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Power System Resilience to Extreme Weather: Fragility Modelling, Probabilistic Impact Assessment and Adaptation Measures

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Outline

1. Introduction
2. Probabilistic Impact Assessment of Extreme Weather
3. “*ΦΛΕΠ*” Resilience Metric System
4. Conclusions

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Introduction

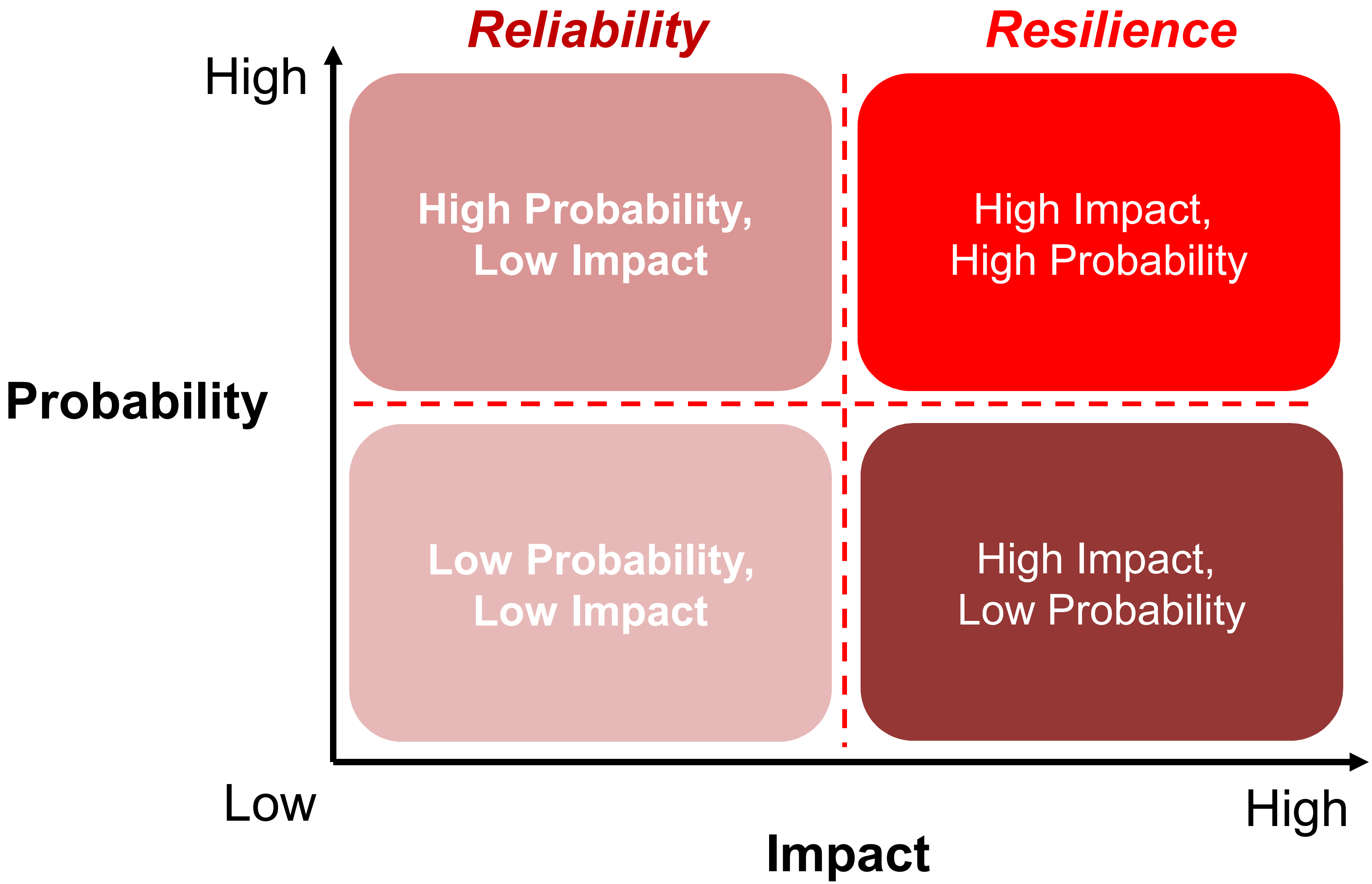
Power systems have been traditionally designed to be reliable to the so-called **typical** or **credible** events, i.e. N-1 or N-2 outages

However, what if a "**black swan**" event occurs?

- Are the traditional average indices (e.g. EENS, LOLF, etc.) sufficient?
- How do we quantify the impact of these extreme events?
- What characteristics should the quantification metrics have?

Need to move towards resilience-thinking and engineering

Introduction (cont.)



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Probabilistic Impact Assessment of Extreme Weather

Bi-level generic procedure:

Component Fragility to the Hazard

↓

System Resilience Assessment

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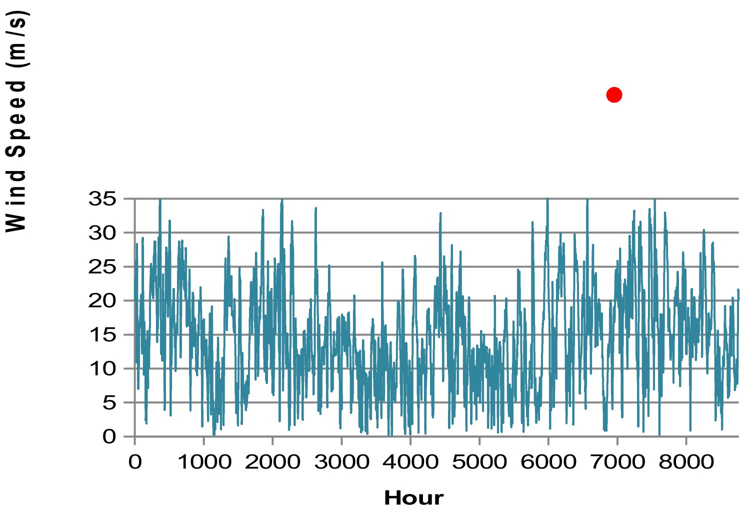
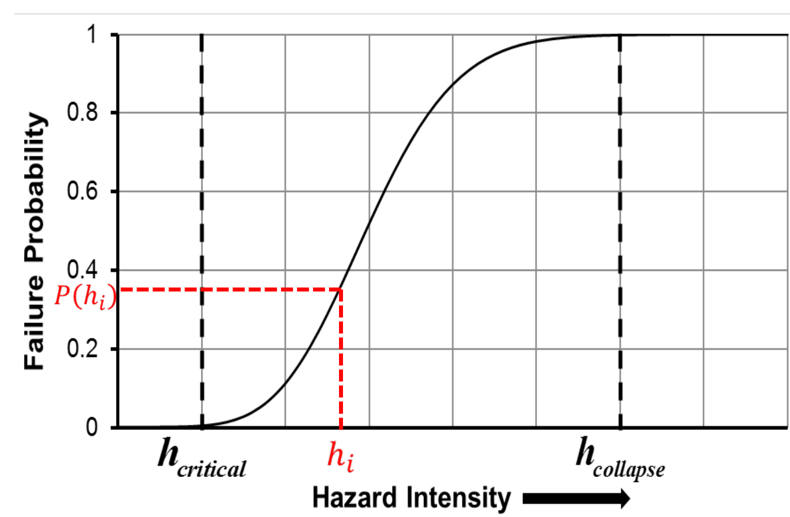
Probabilistic Impact Assessment of Extreme Weather (cont.)

Component Approach for Determining the Effect of a Hazard

Hazard Profile → Integrate hazard profile over fragility functions → Time- and Hazard-Dependent Status of the Components





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

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Probabilistic Impact Assessment of Extreme Weather (cont.)

System Approach for Resilience Assessment

Inputs
- Hazard Profile
- Fragility Curves

→

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

→

Outputs
Calculation of resilience metrics

Time- and Hazard-dependent
Failure Probability

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

→

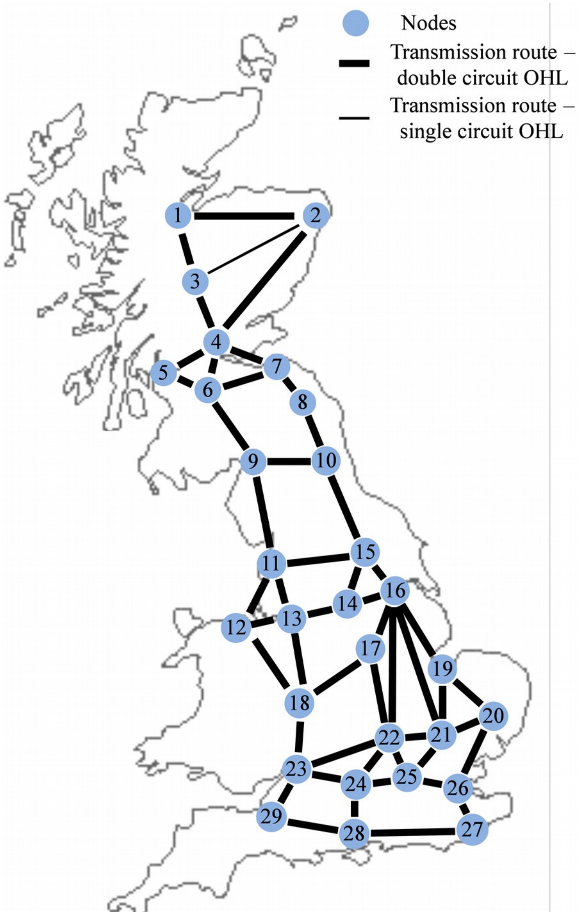
Time- and Hazard-dependent
Failure Function

$$F(h_i) = \begin{cases} 0, & if\ \ P(h_i) < r \\ 1, & if\ \ P(h_i) > r \end{cases}$$

r = uniformly distributed number

Probabilistic Impact Assessment of Extreme Weather (cont.)

Case Study Application



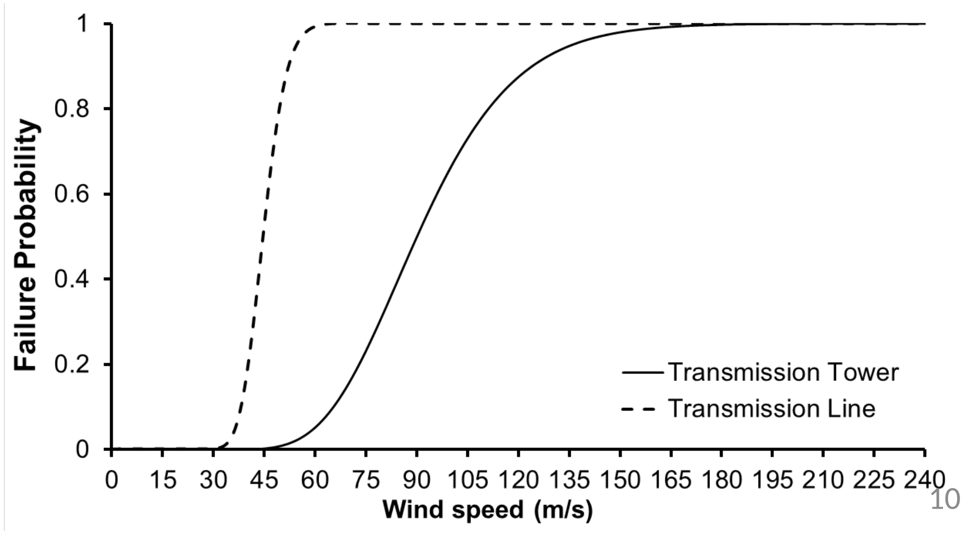
The 29-bus test version of the GB transmission network

Test Network:

- 29 nodes
- 98 overhead transmission lines in double circuit configuration and one single circuit transmission line
- 65 generators with an installed capacity of 75.3GW

Hazard:

- Severe windstorms (with maximum wind speeds up to 60m/s)
- Duration of hazard: 1 week



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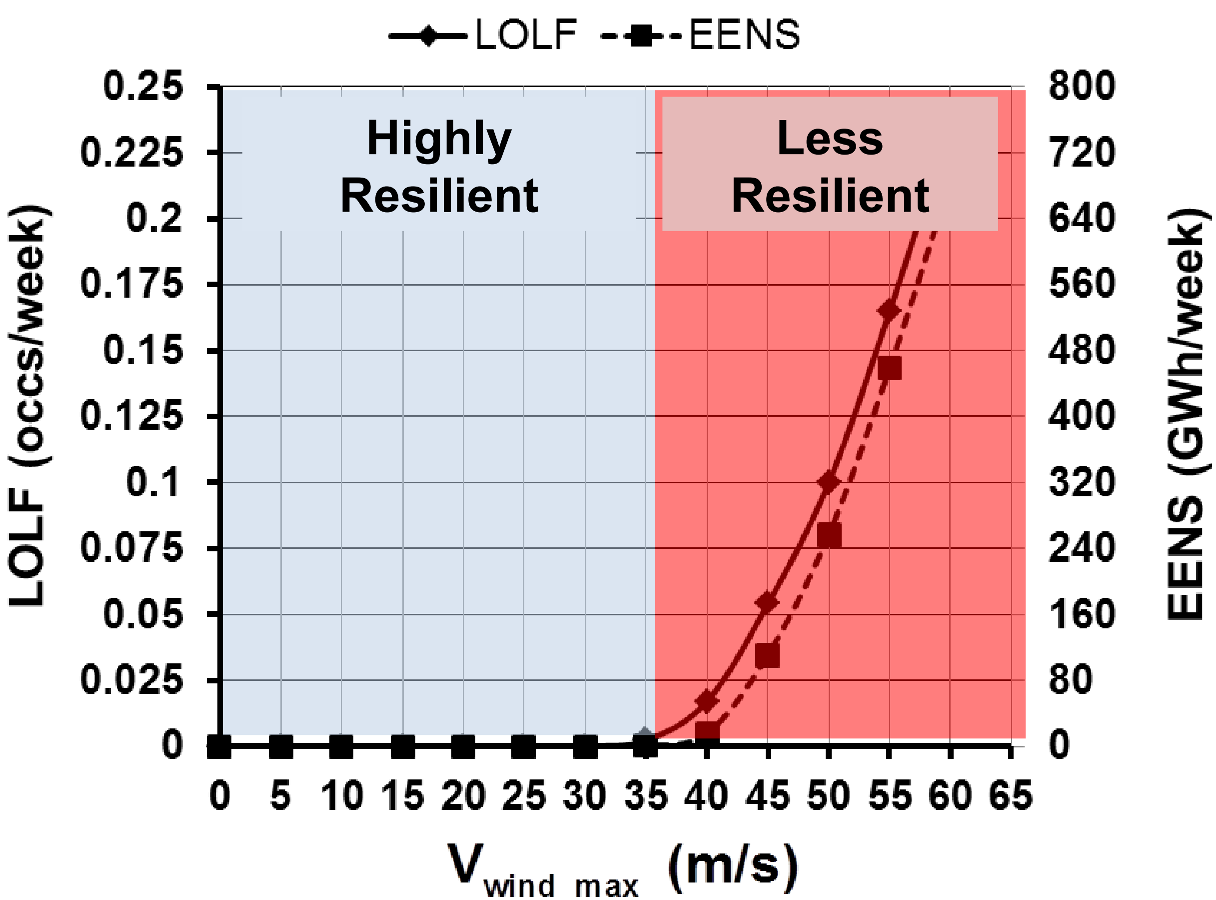
Probabilistic Impact Assessment of Extreme Weather (cont.)

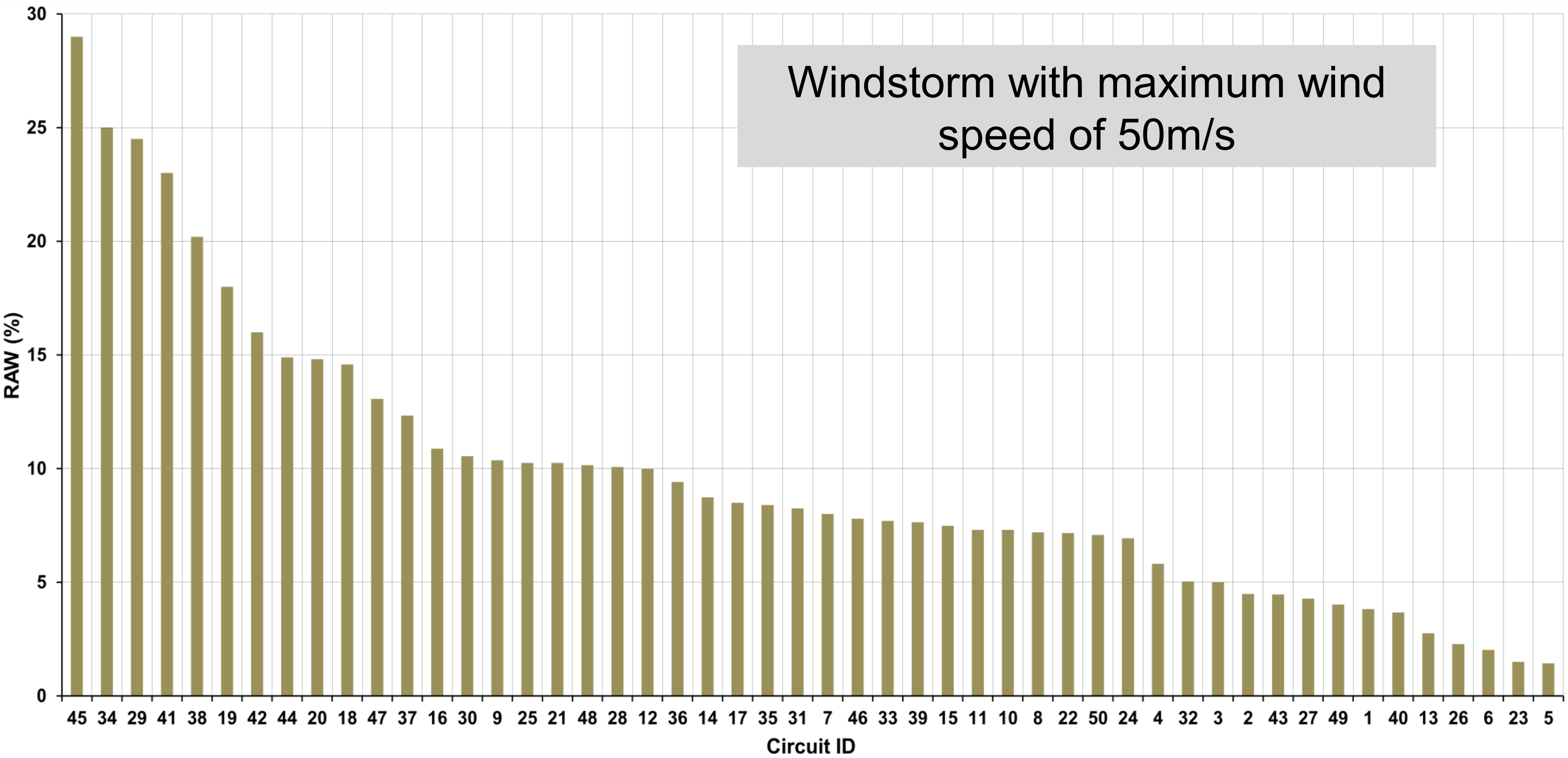
Resilience Metrics:

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



Probabilistic Impact Assessment of Extreme Weather (cont.)

Resilience Achievement Worth: $$RAW = \frac{R_s - R_s(R_n = 1)}{R_s} \times 100$$



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Probabilistic Impact Assessment of Extreme Weather (cont.)

This is good, but:

No information is provided on how the system actually responded during the event or what we can do to improve its robustness and recovery…

A more dynamic, multi-phase assessment of the system resilience is required!

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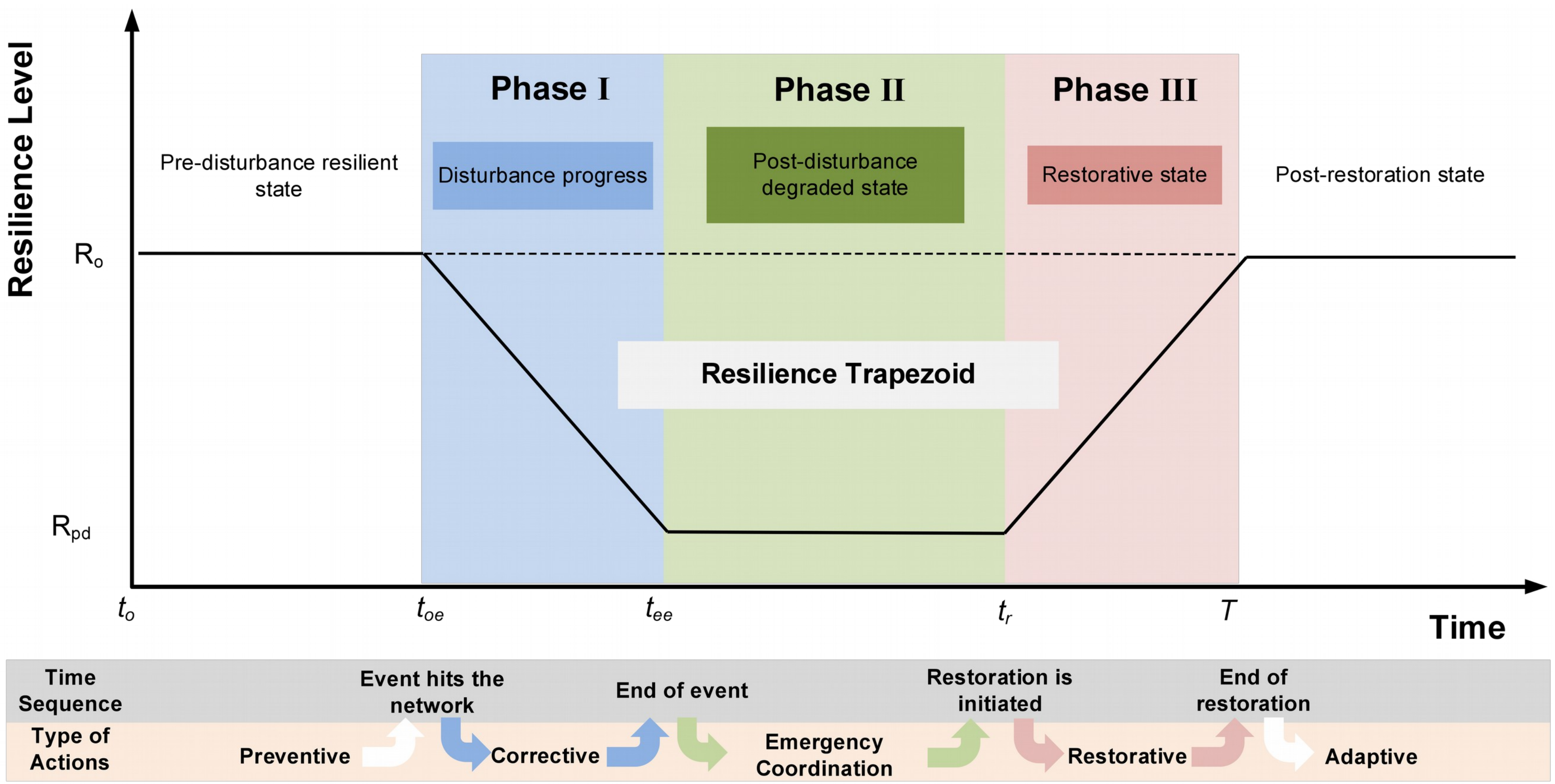
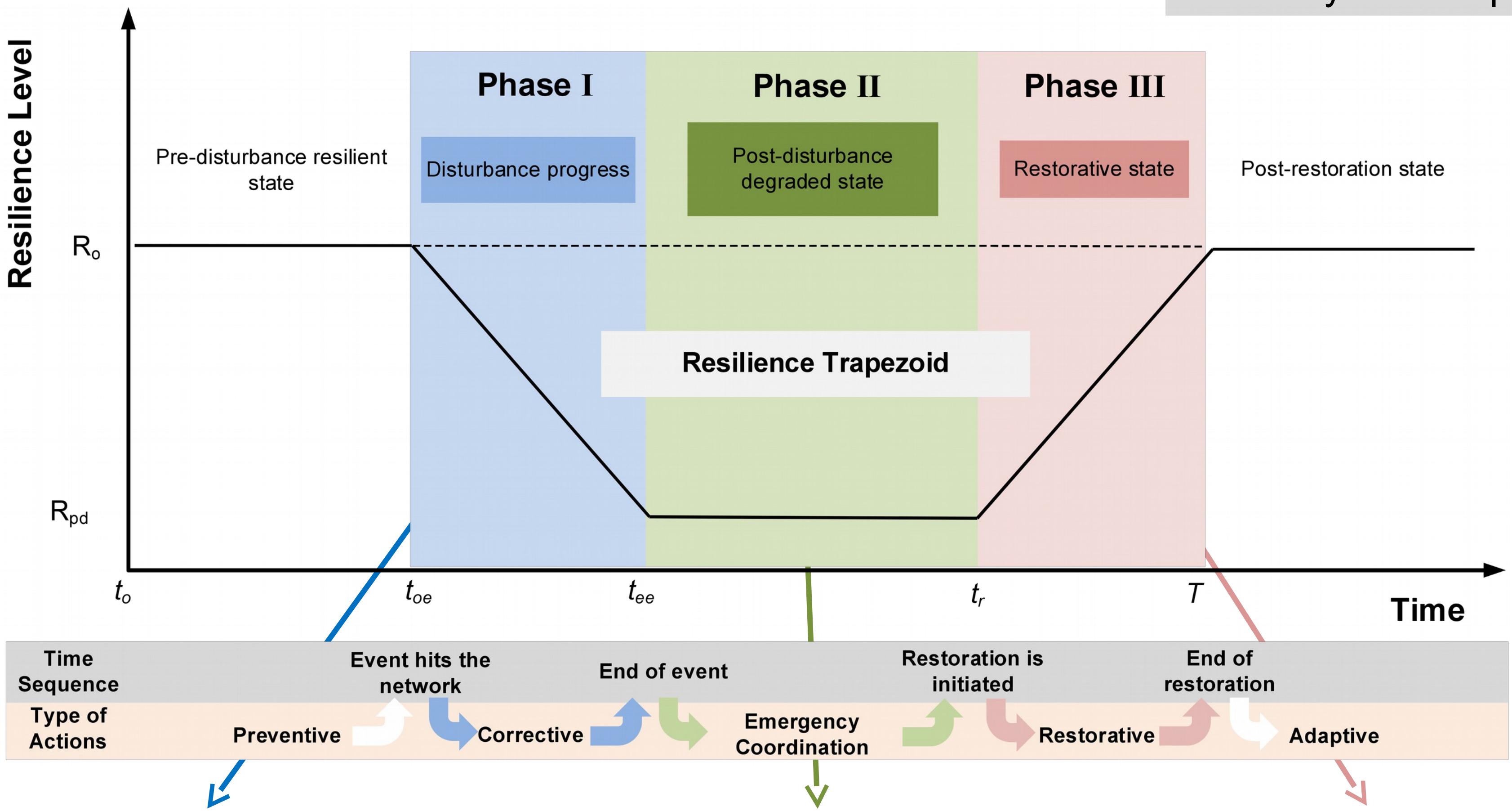
“ΦΛΕΠ” Resilience Metric System

Conceptual Resilience Trapezoid Associated to an Event



"ΦΛΕΠ" Resilience Metric System (cont.)

Resilience Metric System → Quantification of the actual system response



how **f**ast resilience declines? **Φ**

how **l**ow resilience drops? **Λ**

how **e**xtensive is this state? **Ε**

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

"ΦΛΕΠ" Resilience Metric System (cont.)

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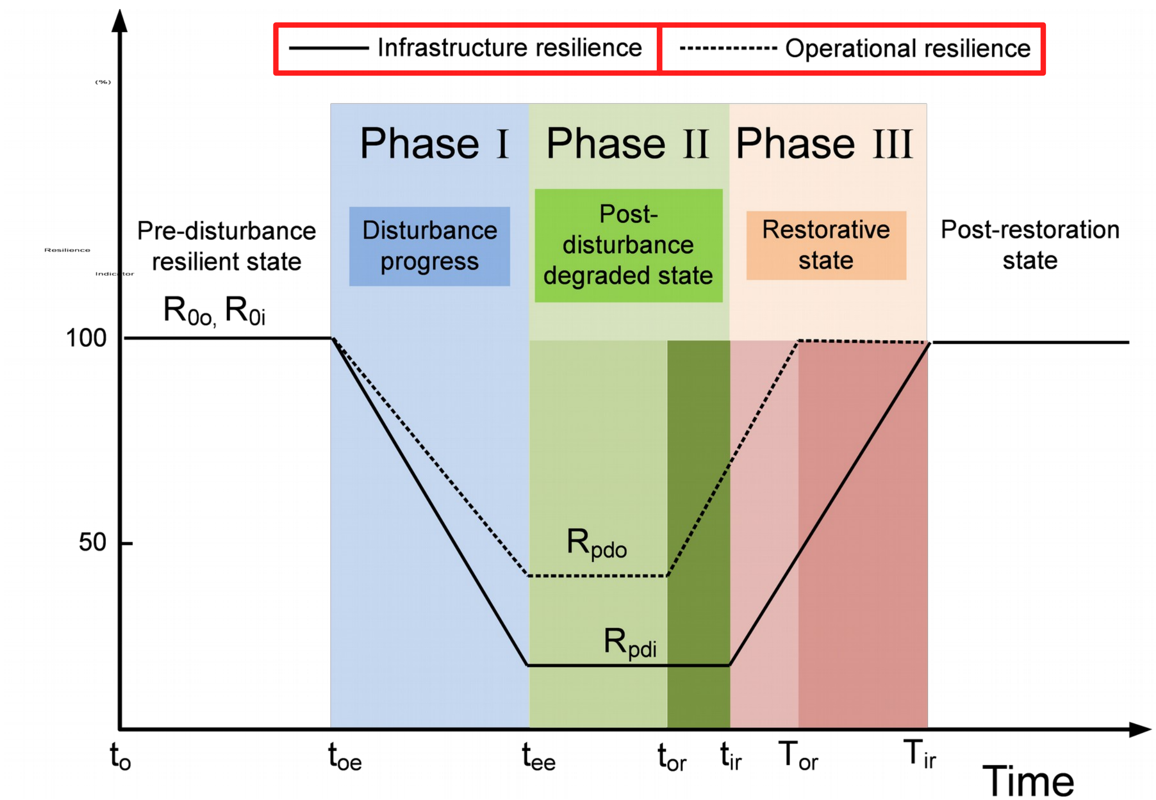
Distinguishing **operational** and **infrastructure** resilience…



Operational resilience: refers to the characteristics that would secure operational strength for a power system

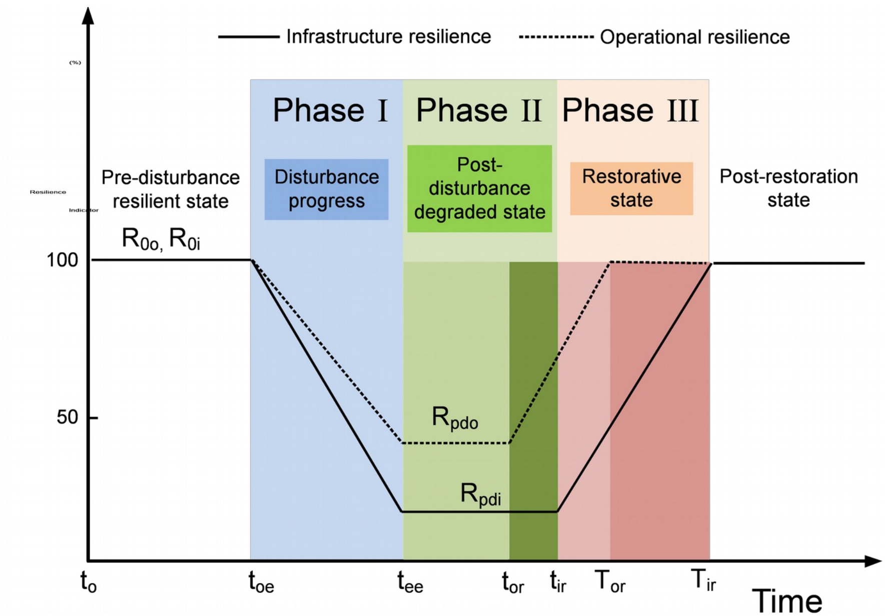
Infrastructure resilience: refers to the physical strength of a power system for mitigating the portion of the system that is damaged, collapsed or in general becomes nonfunctional.

Resilience Indicators:

Operational Resilience: the amount of generation capacity (MW) and load demand (MW) that are connected during the event

Infrastructure Resilience: the number of online transmission lines

"ΦΛΕΠ" Resilience Metric System (cont.)



Mathematical Expression of Trapezoid Areas

Trapezoid Area	Mathematical Expression	
	Operational	Infrastructure
$Area_I$	$\frac{\Lambda_{operational}\ �\ _{windstorm}}{2}$	$\frac{\Lambda_{infrastructure}\ �\ _{windstorm}}{2}$
$Area_{II}$	$\Lambda_{operational}\ �\ E_{operational}$	$\Lambda_{infrastructure}\ �\ E_{infrastructure}$
$Area_{III}$	$\frac{\Lambda_{operational}\ �\ (T_{or} - t_{or})}{2}$	$\frac{\Lambda_{infrastructure}\ �\ (T_{ir} - t_{ir})}{2}$

The *ΦΛΕΠ* Resilience Metric System

Phase	State	Resilience metric	Symbol
I	Disturbance progress	How *fast* resilience drops? How *low* resilience drops?	*Φ* *Λ*
II	Post-disturbance degraded	How *extensive* is the post-disturbance degraded state?	*E*
III	Restorative	How *promptly* does the network recover?	*Π*

Mathematical Formulation of Resilience Metrics

Metric	Mathematical Expression		Measuring Unit	
	Operational	Infrastructure	Operational	Infrastructure
Φ	$\frac{R_{pdo} - R_{0o}}{t_{ee} - t_{oe}}$	$\frac{R_{pdi} - R_{0i}}{t_{ee} - t_{oe}}$	MW/hours	Number of lines tripped/hours
Λ	$R_{0o} - R_{pdo}$	$R_{0i} - R_{pdi}$	MW	Number of lines tripped
E	$t_{or} - t_{ee}$	$t_{ir} - t_{ee}$	Hours	Hours
Π	$\frac{R_{0o} - R_{pdo}}{T_{or} - t_{or}}$	$\frac{R_{0i} - R_{pdi}}{T_{ir} - t_{ir}}$	MW/hours	Number of lines restored/hours
Area	$�_{t_{oe}}^{T_{or}} R_{op}(t)dt$	$�_{t_{oe}}^{T_{ir}} R_i(t)dt$	MW×hours	(Number of lines in service)×hours

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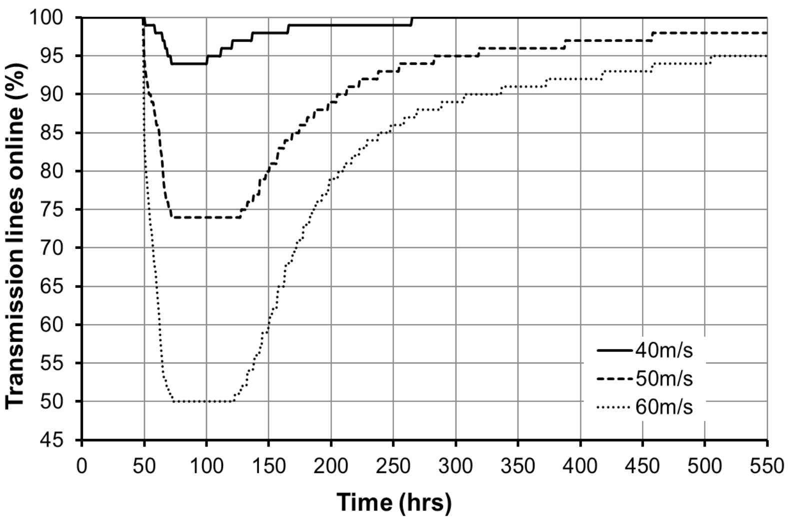
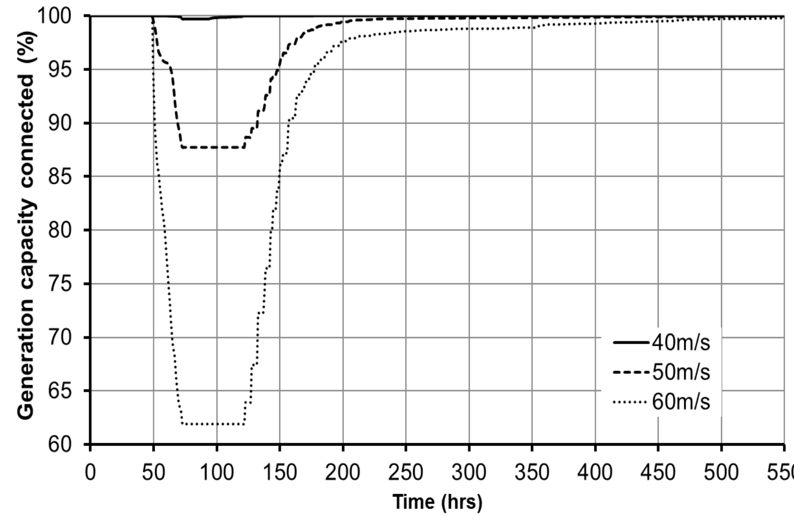
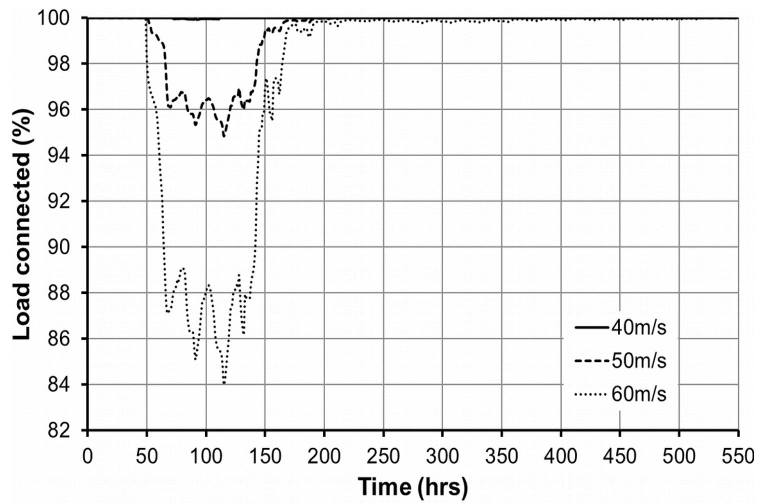
"ΦΛΕΠ" Resilience Metric System (cont.)

Resilience indicators for windstorms with maximum wind speed 40, 50 and 60m/s





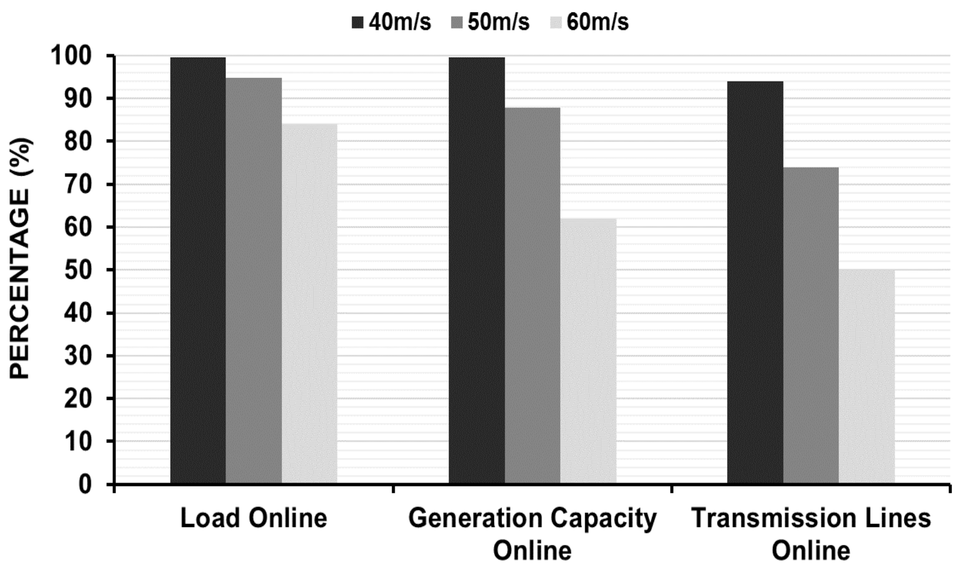


"ΦΛΕΠ" Resilience Metric System (cont.)

The Φ-metric: how fast resilience drops

Event	Resilience Indicator		
	Trans. lines	Gen. Connected	Load Connected
$WS_{40m/s}$	-0.2500	-0.0125	-0.0024
$WS_{50m/s}$	-1.0833	-0.521	-0.249
$WS_{60m/s}$	-2.0833	-1.5876	-0.6668

The Λ-metric: how low resilience drops



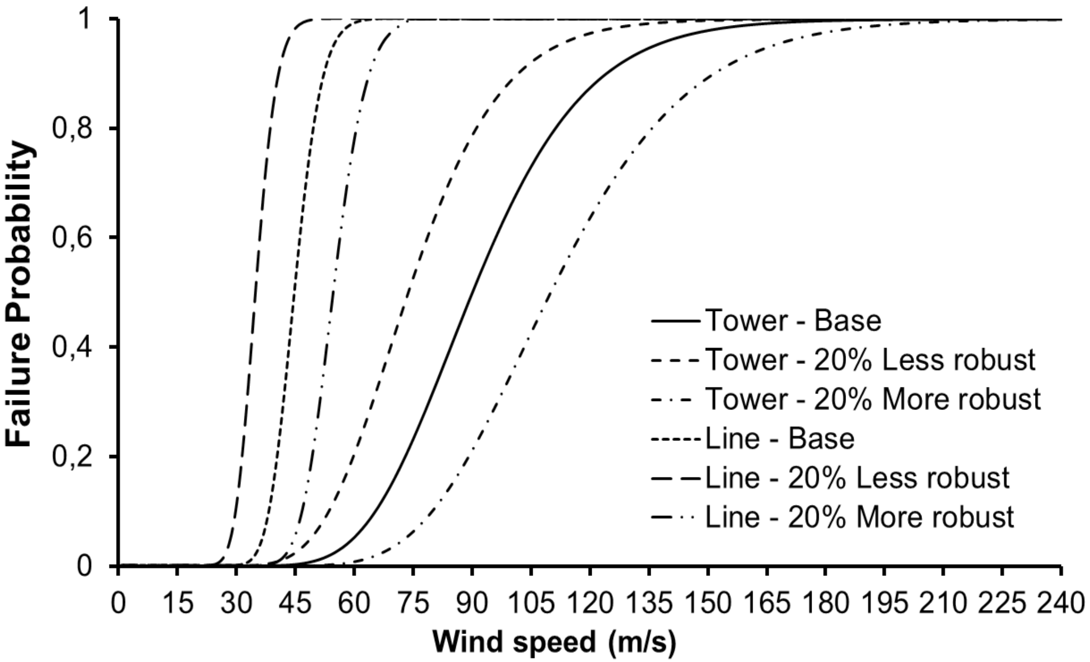
“ΦΛΕΠ” Resilience Metric System (cont.)

Adaptation Strategies:

Robust: the transmission lines and towers are made 20% more and less robust to the windstorm, by adjusting the fragility curves

Response: the responsiveness to the weather event is made 20% better and worse.

Resources: evaluate the effect of unlimited number of repair crews, 5, 10 and 15 is evaluated.



“ΦΛΕΠ” Resilience Metric System (cont.)

Focusing on the windstorm with maximum wind speed 50m/s

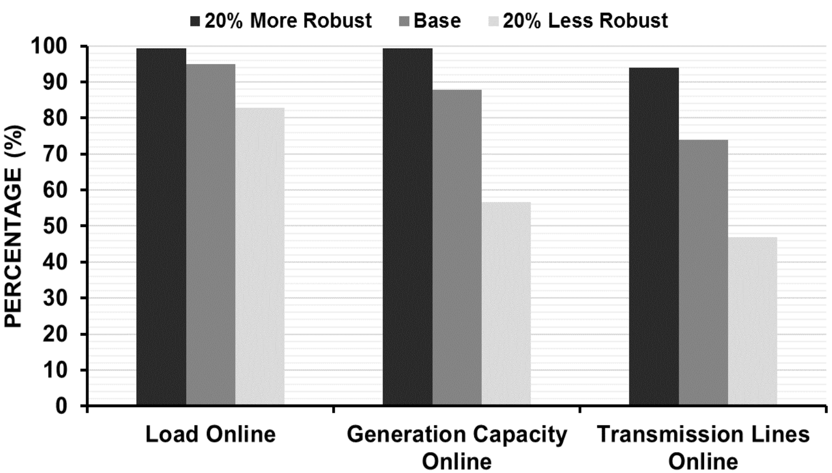
The ***Φ***-metric (robust case scenario)

Event	Resilience Indicator Trans. lines	 Gen. Connected	 Load Connected
20% Less Robust	-2.2083	-1.8083	-0.7132
Base	-1.0833	-0.521	-0.249
20% More Robust	-0.2500	-0.0121	-0.0117

The ***E***-metric (response case scenario)

Case study	Duration of post-event degraded state (hours) Transmission lines	 Generation Capacity	 Load
20%MoreResponse	44	47	48
Base	53	54	57
20%LessResponse	76	80	83

The ***Λ***-metric (robust case scenario)

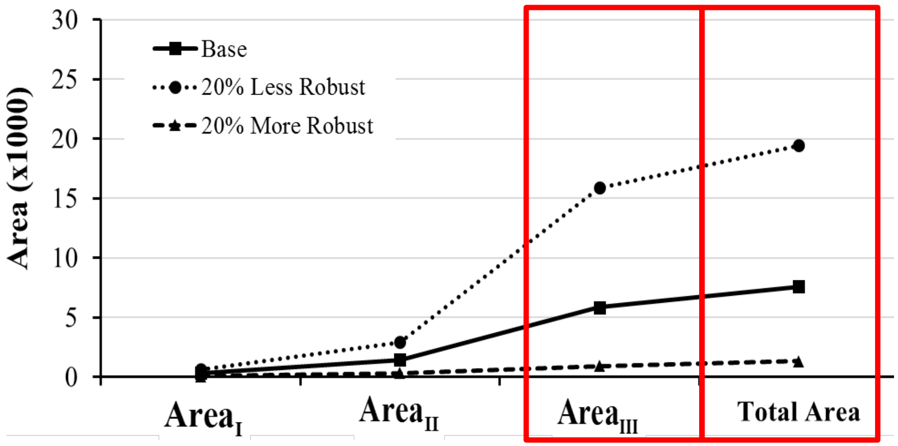


The ***Π***-metric (response and resources case scenarios)

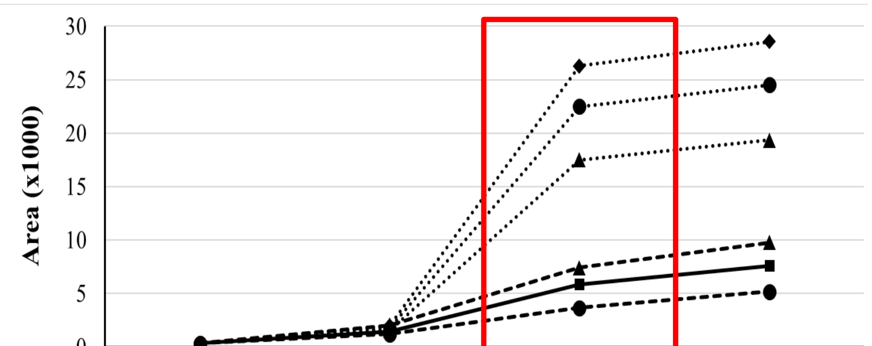
Case Study	Resilience indicator Trans. lines	 Gen. Connected	 Load Connected
5 RCs	0.0128	0.0060	0.0026
10 RCs	0.0137	0.0069	0.0039
15 RCs	0.019	0.0148	0.0076
20%LessResponse	0.0455	0.0266	0.0111
Base	0.0578	0.0330	0.0724
20%MoreResponse	0.0925	0.0354	0.0925

"*ΦΛΕΠ*" Resilience Metric System (cont.)

Calculating the ***area*** metric (using the indicator transmission lines for 50m/s):



Robust Case Scenario



	Area I	Area II	Area III	Total Area
Base	0.31	1.43	5.85	7.59
5 RCs	0.31	1.95	26.29	28.55
10 RCs	0.31	1.69	22.51	24.51
15 RCs	0.31	1.51	17.51	19.33
20% Less Response	0.31	2.03	7.42	9.76
20% More Response	0.31	1.20	3.65	5.16

Response and Resources Case Scenarios

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“ΦΛΕΠ” Resilience Metric System (cont.)

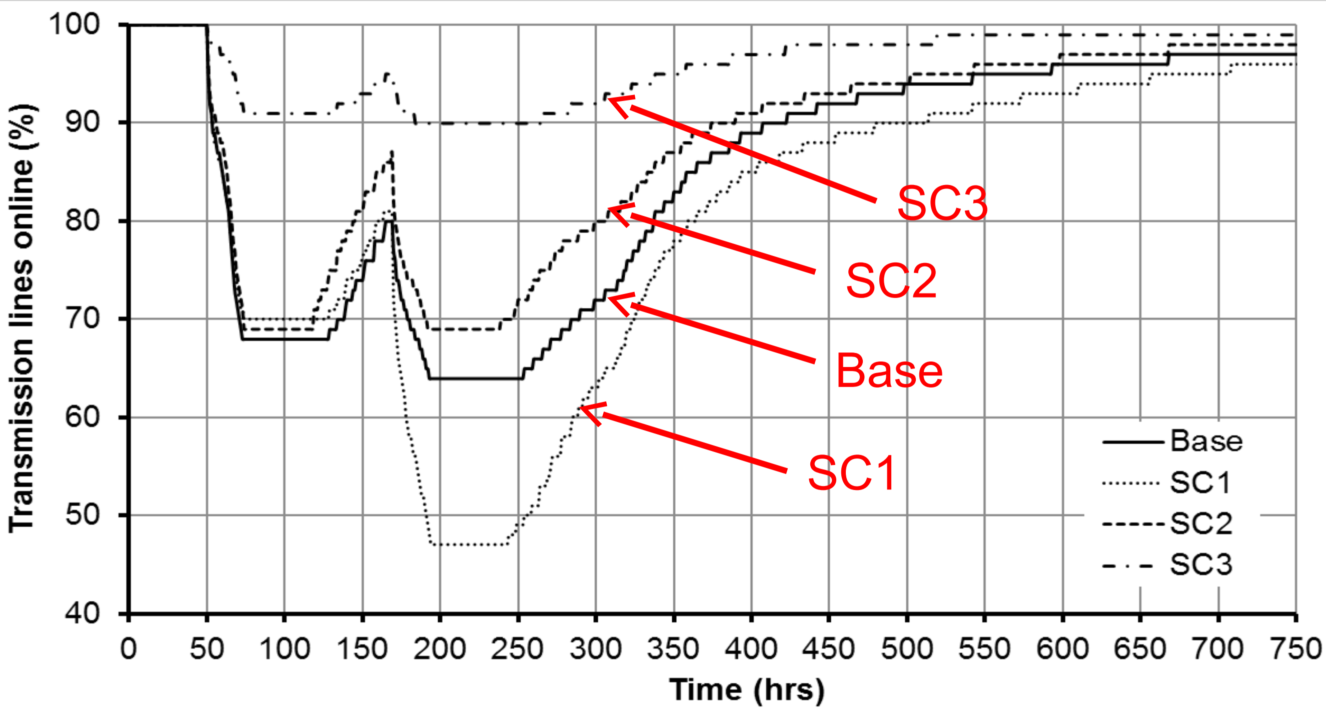
Resilience assessment to multiple, successive windstorms:

Base Scenario: five-day interval between the two events with maximum wind speed 50m/s, i.e., the first event is applied at 50h and the second event at 170h, both with a 24h duration

Scenario 1 (SC1): as base scenario, but different intensity of the windstorms - the maximum wind speed of the first windstorm is 50m/s and of the second 60m/s

Scenario 2 (SC2): as base scenario, but improving the responsiveness by 20%

Scenario 3 (SC3): as base scenario, but improving the robustness by 20%



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Conclusions

- Need to shift from the traditional reliability-oriented paradigms to more **resilience-oriented engineering**
- Determine the **threshold** for which the network becomes less resilient and perform **criticality ranking**.
- Novel **resilience metric system** capable of modelling and quantifying the actual response of a system exposed to extreme weather and natural hazards.
- Development and impact quantification of different **adaptation strategies**

Moving Forward

- Development of adaptive reinforcement strategies for boosting future power systems resilience
- Evaluate the contribution of smart grid technologies, complemented by a cost/benefit analysis

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Related Research Papers

- **M. Panteli** and P. Mancarella, "The Grid: Stronger, Bigger, Smarter? Presenting a Conceptual Framework of Power System Resilience", *IEEE Power and Energy Magazine*, vol. 13, no. 3, pp. 58-66, 2015 May/June issue
- **M. Panteli** and P. Mancarella, "Modelling and Evaluating the Resilience of Critical Electrical Power Infrastructure to Extreme Weather Events", Early access article, *IEEE Systems Journal*, February 2015
- **M. Panteli** and P. Mancarella, "Influence of Extreme Weather and Climate Change on the Resilience of Power Systems: Impacts and Possible Mitigation Strategies", *Electric Power Systems Research*, vol. 127, pp. 259-270, October 2015
- **M. Panteli**, D.N. Trakas, P. Mancarella, and N.D. Hatziargyriou, "Boosting the Power Grid Resilience to Extreme Weather Events Using Defensive Islanding", *IEEE Transactions on Smart Grid,* Special issue on "Power Grid Resilience", vol. 7, no. 6, pp. 2913-2922, March 2016
- S. Espinoza, **M. Panteli**, P. Mancarella, and H. Rudnick, "Multi-phase assessment and adaptation of power systems resilience to natural hazards", *Electric Power Systems Research*, vol. 136, pp. 352-361, July 2016.
- **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*, Early Access, December 2016
- **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*, Early Access, February 2017