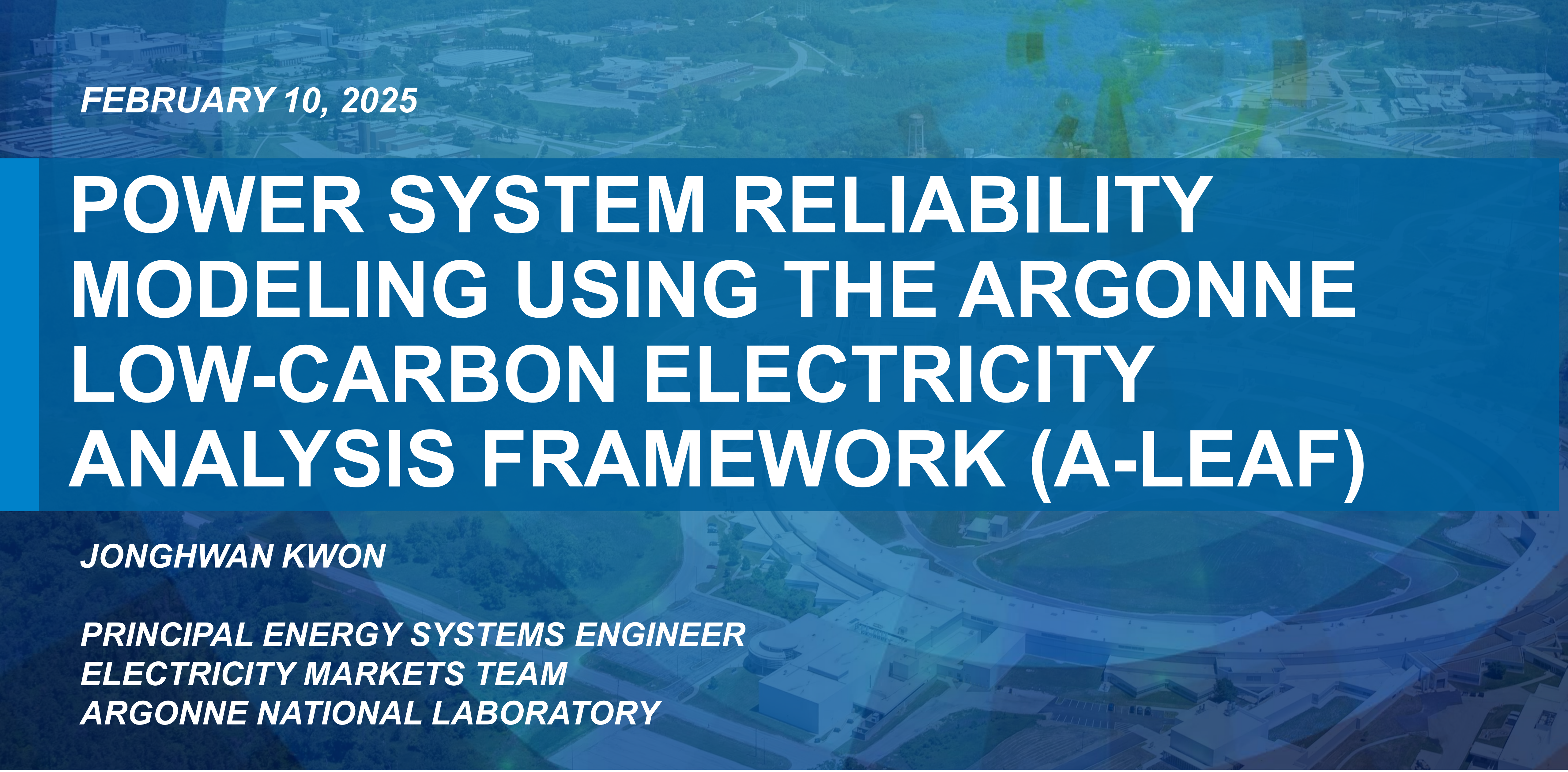

FEBRUARY 10, 2025

POWER SYSTEM RELIABILITY MODELING USING THE ARGONNE LOW-CARBON ELECTRICITY ANALYSIS FRAMEWORK (A-LEAF)

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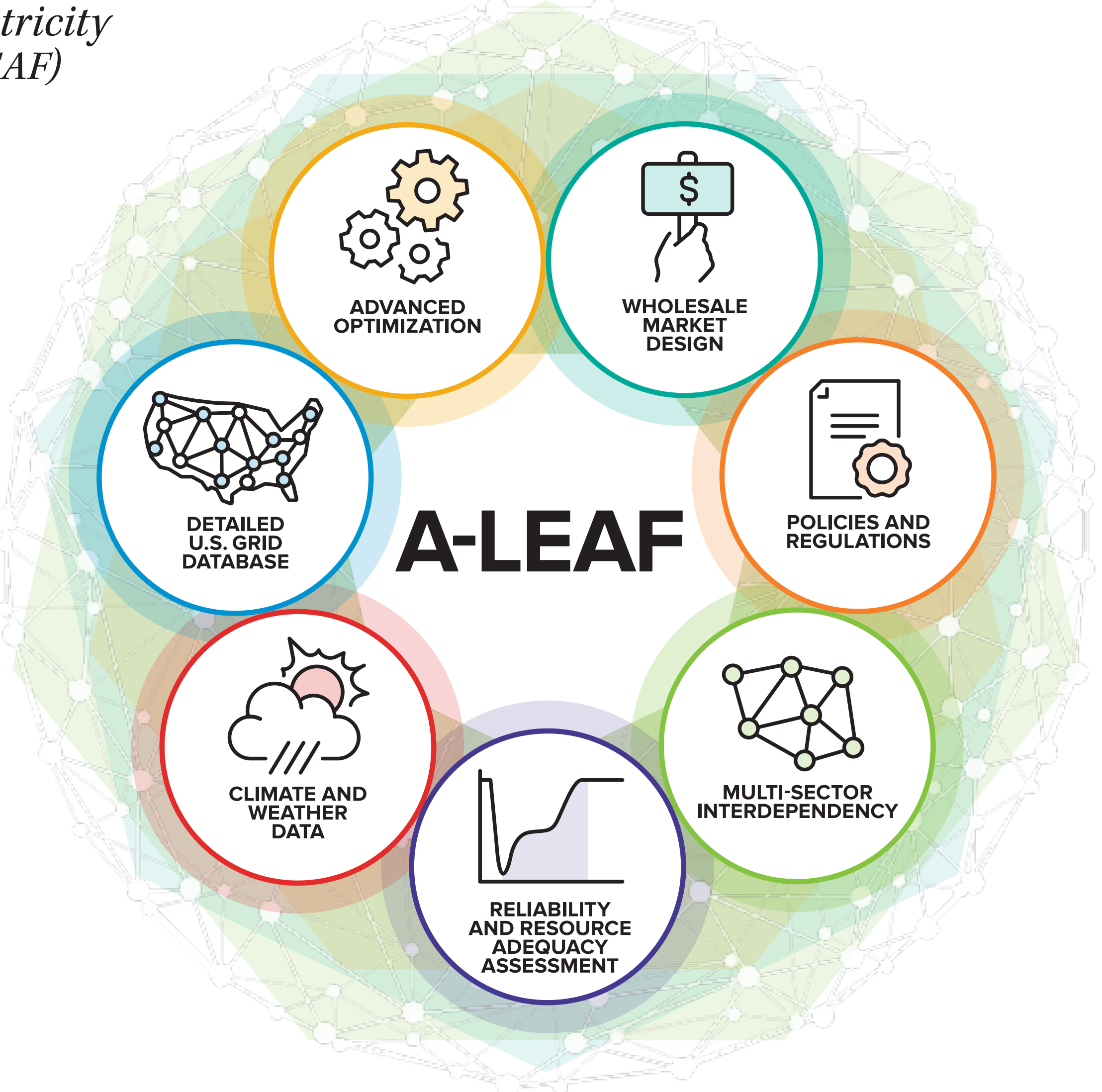
POWER SYSTEM MODELING

Argonne Low-Carbon Electricity Analysis Framework (A-LEAF)



ADVANCED OPTIMIZATION

□ System least-cost planning and operations
□ Strategic investments
□ Sub-hourly dispatch
□ Multiday representative periods
□ Simultaneous generation and transmission, and storage expansion planning

DETAILED U.S. GRID DATABASE

□ Extensive database of 9000+ U.S. generation resources
□ Hourly load profiles for 130+ balancing authorities
□ User-defined transmission zones at any scale
□ 200+ zone county-level Texas system

CLIMATE AND WEATHER DATA

□ Future weather years derived from climate models
□ Extreme weather events
□ Hourly wind and solar availability for current and future scenarios
□ Temperature dependent thermal outages

WHOLESALE MARKET DESIGN

□ Multi-stage market settlement
□ Scarcity pricing mechanisms
□ Forward market modeling

POLICIES AND REGULATIONS

□ National and local policies and incentives
□ Customizable emissions constraints
□ Land use restrictions and resource availability

MULTI-SECTOR INTERDEPENDENCY

□ Coupling with a global energy systems model (TIMES)
□ Water-energy nexus
□ Transportation systems
□ Natural gas infrastructure

RELIABILITY AND RESOURCE ADEQUACY ASSESSMENT

□ Probabilistic reliability assessment
□ Capacity accreditation using ELCC
□ System inertia requirements

U.S. DEPARTMENT OF ENERGY
Argonne National Laboratory is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC.

A-LEAF APPLICATIONS

Argonne Low-Carbon Electricity Analysis Framework

ELECTRICITY SYSTEM DECARBONIZATION

☐ Identify system least-cost decarbonization pathways

☐ Establish the role of transmission expansion in decarbonized futures

☐ Establish the role of energy storage in decarbonized futures

WHOLESALE MARKET ANALYSIS

☐ Compare the price and portfolio implications of enhanced scarcity pricing mechanisms

☐ Explore the implications decarbonization targets and policy incentives

LONG-TERM PLANNING

☐ Conduct high-fidelity capacity expansion analysis with 5-minute dispatch intervals

☐ Establish highly-customized multi-day periods to capture LDES value

☐ Evaluate storage value as a transmission asset

☐ Customize spatial representation to improve computational performance

SHORT-TERM OPERATIONS AND RELIABILITY ASSESSMENT

☐ Conduct full direct current optimal power flow modeling

☐ Simulate stochastic resource outages to determine reliability metrics

☐ Calculate resource effective load carrying capabilities

TECHNOECONOMIC VALUATION

☐ Assess optimal investment decisions from multiple perspectives: owner/operator, system, society

☐ Analyze resource revenues from providing capacity, energy, and reserves

CLIMATE RESILIENCE

☐ Consider 60+ future weather years with downscaled projections from global climate models

☐ Identify and analyze extreme weather events and periods of stressed operating conditions

POWER SYSTEM RELIABILITY

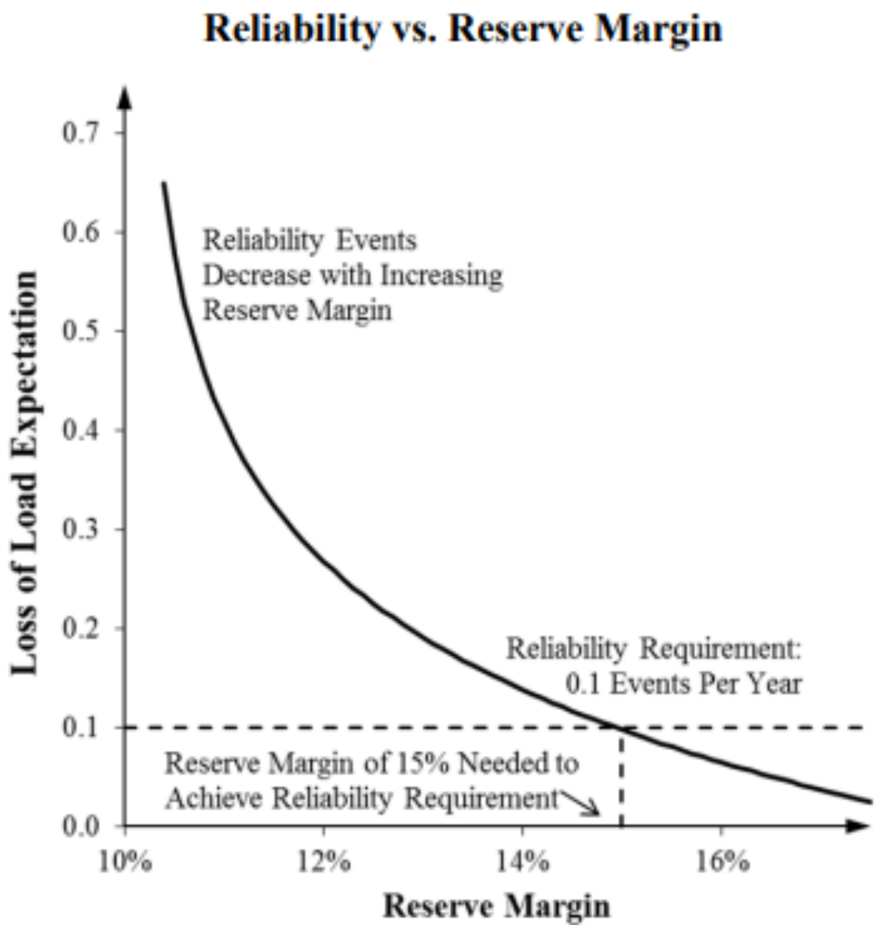
- System operators and planners perform long-term and short-term planning studies to maintain a continuous supply of electric energy
  - Society expects high reliability
  - Cost to society is high if there is a blackout
  - Value of Lost Load (VOLL) is often used to estimate the economic impact of load shedding
- System must be able to handle:
  - Contingencies (N-1, N-k, N-1-1)
  - Uncertainty (Load, area-interchange, renewables)

LONG-TERM RELIABILITY CRITERIA

- Loss of Load Expectation (LOLE)
  - Indicates the expected loss of load over a duration (a year, 10 years)
- Loss of Load Probability (LOLP)
  - The proportion of days per year that there is insufficient generation to meet demand
- Commonly used standard: LOLP should be no more than 1 day in 10 years or 2.4 hours/year
  - Generally used to specify that the length of time that generation is insufficient to meet demand should not exceed 1 day in 10 years

LONG-TERM RELIABILITY CRITERIA

- System-wide and regional reliability metrics (EUE, LOLP, and LOLE) are widely used to inform system planning and market designs.
  - Planning reserve margins
  - Capacity market demand curves
  - Operating reserve demand curves

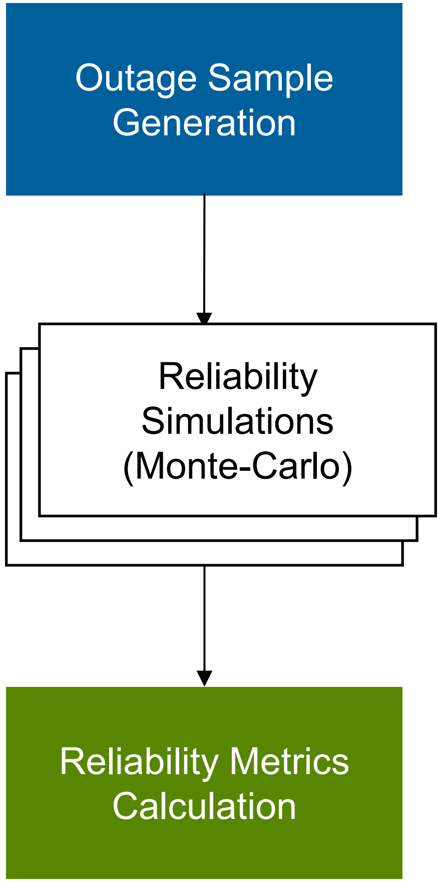


J. P. Pfeifenberger, K. Spees, et al “Resource Adequacy Requirements: Reliability and Economic Implications,” available at: https://www.ferc.gov/sites/default/files/2020-05/02-07-14-consultant-report.pdf

RELIABILITY ASSESSMENT MODELS

- **Industry Status Quo**
  - PJM: Probability Reliability Index Model (PRISM), Multi-Area Reliability Simulation (MARS)
  - NYISO, ISO-NE: MARS
  - MISO: MARS, Strategic Energy & Risk Valuation Model (SERVM)
  - ERCOT: SERVM
- **Challenge**:
  - It is important to achieve a balance between detail and computational tractability.
  - Limited attention has been given to understanding how different modeling assumptions and methods affect reliability metrics.
    - Risk sample size
    - Filtering methods
    - Post-contingency scheduling algorithm

A-LEAF PROBABILISTIC RELIABILITY ASSESSMENT MODEL

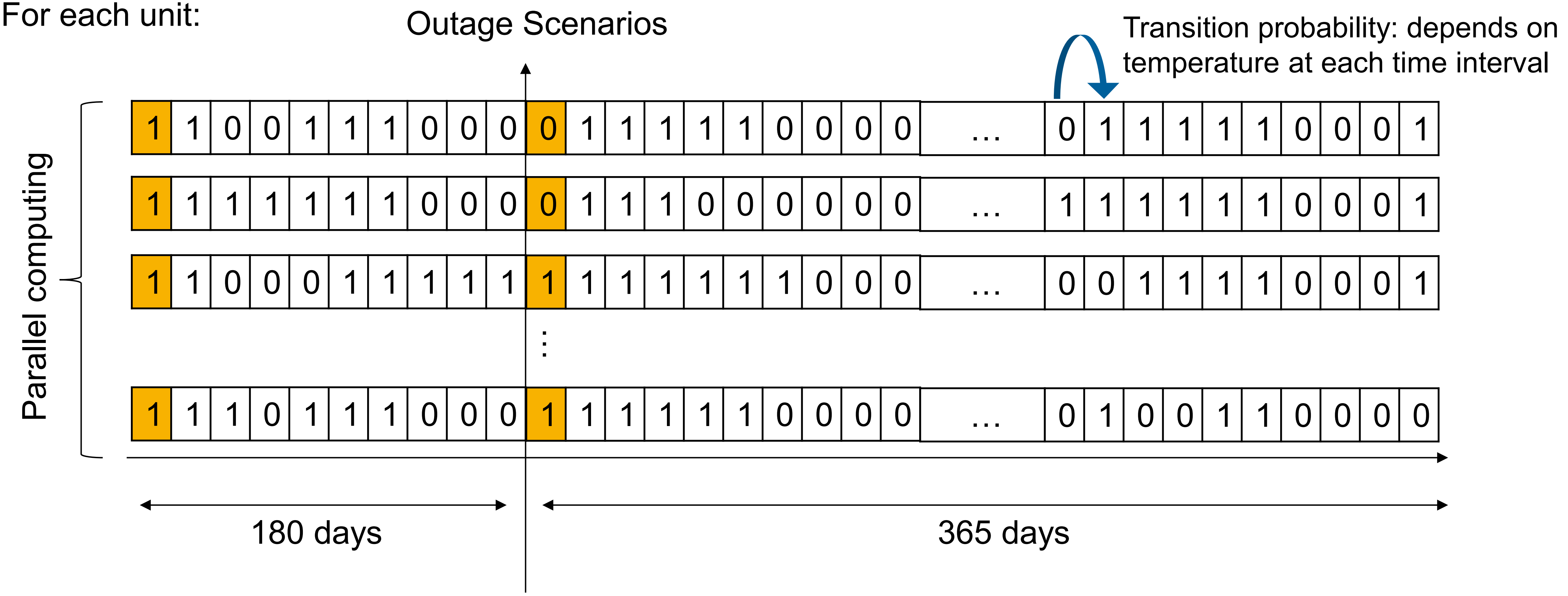


- Temperature-dependent generator outage sampling that utilizes a Markov chain approach to model generator state transitions
  - Sampled hourly over a full year (e.g., 10k samples for each unit for 8760 hours)
- Efficient sample filtering method to reduce the number of risk samples requiring dispatch simulations while maintaining the accuracy of resulting reliability metrics
- Two-stage system dispatch simulations with and without perfect foresight
  - First stage: Steady-state system operations
  - Second stage: Realization of system risks and post-contingency system redispatch
- Determines a range of metrics to evaluate system performance.
  - EUE, NEUE, LOLH, LOLP, and LOLE.
  - Indicators of outage severity (e.g., the maximum consecutive hours with load shedding, and the maximum load-shedding capacity in MW and MWh).

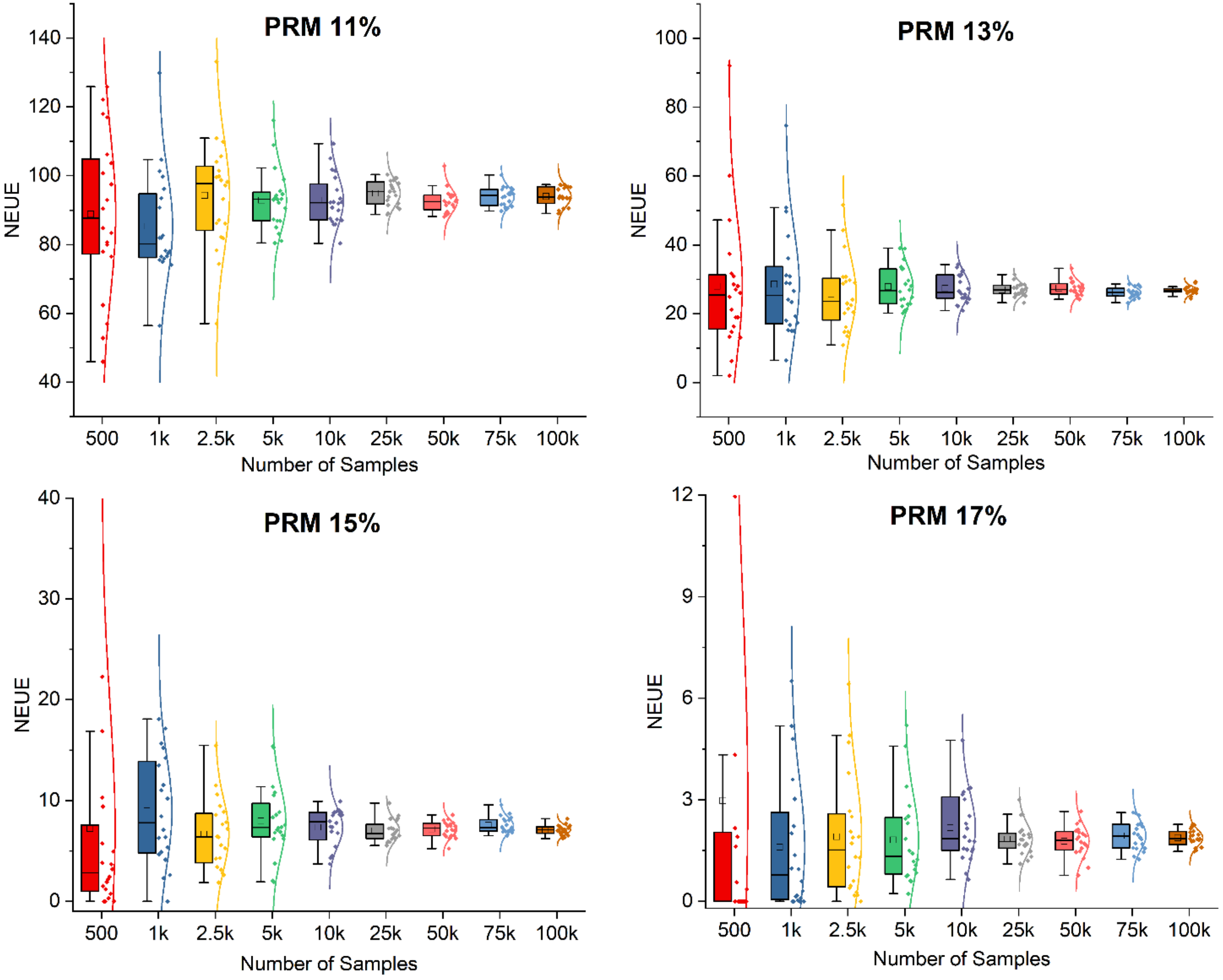
OUTAGE SCENARIO GENERATION

Markov model to simulate weather-dependent forced outage events

For each unit:

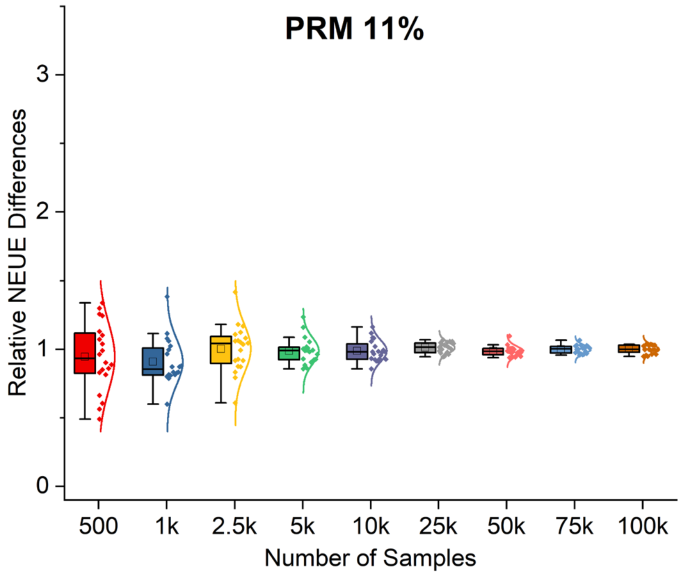


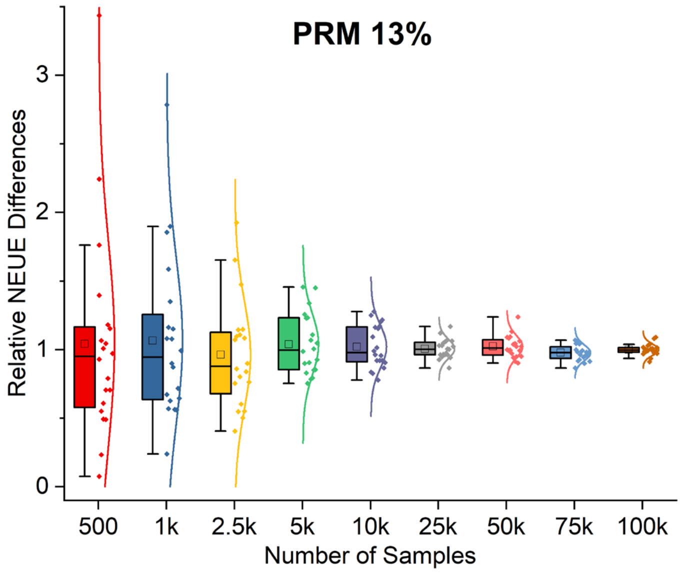
THE IMPACT OF SAMPLE SIZE ON RA METRICS

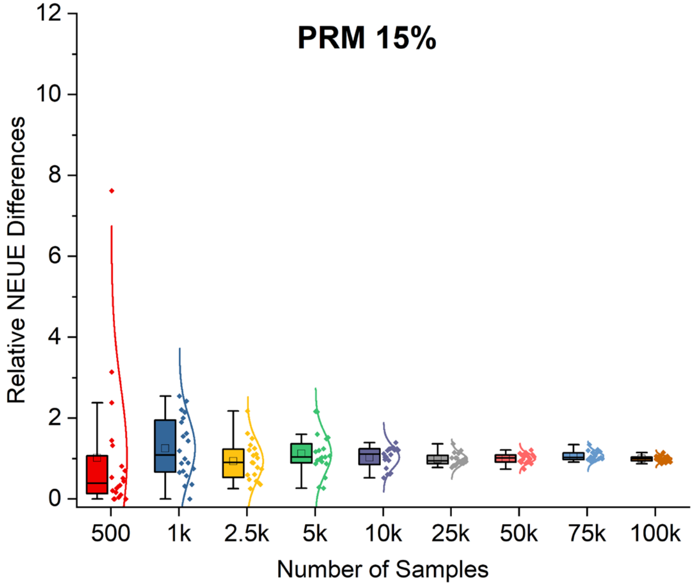


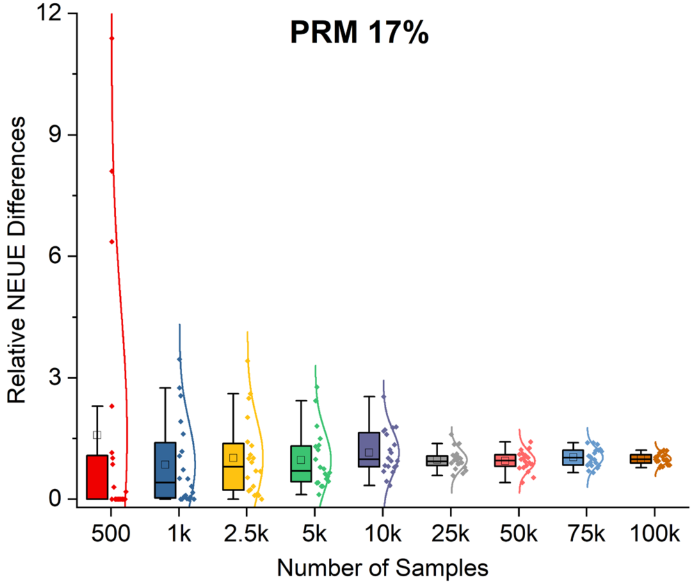
- We assess
  - 4 different PRM levels
  - 20 independent simulations for each sample size
  - No filtering
  - Applied to “ERCOT-like” system
- Across all PRM levels, the variability of NEUE decreases across batches as the number of samples increases.
- Smaller sample sizes cause high variability in absolute EUE values
  - Especially at lower PRMs.

THE IMPACT OF SAMPLE SIZE ON RA METRICS







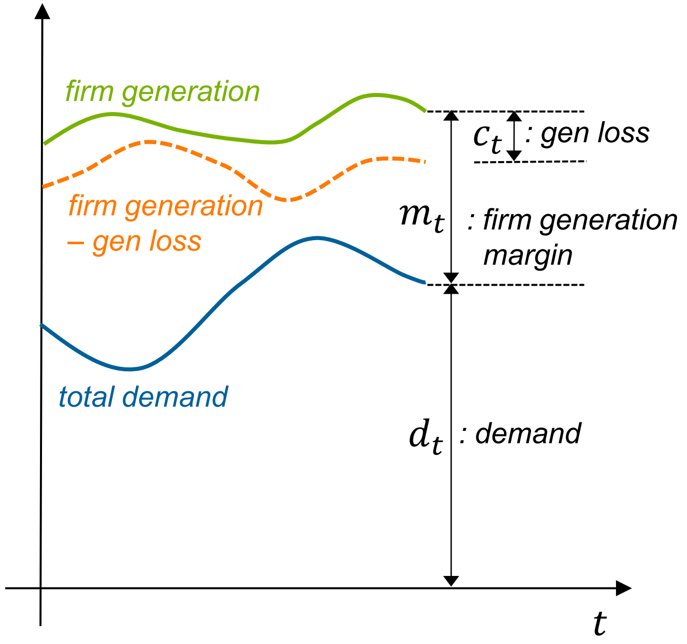


- Systems with high PRMs have low NEUE in absolute terms the variation
- But the relative deviation from low to high sample size is much greater.
- Results seem to converge around ~25k samples

System-specific sensitivity analyses are essential to establish robust results and determine the appropriate sample size

ENHANCING EFFICIENCY IN RELIABILITY ASSESSMENTS THROUGH SAMPLE FILTERING

Three Sample Filtering Methods



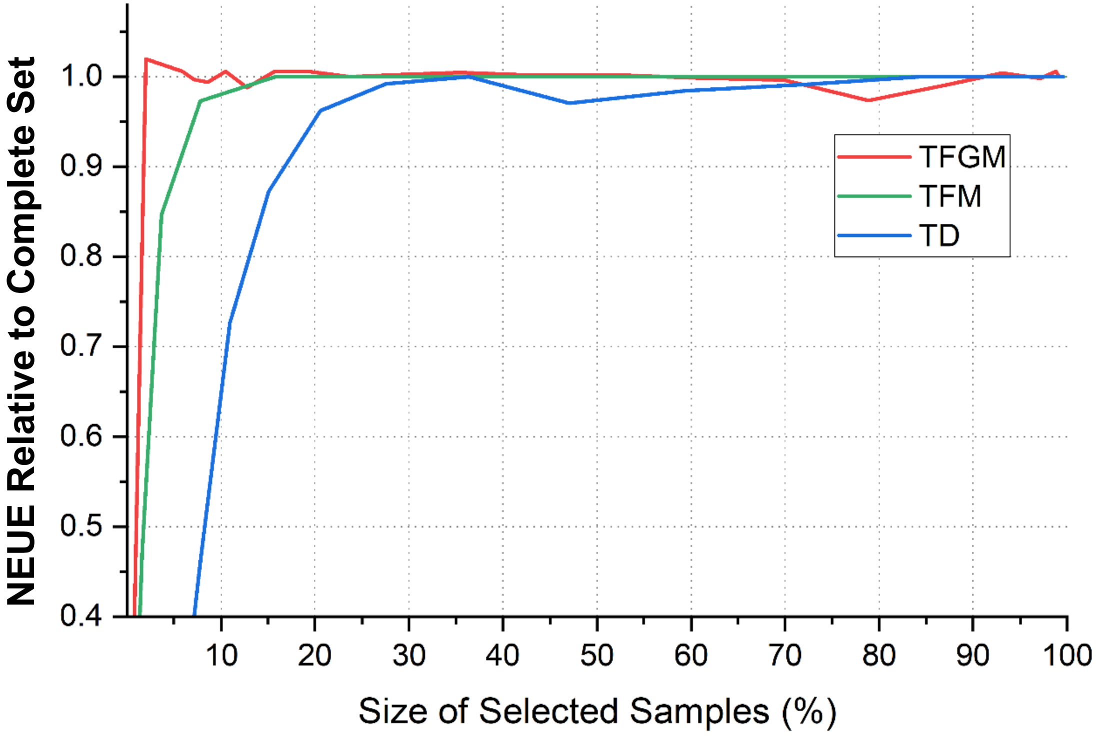
$$TFGM\colon \max_t \frac{c_t}{m_t}$$

$$TFG\colon \max_t \frac{c_t}{(d_t + m_t)}$$

$$TFM\colon \max_t \frac{c_t}{(d_t)}$$

- Simulating a large number of risk samples is challenging even with high-performance computers.
- This study evaluates the performance of sample filtering methods:
  - — ***TFGM***: based on total firm generation margin
  - — ***TFG***: based on total firm generation
  - — ***TD***: based on total demand

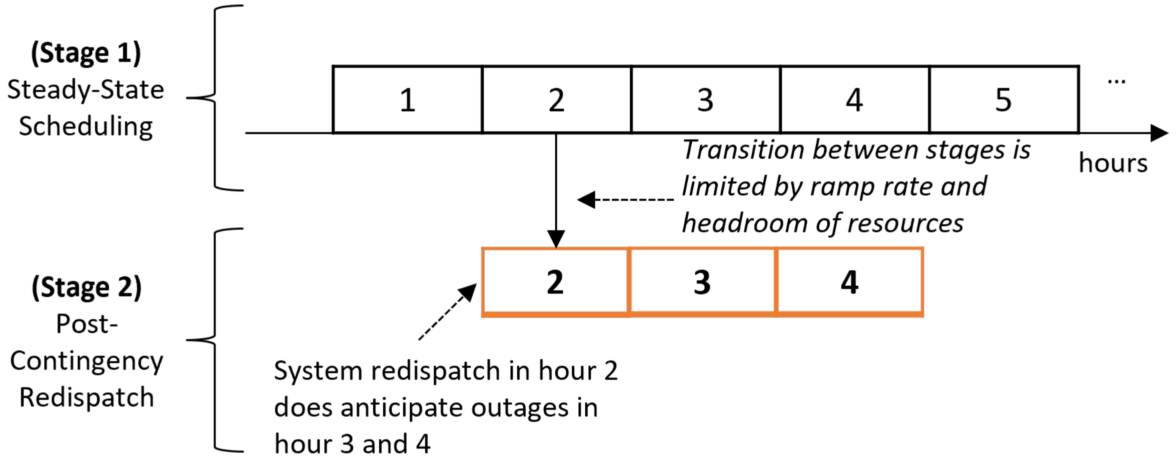
ENHANCING EFFICIENCY IN RELIABILITY ASSESSMENTS THROUGH SAMPLE FILTERING



- Three filtering methods are applied to a full year
  - ***TFGM***: based on total firm generation margin
  - ***TFM***: based on total firm generation
  - ***TD***: based on total demand based
- Referencing the firm generation margin captures more relevant information about the systems' reliability margin and outperforms other methods.
- System NEUE was predicted with reasonable accuracy when only simulating ~5% of total outage draws

Sample filtering can improve the efficiency of reliability assessment models while preserving accuracy

RELIABILITY SIMULATIONS OVERVIEW



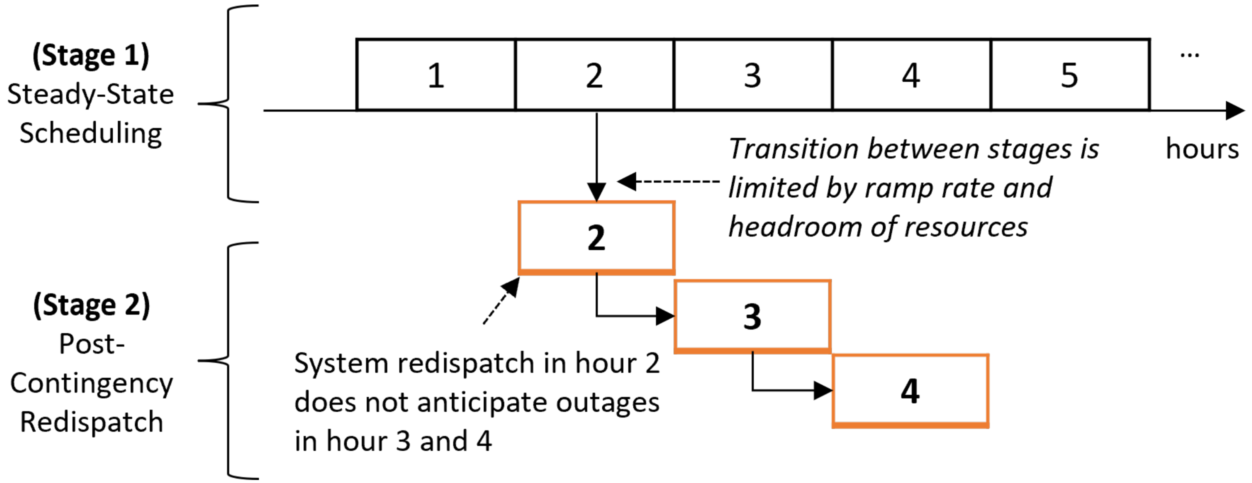
(Stage 1)
Steady-State
Scheduling

Transition between stages is limited by ramp rate and headroom of resources

(Stage 2)
Post-Contingency
Redispatch

System redispatch in hour 2 does anticipate outages in hour 3 and 4

Two-stage structure with perfect foresight



(Stage 1)
Steady-State
Scheduling

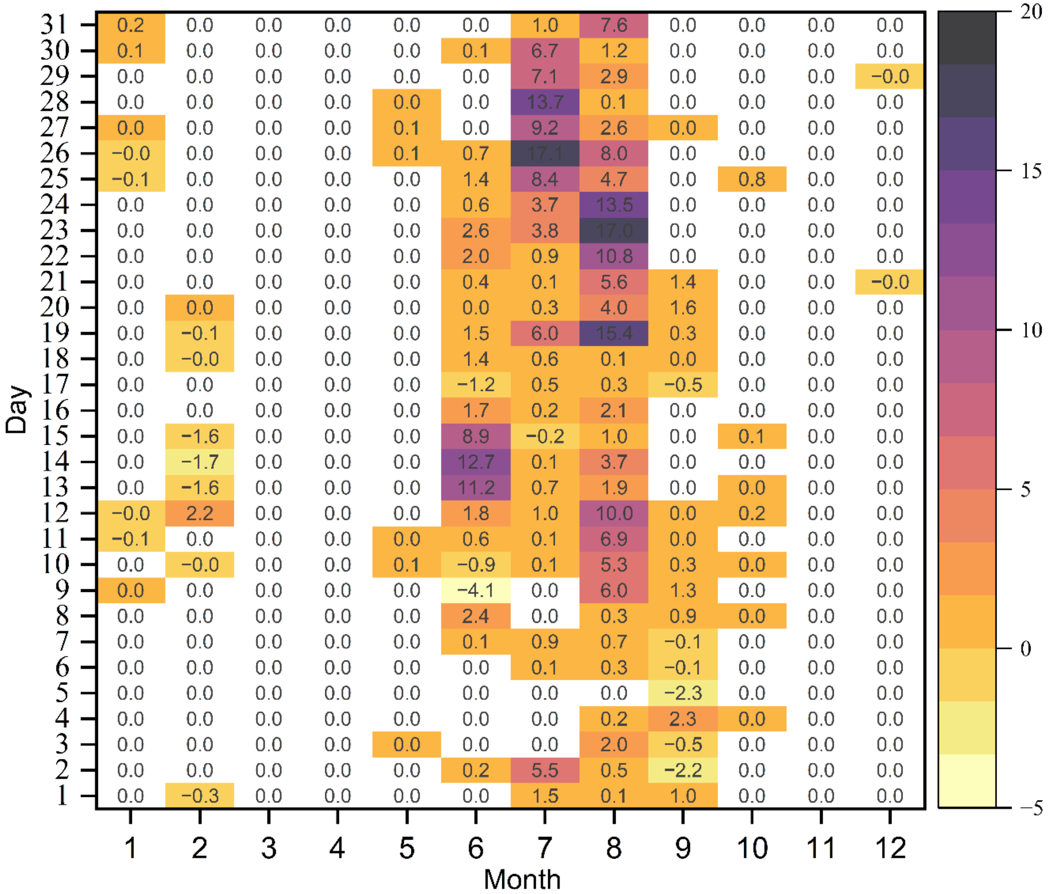
Transition between stages is limited by ramp rate and headroom of resources

(Stage 2)
Post-Contingency
Redispatch

System redispatch in hour 2 does not anticipate outages in hour 3 and 4

Two-stage structure without perfect foresight

THE IMPACT OF IMPERFECT FORESIGHT ON RA METRICS



Day	1	2	3	4	5	6	7	8	9	10	11	12
31	0.2	0.0	0.0	0.0	0.0	0.0	1.0	7.6	0.0	0.0	0.0	0.0
30	0.1	0.0	0.0	0.0	0.0	0.1	6.7	1.2	0.0	0.0	0.0	0.0
29	0.0	0.0	0.0	0.0	0.0	0.0	7.1	2.9	0.0	0.0	0.0	−0.0
28	0.0	0.0	0.0	0.0	0.0	0.0	13.7	0.1	0.0	0.0	0.0	0.0
27	0.0	0.0	0.0	0.0	0.1	0.0	9.2	2.6	0.0	0.0	0.0	0.0
26	−0.0	0.0	0.0	0.0	0.1	0.7	17.1	8.0	0.0	0.0	0.0	0.0
25	−0.1	0.0	0.0	0.0	0.0	1.4	8.4	4.7	0.0	0.8	0.0	0.0
24	0.0	0.0	0.0	0.0	0.0	0.6	3.7	13.5	0.0	0.0	0.0	0.0
23	0.0	0.0	0.0	0.0	0.0	2.6	3.8	17.0	0.0	0.0	0.0	0.0
22	0.0	0.0	0.0	0.0	0.0	2.0	0.9	10.8	0.0	0.0	0.0	0.0
21	0.0	0.0	0.0	0.0	0.0	0.4	0.1	5.6	1.4	0.0	0.0	−0.0
20	0.0	0.0	0.0	0.0	0.0	0.0	0.3	4.0	1.6	0.0	0.0	0.0
19	0.0	−0.1	0.0	0.0	0.0	1.5	6.0	15.4	0.3	0.0	0.0	0.0
18	0.0	−0.0	0.0	0.0	0.0	1.4	0.6	0.1	0.0	0.0	0.0	0.0
17	0.0	0.0	0.0	0.0	0.0	−1.2	0.5	0.3	−0.5	0.0	0.0	0.0
16	0.0	0.0	0.0	0.0	0.0	1.7	0.2	2.1	0.0	0.0	0.0	0.0
15	0.0	−1.6	0.0	0.0	0.0	8.9	−0.2	1.0	0.0	0.1	0.0	0.0
14	0.0	−1.7	0.0	0.0	0.0	12.7	0.1	3.7	0.0	0.0	0.0	0.0
13	0.0	−1.6	0.0	0.0	0.0	11.2	0.7	1.9	0.0	0.0	0.0	0.0
12	−0.0	2.2	0.0	0.0	0.0	1.8	1.0	10.0	0.0	0.2	0.0	0.0
11	−0.1	0.0	0.0	0.0	0.0	0.6	0.1	6.9	0.0	0.0	0.0	0.0
10	0.0	−0.0	0.0	0.0	0.1	−0.9	0.1	5.3	0.3	0.0	0.0	0.0
9	0.0	0.0	0.0	0.0	0.0	−4.1	0.0	6.0	1.3	0.0	0.0	0.0
8	0.0	0.0	0.0	0.0	0.0	2.4	0.0	0.3	0.9	0.0	0.0	0.0
7	0.0	0.0	0.0	0.0	0.0	0.1	0.9	0.7	−0.1	0.0	0.0	0.0
6	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.3	−0.1	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	−2.3	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	2.3	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.0	−0.5	0.0	0.0	0.0
2	0.0	0.0	0.0	0.0	0.0	0.2	5.5	0.5	−2.2	0.0	0.0	0.0
1	0.0	−0.3	0.0	0.0	0.0	0.0	1.5	0.1	1.0	0.0	0.0	0.0

Careful modeling and design of system dispatch algorithms is essential as they can significantly impact reliability outcomes

- Finally, we compare two post-contingency redispatch methods 1) with and 2) without perfect foresight.
- The imperfect foresight case shows that operational uncertainty leads to higher EUE values.
  - Particularly in high-demand periods.
- Perfect foresight post-contingency dispatch models may therefore overestimate system reliability.

Metrics	w/ Perfect Foresight	w/o Perfect Foresight	Difference (%)
EUE (MWh/year)	3,561.7	3,831.6	7.6%
NEUE (ppm)	8.0	8.6	7.6%
LOLH (hours)	2.3	2.5	8.5%
LOLE (hours/year)	0.00027	0.00029	8.5%
Max MW Loss	7,945.3	7,985.5	0.5%
Max MWh Loss	62,293.3	62,701.7	0.7%
Longest Outage (h)	13.0	13.0	0.0%

CONCLUSION

- The reliability assessment model samples generation outages and perform Monte-Carlo simulations to evaluate power system reliability levels.
- Our recent study highlights that an adequate number of samples is critical for accurate reliability studies; however, computational limitations remain a challenge.
  - Additional uncertainties (transmission lines, renewable availability, etc)
  - System dispatch logics
- AI has the potential to enhance reliability assessments.
  - Additionally, the reliability model can serve to provide training data