Flexibility and Resilience in Future Low-Carbon Energy Systems

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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...

First reference to resilience in 1818!!

June 1990
Google Scholar Search – “Power Network/System Resilience”
Increasing Need for Flexibility and Resilience

Emerging need for resilience and flexibility

- Increasing electricity demand
- Increasing dependency on electricity
- Increasing network complexity
- Ageing infrastructure
- More frequent and stronger extreme weather events
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
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

The performance target for NGET is **147MWh** (average ENS).

This is significantly lower than the RIIO-1 target of **316MWh**.

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**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**.

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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

<table>
<thead>
<tr>
<th>Anticipation</th>
<th>Preparation</th>
<th>Absorption</th>
<th>Adaptation</th>
<th>Rapid recovery</th>
<th>Sustainment of critical system operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>- the process by which newly incorporated knowledge gained is used to foresee possible crises and disasters</td>
<td>- the process through which grid operators establish a set of actions to be deployed in case the critical operating condition occurs</td>
<td>- 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</td>
<td>- 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</td>
<td>- the process through which the energy supply to the customers is restored and the damages to the grid infrastructure are repaired</td>
<td>- 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</td>
</tr>
</tbody>
</table>

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

N: Node
E: Electricity price
G: Gas price
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

<table>
<thead>
<tr>
<th>Investment scheme</th>
<th>Expected discounted cost</th>
<th>Regret</th>
</tr>
</thead>
<tbody>
<tr>
<td>Do nothing</td>
<td>£10.496M</td>
<td>£14.935M</td>
</tr>
<tr>
<td>Traditional (risk averse)</td>
<td>£10.496M</td>
<td>£14.935M</td>
</tr>
<tr>
<td>Traditional (risk neutral)</td>
<td>£9.080M</td>
<td>£15.261M</td>
</tr>
<tr>
<td>Traditional (staged) (risk averse)</td>
<td>£7.749M</td>
<td>£11.027M</td>
</tr>
<tr>
<td>Traditional (staged) (risk neutral)</td>
<td>£7.740M</td>
<td>£15.321M</td>
</tr>
<tr>
<td>Options based</td>
<td>£6.500M</td>
<td>£9.055M</td>
</tr>
</tbody>
</table>
Example – Decisions (part 1)

<table>
<thead>
<tr>
<th>N</th>
<th>Traditional (risk neutral)</th>
<th>Traditional (risk averse)</th>
<th>Options based</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EHP</td>
<td>CHP</td>
<td>TES</td>
</tr>
<tr>
<td>1</td>
<td>2500</td>
<td>1500</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>2500</td>
<td>1500</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>2500</td>
<td>1500</td>
<td>0</td>
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<td>4</td>
<td>2500</td>
<td>1500</td>
<td>0</td>
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<td>5</td>
<td>3500</td>
<td>1500</td>
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<td>2500</td>
<td>1500</td>
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<td>7</td>
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</tr>
<tr>
<td>8</td>
<td>3500</td>
<td>1500</td>
<td>450</td>
</tr>
</tbody>
</table>
### Example – Decisions (part 2)

<table>
<thead>
<tr>
<th>N</th>
<th>Traditional (risk neutral)</th>
<th>Traditional (risk averse)</th>
<th>Options based</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EHP</td>
<td>CHP</td>
<td>TES</td>
</tr>
<tr>
<td>9</td>
<td>2500</td>
<td>1500</td>
<td>250</td>
</tr>
<tr>
<td>10</td>
<td>2500</td>
<td>1500</td>
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<td>11</td>
<td>2500</td>
<td>3000</td>
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<tr>
<td>17</td>
<td>3500</td>
<td>1500</td>
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</tr>
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<td>18</td>
<td>3500</td>
<td>1500</td>
<td>300</td>
</tr>
<tr>
<td>19</td>
<td>3500</td>
<td>1500</td>
<td>300</td>
</tr>
</tbody>
</table>
Example – Probability density functions

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

Moving from conventional to smart grids
New complexity in network planning

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

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

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

s.t.:

\[ x(\varepsilon) \in X(\varepsilon); \ \forall \varepsilon \in E \]

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

The general framework: Two layers of uncertainty

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

s.t.: 

\[
x(\varepsilon) \in X(\varepsilon); \ \forall \varepsilon \in E
\]

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

\[
z(\varepsilon, \xi) \in Z(x(\varepsilon), y(\varepsilon), \varepsilon, \xi); \ \forall \varepsilon \in E, \forall \xi \in \Xi
\]

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

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

\[
I_m = \sum_{g \in G} \pi^G_{g} \bar{p}_g,m + \sum_{l \in L} \pi^L_{l} \mu^L_{l,m} + \sum_{b \in B} \pi^B_{b} \bar{p}_b,m + \sum_{l \in L} \pi^Q_{l} \mu^Q_{l,m}; \quad \forall m \in M
\]

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

The importance of uncertainty

### Stochastic solution

<table>
<thead>
<tr>
<th>Expansion plan per epoch and scenario</th>
<th>Scenario 1 Low</th>
<th>Scenario 2 Mid-Low</th>
<th>Scenario 3 Mid-High</th>
<th>Scenario 4 High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epoch 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scenario 1 Low</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scenario 2 Mid-Low</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scenario 3 Mid-High</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scenario 4 High</td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

#### Deterministic (perfect information) solution

<table>
<thead>
<tr>
<th>Expansion plan per epoch and scenario</th>
<th>Scenario 1 Low</th>
<th>Scenario 2 Mid-Low</th>
<th>Scenario 3 Mid-High</th>
<th>Scenario 4 High</th>
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<tr>
<td>Epoch 1</td>
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<tr>
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<td></td>
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<tr>
<td>Scenario 2 Mid-Low</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scenario 3 Mid-High</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scenario 4 High</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The importance of the operational details

**Stochastic solution**

<table>
<thead>
<tr>
<th>Scenario 1 low</th>
<th>Scenario 2 mid-low</th>
<th>Scenario 3 mid-high</th>
<th>Scenario 4 high</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Stochastic solution (no ramp rate constraints)**

<table>
<thead>
<tr>
<th>Scenario 1 low</th>
<th>Scenario 2 mid-low</th>
<th>Scenario 3 mid-high</th>
<th>Scenario 4 high</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

Co-optimising network and storage infrastructure: Australia

Results: More batteries with more detailed uncertainty representation

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

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

Infrastructure planning and operation considering uncertain extreme events
Multi-Phase Resilience Assessment


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

\[ P_i(h) = \begin{cases} 
0, & \text{if } h < h_{\text{critical}} \\
1, & \text{if } h_{\text{critical}} \leq h < h_{\text{collapse}} \\
P(h), & \text{if } h \geq h_{\text{collapse}} 
\end{cases} \]
Examples of Fragility Curves – Investing in more robust assets?

![Fragility Curves Example](image)

- **Wind speed (m/s)**
  - Tower - Base
  - Tower - 20% Less robust
  - Tower - 20% More robust
  - Line - Base
  - Line - 20% Less robust
  - Line - 20% More robust

- **Probability of failure [%]**
  - Complete damage
  - Moderate damage
  - Minor damage

- **Accumulated rainfall [mm]**
  - Intense (3 hours)
  - Prolonged (10 hours)

- **Probability of failure [%]**
  - POA [μ]
  - Minor
  - Moderate
  - Extensive
  - Complete
Decision-dependent ambiguity sets

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

Integrate hazard profile over fragility functions

Simulation:
- Sequential Monte Carlo
- Spatiotemporal analysis
- Record system information every simulation step

Outputs
Calculation of resilience metrics
### Resilience Trapezoid and FLEP Resilience Metric System

<table>
<thead>
<tr>
<th>Type of Actions</th>
<th>Time Sequence</th>
<th>Resilience Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preventive</td>
<td>$t_0$</td>
<td>Pre-disturbance resilient state</td>
</tr>
<tr>
<td>Corrective</td>
<td>$t_{ce}$</td>
<td>Disturbance progress</td>
</tr>
<tr>
<td>Emergency Coordination</td>
<td>$t_{ee}$</td>
<td>Post-disturbance degraded state</td>
</tr>
<tr>
<td>Restorative</td>
<td>$t_r$</td>
<td>Restorative state</td>
</tr>
<tr>
<td>Adaptive</td>
<td>$T$</td>
<td>Post-restoration state</td>
</tr>
</tbody>
</table>

**How fast resilience declines?**

**How low resilience drops?**

**How extensive is this state?**

**How promptly does the network recover?**

---

### Illustrative Example

**Time-dependent resilience indicators (base case study)**

<table>
<thead>
<tr>
<th>Resilience Metric</th>
<th>Transmission Lines</th>
<th>Generation Connected</th>
<th>Load Connected</th>
</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>-1.083 (% of Lines tripped/h)</td>
<td>-0.521 (% of MW lost/h)</td>
<td>-0.249 (% of MW lost/h)</td>
</tr>
<tr>
<td>L</td>
<td>26 (% of Lines tripped)</td>
<td>12.5 (% of MW lost)</td>
<td>5.99 (% of MW lost)</td>
</tr>
<tr>
<td>E</td>
<td>53 (hrs)</td>
<td>54 (hrs)</td>
<td>57 (hrs)</td>
</tr>
<tr>
<td>P</td>
<td>0.058 (% of Lines restored/h)</td>
<td>0.033 (MW restored/h)</td>
<td>0.072 (MW restored/h)</td>
</tr>
</tbody>
</table>
Illustrative Example – Varying Robustness and Responsiveness

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

<table>
<thead>
<tr>
<th>Resilience Metric</th>
<th>Resilience Indicator</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Base</td>
</tr>
<tr>
<td>F</td>
<td>-1.083 (% of Lines tripped/hr)</td>
</tr>
<tr>
<td>L</td>
<td>26 (% of Lines tripped)</td>
</tr>
<tr>
<td>E</td>
<td>53 (hrs)</td>
</tr>
<tr>
<td>P</td>
<td>0.058 (% of Lines restored/hr)</td>
</tr>
<tr>
<td></td>
<td>20% More Robust</td>
</tr>
<tr>
<td>F</td>
<td>-0.25 (% of Lines tripped/hr)</td>
</tr>
<tr>
<td>L</td>
<td>6 (% of Lines tripped)</td>
</tr>
<tr>
<td>E</td>
<td>53 (hrs)</td>
</tr>
<tr>
<td>P</td>
<td>0.019 (% of Lines restored/hr)</td>
</tr>
<tr>
<td></td>
<td>20% More Response</td>
</tr>
<tr>
<td>F</td>
<td>-1.083 (% of Lines tripped/hr)</td>
</tr>
<tr>
<td>L</td>
<td>26 (% of Lines tripped)</td>
</tr>
<tr>
<td>E</td>
<td>44 (hrs)</td>
</tr>
<tr>
<td>P</td>
<td>0.092 (% of Lines restored/hr)</td>
</tr>
</tbody>
</table>
Average Vs Conditional Values

**Value at Risk**

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

**Conditional Value at Risk**

\[ CVaR_\alpha (x) = E[x \mid x \geq VaR_\alpha (x)] \]
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

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

**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

Flowchart:
- **Trip island**
  - Run OPF without line constraints, all loads dispatchable, no lower voltage limit
  - PF converged?
    - no
      - VCLS
    - yes
      - UFLS
      - OFGS
  - OPF converged?
    - no
      - Cascades continue
    - yes
      - Cascade halted

- Frequency
  - UFLS or OFGS applied?
    - no
      - OXL / UXL
    - yes
      - UVLS

- Voltage
  - Conditions changed?
    - yes
      - OLP
    - no
      - Cascades halted
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

Dynamic Cascading Modelling

- Dynamic phenomena
- Cascading events

- Inertia Response
- Primary Control
- Automatic Generation Control
- Voltage Regulation
- Demand Variation
- Power Rebalancing
- Branch Overload Protection
- OXL/U XL
- UFLS/UVLS
- Faulty Element Outage
- Redispatch
- Demand Variation

Time scales:
- Milliseconds
- Seconds
- Minutes
- Hours
- Days

- Short-term
- Mid-term
- Long-term
Dynamic Cascading Modelling

Start

Preparation work

DlgsILENT PowerFactory set-up

Modification to power system model

Adding controllers and protection relays

Initial event(s) set-up

Running simulations and accessing results

Identification of cascading events

Data processing and visualization

Stop

Compute initial power flow

Apply initial outage(s)

Network separation?

Yes

Update network admittance matrix for each active island

No

Solve the continuous differential-algebraic equations

Execute cascading event(s)

Any cascading events?

No

Is end time reached?

No

Yes

End of simulation
Code available via Github: https://github.com/YitianDai/Dynamic-cascading-failure-simulator

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

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

\[ \text{Mean} = \int_0^D x \cdot f(x) \, dx \]
\[ \text{CVaR} = \frac{1}{1 - \alpha} \int_{z}^{D} x \cdot f(x) \, dx \]
\[ 1 - \alpha = \int_z^D f(x) \, dx \]
An illustrative example

<table>
<thead>
<tr>
<th>Metric</th>
<th>N-0 base case</th>
<th>N-1</th>
<th>N-0 shorter repair time</th>
<th>N-0 underground</th>
</tr>
</thead>
<tbody>
<tr>
<td>VoLL x EENS [€]</td>
<td>538,532</td>
<td>470,506</td>
<td>280,428</td>
<td></td>
</tr>
<tr>
<td>VoLL x CVaR [€]</td>
<td>4,113,206,199</td>
<td>3,846,412,398</td>
<td>2,690,095,838</td>
<td>2,837,833,988</td>
</tr>
<tr>
<td>Probability of double outage under adverse weather [%]</td>
<td>7.7%</td>
<td>7.7%</td>
<td>2.0%</td>
<td>2.6%</td>
</tr>
</tbody>
</table>

An illustrative example
An illustrative example

<table>
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<tr>
<th>Metric</th>
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</tbody>
</table>

Reliable  Resilient  Compromise
From static to time domain modeling

Pre-contingency state

Drop

Supplied demand

ENS

System restoration

Rate

Time
Stochastic simulations

System infrastructure (common to all scenarios)

Hazard 1 → Vulnerability assessment 1 → Outage 1 → System response 1 → Repair 1 → System restoration 1

Scenario 1

Hazard 2 → Vulnerability assessment 2 → Outage 2 → System response 2 → Repair 2 → System restoration 2

Scenario 2

Hazard N → Vulnerability assessment N → Outage N → System response N → Repair N → System restoration N

Scenario N

Pre-contingency state

Hazard and system response

System restoration

Probability of failure vs. Intensity

Supplied demand vs. Time
Mathematical program

Formulation: \[ \min_x \{ \text{RiskMeasure}(\text{ResilienceMetric}_s(x)) \} \]

s.t. \[ \sum_{i \in I} c_i \cdot x_i \leq \text{budget} \]

\[ x_i \in \{0,1\} \ \forall i \in I \]

OvS:

**First stage**
Propositions of new system enhancement options through optimization of resilience metric

**Enhancement option**

**Second stage**
Simulations of system impact and response and restoration after random natural hazards occur

**Resilience metric**
Resilience trilemma tackled through optimisation

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

- **Stronger?**
  - Upgrade existing infrastructure, asset life extension, etc.

- **Bigger?**
  - Build new infrastructure, e.g. transmission lines, substation, etc.
Q&A
Coffee Break
Infrastructure planning and operation for flexible and adaptive energy systems
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

- Technology
  - Operation
  - Sizing
- Transports
  - Technology
  - Charging
  - Vector
- Network
  - Primary
  - BSP
  - GSP
- Profiles
  - Annual
  - Peak
- Pathway
- Heating
- Buildings
- Insulation
- Energy
- Vehicles
  - HGV
  - LGV
- Temp.
  - Post-code
  - Energy mix
- Historical data

Historical data
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)
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

\[
\begin{bmatrix}
A & 0 & B \\
0 & C & 0 \\
0 & 0 & D
\end{bmatrix} \rightarrow
\begin{bmatrix}
1 & 3 & 4 \\
2 & 3 & 4
\end{bmatrix}
\]

\[
\begin{array}{l|l|l|l}
\text{Head} & \text{Index} & \text{Data (Value)} & \text{Data (Column)} & \text{Next} \\
\hline
\text{Row} & 1 & A & 1 & 2, \text{Block 1} \\
3 & B & 3 & 0, \text{Block 2} \\
4 & C & 2 & 0, \text{Block 3} \\
4 & D & 3 & 0, \text{Block 4}
\end{array}
\]
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:

\[
\text{Network\_Flow} = K + \sum \frac{\partial \text{Active\_Constraint}}{\partial \text{Building\_Export}_x} \times \text{Building\_Export}_x
\]

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

<table>
<thead>
<tr>
<th>Installed capacity</th>
<th>Network constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td>EES</td>
<td>TES</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1kW</td>
<td>1 m³</td>
</tr>
<tr>
<td>10 kW</td>
<td>10 m³</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Installed capacity</th>
<th>Deterministic (One scenario)</th>
<th>Stochastic (Five scenarios)</th>
<th>VPI</th>
</tr>
</thead>
<tbody>
<tr>
<td>EES</td>
<td>TES</td>
<td>Cost</td>
<td>VPI</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>25.5 k£</td>
<td>28.2 k£</td>
</tr>
<tr>
<td>1kW</td>
<td>1 m³</td>
<td>25.4 k£</td>
<td>27.8 k£</td>
</tr>
<tr>
<td>10 kW</td>
<td>10 m³</td>
<td>25.1 k£</td>
<td>25.4 k£</td>
</tr>
</tbody>
</table>
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

AC-CFM: Illustrative Results
AC-CFM: Illustrative Results

The diagram shows the average lost load with additional loading for different percentages of loading increase. The bars represent UFLS, VCLS, UVLS, and tripped buses.

The charts on the right display the metrics $\phi$ and $\Lambda$ for different categories: additional loading (%), lost load (MW), lost lines, lost buses, and lost generators.
AC-CFM: Illustrative Results

Reduced lost load with higher ratio of DG buses.

Graph showing average lost load (MW) vs. ratio of DG buses (%), with metrics for UFLS, VCLS, UVLS, and tripped buses.

Graph showing metrics for ratio of DG buses (in %), lost load (MW), lost lines, lost buses, and lost generators.
Dynamic Risk Metrics with Increased Wind Penetration

Application to ACTIVSg200 Network

<table>
<thead>
<tr>
<th>RES Penetration level (%)</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
<th>60</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inertia level (GVA's)</td>
<td>17.01</td>
<td>16.33</td>
<td>14.38</td>
<td>13.57</td>
<td>12.88</td>
<td>9.05</td>
</tr>
<tr>
<td>COI frequency nadir without FFR (p.u.)</td>
<td>0.991</td>
<td>0.987</td>
<td>0.985</td>
<td>0.981</td>
<td>0.977</td>
<td>0.976</td>
</tr>
<tr>
<td>Required BESS capacity (MW)</td>
<td>Near RES</td>
<td>0</td>
<td>12</td>
<td>36</td>
<td>60</td>
<td>132</td>
</tr>
<tr>
<td></td>
<td>Near demand</td>
<td>0</td>
<td>12</td>
<td>30</td>
<td>66</td>
<td>132</td>
</tr>
</tbody>
</table>

Unserved demand (MW) vs Wind penetration level (%)

CVaR0.5 VaR0.5 EDNS w/o FFR with FFR

Dynamic Risk Metrics with Increased Wind Penetration

Application to ACTIVSg200 Network

Graph showing the probability of unserved demand exceeding a certain threshold for different wind penetration levels.
Static Vs Dynamic Cascading Modelling

Application to ACTIVSg200 Network

Graph showing the risk of blackout size (MW) versus demand level (percent) for different margin percentages. The graph compares static and dynamic models with margins of 10%, 20%, 30%, and 40%.
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/
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

$E > 7\text{Mw since 1900}$

2010 Chile (8.8Mw)
Examples on earthquakes (2)

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

Massive 8.8Mw earthquake in Chile 2010
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

Reliability based

Resilience based
Detailed ranking

**Resilience and Reliability Rankings of Single Network Enhancement Propositions.**

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

*10,000 evaluations; 95% confidence intervals equal to ±0.42 [MWh] for resilience and ±0.03 [MWh] for reliability.
Trade-offs between reliable and resilient investments

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

Portfolios and DG

### Optimal Investment Portfolios for budget = 0, 1, 2, 3, 5, 7.

<table>
<thead>
<tr>
<th>Budget</th>
<th>Without DG</th>
<th>With DG</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Solution</td>
<td>CEENS*[MWh]</td>
</tr>
<tr>
<td>0</td>
<td>Base case</td>
<td>872.1</td>
</tr>
<tr>
<td>1</td>
<td>B3</td>
<td>739.1</td>
</tr>
<tr>
<td>2</td>
<td>B3 B4</td>
<td>683.6</td>
</tr>
<tr>
<td>3</td>
<td>B3 B4 B6</td>
<td>651.1</td>
</tr>
<tr>
<td>5</td>
<td>B3 B4 B5 B6 L1,12</td>
<td>623.2</td>
</tr>
<tr>
<td>7</td>
<td>B3 B4 B5 B6 B8 L11,14, L6,13</td>
<td>616.7</td>
</tr>
</tbody>
</table>

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

---

Optimizing different resilience metrics

<table>
<thead>
<tr>
<th>Minimizing drop</th>
<th>Maximizing recovery rate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Drop* [MW]</td>
</tr>
<tr>
<td>B3</td>
<td>10.2</td>
</tr>
<tr>
<td>B4</td>
<td>10.92</td>
</tr>
<tr>
<td>B5</td>
<td>11.23</td>
</tr>
</tbody>
</table>

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

The importance of dependencies and flexibility

Chilean power system

- **Chilean power system**
- **Diagram** showing the power system with labels for different power sources and regions.
- **Table** showing the percentages of power sources:
  - Hydro: 28%
  - Coal: 13%
  - Gas: 13%
  - Wind & Solar: 13%
  - Diesel: 2%
  - Other: 24%

- **Text** mentioning specific regions and power plants:
  - Tarapaca
  - Lugnas
  - Lucar
  - Chacra y Encuentro
  - Los Chacons 220
  - Llantarito & Donoso
  - Los Chacons 500
  - Atacama & Mejillones
  - Paposo
  - Cumbre 500
  - Lalakama
  - Enalco
  - Cumbre 220
  - Diego de Almagro
  - Cardones 220
  - Maitencillo 220
  - Cardones 500
  - Punta Colorada
  - Maitencillo 500
  - Pan de Azucar 220
  - Las Palmas
  - Pan de Azucar 500
  - Los Vilos
  - Voles
  - Quillota
  - Polanco
  - Tapi
  - Melipilla
  - Cerro Navia & Lo Aguirre
  - Alto Jaluel
  - Limari
  - Laiva
  - Ancoa
  - Charrua
  - Colpo
  - Puerto Montt
  - Caulin & Temuco
  - Rabac
  - Pichicopuli
  - Curoles & Valdivia

- **Network diagram** showing connections and power transfers.
## Reliability vs resilience in Chile

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

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

### N-1 solution!

Portfolio vs budget: The value of flexible technologies in Chile

Case study 2: Windy conditions
Building fragility curves from historical data
Reliability and resilience effectiveness
Reliability and resilience effectiveness

<table>
<thead>
<tr>
<th></th>
<th>EENS [MWh]</th>
<th>EENS [%]</th>
<th>CEENS [MWh]</th>
<th>CEENS [%]</th>
<th>Costo de Implementación [US$]</th>
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<td>28.659</td>
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<td>Almacenamiento 3 (BESS3)</td>
<td>2.1284</td>
<td>1.153</td>
<td>59.9879</td>
<td>32.487</td>
<td>7,829.12</td>
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</tbody>
</table>
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/)

Illustrative example – Optimal design

✓ 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.

Illustrative example – Results

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

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

- Database of weather conditions
- Extract weather conditions from the database
- Time series of weather conditions
- Model the energy demand of the microgrid as well as the renewable availability
- Time series of energy demand as well as renewable generation
- Operation models (for scheduling) of the microgrid
- Scheduled operation of the microgrid under the considered conditions and selected operation strategy
- Profiles indicating scheduled operation of the microgrid
- Varying the starting time and duration of reserve services in real time whereby a microgrid maximises its contribution
- Capacity provided by the microgrid to reserve services in real time
- All starting times and durations?
- Are all conditions considered?
- Probabilistic capacity table of a microgrid
System-Level Reliability and Resilience Services by Aggregated Distributed Energy Resources

![Graph showing probability distribution of minimum capacity surplus (MW) at different durations of reserve service (Hour)].

Legend:
- 1 hour
- 2 hours
- 3 hours
- 4 hours
- 5 hours
- 10 hours
- 15 hours
- 20 hours
- 24 hours

Duration of Reserve Service (Hour):

- 1
- 2
- 3
- 4
- 5
- 10
- 15
- 20
- 24

Minimum Capacity Surplus (MW):

- 10
- 15
- 20
- 25
- 30
- 35
- 40

Probability:

- 0.0%
- 0.1%
- 0.2%
Applications to Borneo Island, Malaysia – Resilient Electrification Planning

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

Risk = P[event] · Consequence

<table>
<thead>
<tr>
<th>Consequence</th>
<th>Extremely high</th>
<th>Very high</th>
</tr>
</thead>
<tbody>
<tr>
<td>Likely (&gt;1%)</td>
<td>Moderate</td>
<td>Moderate</td>
</tr>
<tr>
<td>Probable (&gt;10%)</td>
<td>High</td>
<td>Moderate</td>
</tr>
<tr>
<td>Unlikely (&lt;1%)</td>
<td>Low</td>
<td>Low</td>
</tr>
</tbody>
</table>
Worried about delivering a low-carbon energy system?

Affordability

Low-carbon energy

Reliability and Resilience

Decarbonisation
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**

<table>
<thead>
<tr>
<th>Risk</th>
<th>Emerging issues</th>
<th>Possible Mitigations</th>
</tr>
</thead>
<tbody>
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<td>Frequency control and inertia</td>
<td>- Sustained frequency excursions (regulation)</td>
<td>- Minimum inertia levels</td>
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<tr>
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<td>- High Rate of Change of Frequency (ROCOF) following contingency</td>
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</tbody>
</table>

Interaction between active and reactive power services

# Fragility of a low-carbon grid

## Increasing need for frequency control services of different types

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Interaction between multiple frequency control services

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

Much tighter link between energy and security services

Case Study: Australia cascading and separation event 25 Aug 18

- 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.

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

- 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

Source: AEMO
## Fragility of a low-carbon grid

### Increasing need for forecasting and DER visibility

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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
### 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

### Possible Mitigations
- 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
- Visibility of Distributed Energy Resources (DER)

### Possible Mitigations
- 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

### Possible Mitigations
- 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”**


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

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

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

Resilience from new technologies: not only batteries


Need for resilience in low-carbon grids

Worried about delivering a low-carbon energy system?

Affordability

Reliability and Resilience

Low-carbon energy

Decarbonisation
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

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

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

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

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...


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.
Acknowledgments

- Resilient Electricity Networks for Great Britain (RESNET), Engineering and Physical Sciences Research Council (EPSRC), EP/I035781/1
- Disaster management and resilience in electric power systems, EPSRC UK – Conicyt Chile, EP/N034899/1
- TERSE: Techno-Economic framework for Resilient and Sustainable Electrification, EPSRC, EP/R030294/1
- Resilient Planning of Low Carbon Power Systems, Newton Fund
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- Forward Resilience Measures, ENA, NIA, NIA_NGT0049

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Thank you
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Planning under uncertainty – general aspects


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Resilience Definition, Methods and Metrics (4)


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Resilience Definition, Methods and Metrics (5)

