Towards a framework for measurements of power systems resiliency: Comprehensive review and development of graph and vector-based resilience metrics

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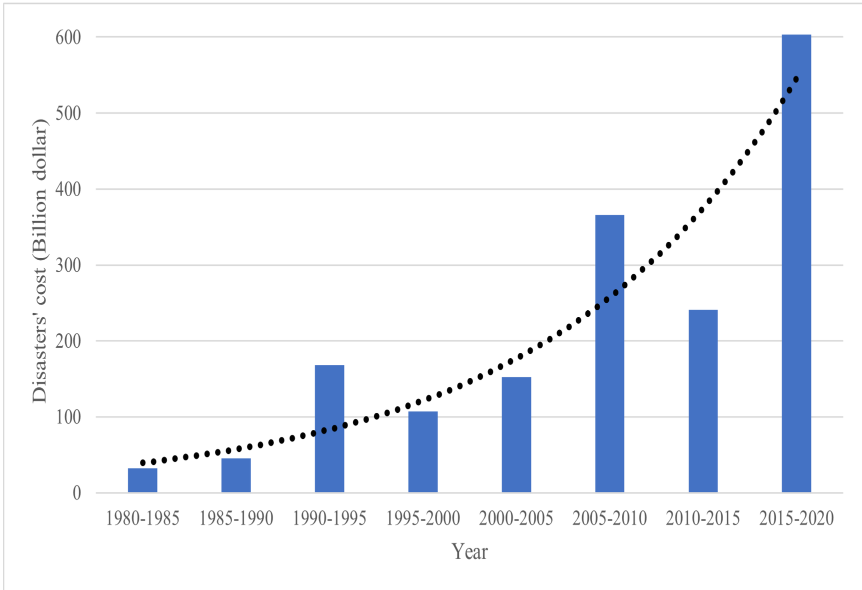
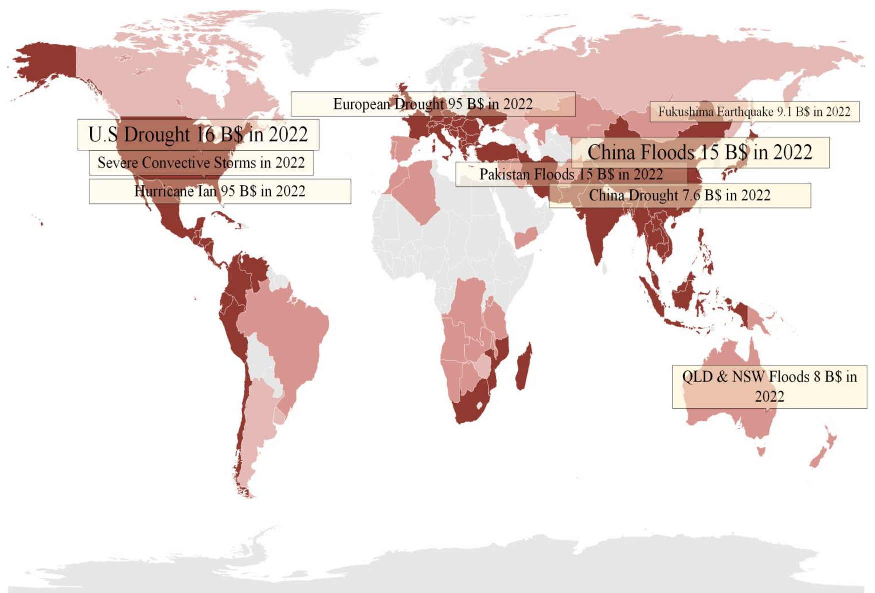
Introduction

- **Rising HILP Events Highlight Resilience:** The increasing trend of High Impact Low Probability (HILP) events, such as natural disasters and cyber attacks, has made the study of resilience in the power grid a hot topic, as reliability is no longer an issue in modern power systems.
- **Resilience Needs Clear Metrics:** Unlike the well-established concepts in reliability analysis, resilience lacks exact definitions and precise quantitative metrics in the literature, despite its growing importance due to the rise in HILP events.
- **IEEE PES Definition of Resilience:** *"Resilience is the capacity to resist and reduce the impact and/or duration of disruptive events, including the ability to foresee, absorb, adapt to, and/or quickly recover from such an event."*



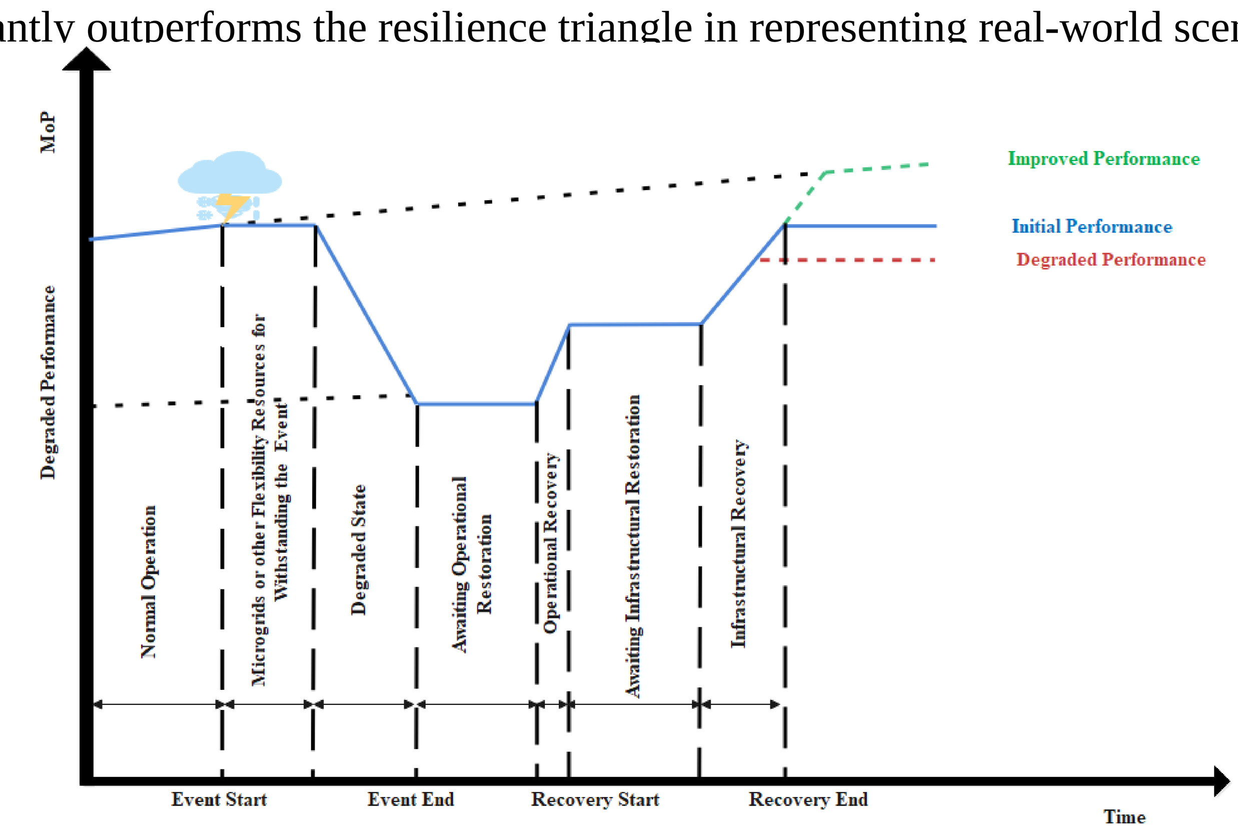
Billion Dollar Disasters' Cost in the U.S.



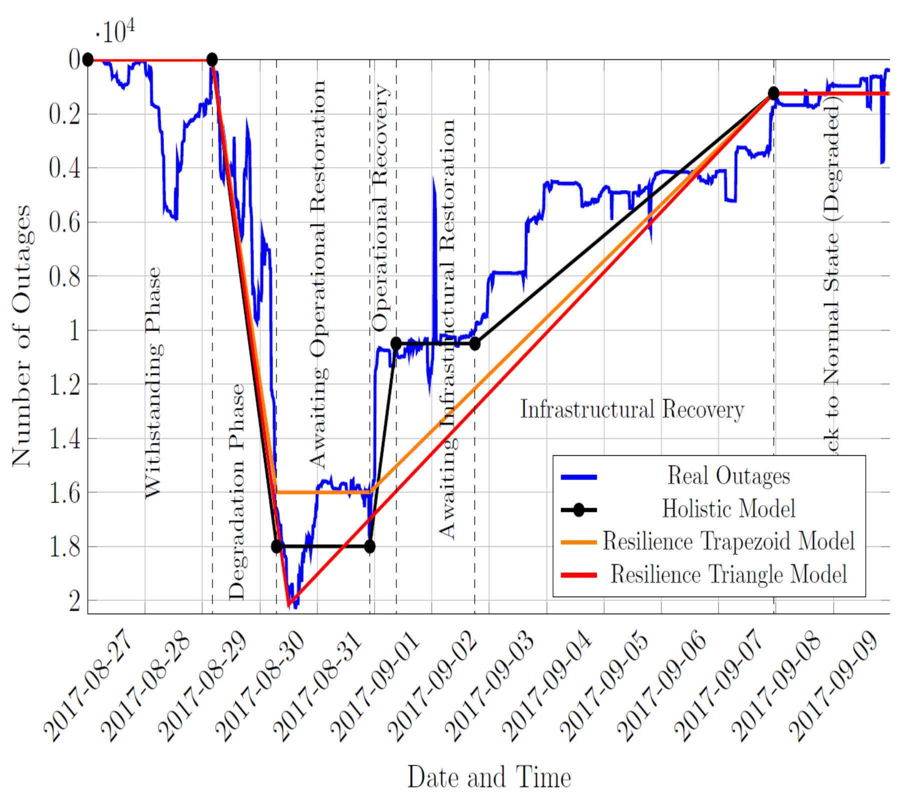
Countries Suffered From HILP

Key Points

- **Evolution of Resilience Curves:** Initial articles use a basic resilience triangle approach, progressing to a refined resilience trapezoid. With integrating suggestions from various articles, we form a holistic resiliency curve. Flexibility options, such as microgrids, help maintain system performance initially. Operational recovery achievable in a short timeframe, while structural recovery requires more time.
- **Comparative Analysis with Real Data:** We conduct a comparative analysis between the holistic resilience curve and real data from the EAGLE-I database, focusing on Hurricane Harvey's impact on Jefferson County, Texas, to assess the curve's utility.
- **Analysis Results:** The holistic model shows greater accuracy compared to the trapezoid model and significantly outperforms the resilience triangle in representing real-world scenarios.



Holistic Resilience Curve



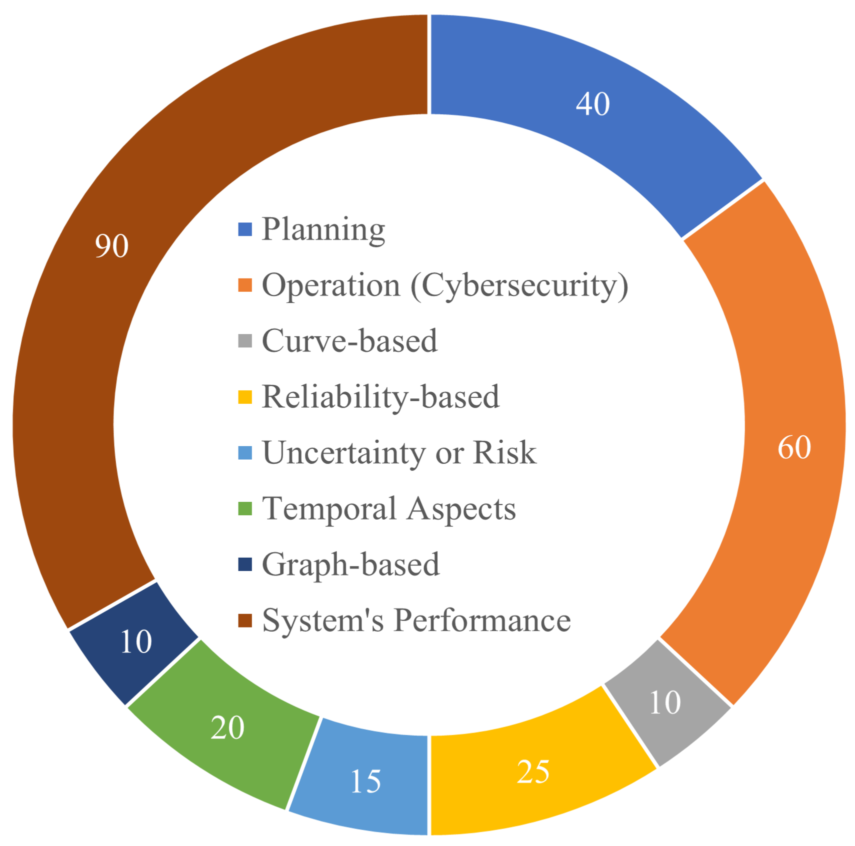
Real Outage Curve

Resiliency curve	Cumulative impact	Errors
Real Outage	2,090,939	-
Resilience Triangle	2,556,000	22.2%
Resilience Trapezoid	2,358,976	12.8%
Holistic Resilience	2,244,064	7.3%

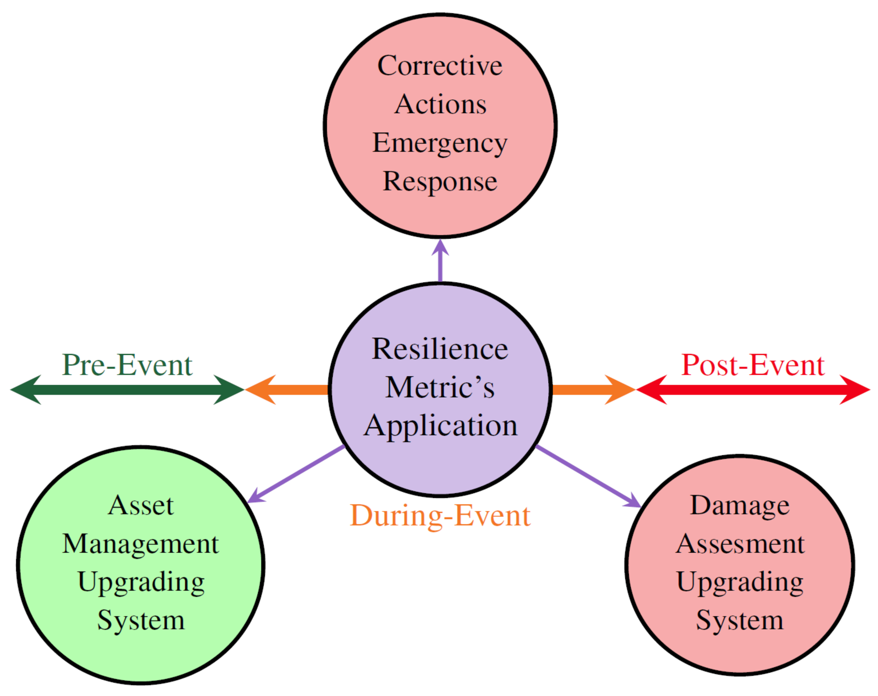
Real Outage Modelling

Resilience Metrics

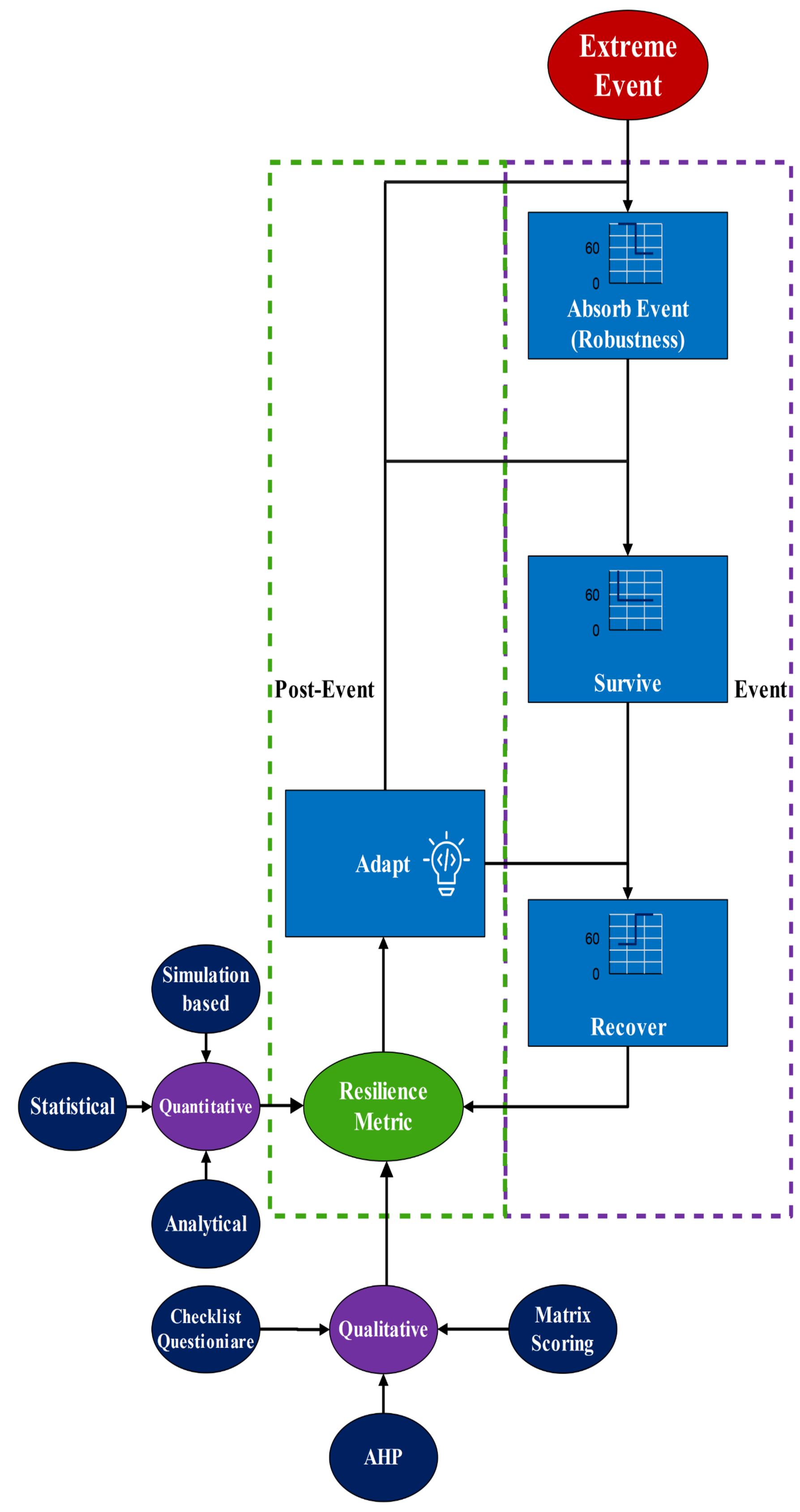
- **Interdependence of Resilience and Reliability:** Overlapping metrics necessitate a coordinated approach; reliability was often used in early resilience research.
- **Essential Elements of Resilience Metrics:** Usefulness in decision-making, facilitation of comparisons across different systems, applicability in both operational and planning contexts, scalability in time and geography, quantifiability, reflection of uncertainties, support for a risk-based approach, and consideration of recovery time.
- **Metrics' Applications:** Resilience metrics are valuable during pre-event, during-event, and post-event stages. **Pre-event:** system enhancements, conductor burial, and transmission line strengthening. **During events:** corrective actions and emergency responses like load shedding and islanding. **Post-event**: damage assessment and recovery efforts, including forming microgrids and deploying mobile energy resources.



Resilience Metrics' Categorization



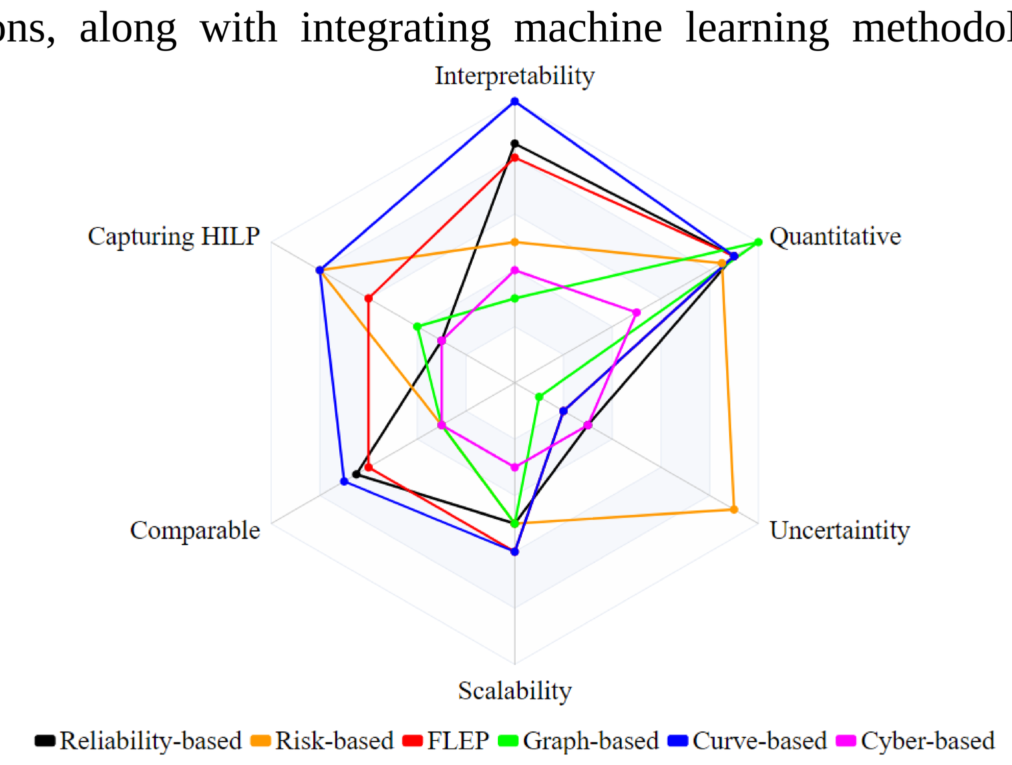
Resilience Metrics' Applications



Framework for Utilizing Resilience Metrics

Conclusion

- **Key Attributes of an Ideal Resilience Metric:** An ideal resilience metric for power systems should be scalable, comparable, interpretable, and quantifiable. It should also capture High Impact Low Probability (HILP) events and account for uncertainty. A comparative analysis of six key types of metrics—reliability-based, risk-based, graph-based, cyber-based, curve-based, and FLEP metrics—utilizes a spider diagram to illustrate their respective strengths and weaknesses.
- **Proposed Comprehensive Resilience Metric:** A combination of risk-based and curve-based metrics is deemed adequate, ensuring coverage of all essential attributes for an ideal resilience metric for most stakeholders. Additional research is required to establish connections or formulate metrics related to cybersecurity, interdisciplinary considerations, and multi-energy carrier considerations, along with integrating machine learning methodologies in resilience studies.



Evaluation of key metrics based on essential attributes of an ideal resilience metric

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