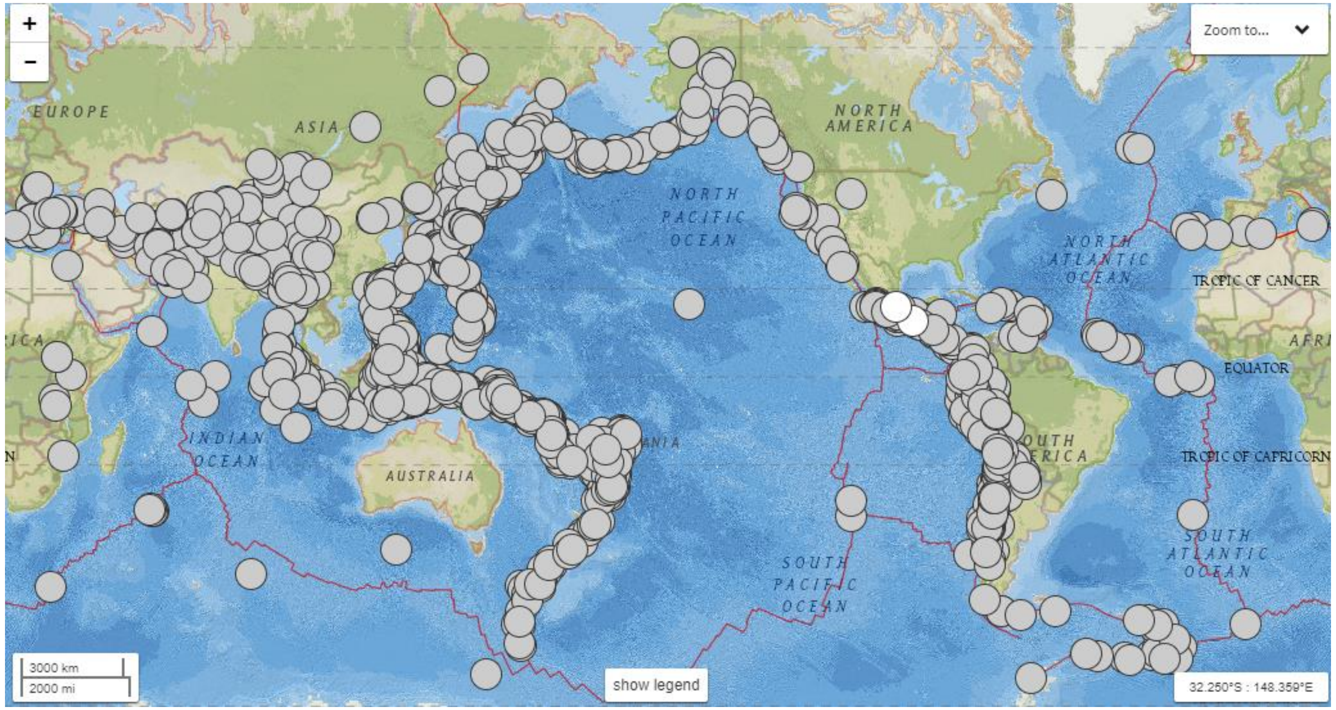
Planning and operating the grid against extreme events

Case study 1: Earthquakes

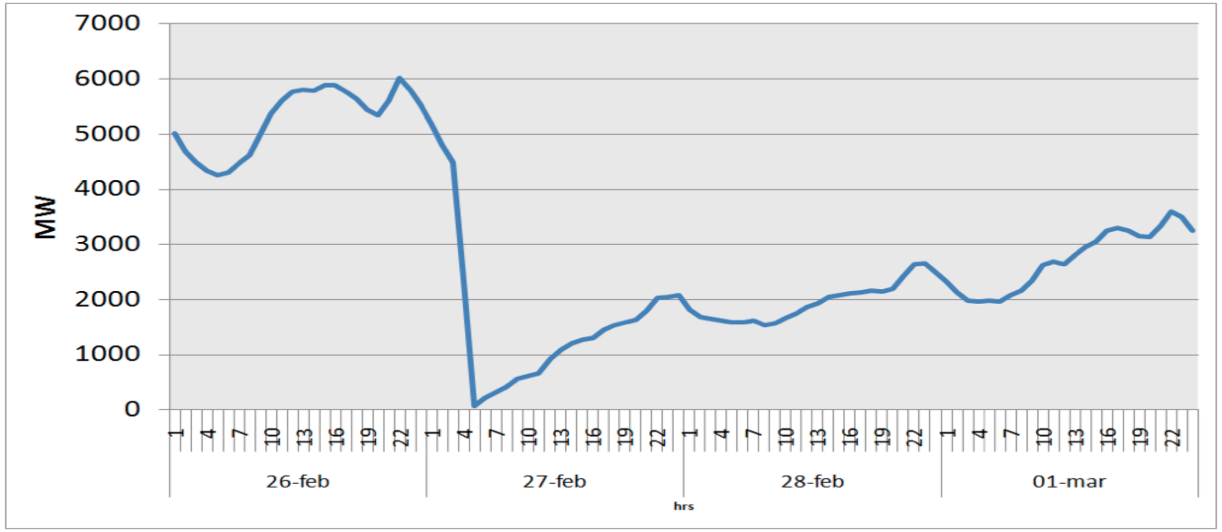
Examples on earthquakes (1)

Earthquakes do present a real threat to electricity systems in several countries

E > 7Mw since 1900



2010 Chile (8.8Mw)



Examples on earthquakes (2)

Earthquakes do present a real threat to electricity systems in several countries

<u>Massive 8.8Mw earthquake in Chile 2010</u>

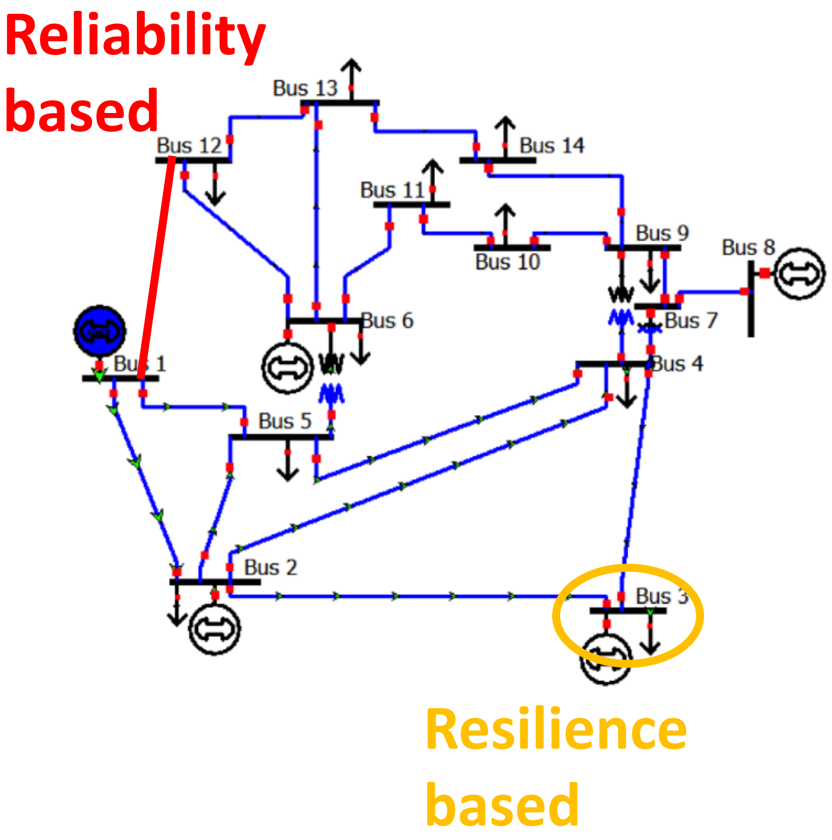
Substations: 12 out of 46 substations (26%) damaged in the HV transmission network:

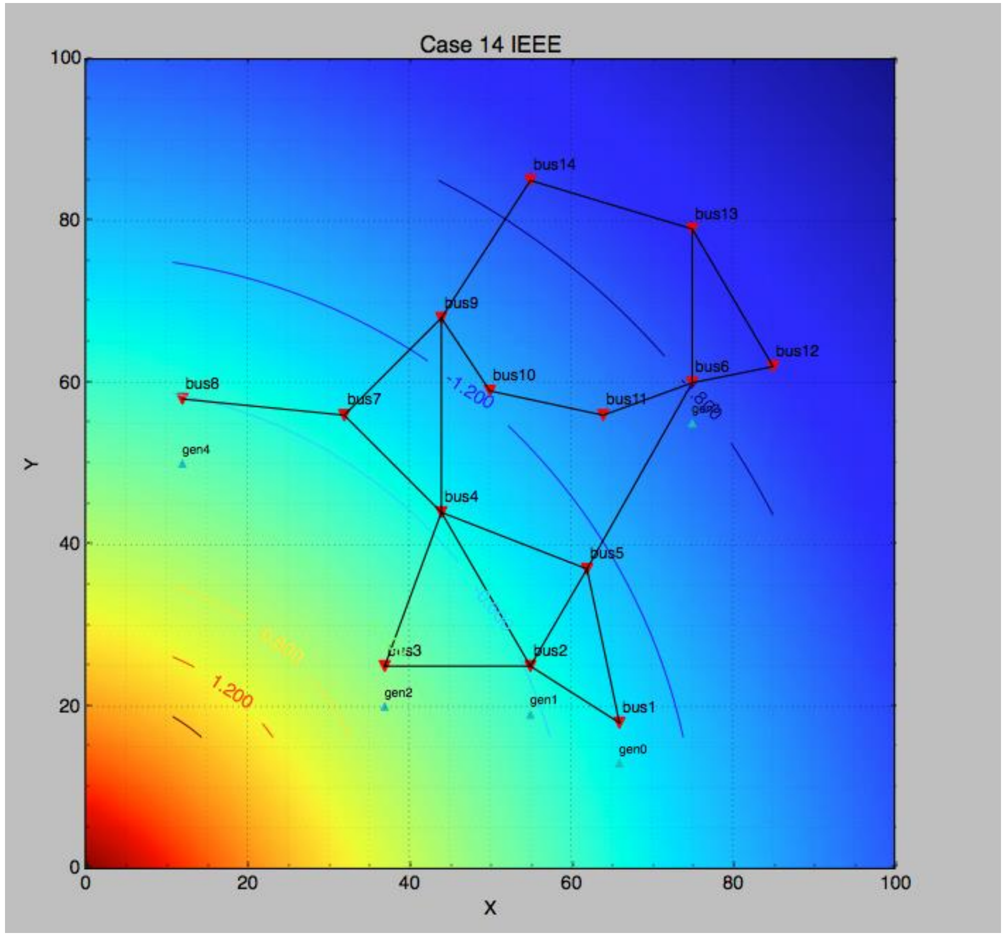
- 500 kV bushings (high failure rate, particularly in transmission bushings)
- 500 kV pantograph disconnector switches
- 220 kV circuit breakers (live tank type)
- 154 kV circuit breakers (air compressed type)

Candidate decisions

1. New lines (all voltage levels) to create alternative “routes” to transfer electricity from production to consumption centres
2. Hardening substations (anchoring) to make them more “robust” against earthquakes
3. New technologies: storage plants, FACTS, HVDC
4. Distributed generation
5. Shorter response times by enhanced stocks, more crews and online monitoring and control
6. Additional reactive power related infrastructure

Investment on IEEE test network





Detailed ranking

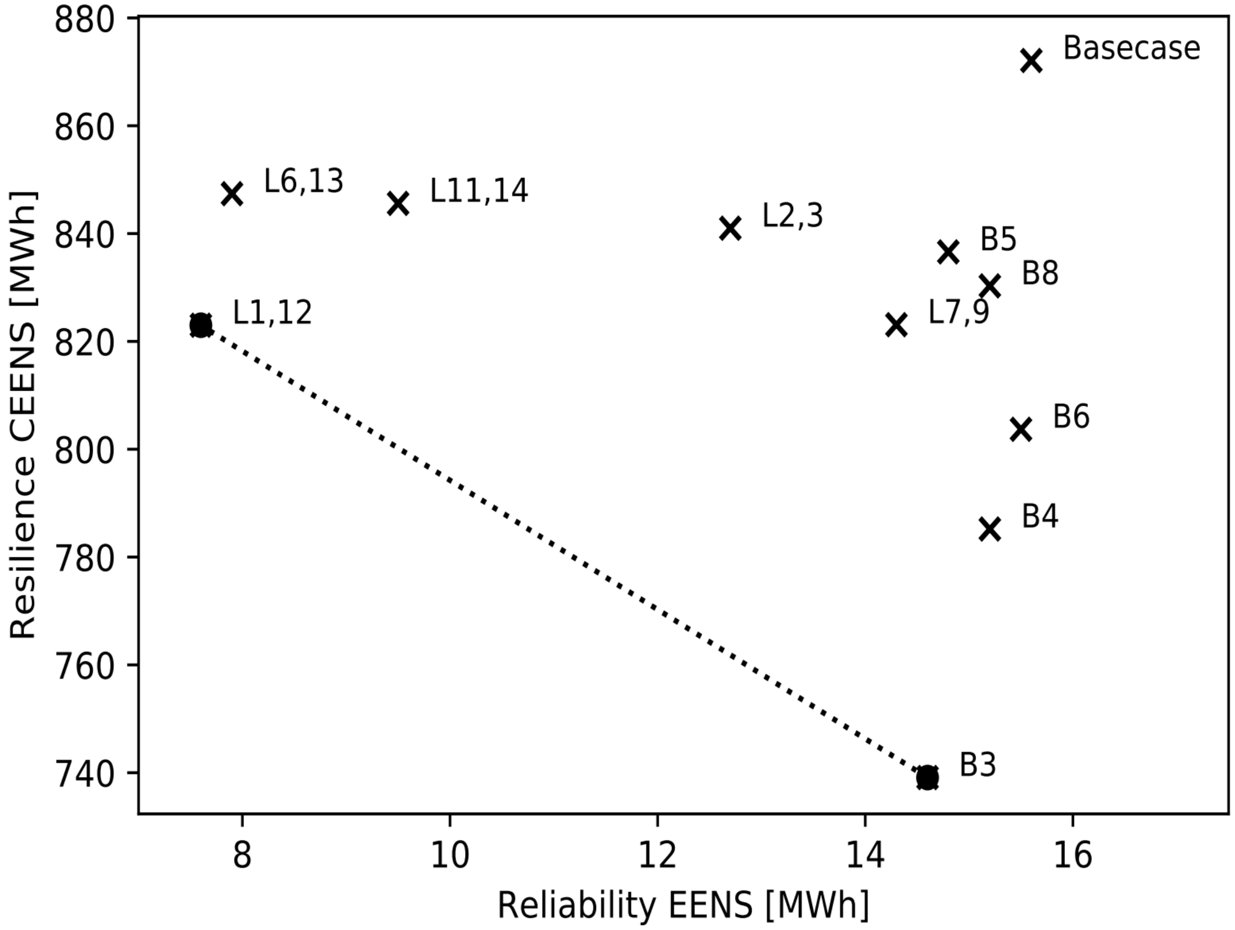
RESILIENCE AND RELIABILITY RANKINGS OF SINGLE NETWORK ENHANCEMENT PROPOSITIONS.

Reliability		Resilience	
Solution	EENS* $[MWh]$	Solution	CEENS* $[MWh]$
L1,12	7.6	B3	739.1
L6,13	7.9	B4	785.2
L11,14	9.5	B6	803.7
L2,3	12.7	L1,12	823
L7,9	14.3	L7,9	823.1
B3	14.6	B8	830.3
B5	14.8	B5	836.6
B8	15.2	L2,3	841
B4	15.2	L11,14	845.6
B6	15.5	L6,13	847.4
Base case	15.6	Base case	872.1

*10,000 evaluations; 95% confidence intervals equal to ± 0.42 [MWh] for resilience and ± 0.03 [MWh] for reliability.

Lagos, T., Moreno, R., Navarro, A., Panteli, M., Sacaan, R., Ordonez, F., Rudnick, H., Mancarella, P., "Identifying Optimal Portfolios of Resilient Network Investments Against Natural Hazards, With Applications to Earthquakes", IEEE Transactions on Power Systems, Vol 35, Issue 2, pp 1411 - 1421, Mar 2020.

Trade offs between reliable and resilient investments



$$\lambda_1 f_{EENS}(x) + \lambda_2 f_{CEENS}(x)$$

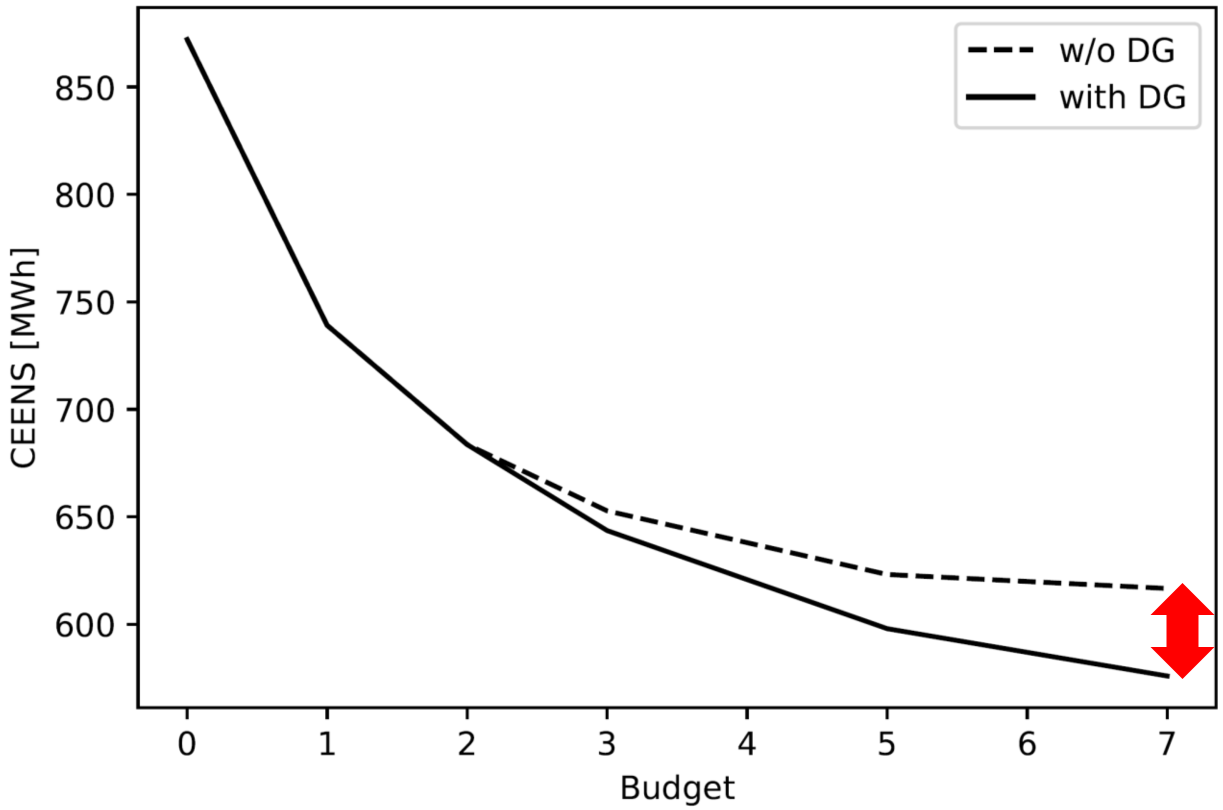
Lagos, T., Moreno, R., Navarro, A., Panteli, M., Sacaan, R., Ordonez, F., Rudnick, H., Mancarella, P., "Identifying Optimal Portfolios of Resilient Network Investments Against Natural Hazards, With Applications to Earthquakes", IEEE Transactions on Power Systems, Vol 35, Issue 2, pp 1411 - 1421, Mar 2020.

Portfolios and DG

OPTIMAL INVESTMENT PORTFOLIOS FOR *budget* $= 0, 1, 2, 3, 5, 7$.

	Without DG		With DG	
Budget	Solution	CEENS* $[MWh]$	Solution	CEENS* $[MWh]$
0	Base case	872.1	Base case	872.1
1	B3	739.1	B3	739.1
2	B3 B4	683.6	B3 B4	683.6
3	B3 B4 B6	651.1	B3 B4 1xDG3	643.6
5	B3 B4 B5 B6 L1,12	623.2	B3 B4 B6 2xDG3	598.0
7	B3 B4 B5 B6 B8 L11,14 L6,13	616.7	B3 B4 B6 2xDG3 1xDG4 2xDG6	575.9

*95% confidence interval equal to ±0.42 [MWh].



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Optimizing different resilience metrics

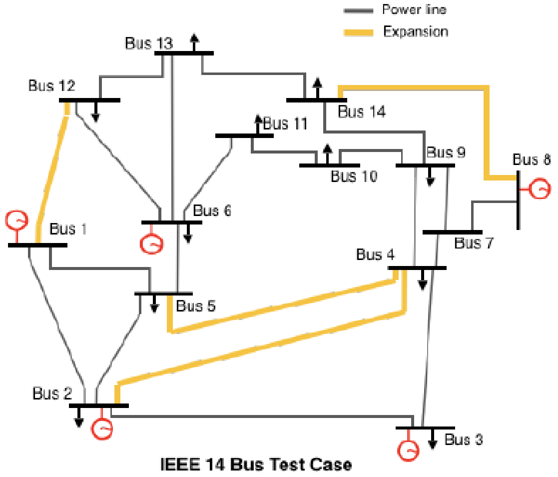
RANKING OF SINGLE NETWORK ENHANCEMENT PROPOSITIONS OBTAINED BY OPTIMIZING TWO DIFFERENT RESILIENCE METRICS.

Minimizing drop		Maximizing recovery rate	
Solution	Drop* $[MW]$	Solution	Rate* $[MW/120h]$
B3	10.2	L7,9	8.76
B4	10.92	L2,3	8.71
B5	11.23	B8	8.66

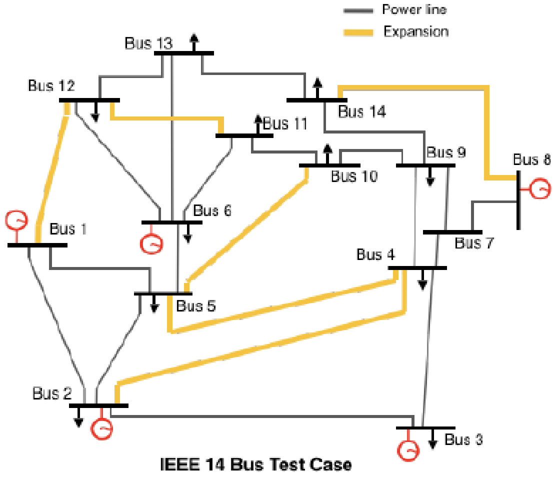
*10,000 evaluations; 95% confidence intervals equal to ±0.01 [MW] and ±0.01 [MW/120h].

Lagos, T., Moreno, R., Navarro, A., Panteli, M., Sacaan, R., Ordonez, F., Rudnick, H., Mancarella, P., "Identifying Optimal Portfolios of Resilient Network Investments Against Natural Hazards, With Applications to Earthquakes", IEEE Transactions on Power Systems, Vol 35, Issue 2, pp 1411 - 1421, Mar 2020.

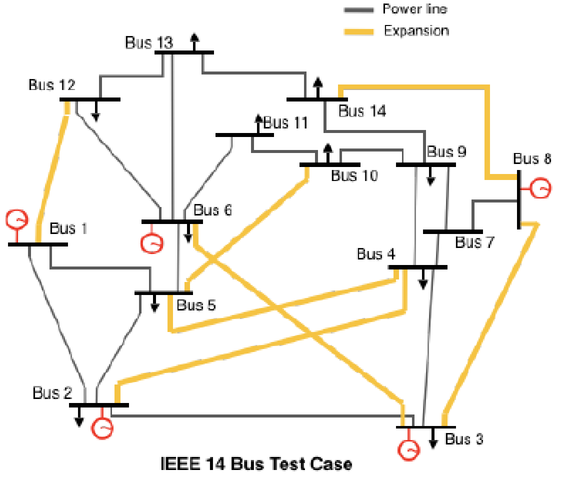
The importance of dependencies and flexibility



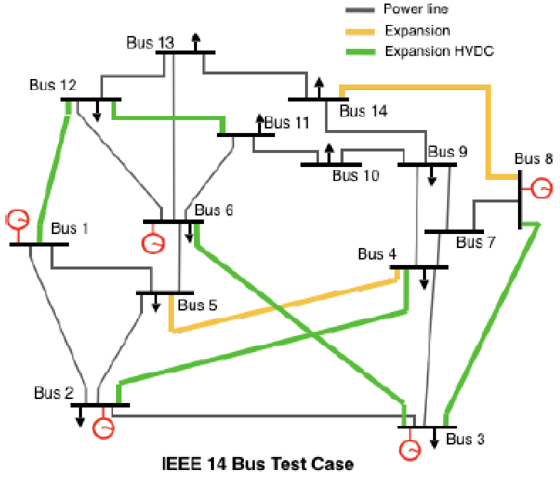
(a) ED



(b) EI



(c) RN-1

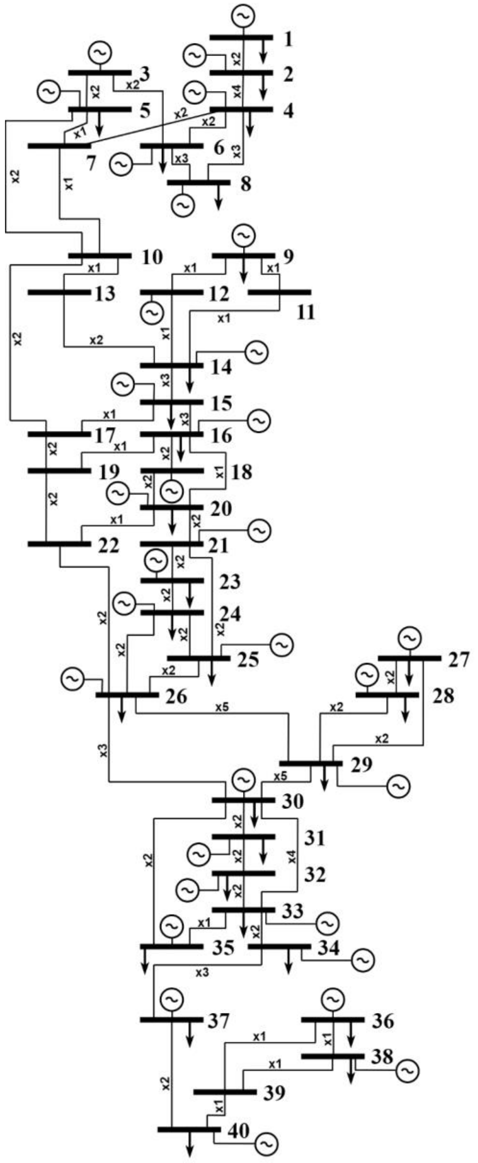


(d) ED-HVDC

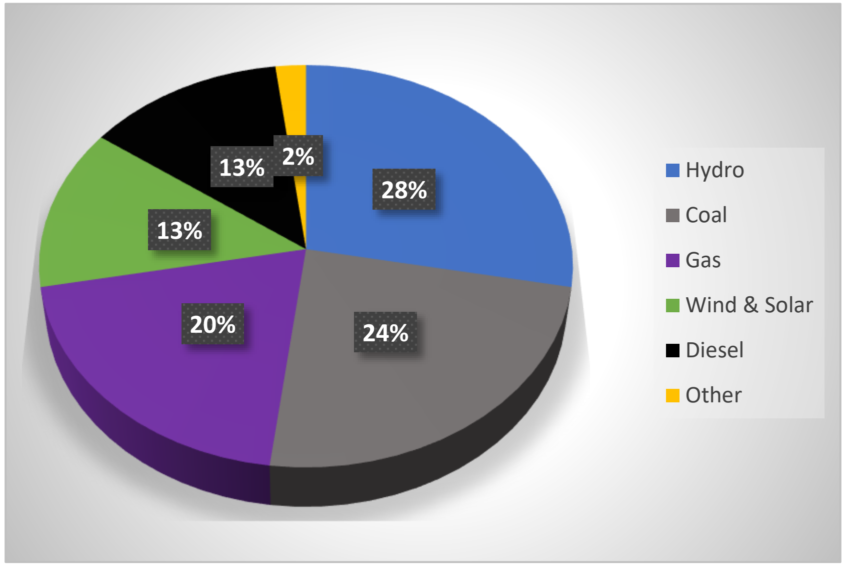
	ED-HVDC	**ED**	**EI**	**RN-1**
Investment	7.3M	2.8M	3.7M	5.6M
Generation	118.3M	138.8M	144.4M	134.7M
	[118.0M - 118.4M]	[138.6M - 139.0M]	[144.1M - 144.6M]	[134.4M - 134.9M]
Lost-Load	135.2M	138.9M	142.7M	155.5M
	[0 - 618.2M]	[0 - 628.3M]	[0 - 694.8M]	[0 - 701.3M]
Total Cost	260.8M	280.5M	290.8M	295.8M

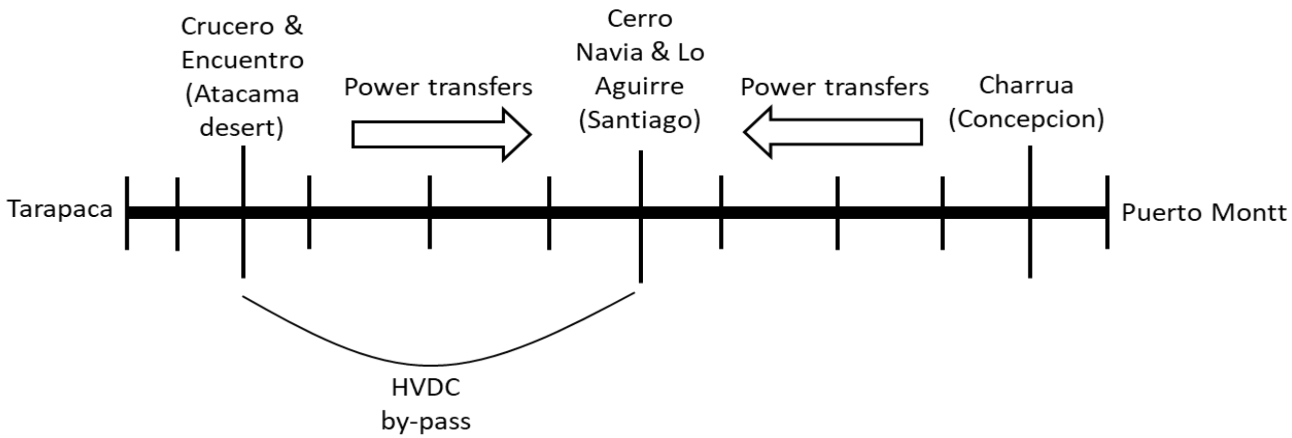
Barrera, J., Beaupuits, P., Moreno, E., Moreno, R., & Muñoz, F. D. Planning resilient networks against natural hazards: Understanding the importance of correlated failures and the value of flexible transmission assets. Electric Power Systems Research, Vol 197, 107280, 2021.

Chilean power system



1 Tarapaca
2 Lagunas
3 Kapatur
4 Crucero & Encuentro
5 Los Changos 220
6 Laberinto & Domeyko
7 Los Changos 500
8 Atacama & Mejillones
9 Paposo
10 Cumbre 500
11 Lalackama
12 Etaltal
13 Cumbre 220
14 Diego de Almagro
15 Cardones 220
16 Maitencillo 220
17 Cardones 500
18 Punta Colorada
19 Maitencillo 500
20 Pan de Azucar 220
21 Las Palmas
22 Pan de Azucar 500
23 Los Vilos
24 Nogales
25 Quillota
26 Polpaico
27 Rapel
28 Melipilla
29 Cerro Navia & Lo Aguirre
30 Alto Jahuel
31 Tinguiririca
32 Itahue
33 Ancoa
34 Charrua
35 Colbun
36 Puerto Montt
37 Cautin & Temuco
38 Rahue
39 Pichirropulli
40 Ciruelos & Valdivia





Reliability vs resilience in Chile

Reliability

Rank	Enhancement	EENS [MWh]
1	L: HVDC link	348
2	L: Laberinto - Cumbre	392
3	L: Ciruelos - Pichirropulli	523
4	L: Cautin - Charrua	580
5	L: Ciruelos - Cautin	617
6	Ss: Crucero	696
7	Ss: C. Navia	696
8	Ss: A. Jahuel	696
9	Ss: Charrua	696
10	Base case	696

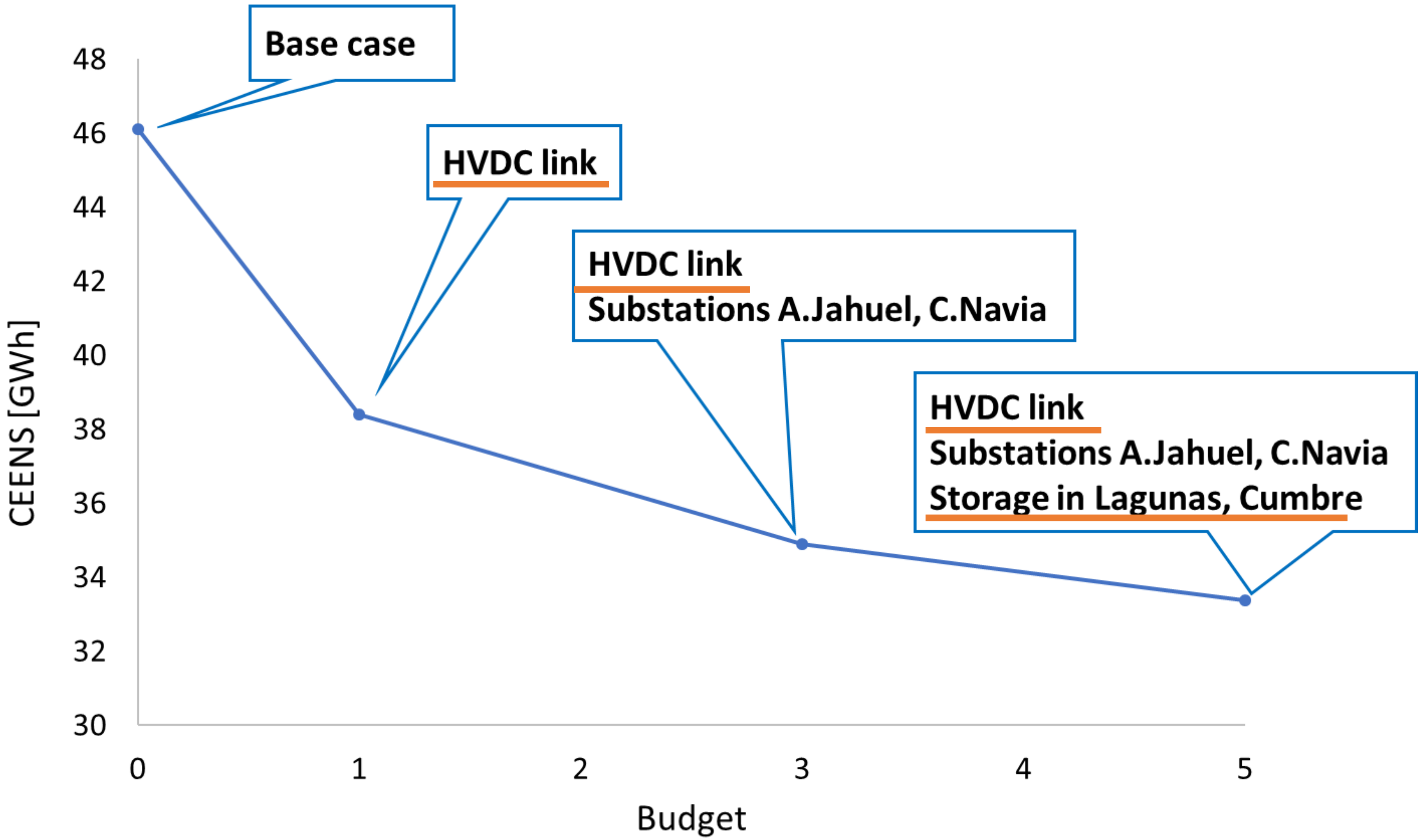
Resilience

Rank	Enhancement	CEENS [GWh]
1	L: HVDC link	38
2	Ss: C. Navia	43
3	Ss: A. Jahuel	43
4	Ss: Charrua	44
5	Ss: Crucero	45
6	L: Laberinto - Cumbre	46
7	L: Ciruelos - Cautin	46
8	L: Cautin - Charrua	46
9	L: Ciruelos - Pichirropulli	46
10	Base case	46

N-1 solution!

Moreno, R., Panteli, M., Mancarella, P., Rudnick, H., Lagos, T., Navarro, A., Ordoñez, F. & Araneda, J. C. From Reliability to Resilience: Planning the Grid Against the Extremes. IEEE Power and Energy Magazine, 18(4), 41-53, Jul 2020.

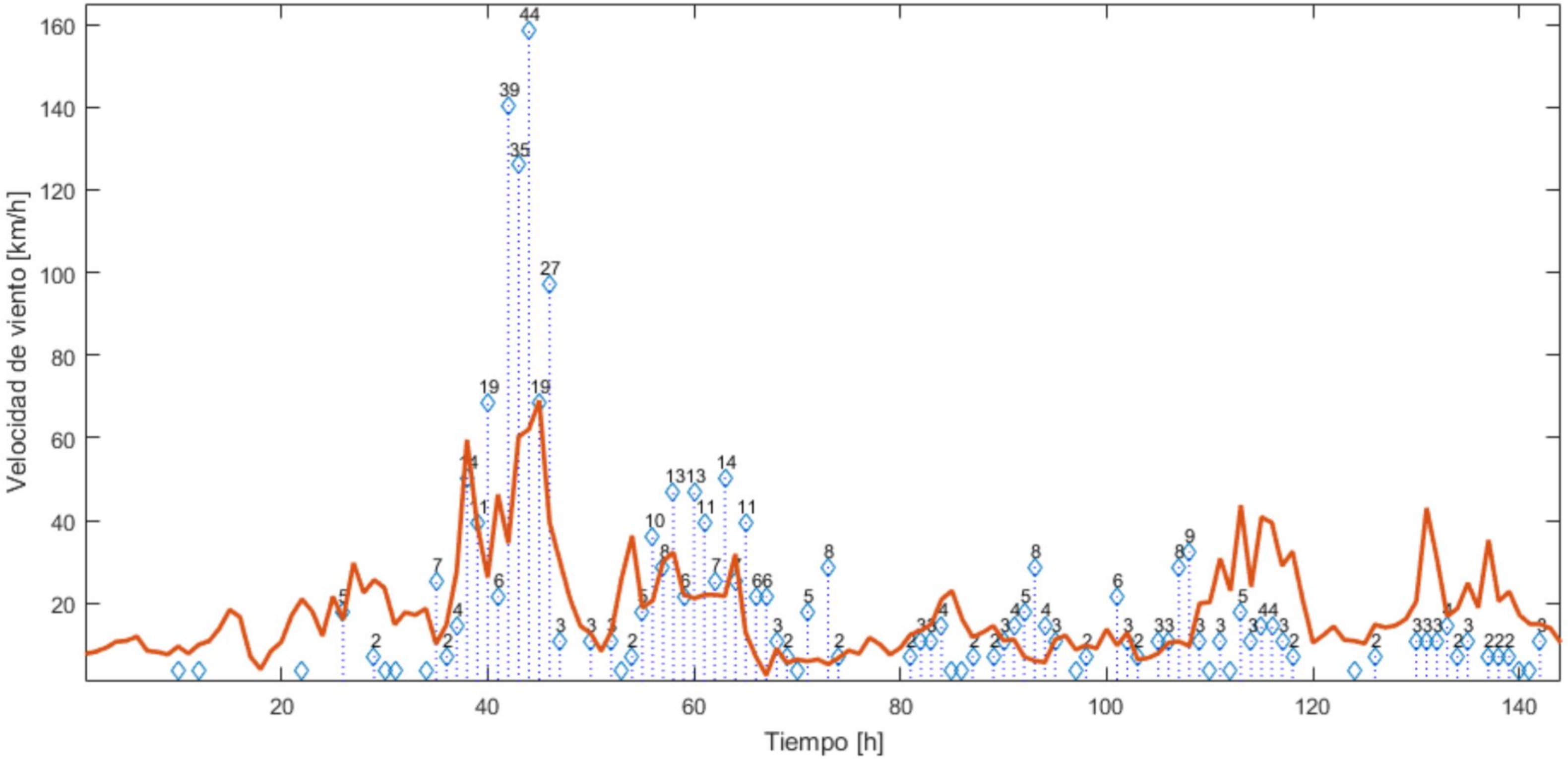
Portfolio vs budget: The value of flexible technologies in Chile

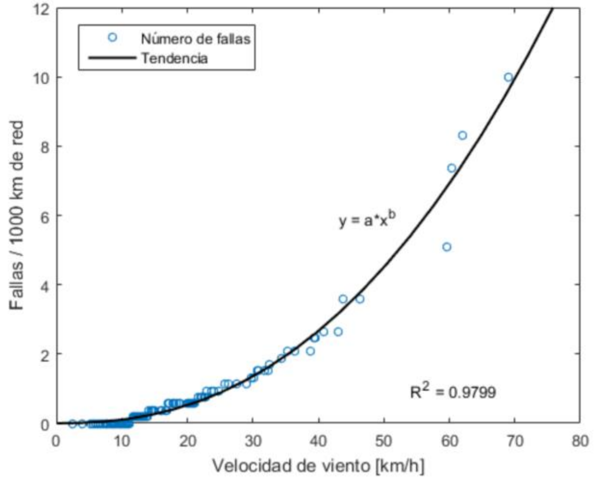


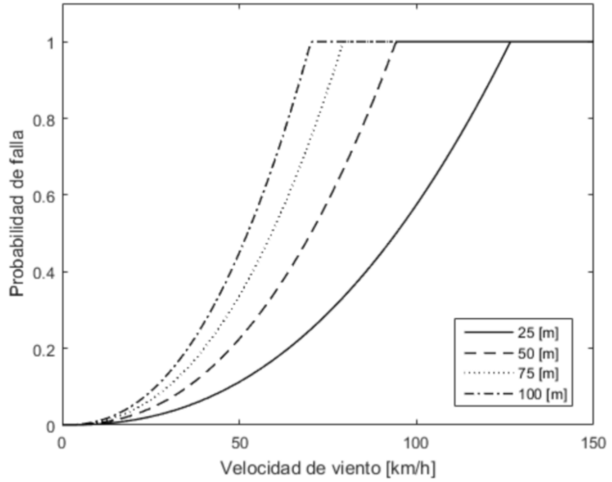
Moreno, R., Panteli, M., Mancarella, P., Rudnick, H., Lagos, T., Navarro, A., Ordoñez, F. & Araneda, J. C. From Reliability to Resilience: Planning the Grid Against the Extremes. IEEE Power and Energy Magazine, 18(4), 41-53, Jul 2020.

Case study 2: Windy conditions

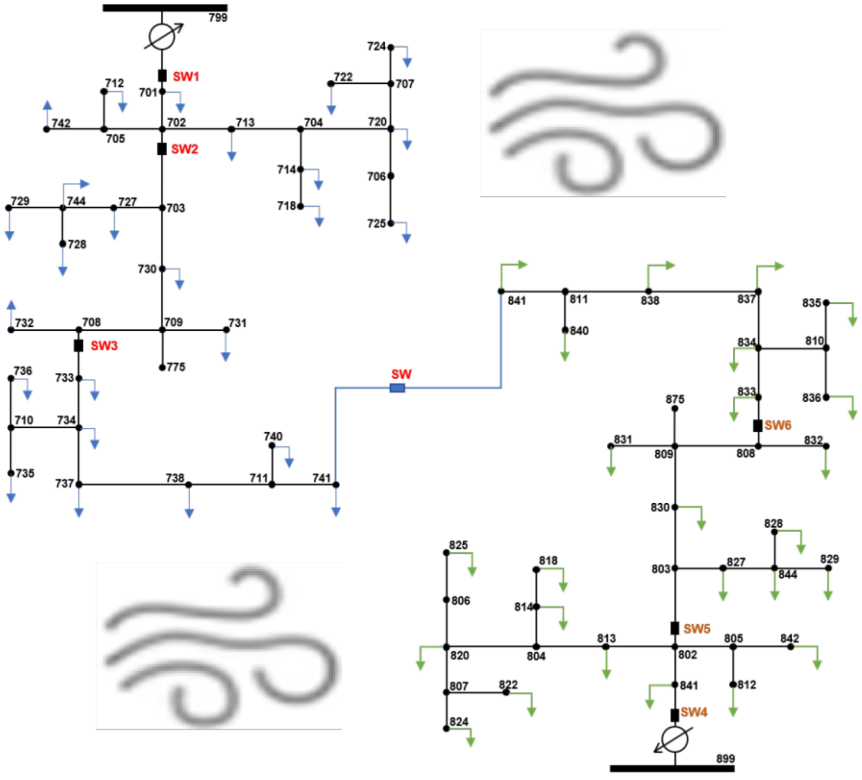
Building fragility curves from historical data

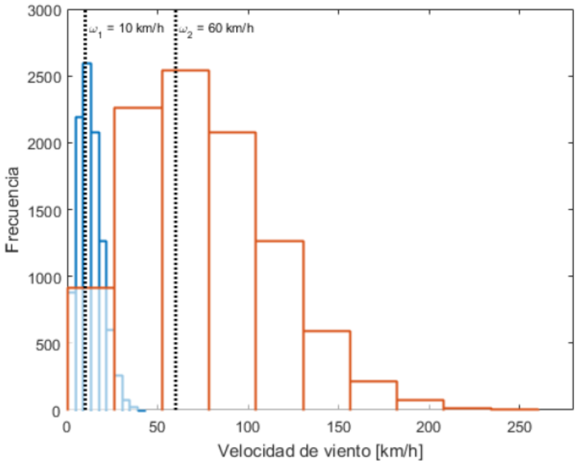


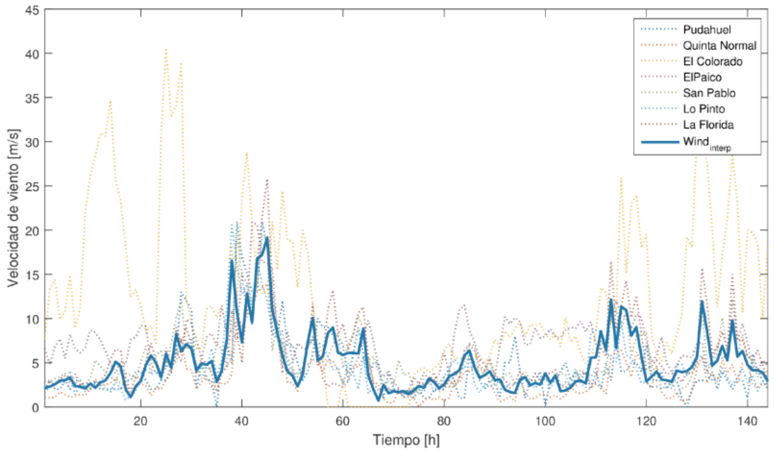


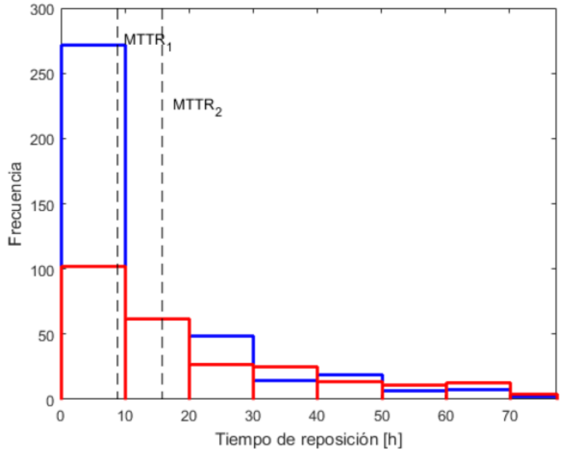


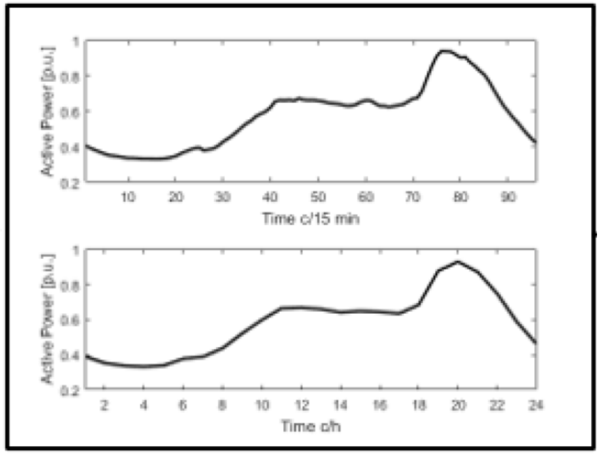
Reliability and resilience effectiveness



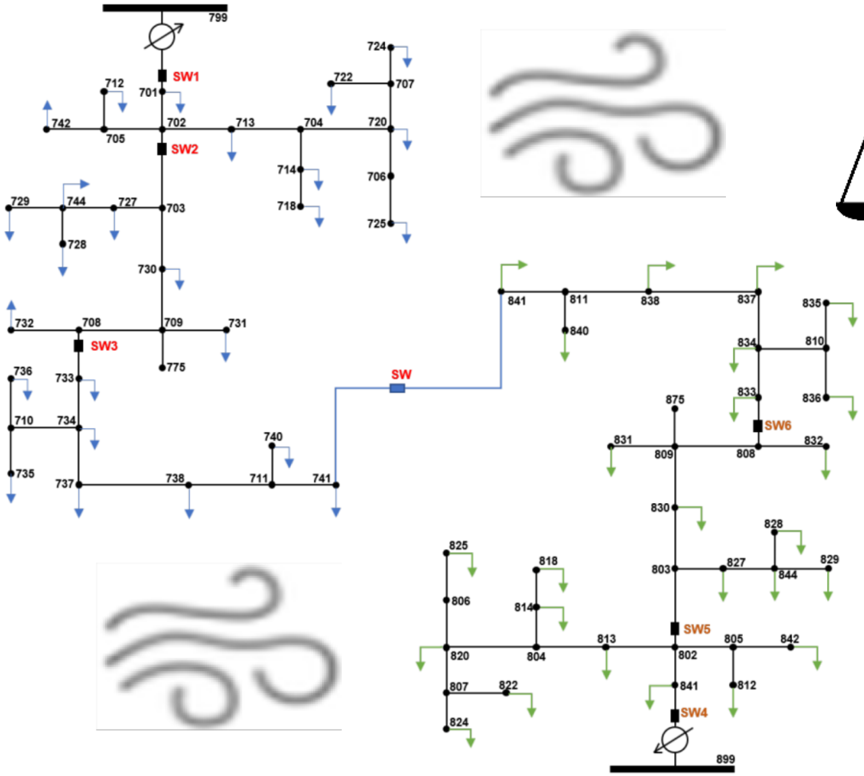








Reliability and resilience effectiveness



	EENS [MWh]	EENS [%]	CEENS [MWh]	CEENS [%]	Costo de Implementación [US$]
Caso Base (CB)	3.226	1.747	70.034	37.928	244.10
Seccionamiento 1 (Sw1)	2.767	1.498	58.254	31.548	457.44
Seccionamiento 2 (Sw2)	2.533	1.372	56.618	30.662	682.18
Seccionamiento 3 (Sw3)	2.197	1.190	54.646	29.594	906.92
Soterramiento 1 (Un1)	0.964	0.522	28.659	15.521	3,953.33
Soterramiento 2 (Un2)	0.514	0.278	14.730	7.977	5,933.45
Soterramiento 3 (Un3)	0.051	0.027	3.926	2.126	8,025.12
Almacenamiento 1 (BESS1)	2.953	1.599	66.224	35.865	2,772.44
Almacenamiento 2 (BESS2)	2.5891	1.402	63.716	34.506	5,300.78
Almacenamiento 3 (BESS3)	2.1284	1.153	59.9879	32.487	7,829.12

Case study 3: Wildfires

Example on wildfire in Chile

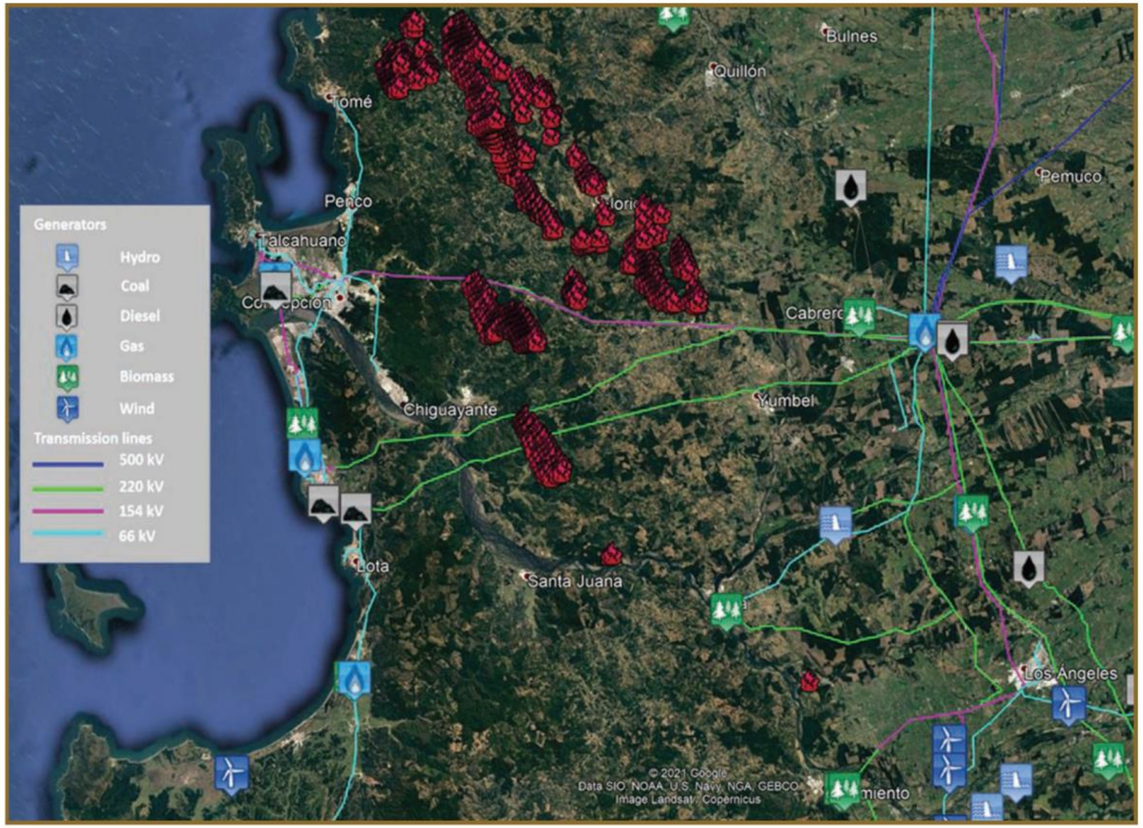


figure 7. A representation of wildfires in Chile on 26 January 2017.

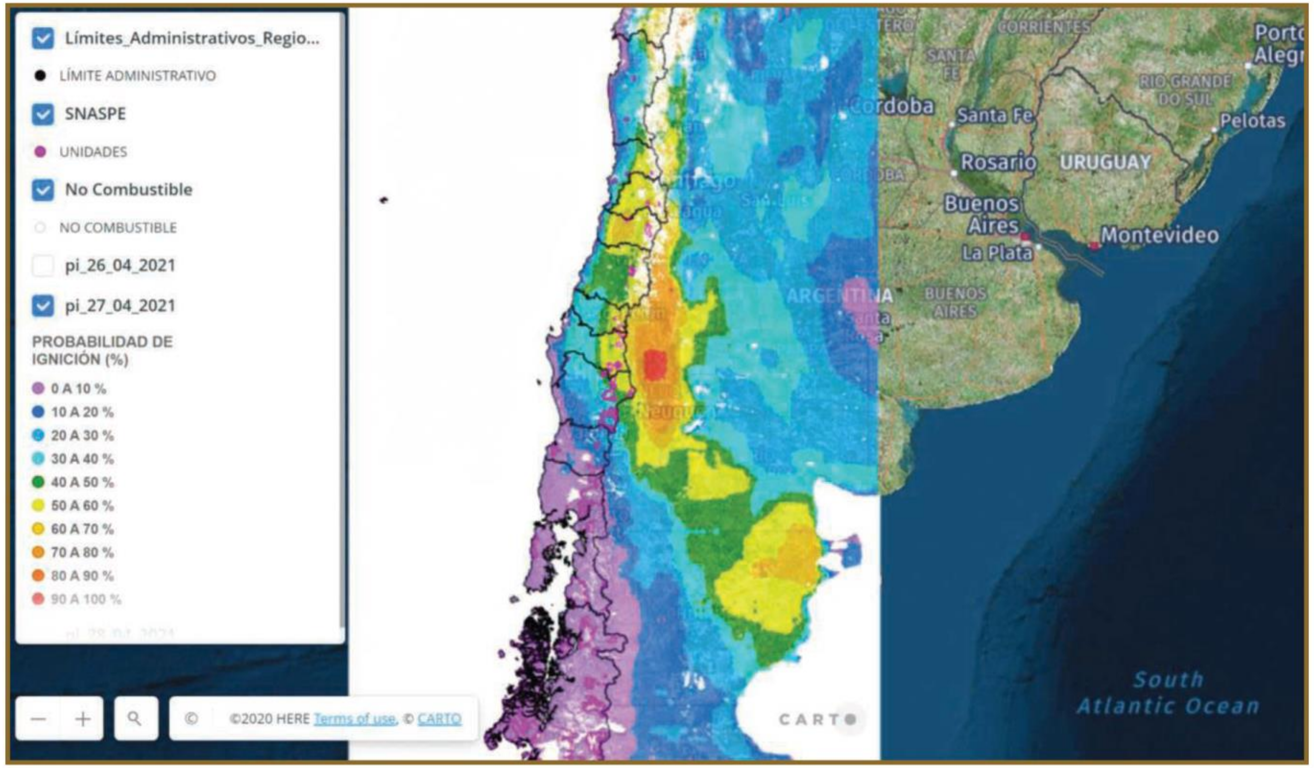


figure 6. The Forest Fire Ignition Probability Map, 27 April 2021. (Source: https://geprif.carto.com/.)

Moreno, R., Trakas, D. N., Jamieson, M., Panteli, M., Mancarella, P., Strbac, G., ... & Hatziargyriou, N. (2022). Microgrids Against Wildfires: Distributed Energy Resources Enhance System Resilience. IEEE Power and Energy Magazine, 20(1), 78-89.

Illustrative example – Optimal design

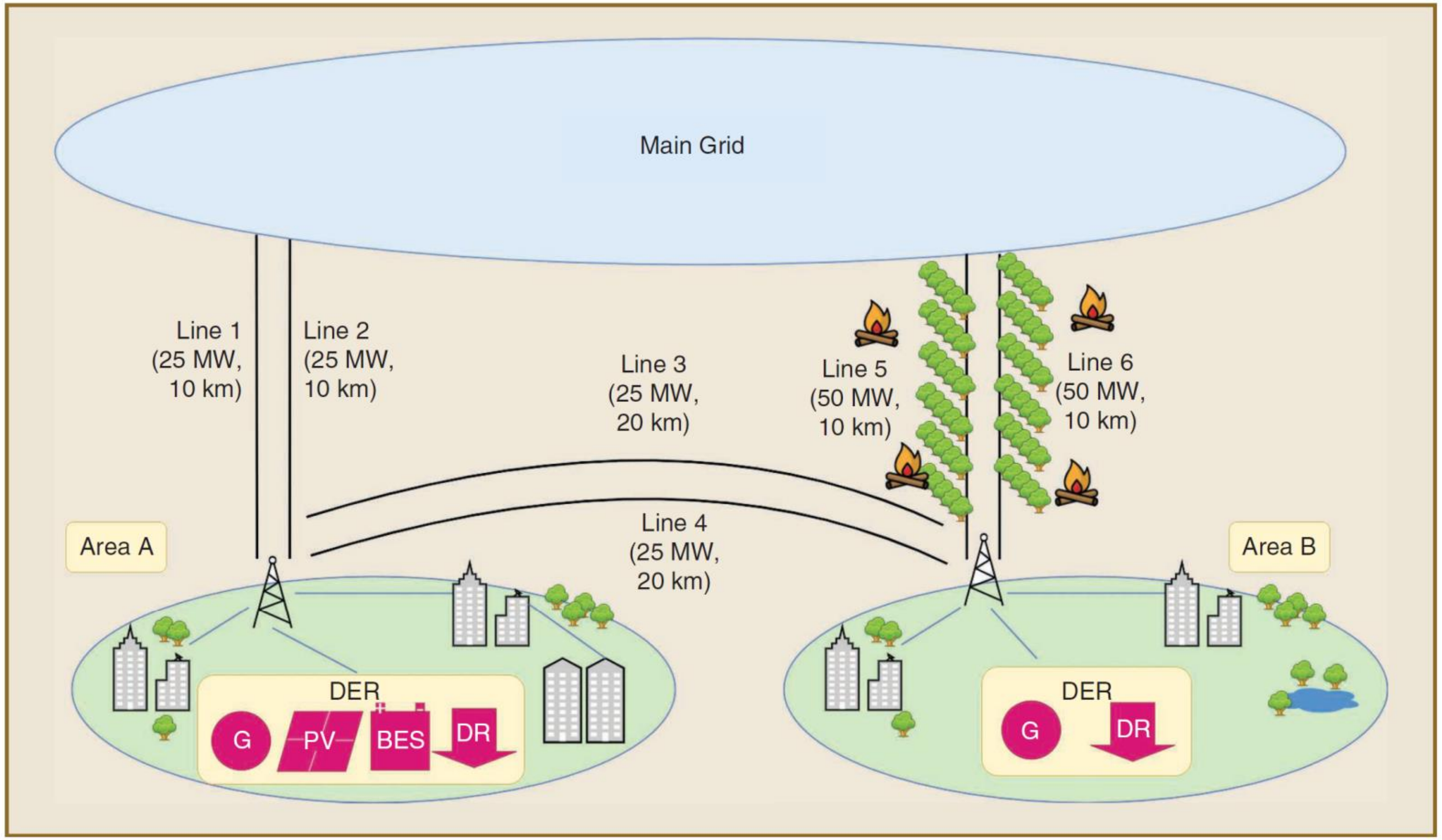


figure 8. The electricity network and DER candidates along with areas exposed to wildfires. BES: battery energy storage.

- ✔ *Preventive measures*: Investments in DER equipment such as storage plants, backup generation, and network investments. The model also finds the optimal volume of demand response contracted. These measures are made up front, precontingency, and thus are present in all scenarios.
- ✔ *Corrective measures*: These measures depend on the specific contingency and are scenario-dependent. We model two types of corrective measures, fast and slow:
  - *Fast*: Refers to the distribution system operation itself, including demand curtailments and a (smart) operation of system assets (topology control and dispatchable DER). These actions can occur right after a contingency occurs.
  - *Slow*: Installing and dispatching mobile DER. These actions feature a lag associated with the arrival of mobile equipment.

Moreno, R., Trakas, D. N., Jamieson, M., Panteli, M., Mancarella, P., Strbac, G., ... & Hatziargyriou, N. (2022). Microgrids Against Wildfires: Distributed Energy Resources Enhance System Resilience. IEEE Power and Energy Magazine, 20(1), 78-89.

Illustrative example – Results

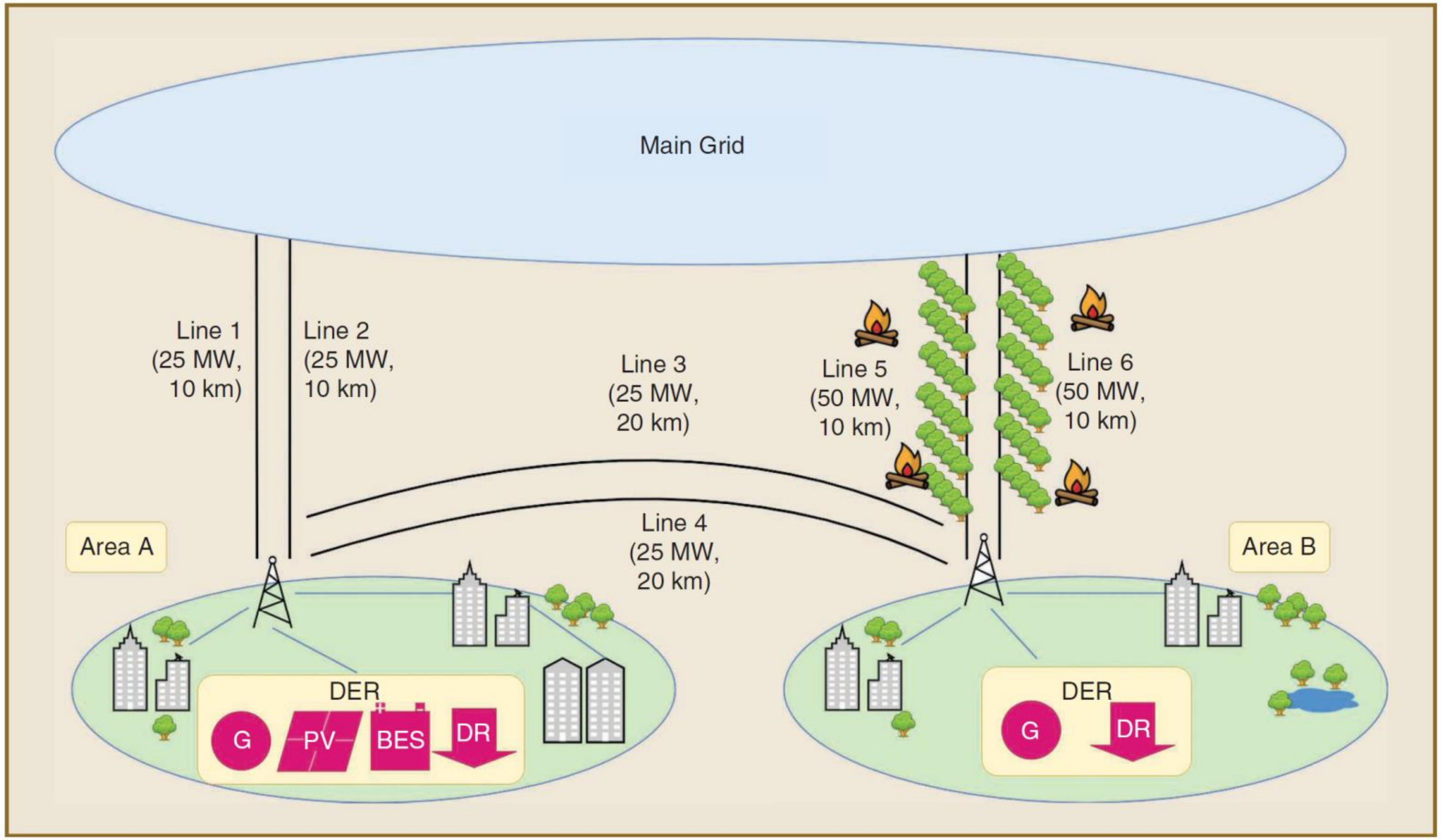


figure 8. The electricity network and DER candidates along with areas exposed to wildfires. BES: battery energy storage.

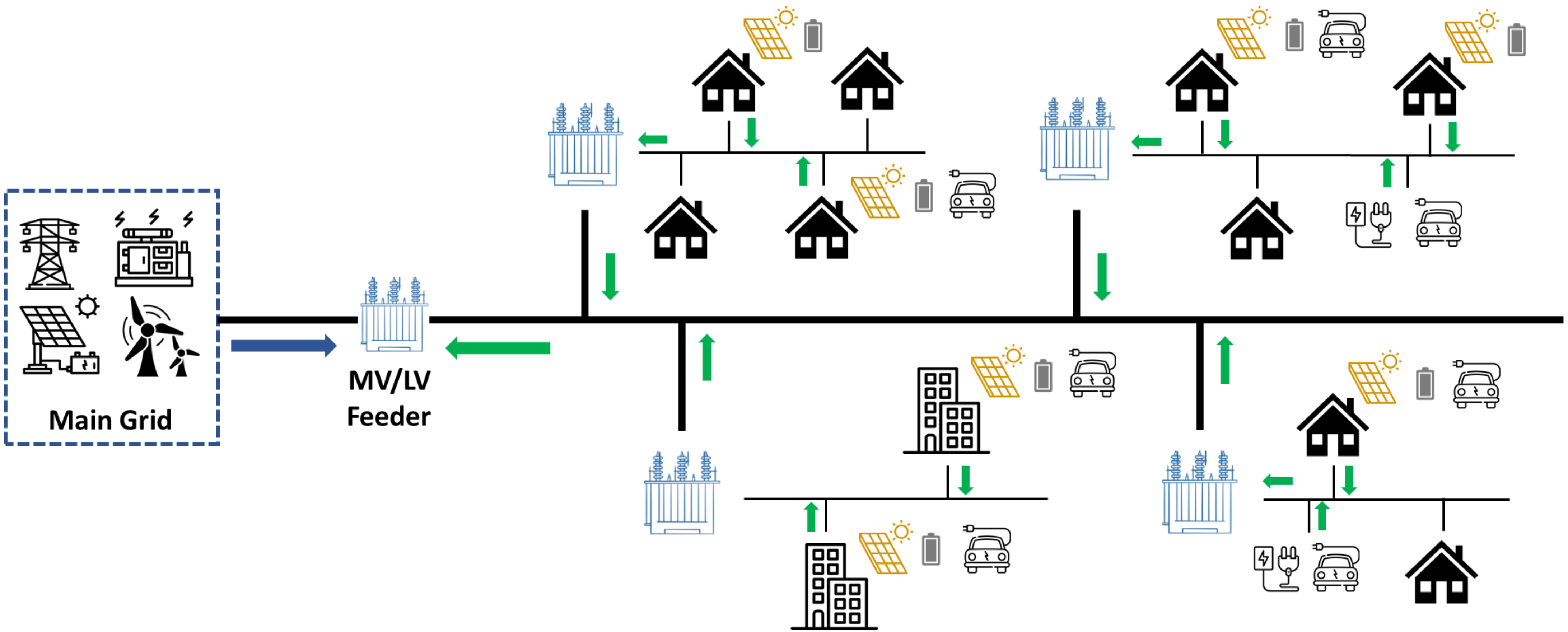
table 2. Results with costs in thousand U.S. dollars (kUS$) per year.

	N-1 Case A	Case A (Reevaluated)	Case B
Assets and measures	L1, L2, L5, L6, MG, DR	L1, L2, L5, L6, MG, DR	L1, L2, L3, L4, L5, PV, BES, MG, DR
PV + BES investment cost	—	—	11,500
Line investment cost	113	113	150
Operational cost	32,850	33,115	21,901
Lost-load cost	27	19,665	6
Total cost	32,990	52,893	33,558

L: line; MG: mobile generator.

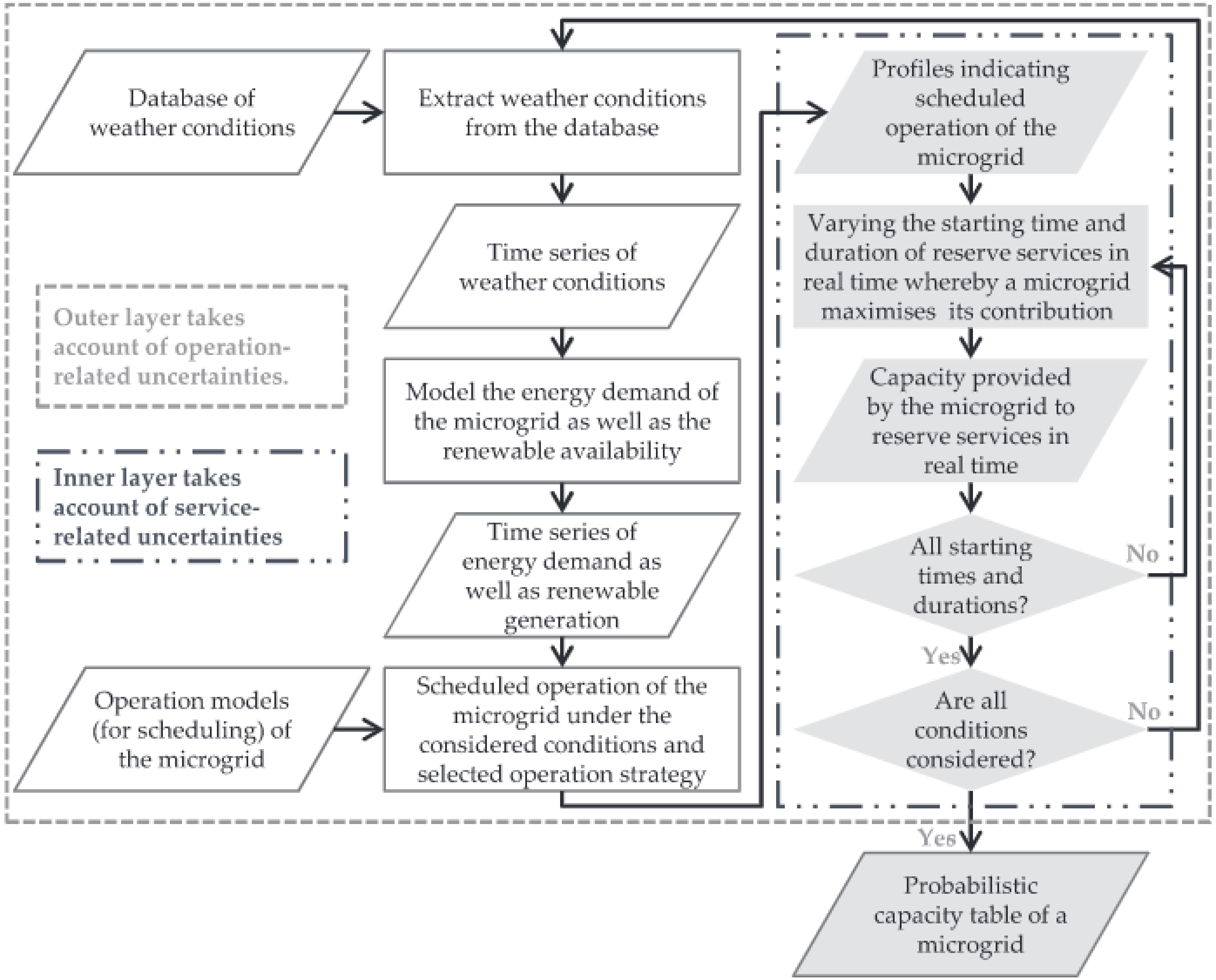
Moreno, R., Trakas, D. N., Jamieson, M., Panteli, M., Mancarella, P., Strbac, G., ... & Hatziargyriou, N. (2022). Microgrids Against Wildfires: Distributed Energy Resources Enhance System Resilience. IEEE Power and Energy Magazine, 20(1), 78-89.

System-Level Reliability and Resilience Services by Aggregated Distributed Energy Resources

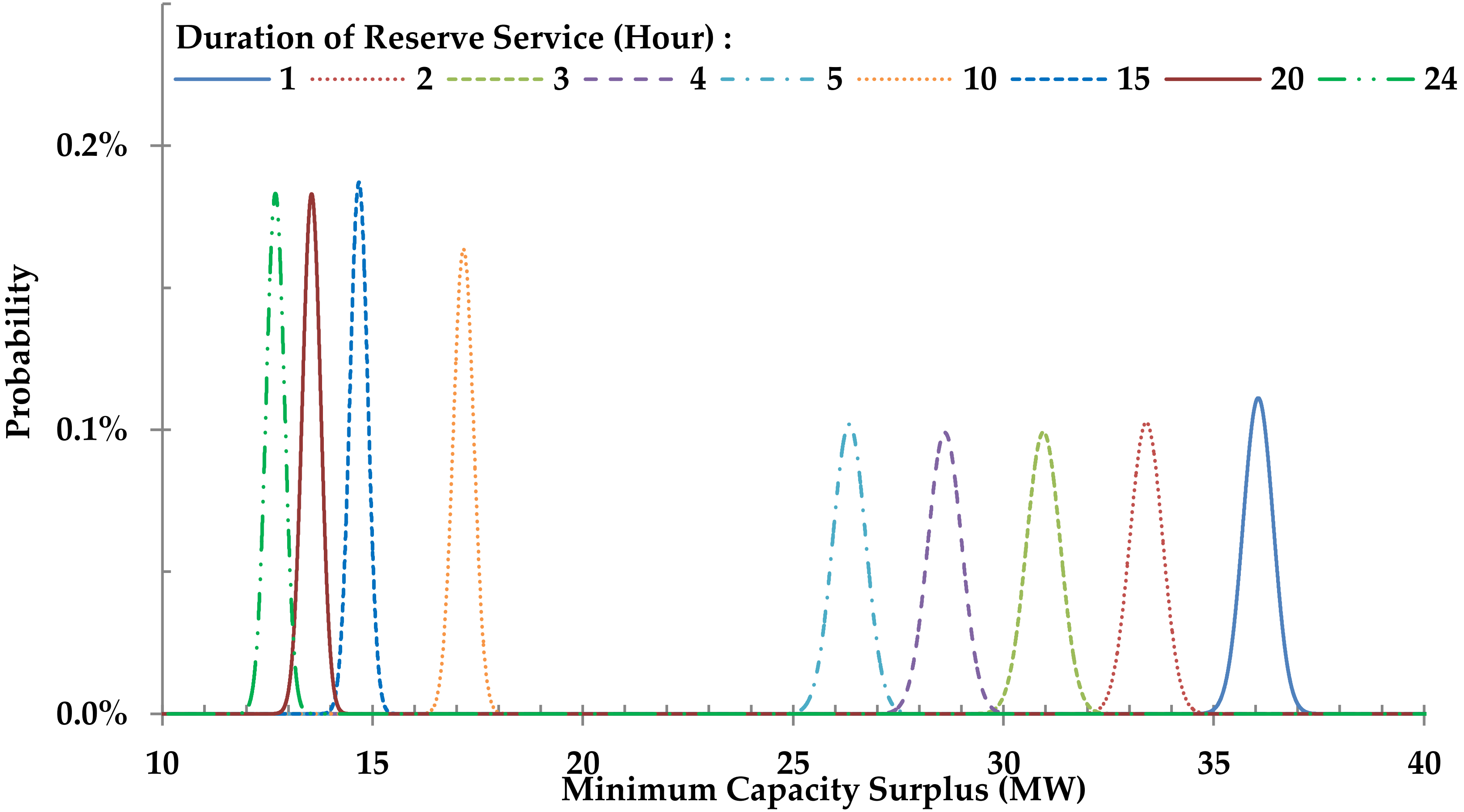


Y. Zhou, M. Panteli, R. Moreno and P. Mancarella, “System-Level Assessment of Reliability and Resilience Provision from Microgrids”, Applied Energy, Vol. 230, November 2018

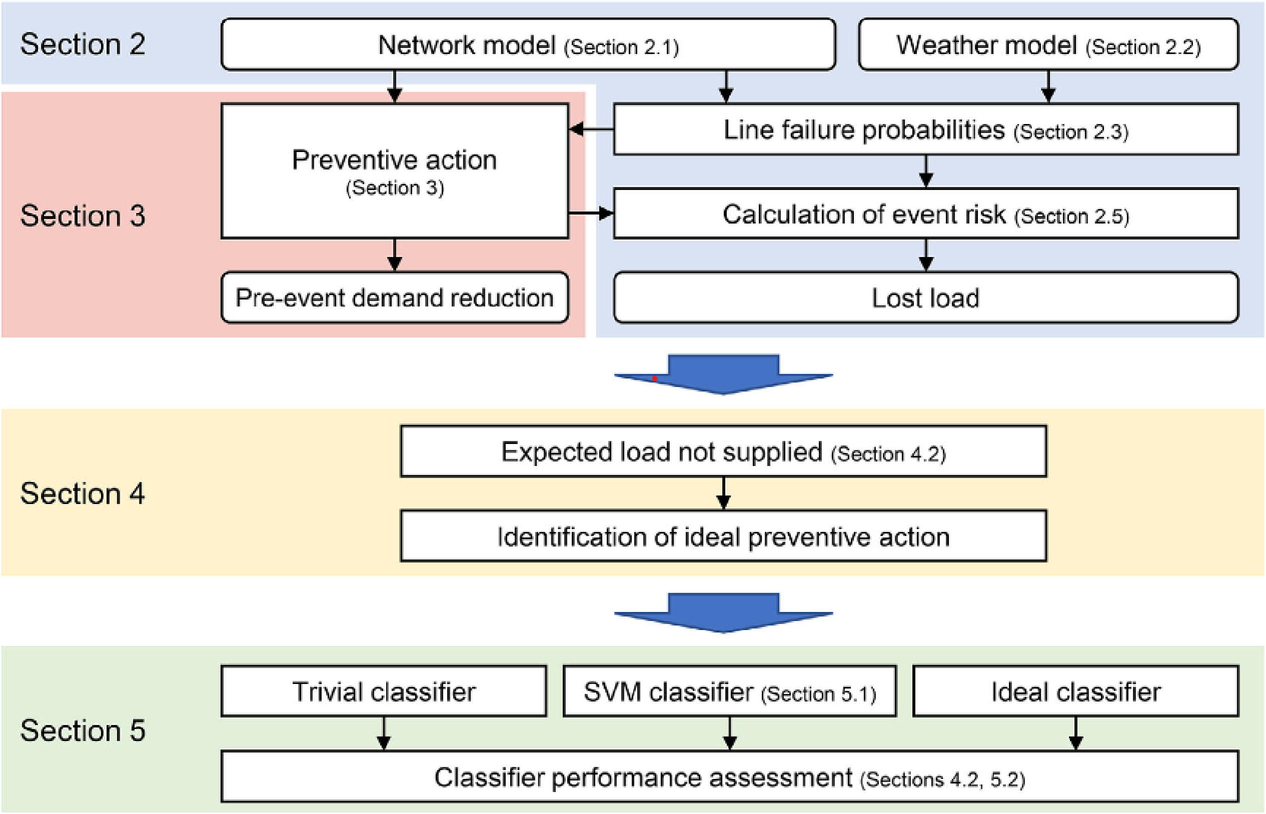
System-Level Reliability and Resilience Services by Aggregated Distributed Energy Resources

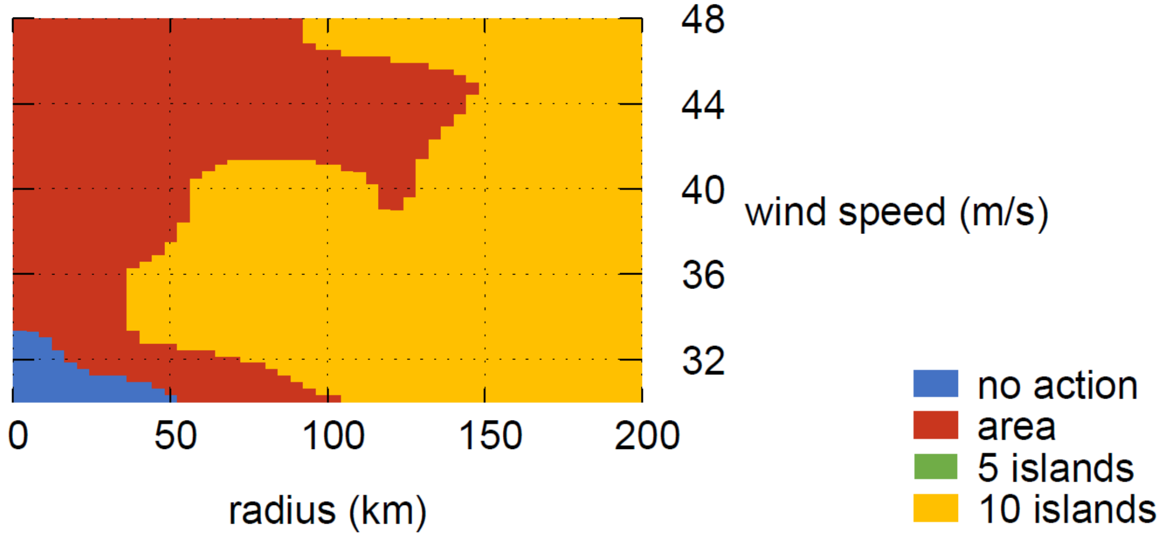


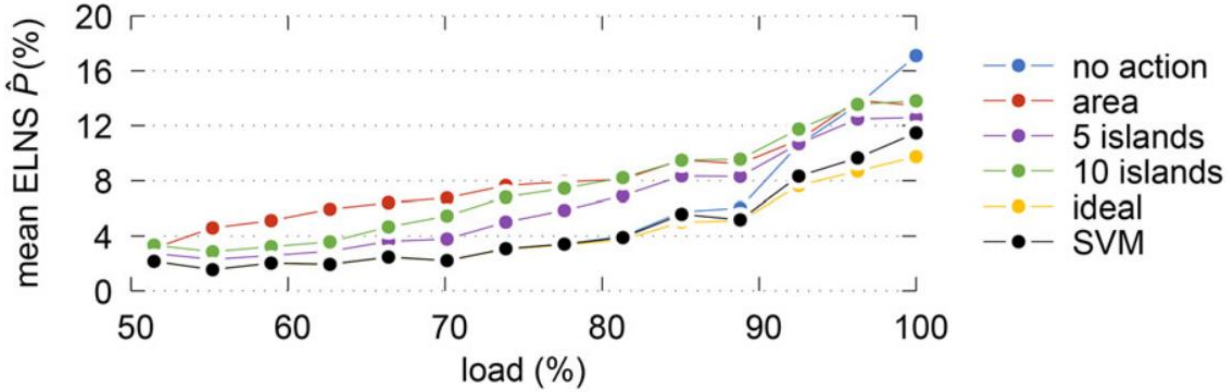
System-Level Reliability and Resilience Services by Aggregated Distributed Energy Resources



Machine-Learning Driven Operational Decision-Making

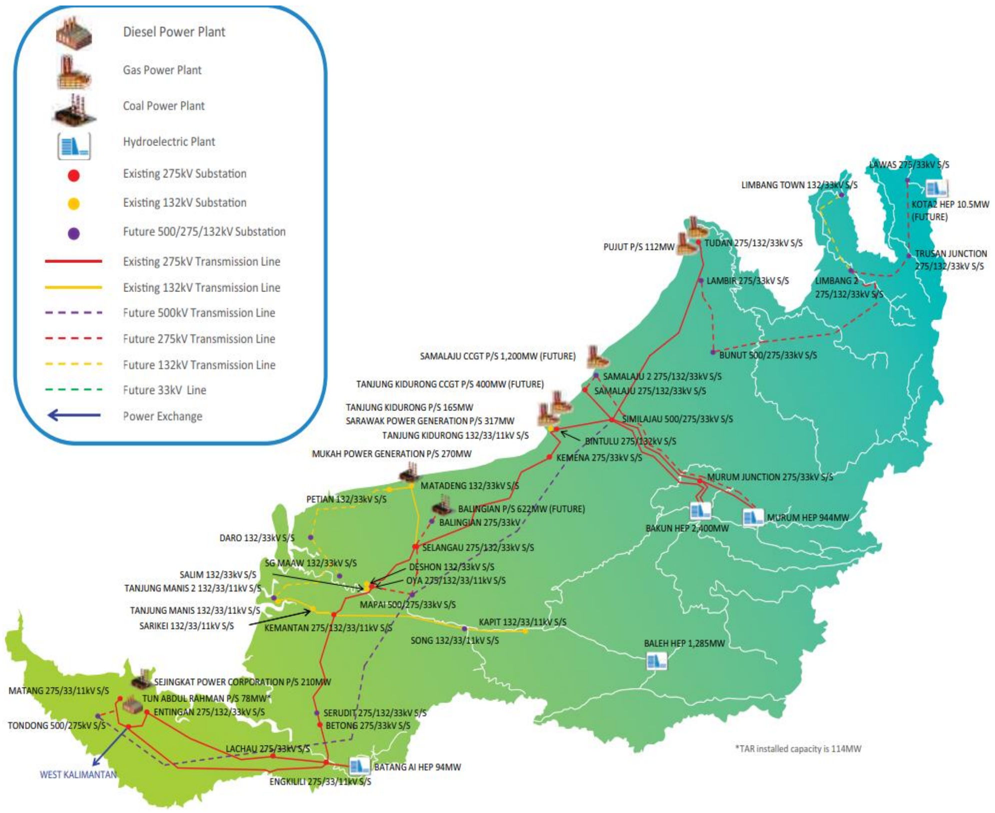






M. Noebels, R. Preece, and M. Panteli, "A Machine Learning Approach for Real-time Selection of Preventive Actions Improving Power Network Resilience", Early Access, IET Generation, Transmission and Distribution, October 2021

Applications to Borneo Island, Malaysia – Resilient Electrification Planning



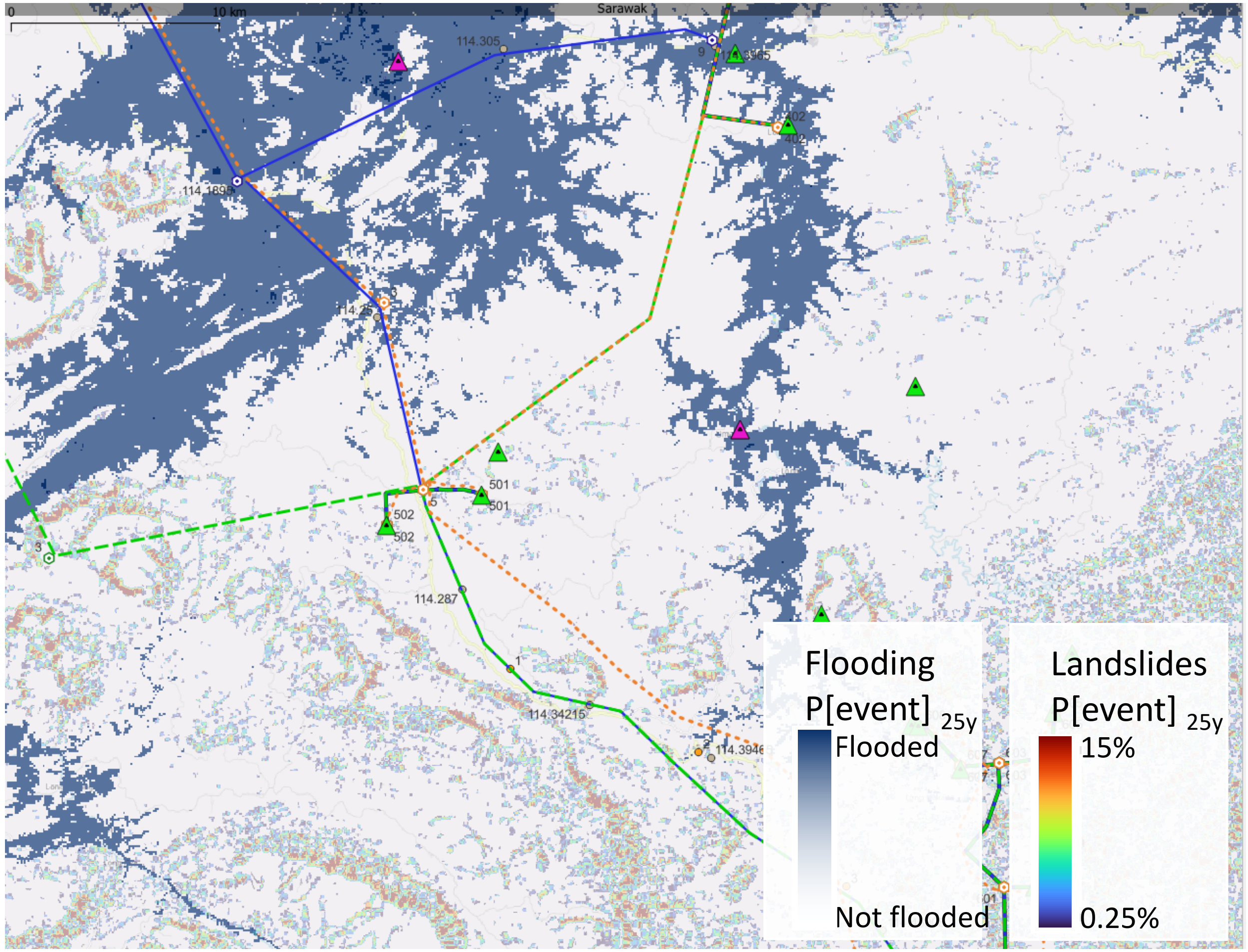
Area of interest: Sarawak Power Generation and Network

Energy planning considering:

- Grid expansion vs off-grid applications
- Hybrid micro-grids based on renewable energy sources
- Considering geographical conditions and road access
- Estimation of energy demand for lighting, cooking, power
- Analysis of social impacts from energy access, e.g. health, education, employment and economic benefits
- Examination of community organisation and its relationship to energy infrastructure
- ***Single and Multi-hazard risk analysis***

Landslides and flooding

- There can be trade-offs between the exposure to different hazards, e.g., areas with lower flooding risks may experience higher landslide risks



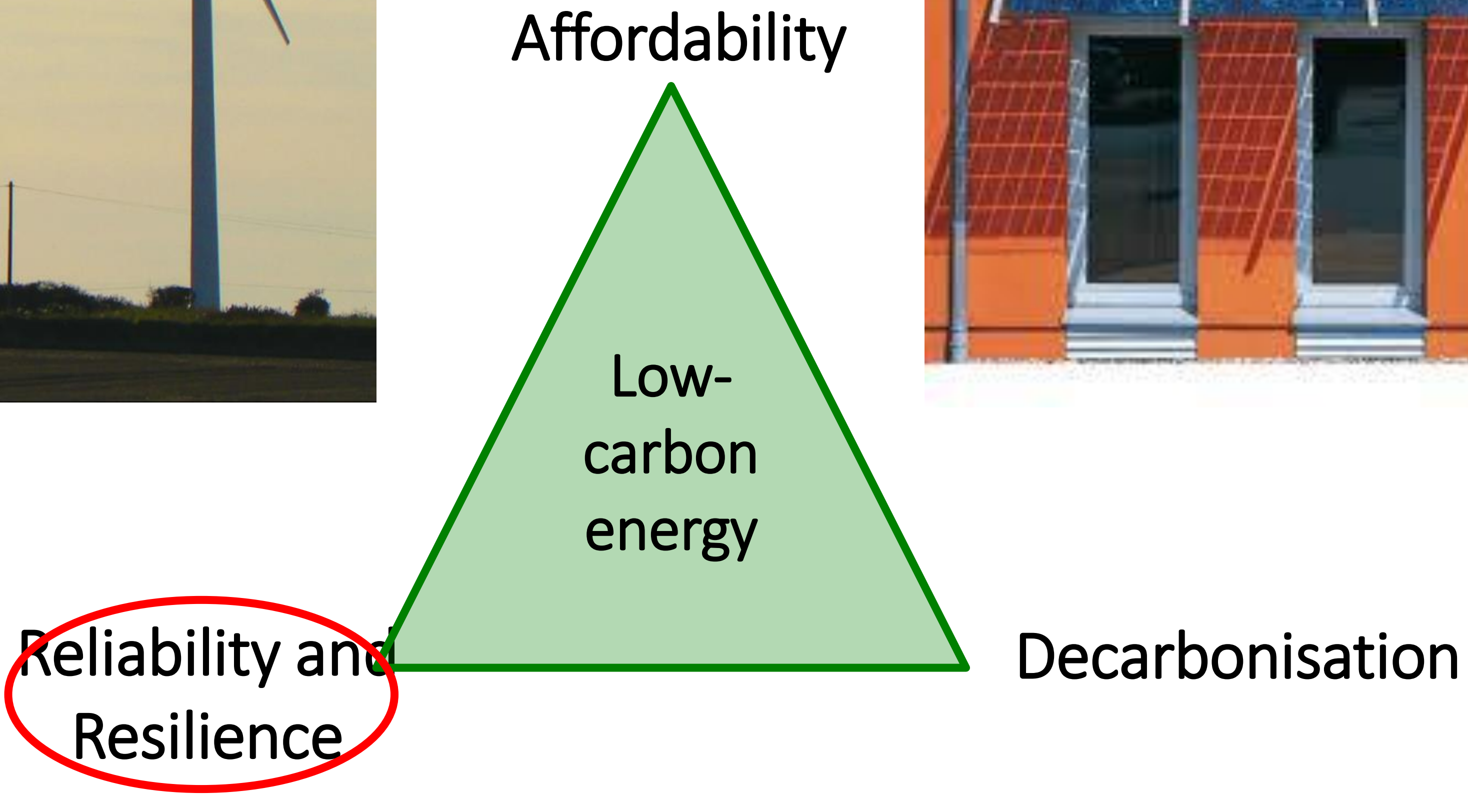
Scenarios:

1. Access – following existing roads
2. Avoiding areas with moderate/high risk of landslides
3. Avoiding areas with moderate/high risk of flooding

$$\boldsymbol{Risk = P[event] \cdot Consequence}$$

Consequence → Likelihood ↓	Extremely high	Very high
Probable (>10%)	High	Moderate
Likely (> 1%)	Moderate	Moderate
Unlikely (< 1%)	Low	Low

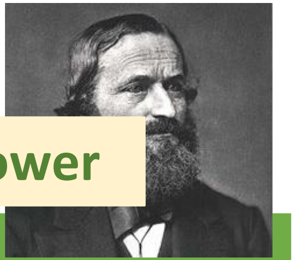
Worried about delivering a low-carbon energy system?



Low-carbon grids are more fragile… and so less secure and resilient!

- The transition to synchronously-decoupled technology introduces never-before seen **technical scarcities** (e.g., inertia, system strength)
- Power system parameters are increasingly **interactive, uncertain and unpredictable** – with potential for co-optimization but also undesired cross-service effects
- Interactions between **old electro-mechanical and new power electronic control** systems need to be understood in detail
- **New technology** has the potential to offer solutions, but requires careful **technical design** and **regulatory and/or market incentives** to implement
- **New operational mechanisms** also need to be put in place to incentivise optimal solutions and identify the true trade-offs

Fragility of a low-carbon grid

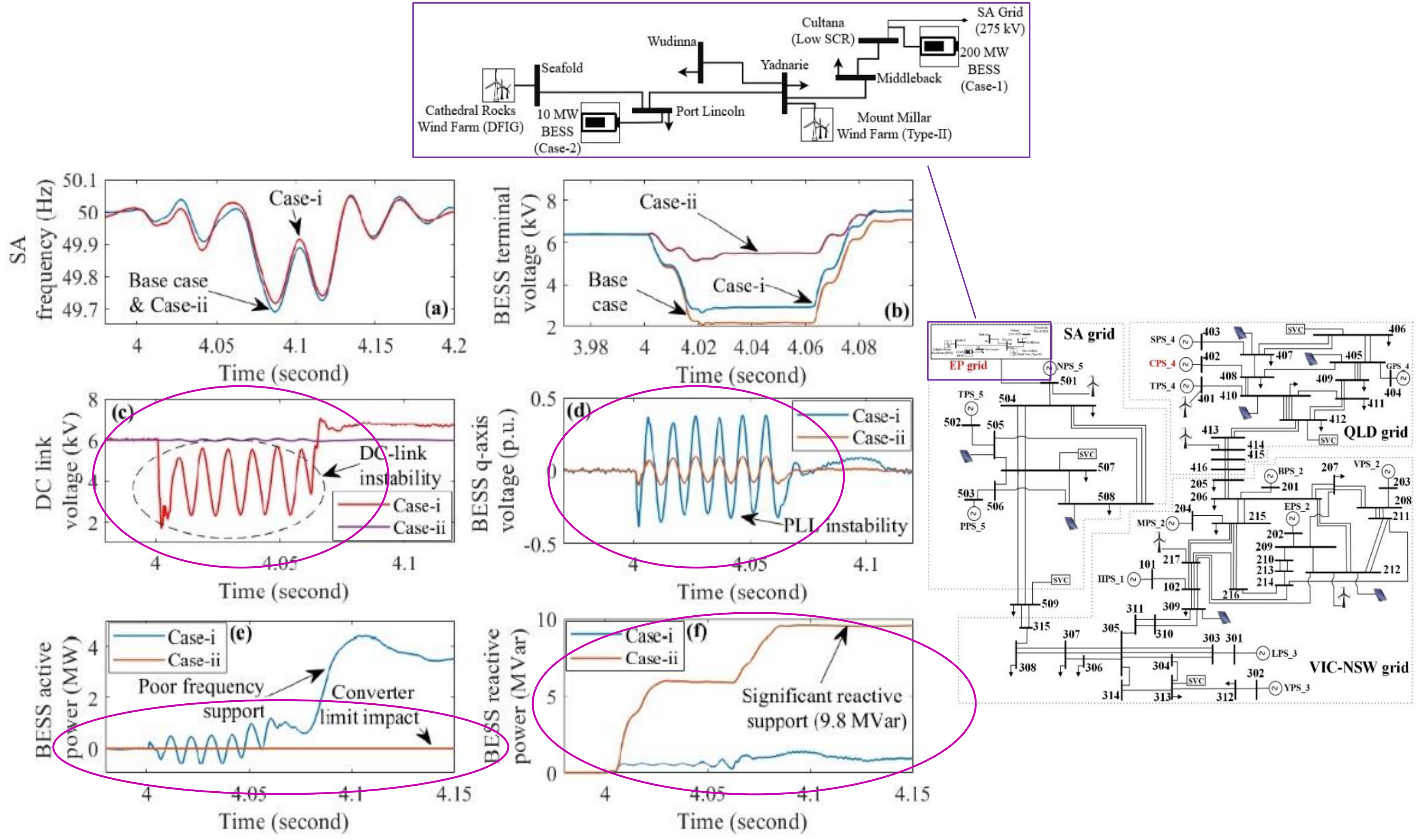


Increasing links between different dynamic phenomena and active and reactive power

Risk	Emerging issues	Possible Mitigations
Frequency control and inertia	- Sustained frequency excursions (regulation) - High Rate of Change of Frequency (ROCOF) following contingency - Insufficient regional inertia - Insufficient Primary Frequency Response (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) - Distribution System Operation and Distributed Energy Marketplaces
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

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

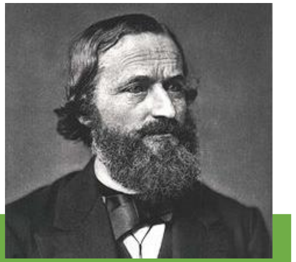
Interaction between active and reactive power services



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

Fragility of a low-carbon grid



Increasing need for frequency control services of different types

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) - Distribution System Operation and Distributed Energy Marketplaces
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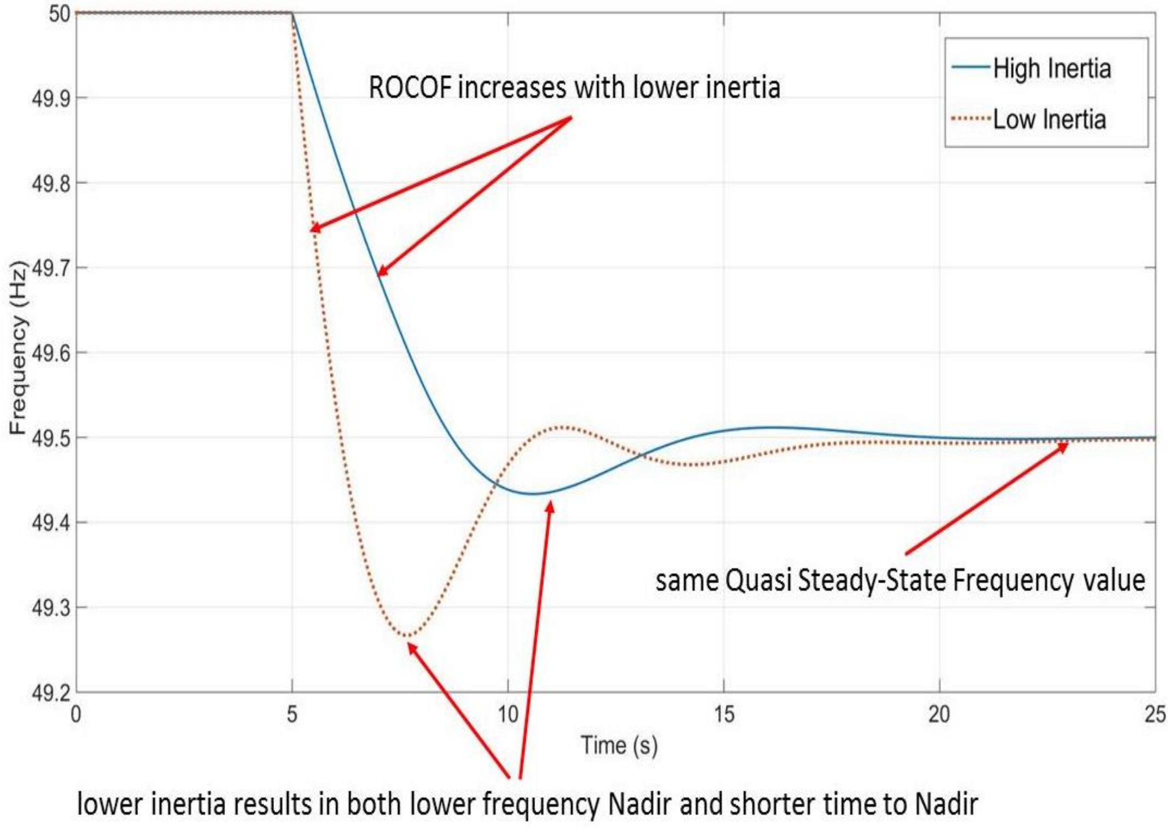
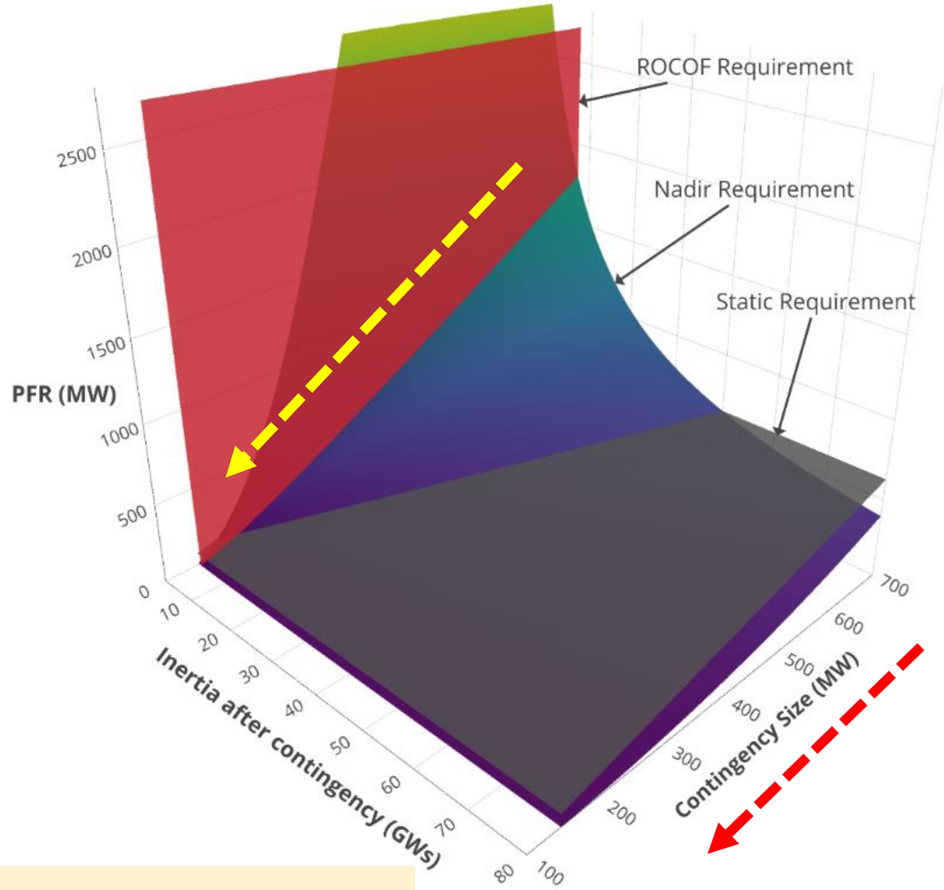
Source: P. Mancarella and F. Billimoria, 'The Fragile Grid – Physics and economics of security services in low-carbon power systems: The case of Australia", *IEEE Power and Energy Magazine*, 2021

Interaction between multiple frequency control services

Trade-off between inertia, frequency response, and contingency size

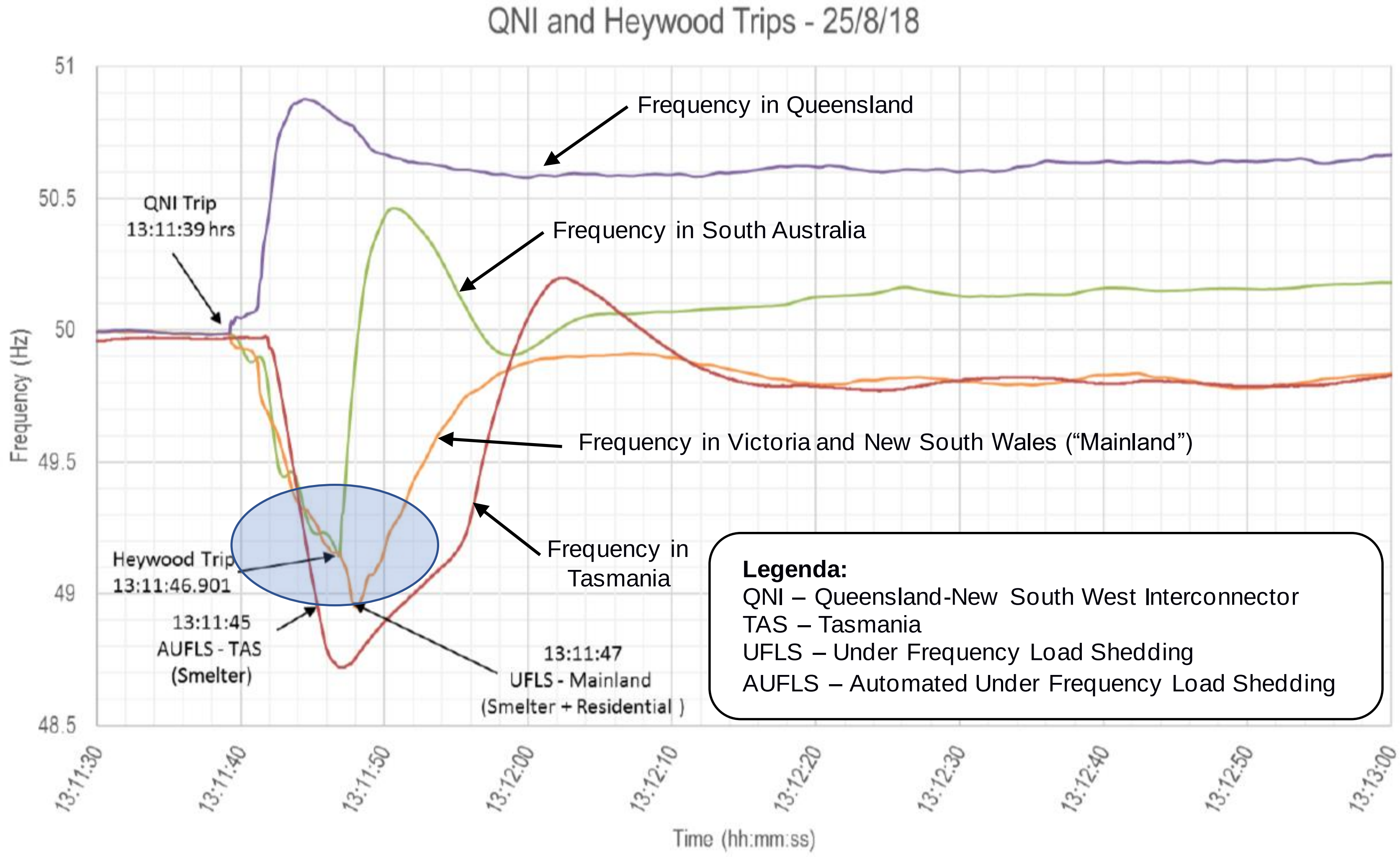




Much tighter link between energy and security services

Reference: 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

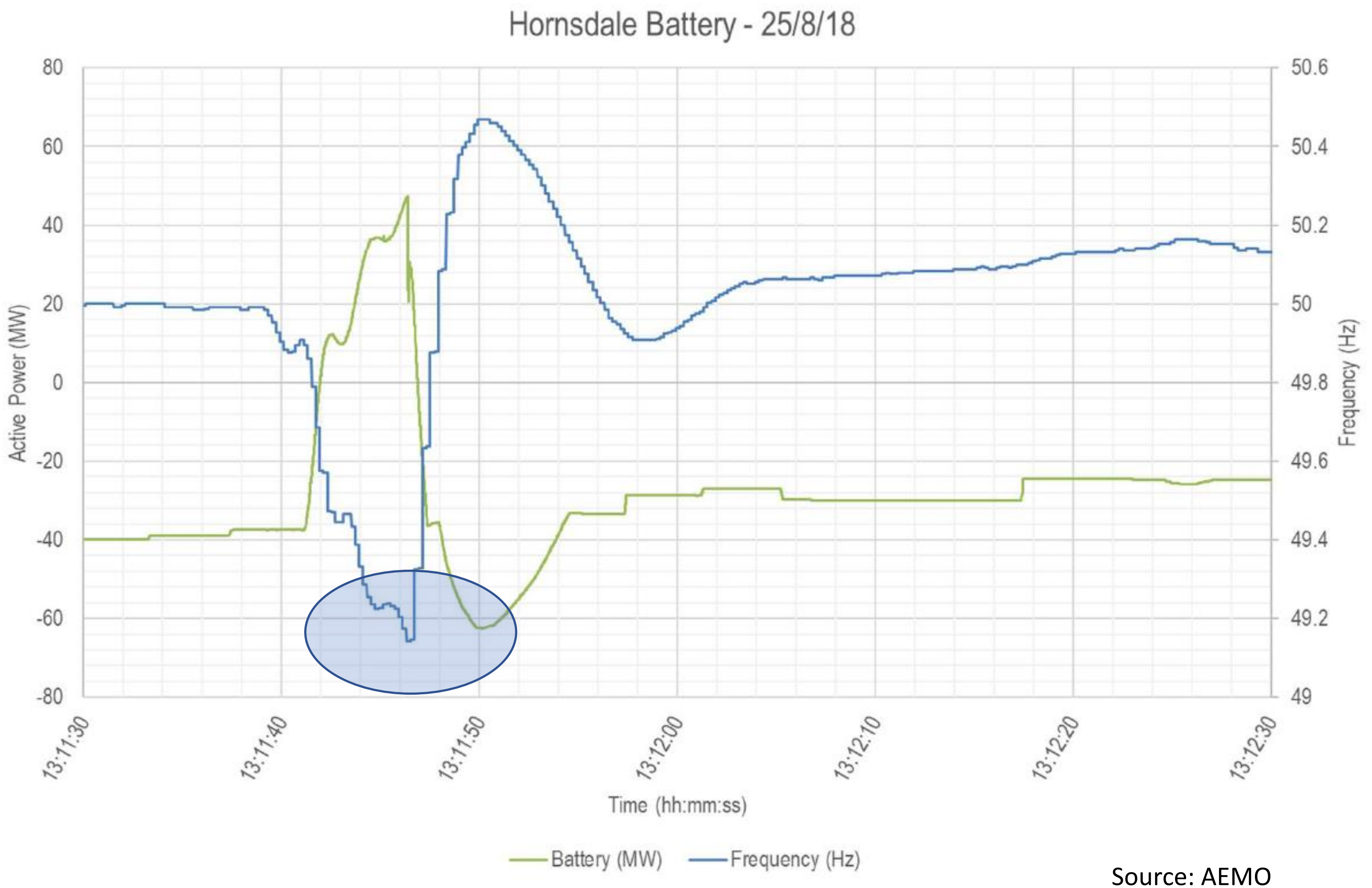
Case Study: Australia cascading and separation event 25 Aug 18



Source: AEMO

- Lightning strikes tripped the transmission interconnector between Queensland (QLD) and New South Wales (NSW), leaving QLD as an island
- QLD experienced over-frequency conditions while the remainder of the NEM experienced low frequency
- Generators in South Australia (SA), including Hornsdale battery, increased output to restore system frequency, which led to a rapid rise in active power flowing through SA-Victoria interconnector
- The interconnector eventually tripped due to dynamic protection mechanisms, 8s after the QLD-NSW trip

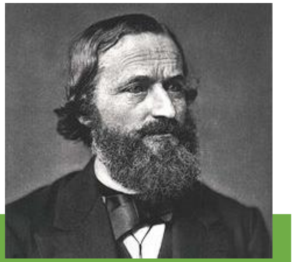
Role of new technologies: Did it provide resilience or make it worse?



Source: AEMO

- 100MW/129MWh Hornsdale Power Reserve
- Super-rapid response (FFR) to low frequency condition in South Australia, but…
- Was the response too fast?
- Activation of protection relays, and interconnector trips
- Overall role is unclear, but emphasizes need for inter-regional co-ordination and analysis

Fragility of a low-carbon grid



Increasing need for forecasting and DER visibility

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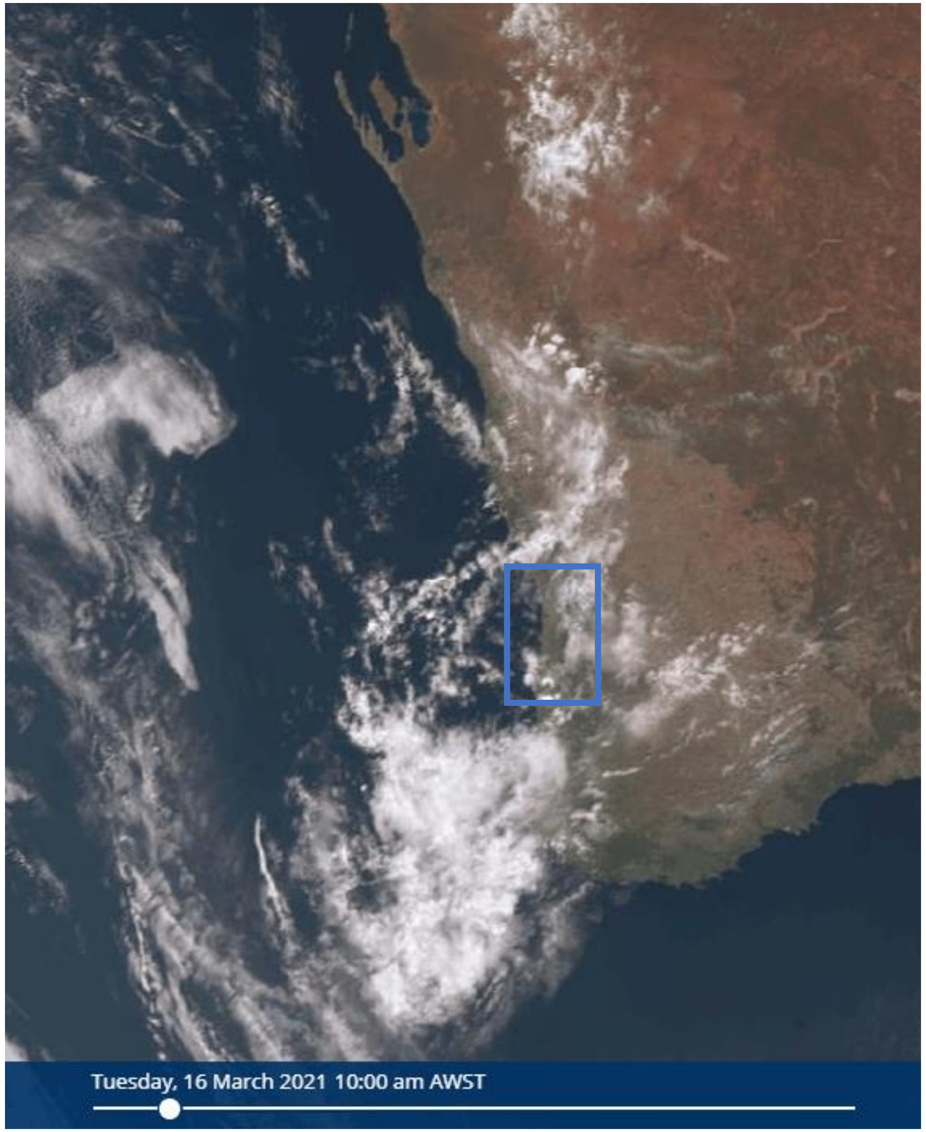
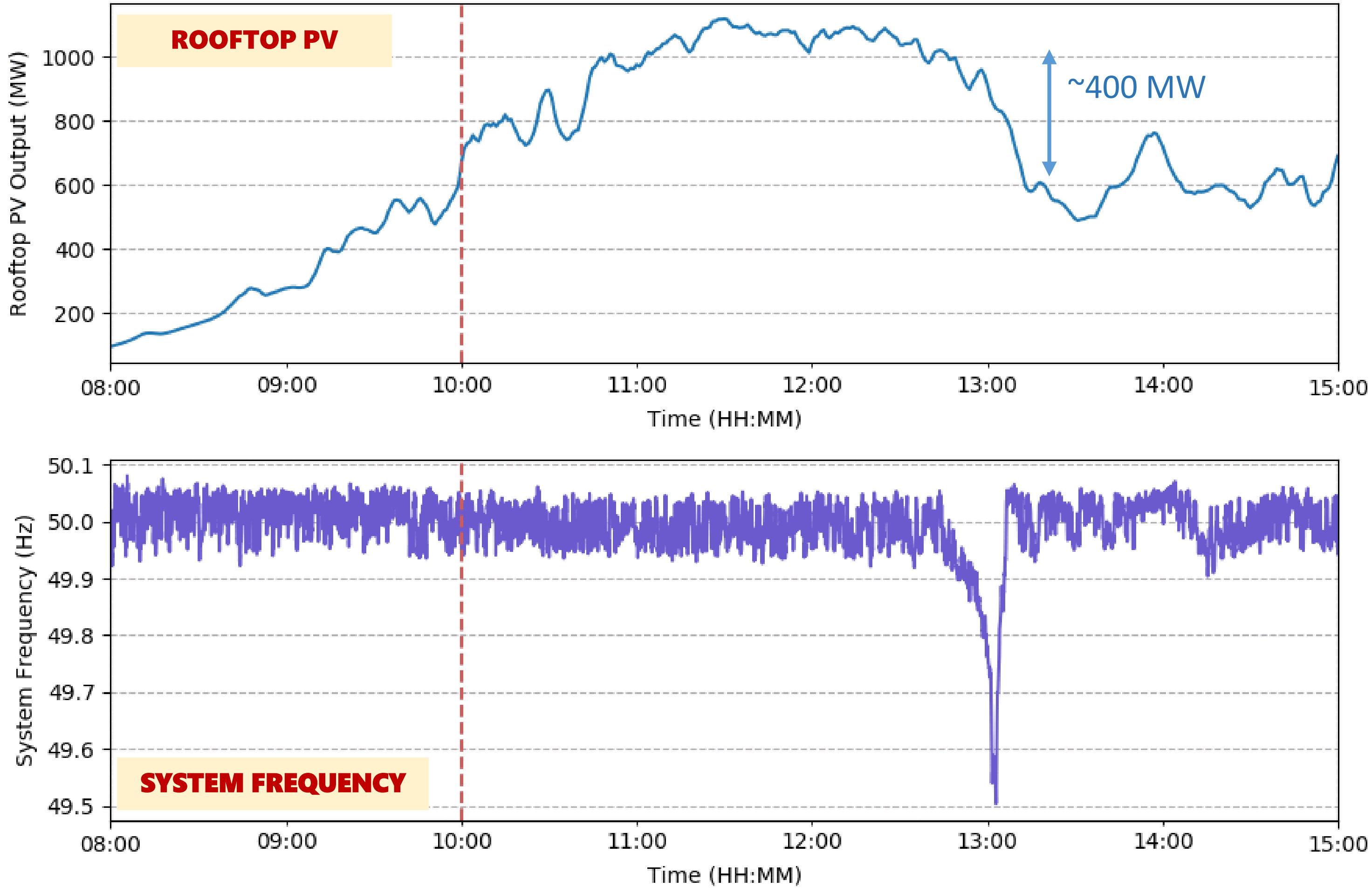
Source: P. Mancarella and F. Billimoria, 'The Fragile Grid – Physics and economics of security services in low-carbon power systems: The case of Australia", *IEEE Power and Energy Magazine*, 2021

Case study: Rapid cloud formation in Western Australia, 16 March 2021



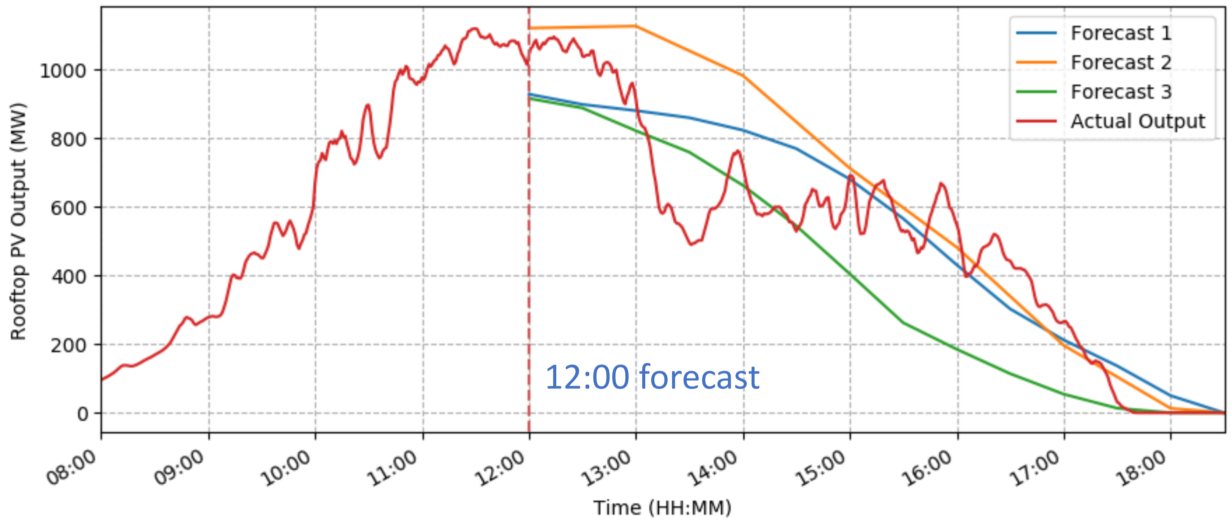


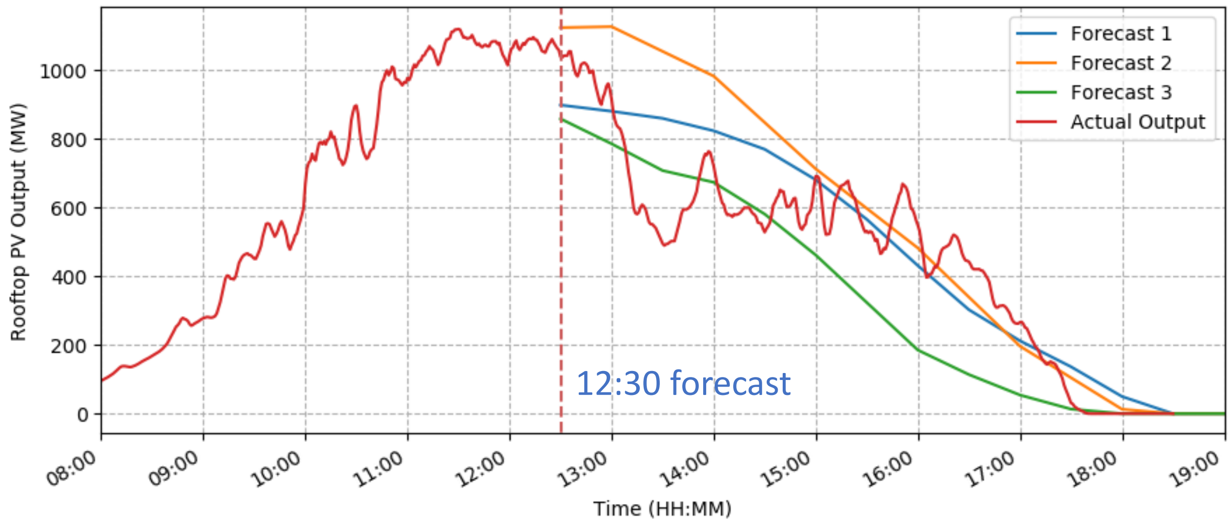
Slide courtesy of Julius Susanto, AEMO and AEMC

Case study: Rapid cloud formation in Western Australia, 16 March 2021

- AEMO real-time control has access to continuous data feeds from several weather forecast providers for short-term rooftop PV forecasts in the Western Australia grid

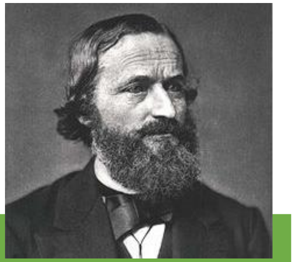
- During this event, the 1-hour or 30-min ahead forecasts did not provide any indication of the severity of the PV output reduction





Slide courtesy of Julius Susanto, AEMO and AEMC

Fragility of a low-carbon grid



Increasing need for "extreme event" and "cascading" predictors

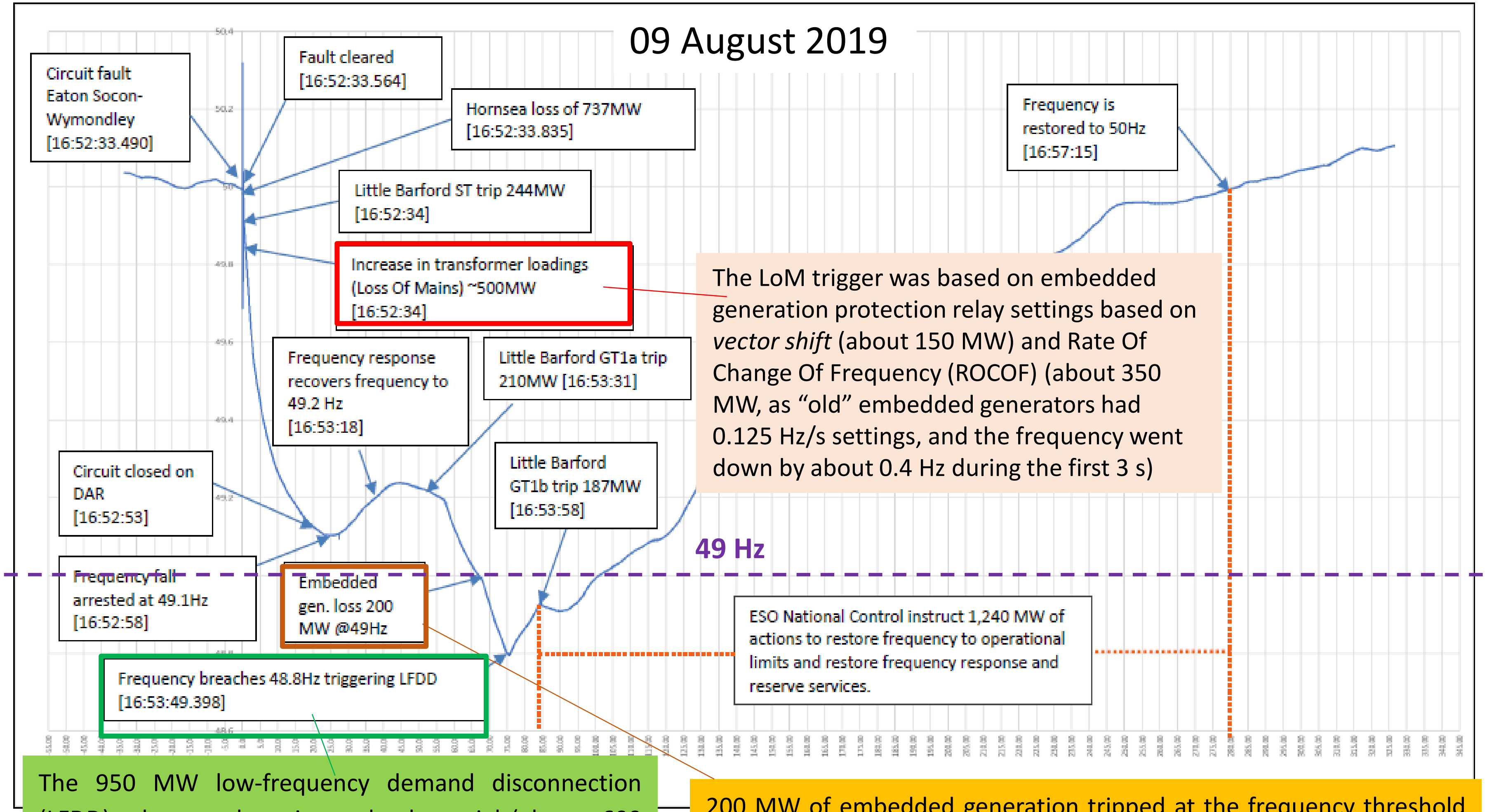
Risk	Emerging issues	Possible Mitigations
Frequency control and inertia	- Sustained frequency excursions (regulation) - High ROCOF following contingency - Insufficient regional inertia - Insufficient PFR - Risk of low-inertia and insufficient PFR after separation	- Minimum inertia levels - Compulsory 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
Vari… uncertainty and visibility	- Visibility of Distributed Energy Resources (DER)	…s) - Use of more flexible resources including energy storage (e.g., pumped hydro) - Distribution System Operation and Distributed Energy Marketplaces
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

In a fragile grid, security and resilience "blend"

See also: 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

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

Case study example: demand disconnection event in the UK

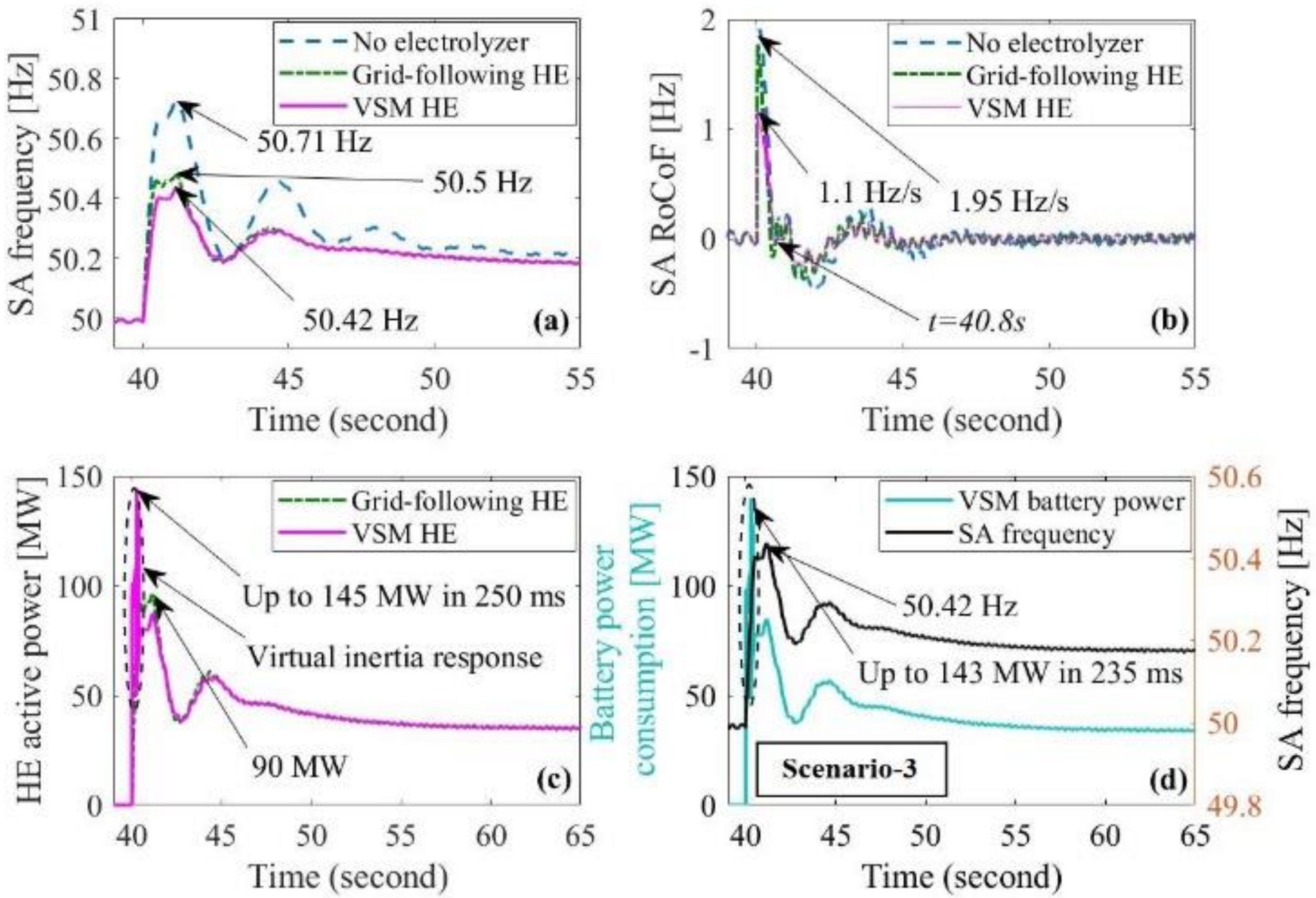


The 950 MW low-frequency demand disconnection (LFDD) schemes also triggered substantial (almost 600 MW!) embedded generation disconnection, so that the net demand disconnection was actually only 350 MW

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

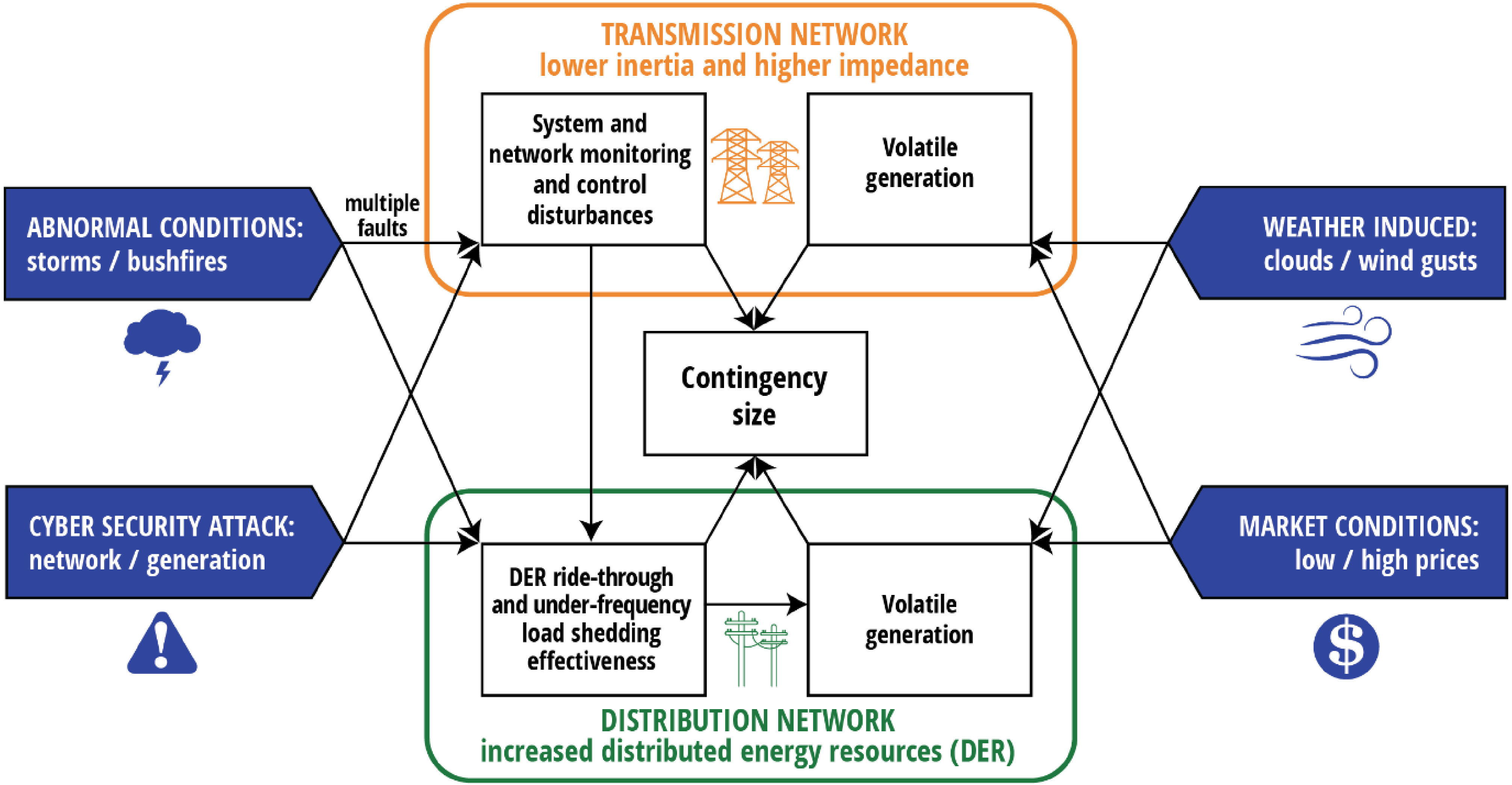
Resilience from new technologies: not only batteries



M. Ghazavi Dozein, A. M. De Corato, P. Mancarella, "Virtual Inertia Response and Frequency Control Ancillary Services from Hydrogen Electrolyzers", *IEEE Transactions on Power Systems*, 2022

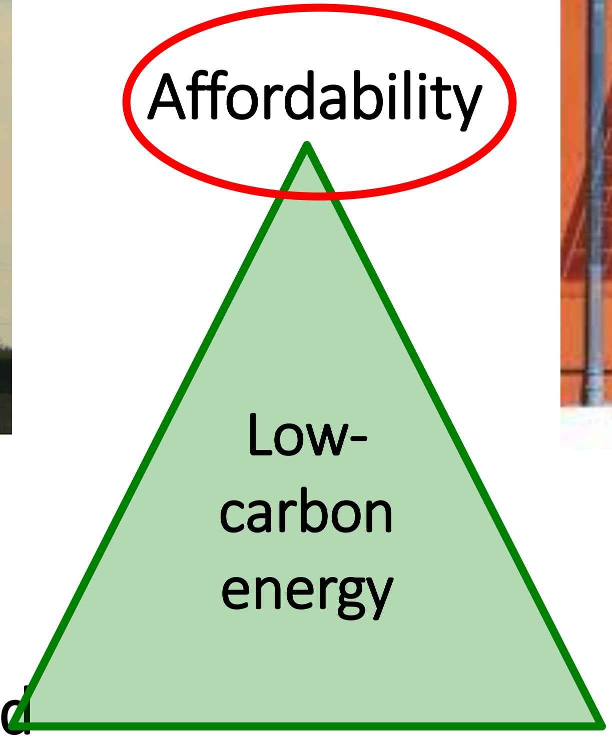
M. Ghazavi, A. Jalali, and P. Mancarella, "Fast frequency response from utility scale hydrogen electrolysers", *IEEE Trans. Sustainable Energy*, 2021

Need for resilience in low-carbon grids



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

Worried about delivering a low-carbon energy system?



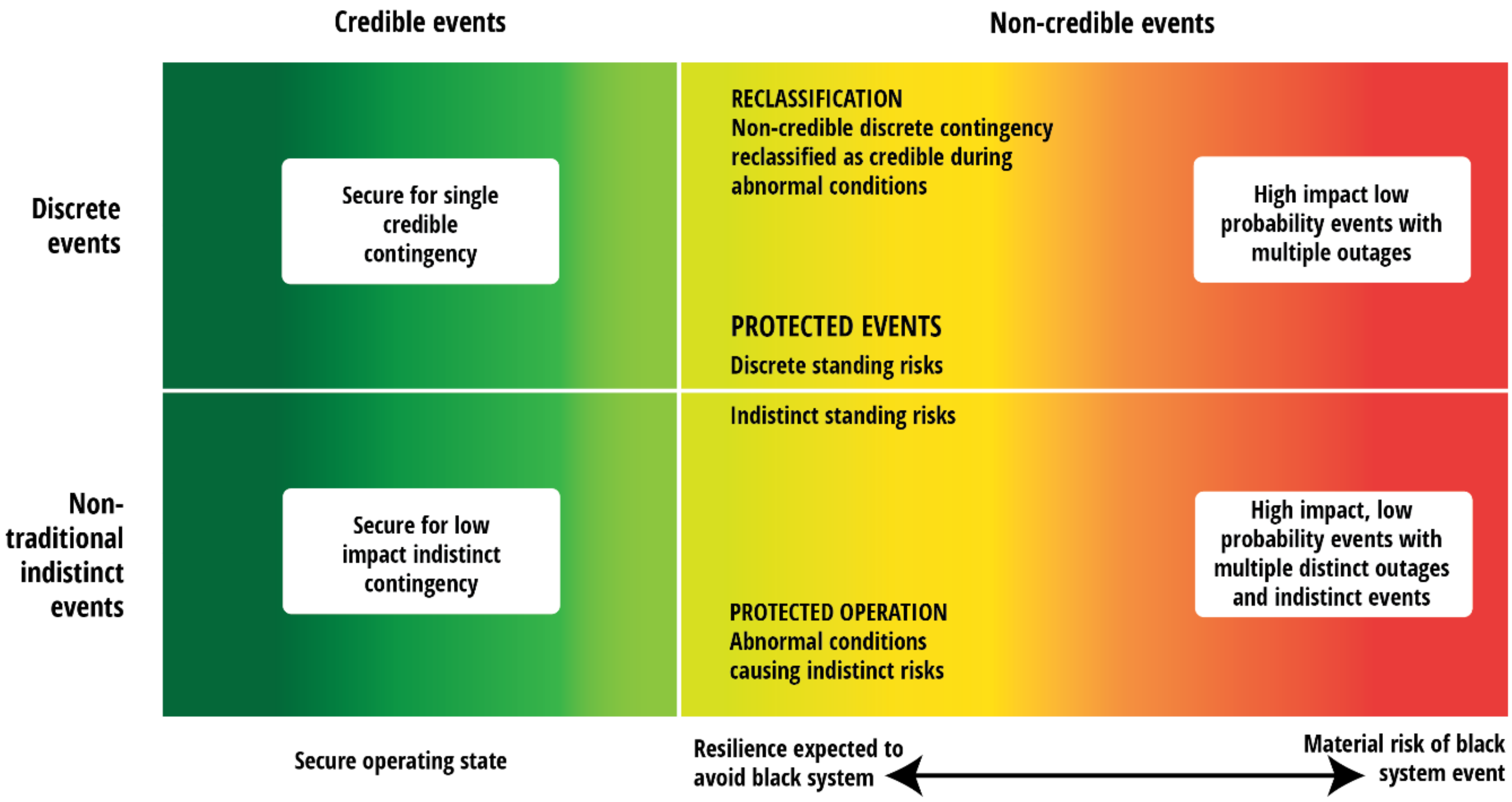
Worried about delivering a low-carbon energy system?

- Well, it’s not only about engineering…

- The system’s ‘new physics’ has direct impacts on the **economics** given the multitude of grid services with differing characteristics
  - ***A failure to link technical requirements to economics risks incentive-incompatible market design***

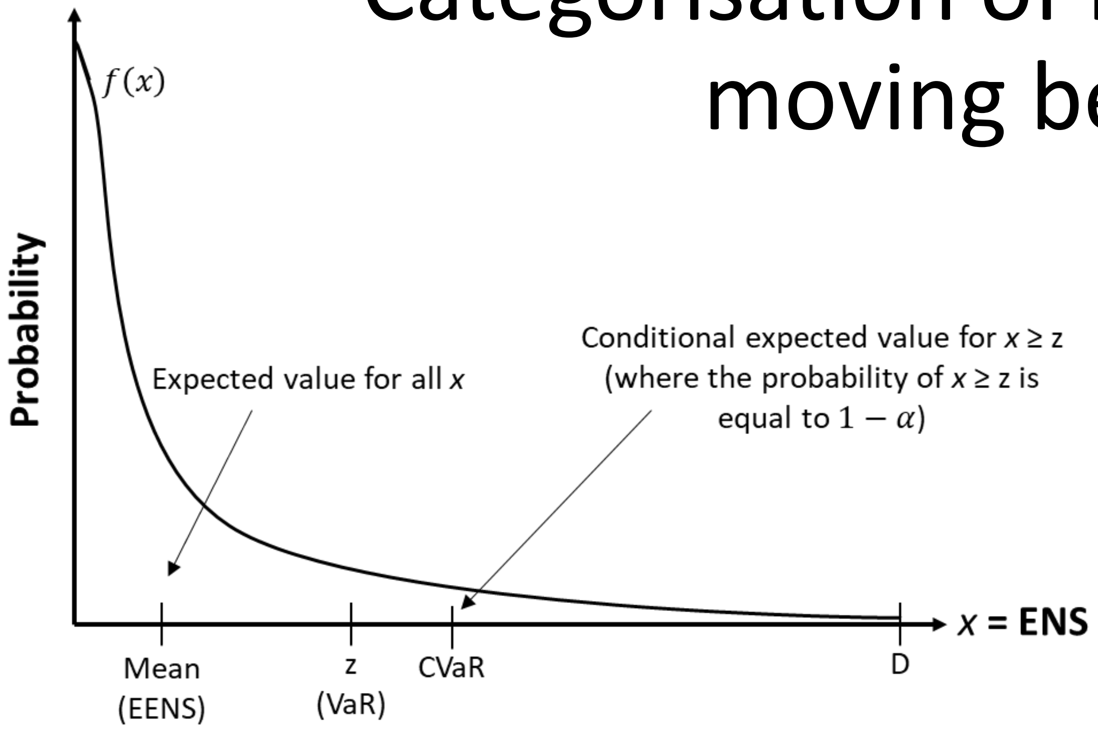
- Suitable technical, commercial, regulatory, and policy measures need to be put in place in a coherent manner

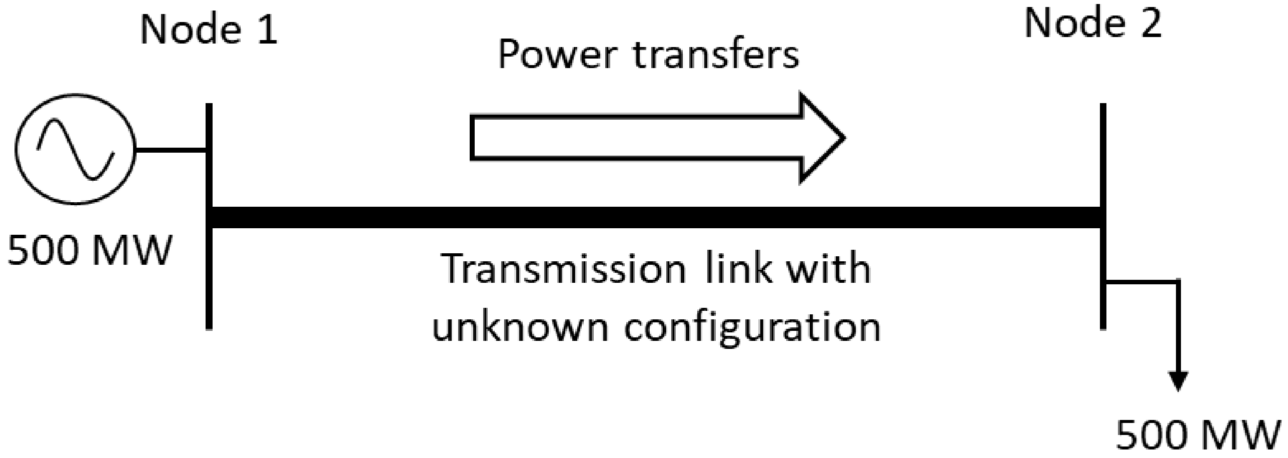
Categorisation of new, "resilience" events: moving beyond *security*



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

Categorisation of new, "resilience" events: moving beyond *adequacy*





Metric	N-0 base case	N-1	N-0 shorter repair time	N-0 underground
VoLL x EENS [$]	538,532	38,464	470,506	280,428
VoLL x CVaR [$]	4,113,206,199	3,846,412,398	2,690,095,838	2,837,833,988
Probability of double outage under adverse weather [%]	7.7%	7.7%	2.0%	2.6%

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

Recognising complementarity and competition between network and non-network solutions in providing resilience

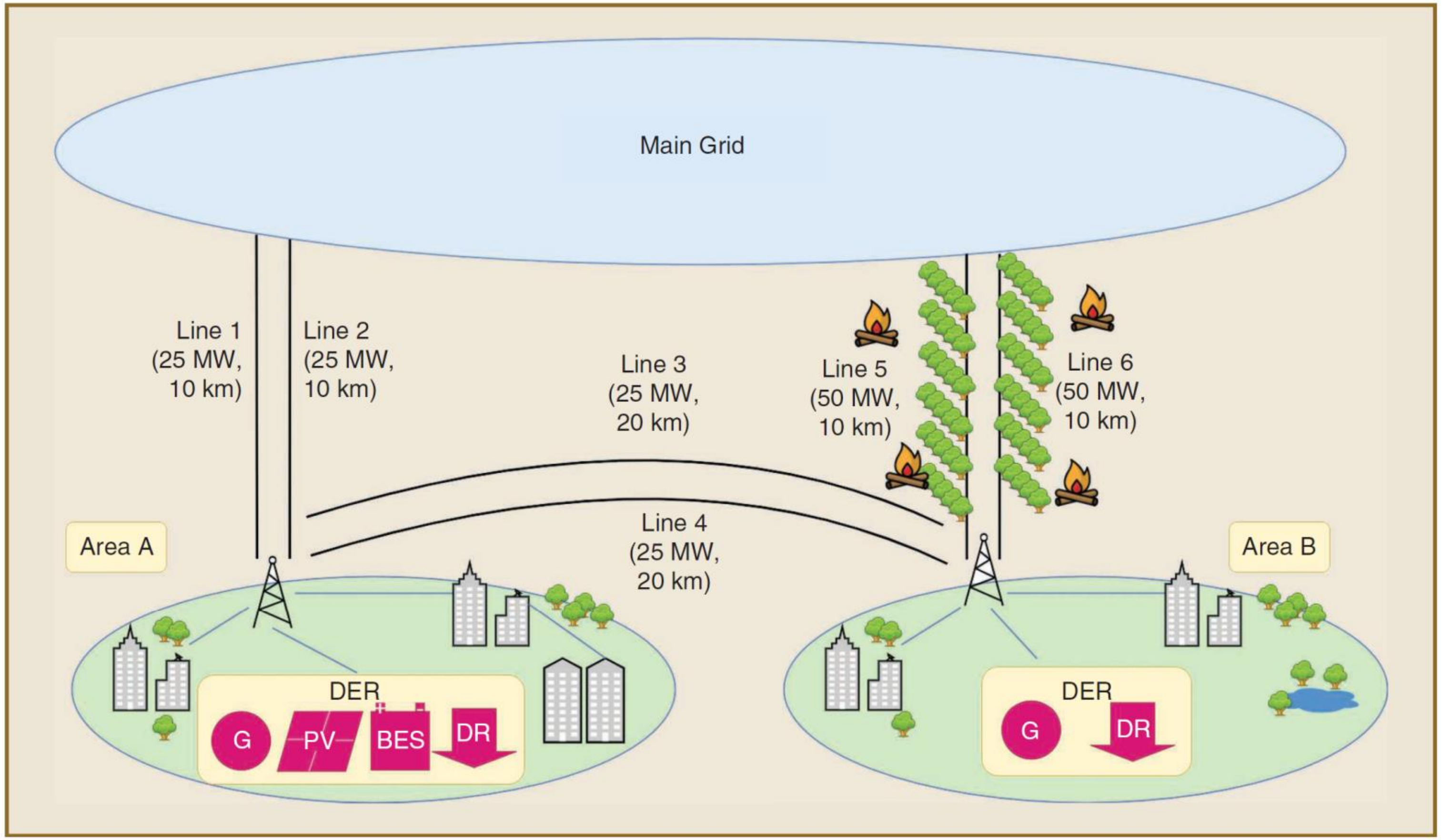


figure 8. The electricity network and DER candidates along with areas exposed to wildfires. BES: battery energy storage.

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

	N-1 Case A	Case A (Reevaluated)	Case B
Assets and measures	L1, L2, L5, L6, MG, DR	L1, L2, L5, L6, MG, DR	L1, L2, L3, L4, L5, PV, BES, MG, DR
PV + BES investment cost	—	—	11,500
Line investment cost	113	113	150
Operational cost	32,850	33,115	21,901
Lost-load cost	27	19,665	6
Total cost	32,990	52,893	33,558

L: line; MG: mobile generator.

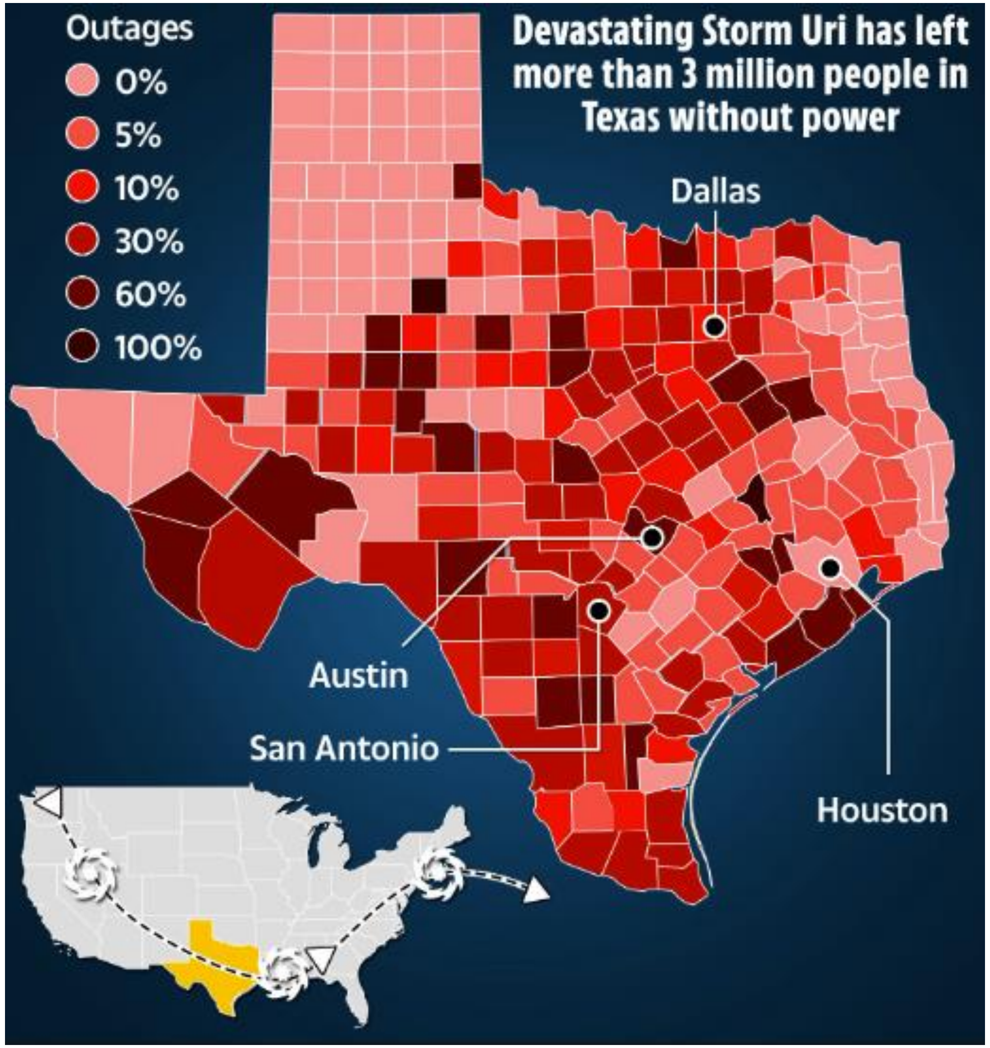
Moreno, R., Trakas, D. N., Jamieson, M., Panteli, M., Mancarella, P., Strbac, G., ... & Hatziargyriou, N. (2022). Microgrids Against Wildfires: Distributed Energy Resources Enhance System Resilience. IEEE Power and Energy Magazine, 20(1), 78-89.

Why markets alone cannot deliver resilience

- As generation, storage and DER may compete against network infrastructure (usually built in a regulated fashion) for as reliability and resilience, some form of **coordination** may be needed
- For appropriate market-driven investments in generation, storage and DER, **scarcity pricing** (e.g., after a threat!) should be equal to the VoLL precisely where demand is being curtailed
  - But given the extreme social conditions associated with natural hazards, it may be **politically impractical** to maintain extremely high prices under such circumstances
- Even with efficient pricing, **concerns** would remain regarding the **performance of market-driven investments**:
  - Probability distribution functions of rare events are unknown and non-stationary due to climate change
  - Private-led investment portfolio meant to hedge these risks would be difficult to justify
    - This problem is exacerbated by the risk aversion of self-interest investors, who require more confidence about the revenue streams associated with their investments
  - Also, investors might act strategically to not fully provide a robust system design, preserving high prices in times of scarcity conditions!

We’ve seen it all in the February 2021 ERCOT events…

- **Different customer experiences**
  - Many were fully interrupted while parts of the grid remained unaffected
  - Would priority curtailment services or mandatory rationing schemes help?
- What could the operator have done with a **larger operational tool set**, or with different services?
- ***What could the economics do against the physics***?
- How would **weatherization** be incentivised, in practice?
- Furthermore, **multi-energy system** dependencies clearly emerged:
  - Electricity requires gas, but… gas (for homes, industry) requires working electricity connection!



Source: Heatspring magazine

Courtesy of F. Billimoria, University of Oxford

From physics to economics: What Regulation do we need for resilience?

- The **“new physics”** calls for new services, possibly provided by new technologies and **new** operational and planning **(technical and market) arrangements**
- **Markets** alone **cannot provide resilience**
- It will be therefore key to develop suitable **regulatory frameworks** that can:
  - Discriminate resilience events from reliability ones
  - Recognise risk awareness and aversion in decision making
  - Assess and value the impact of resilience events
  - Efficiently incorporate resilience into cost benefit analysis adopted for reliability decisions
  - Allocate resilience costs (and benefits) in a “fair” way
  - Determine the most suitable mechanisms to provide resilience (standards and mandates or market approaches?)
  - Coordinate (regulated) network and (market-based) nonnetwork investments
  - Create suitable incentives to provide resilience
  - Operate across multi-energy systems and infrastructures

Source: Cigre WG 4.47, “Power system resilience”, Task 3, “Regulatory aspects of power system resilience”

Developing an array of regulatory and market instruments

Mechanism	Examples
Mandatory Licenses	• Virtual inertia provision (Quebec, Ontario) • Primary frequency control (NEM, National Grid UK) • Mandatory system reserves (Spain) • “Do no harm’ generator technical requirements (NEM) • Obligatory reactive power service (National Grid UK)
Regulated procurement	• Minimum system strength and inertia levels (NEM) • DS3 System Services Regulated (Eirgrid, Ireland)
Central agency delegation	• System integrity protection schemes (NEM) • Network support and control ancillary services (NEM) • System stability, voltage, and network pathfinders (National Grid UK) • Enhanced frequency response (National Grid UK) • “Delivering a Secure, Sustainable Electricity System” (DS3) Tender (Eirgrid, Ireland) • Enhanced Reactive Power Service (National Grid UK) • Megavolt-amp reactive power services tender (Belgium)
Spot markets	• Fast regulation markets (PJM, MISO) • Ramping products (CAISO, MISO) • Primary frequency reserve (WEM, proposed)
Market constraints and interventions	• Residual unit commitments (US) • Market intervention / directions (NEM)

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

Regulation for the future low-carbon grid

- Future low-carbon grids are characterised by a **high degree of uncertainty**, both short-term (operation) and, even more markedly, long-term (planning)
- It is essential that **regulatory frameworks** be able to develop mechanisms to value **flexibility in planning**
- Flexible planning mechanisms should then be augmented by **risk analysis**, especially to deal with resilience (the most uncertain events!)
- These same mechanisms should and would allow investments in **network and nonnetwork solutions** to be evaluated on a more level playing field
  - Enabling development of optimal portfolios for both reliability and resilience
- There's lots of work to do, but things are fortunately moving forward…

R. Moreno, et al., "Planning low-carbon electricity systems under uncertainty considering operational flexibility and smart grid technologies", *Philosophical Transactions of the Royal Society A*, Vol. 375, Issue 2100, Aug 2017, pp. 1-29

B. Moya et al., "Uncertainty representation in investment planning of low-carbon power systems", *Power System Computation Conference*, 2022

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

Concluding Remarks

Concluding Remarks

- Modelling under uncertainty is key to properly assess and enhance resilience and flexibility in operation and planning
- New risk-averse and resilience-informed planning and operation methods need to be applied for investment decision-making and for utilizing the benefits of flexible solutions in modern power systems under uncertain and extreme conditions.
- However, new regulatory frameworks need to be developed and adopted to value flexibility in network planning and to incentivize resilience-driven approaches.

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- TERSE: Techno-Economic framework for Resilient and Sustainable Electrification, EPSRC, EP/R030294/1
- Resilient Planning of Low Carbon Power Systems, Newton Fund
- ATTEST: Advanced Tools Towards Cost-efficient Decarbonisation of Future Reliable Energy Systems, H2020, European Commission (EC), Grant agreement ID: 864298
- Market Enabling Interface to Unlock Flexibility Solutions for Cost-effective Management of Smarter Distribution Grids (EUniversal), H2020, EC, Grant agreement ID: 864334
- Multi energy vector modelling, Energy Networks Association (ENA), Network Innovation Allowance (NIA), NIA_NGTO037
- Forward Resilience Measures, ENA, NIA, NIA_NGT0049

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Thank you
Any Questions?

panteli.mathaios@ucy.ac.cy

rmorenovieyra@ing.uchile.cl

pierluigi.mancarella@unimelb.edu.au

alex.martinezcesena@manchester.ac.uk

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