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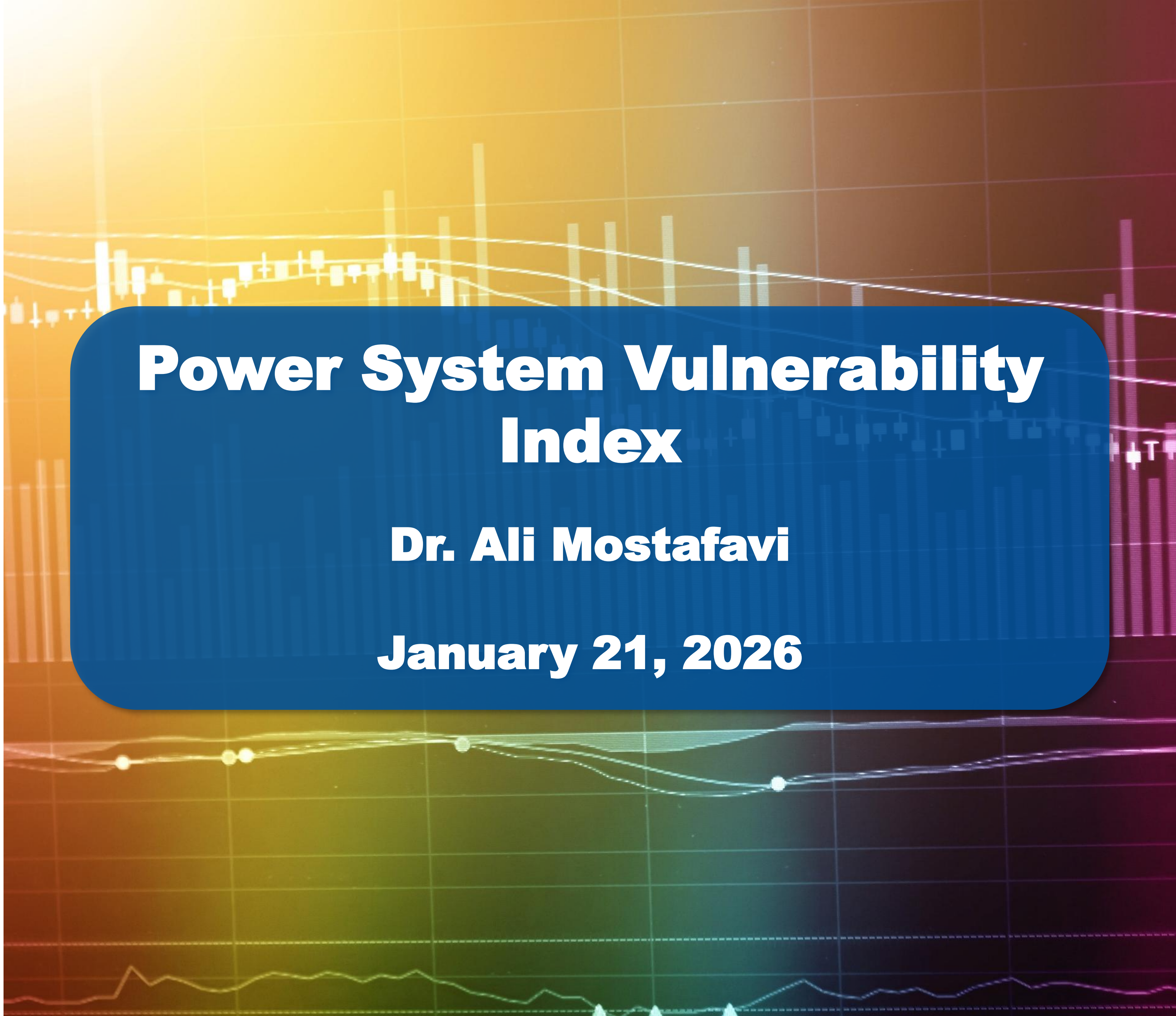

Power System Vulnerability Index

Dr. Ali Mostafavi

January 21, 2026

Antitrust Admonition

Because this event brings together market participants who may be viewed as actual or potential competitors, we must be mindful to conduct it in a manner that is consistent with the antitrust and competition laws. Participants should not disclose non-public, proprietary, or competitively sensitive information.

Attendees should exercise independent judgment and avoid even the appearance of discussions of agreements or concerted actions that may be viewed as restraining competition. Any questions on Texas RE's Antitrust Compliance Corporate Policy may be directed to Texas RE's General Counsel.

Upcoming Texas RE Events

February 23, 2026

NERC and ERCOT Reliability Assessments

March 10, 2026

Regional Risk Series: Artificial Intelligence

March 17, 2026

Regional Risk Series: Supply Chain

Upcoming Texas RE Events

February 25, 2026

Q1 MRC, AGR&F, and Board Meetings

April 1, 2026

Spring Standards, Security, & Reliability Workshop

August 19, 2025

Winter Weatherization Workshop

Upcoming ERO Enterprise Events

Date	Event
February 3-5, 2026	SERC Physical Security Workshop
February 24-24, 2026	WECC Grid Fundamentals
February 24-25, 2025	RF Internal Controls Workshop
February 25-26, 2026	2026 ERO Women's Leadership Conference

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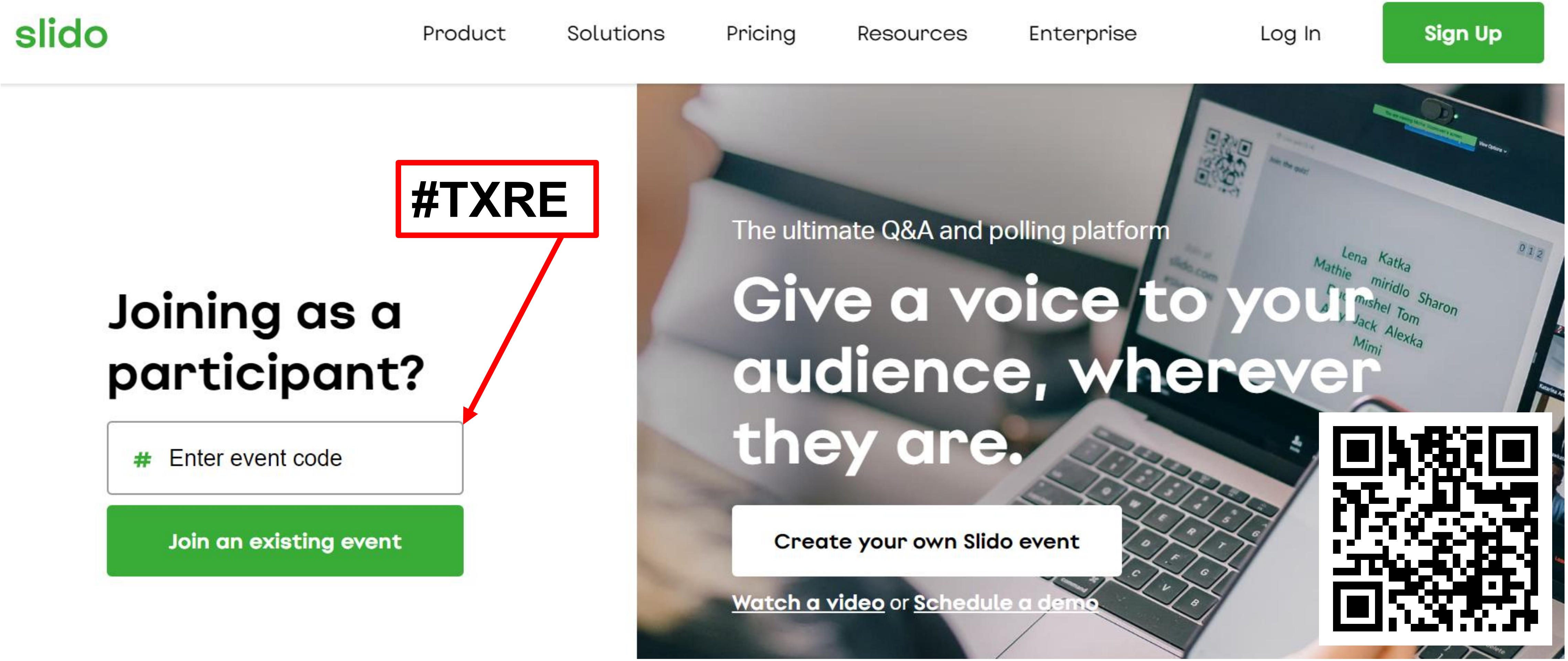

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Power System Vulnerability: From Diagnosis to Quantification

A Data-Driven Approach to Grid Resilience

Professor Ali Mostafavi

Zachry Department of Civil and Environmental Engineering
Texas A&M University
Director, Urban Resilience.AI Lab
Director, Disaster AI Initiative, Institute for Disaster Resilient Texas

Today's Journey: Understanding & Predicting Power System Vulnerability

Part 01

The Growing Power Outage Crisis

- Temporal trends: frequency, duration, intensity
- Spatial patterns & vulnerable regions
- Climate & socioeconomic drivers

Part 02

Machine Learning Solution (PSVI)

- Interpretable ML framework
- Nationwide vulnerability maps
- Model performance & validation

Part 03

Implications for the Industry

- Investment prioritization
- Resilience planning strategies
- Future collaboration opportunities

Power Outages Have Reached Unprecedented Levels Across the United States

Analysis of 179 million records reveals the magnitude of the crisis (2014-2023)

7.86 Billion

Customer-Hours of Outage Time

Cumulative total over the past decade

3,022,915

Power Outage Events

Identified across 3,022 U.S. counties

Every Week

Average Frequency

Mean inter-event time: 7.16 days

3.65%

Time Without Power

Average time residents spent in darkness

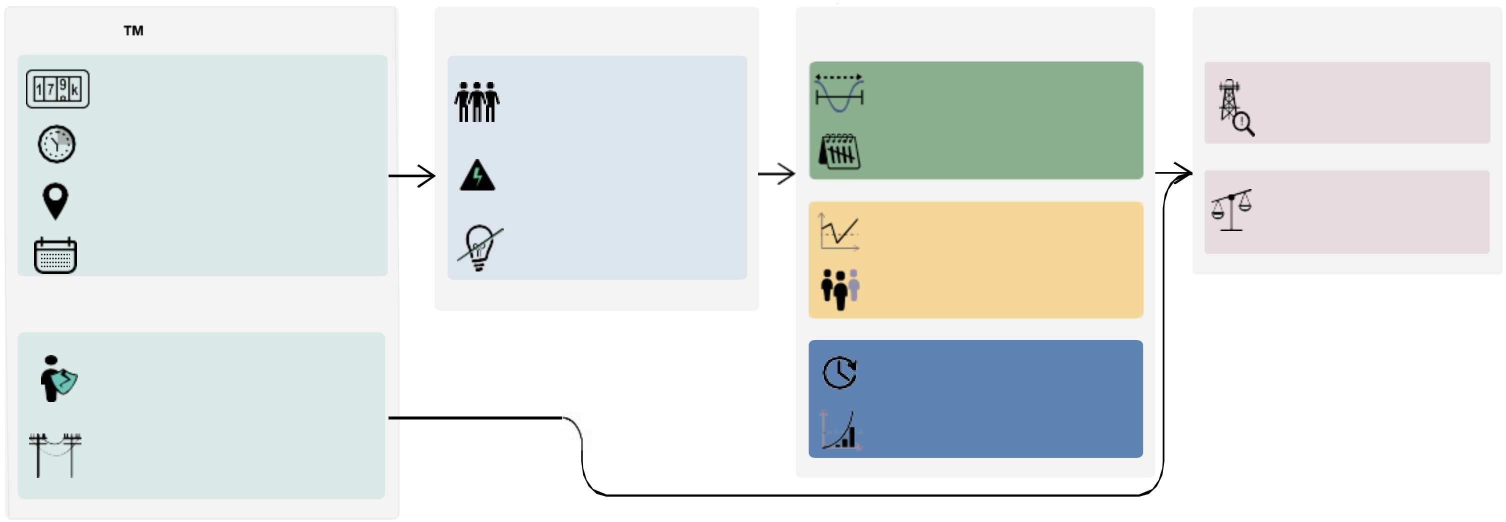

Figure 1: Power System Vulnerability Assessment Workflow (Source: Li et al., 2025)

Data Source: EAGLE-I ™ Dataset (15-minute interval resolution)

A Comprehensive Three-Dimensional Framework Captures the Full Extent of Power System Vulnerability

Frequency

- Number of outage events
- Average inter-event time
- Events affecting >5% customers

Duration

- Average outage duration
- Total cumulative duration
- Long-duration events (>12 hours)

Intensity

- Average outage rate (% customers)
- Number of customers affected
- Peak outage intensity

Methodology: Analyzed 180 million outage records at 15-minute intervals (Nov 2014 - Dec 2023) across 3,022 counties.

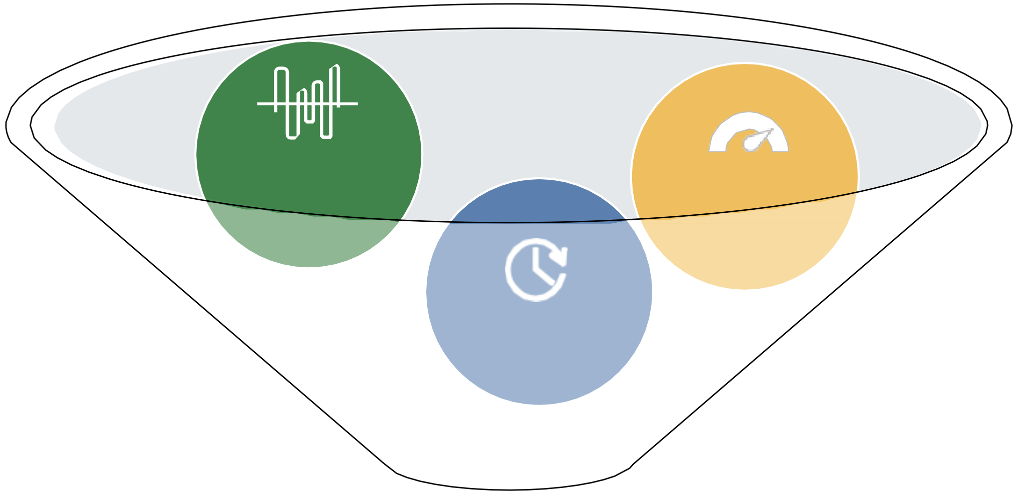

Figure 2: Conceptual Framework for Assessing Power System Vulnerability (Source: Li et al., 2025)

Source: Paper 2 - Ma et al. (2025)

Power Outages Are Becoming More Frequent, Prolonged, and Intense

Six key metrics reveal widespread and growing vulnerability (2014-2023)

- **Number of Events:**
  Mean 999/county, concentrated in Eastern U.S.
- **Average Outage Rate:**
  Mean 1.51%, widespread distribution.
- **Total Duration:**
  Mean 118.79 days, highest in coastal regions.
- **Inter-Event Time:**
  Mean 7.16 days, shorter in East (higher frequency).
- **Customers Affected:**
  Mean 540k, high in populous regions.
- **Cumulative Time:**
  Mean 2.5M hours, concentrated in East/Coastal.

Critical Finding

All six metrics show increasing trends from 2014 to 2023. Outage events surged ~30% after 2017.

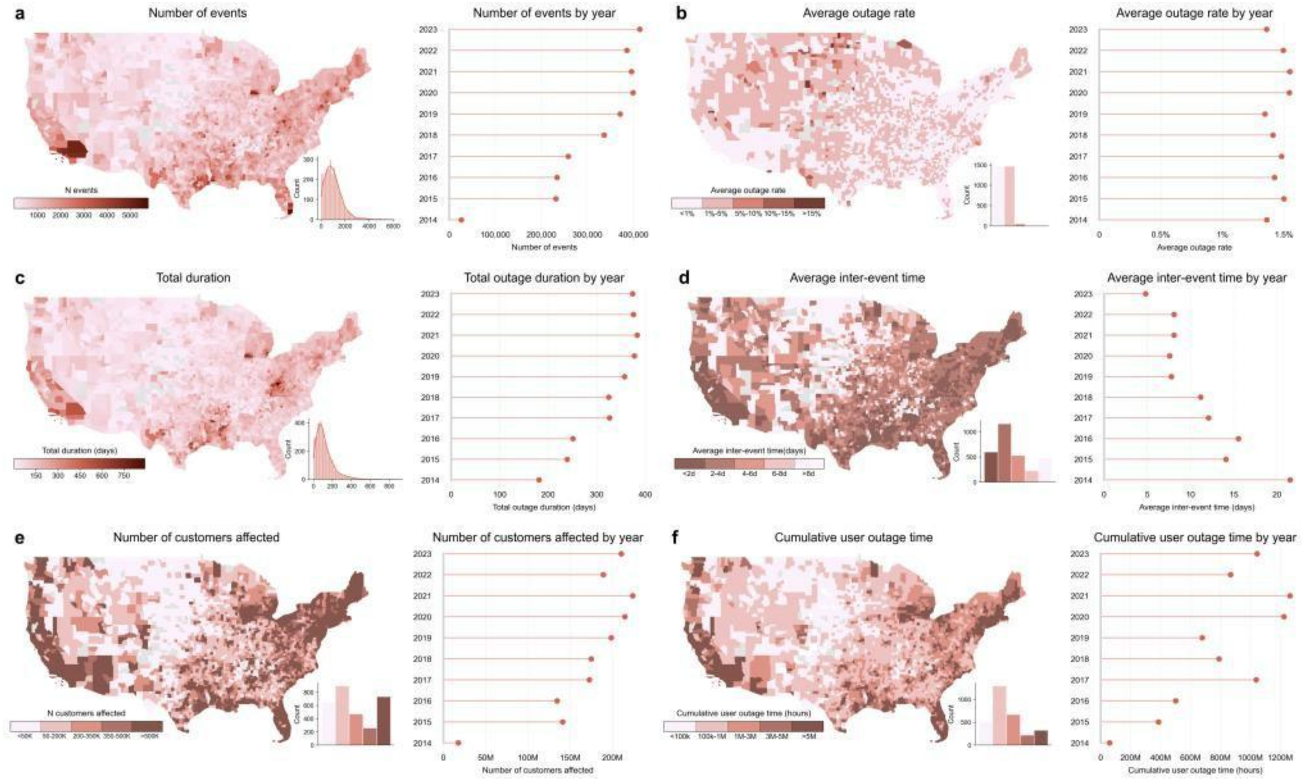

Figure 3:Overview of US Power Outage Trends . (Source: Li et al., 2025)

Power Outage Duration Has Increased Significantly

Prolonged outages are becoming the new normal across the U.S.

Temporal Shift

Outage duration in 2019-2023 was significantly higher than 2014-2018 ($p<0.05$), with a systematic shift toward prolonged events.

Geographic Expansion

Hotspots of prolonged outages have expanded from isolated eastern states to cover nearly the entire continental United States.

Nationwide

Expansion of prolonged outage hotspots (2019-2023)

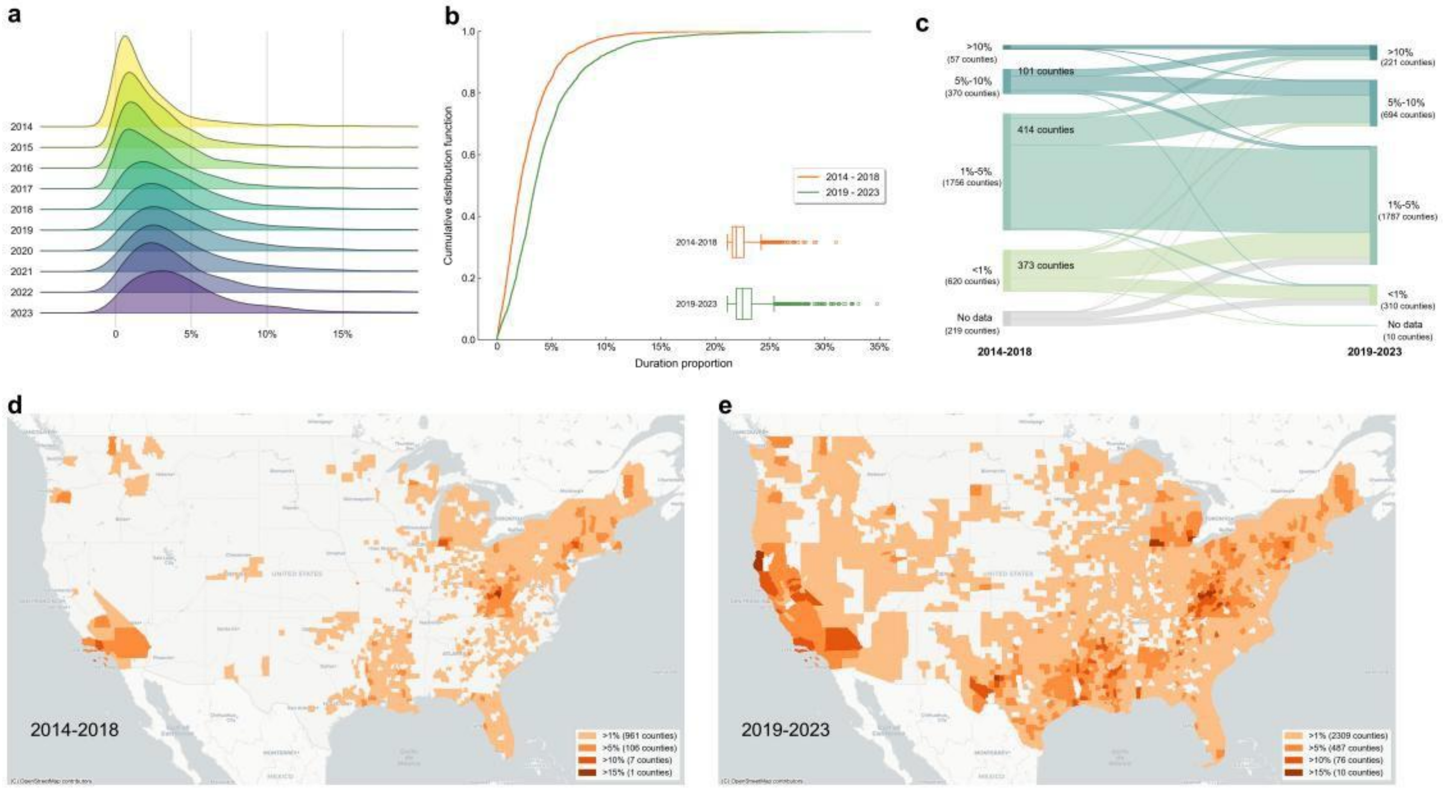

Figure 4: (a) Probability density of duration, (b) Distribution plots, (c) Sankey plot of duration changes, (d-e) Spatial distribution of prolonged outage hotspots. (Source: Li et al., 2025)

More Customers Are Experiencing More Severe Outages, With Peak Impacts Reaching Record Levels

Intensity metrics show systematic escalation in customer impacts (2014-2023)

Escalating Peak Impact

Peak customers affected proportion surged from **5% to 30%** of total served customers. Maximum peak reached 8,958 customers in 2023.

Rising Outage Rate

Average outage rate in 2019-2023 was **significantly higher** than 2014-2018 ($p<0.05$). Mean rate: 1.51%.

Geographic Concentration

High-intensity impacts concentrated in **Coastal regions** (CA, FL, NJ, TX) and the Great Lakes megalopolis.

Implication: The escalation in peak customer impacts requires enhanced situational awareness systems and scalable emergency response protocols.

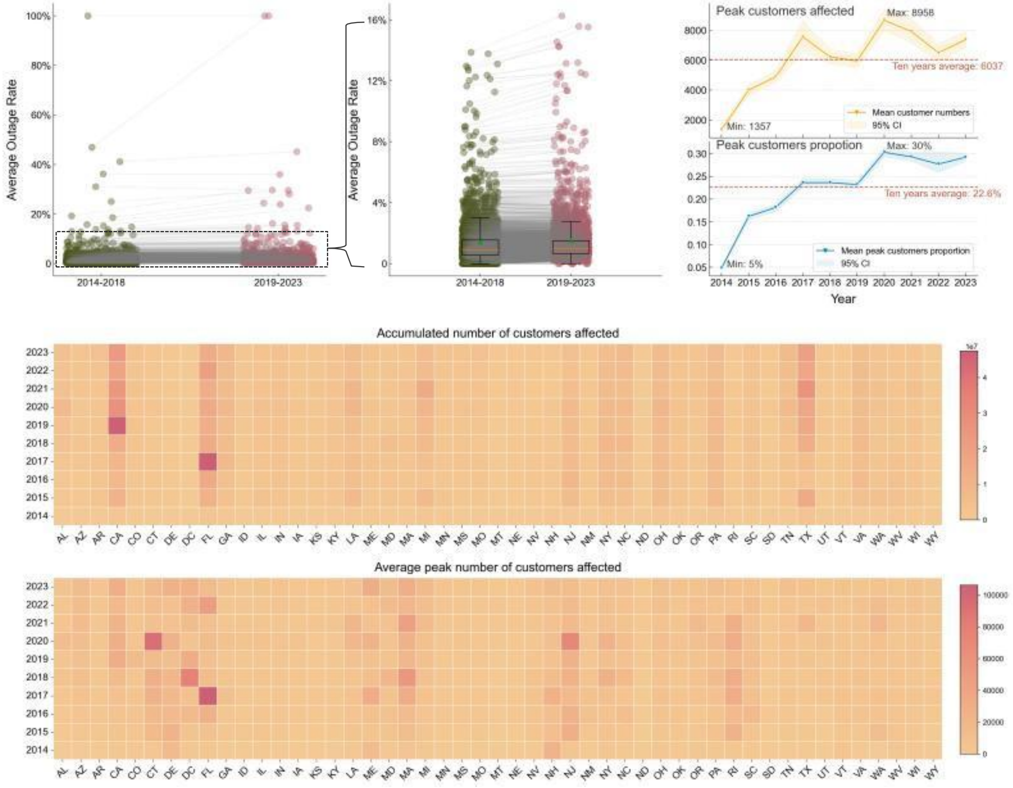

Figure 5: Descriptive statistics on power outage intensity. (a) Average outage rate comparison; (b) Peak customers affected over time; (c) Heatmap of accumulated customers affected.

The Time Between Outages Is Shrinking, With Communities Experiencing Disruptions Nearly Every Week

Frequency analysis reveals systematic deterioration in grid reliability (2014-2023)

Inter-Event Time Analysis

Outages are not random but follow predictable power law patterns. The interval between events is significantly decreasing.

7.16 Days

Avg Inter-Event Time

3.37 Days

Median Interval

Frequency Trends

- Events across all intensity levels (5-50%) show upward trends
- Sharp increase in event frequency observed after 2017 (~30% surge)
- Power law alpha increased from 1.90 to 2.13, indicating shorter intervals

IMPLICATION FOR UTILITIES

More frequent outages strain crew availability and equipment reserves. Utilities need predictive models to anticipate high-frequency periods and pre-position resources.

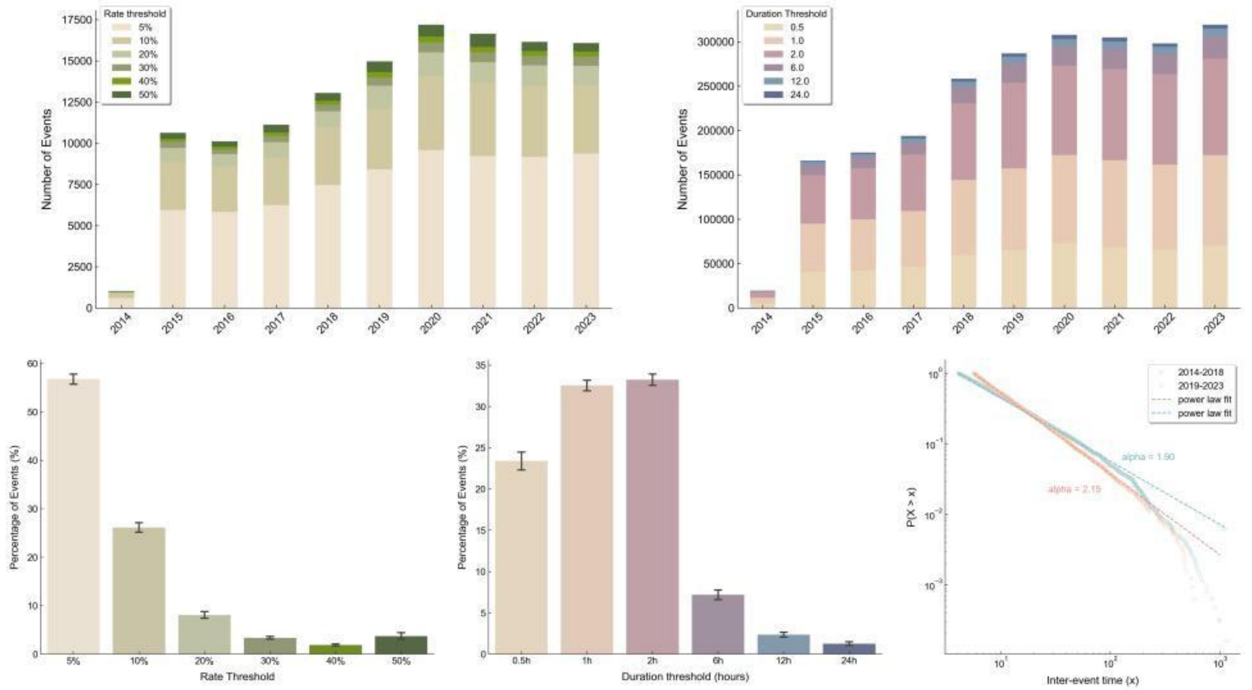

Figure 6: Descriptive analysis of power outage frequency (a-b) Stacked bar plots of event numbers by intensity/duration; (c-d) Relative proportions; (e) Cumulative probability distribution of inter-event time. (Source: Li et al., 2025).

Counties with High Social Vulnerability Experience More Severe and Frequent Outages, Creating a "Dual Burden"

Spatial analysis reveals the intersection of grid instability and social disadvantage

The "Dual Burden" Phenomenon

Occurs when communities face the compounding challenges of **high social vulnerability** (top decile SVI) and **severe power outages** (top decile in frequency, duration, or intensity).

Disproportionate Impact

Socially vulnerable counties are statistically more likely to experience longer durations and higher frequencies of outages compared to affluent regions.

Geographic Hotspots

The dual burden is most acute in rural areas of **Louisiana, Arkansas, and North Carolina**, where infrastructure fragility meets socioeconomic hardship.

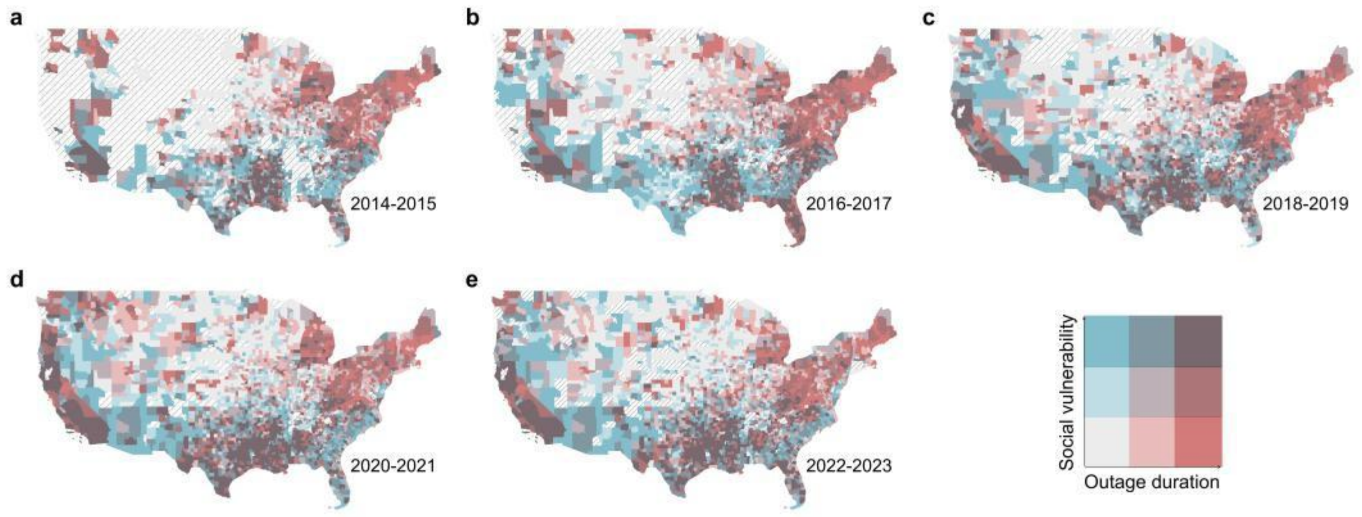

Figure 7: Bivariate maps illustrating the "Dual Burden" - the spatial overlap of high social vulnerability (SVI) and severe power outage metrics (Duration, Frequency, Intensity). (Source: Li et al., 2025)

The Association Between Social Vulnerability and Power Outages Is Increasing Over Time

Regression analysis confirms a widening disparity gap (2014-2023)

Consistent Disparity

OLS regression reveals a statistically significant positive association between Social Vulnerability Index (SVI) and all six outage metrics across the decade.

Strengthening Link

The regression coefficients have increased over time, indicating that the impact of social vulnerability on outage severity is becoming more pronounced.

Growing Gap

As the grid deteriorates, socially vulnerable communities are bearing a disproportionately heavier burden of the crisis.

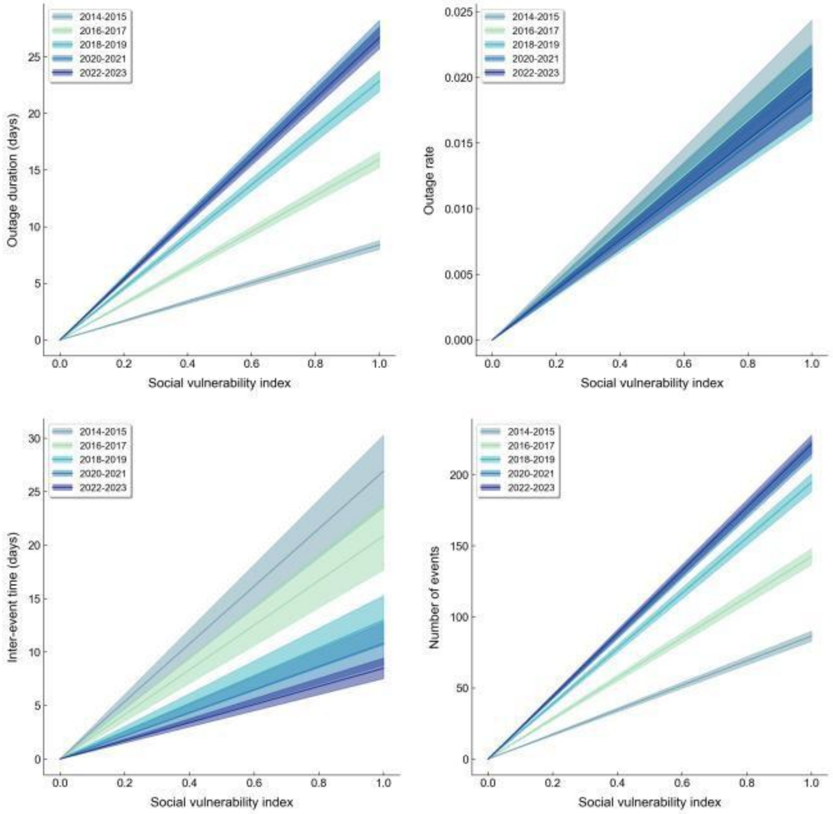

Figure 8: OLS regression results showing the association between Social Vulnerability Index (SVI) and four power outage metrics over time. (Source: Li et al., 2025)

Counties with Both High Social Vulnerability and Severe Outages Show Deteriorating Trends

Distribution analysis reveals worsening conditions in "Dual Burden" areas

Systematic Shift

The probability distributions for outage duration and frequency in dual-burden counties have **shifted significantly to the right** in recent years (2019-2023) compared to the past (2014-2018).

Compounding Risk

These communities are not only facing more frequent disruptions but are also experiencing **longer recovery times**, exacerbating the impact on socially vulnerable populations who have fewer resources to cope.

Figure Interpretation: The red curves (Dual Burden counties) show higher density at extreme values compared to blue curves (Non-Dual Burden), and dashed lines (recent period) show worse performance than solid lines (past period).

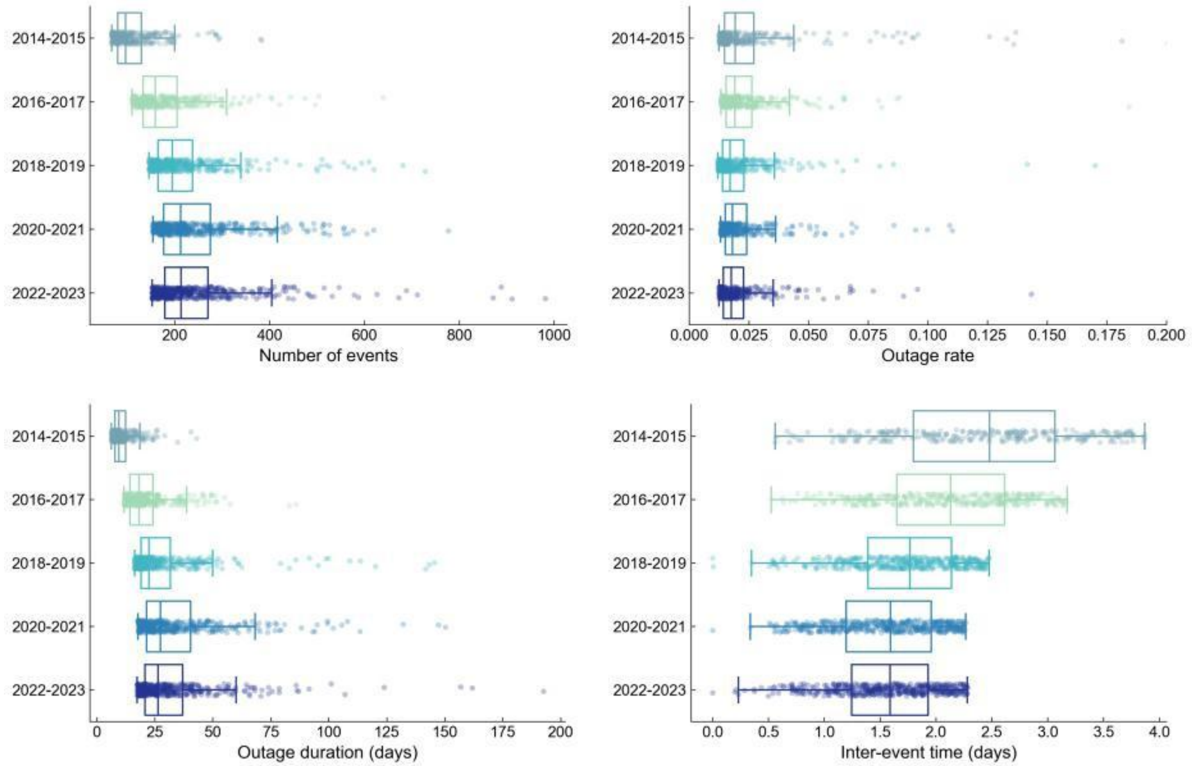

Figure 9: Probability density functions of outage metrics comparing Dual Burden (Red) vs. Non-Dual Burden (Blue) counties across two time periods. (Source: Li et al., 2025)

Urban Regions Experience High-Frequency, Short-Duration Outages While Rural Areas Face Low-Frequency, Prolonged Disruptions

Distinct vulnerability profiles driven by population density and infrastructure (2014-2023)

Urban Areas

High Frequency, Short Duration

Higher population density leads to more frequent interruptions, but better resource availability allows for faster restoration.

Rural Areas

Low Frequency, Long Duration

Fewer events occur, but logistical challenges and lower priority for crews result in significantly longer outage durations.

Disparity is statistically significant ($p < 0.001$)

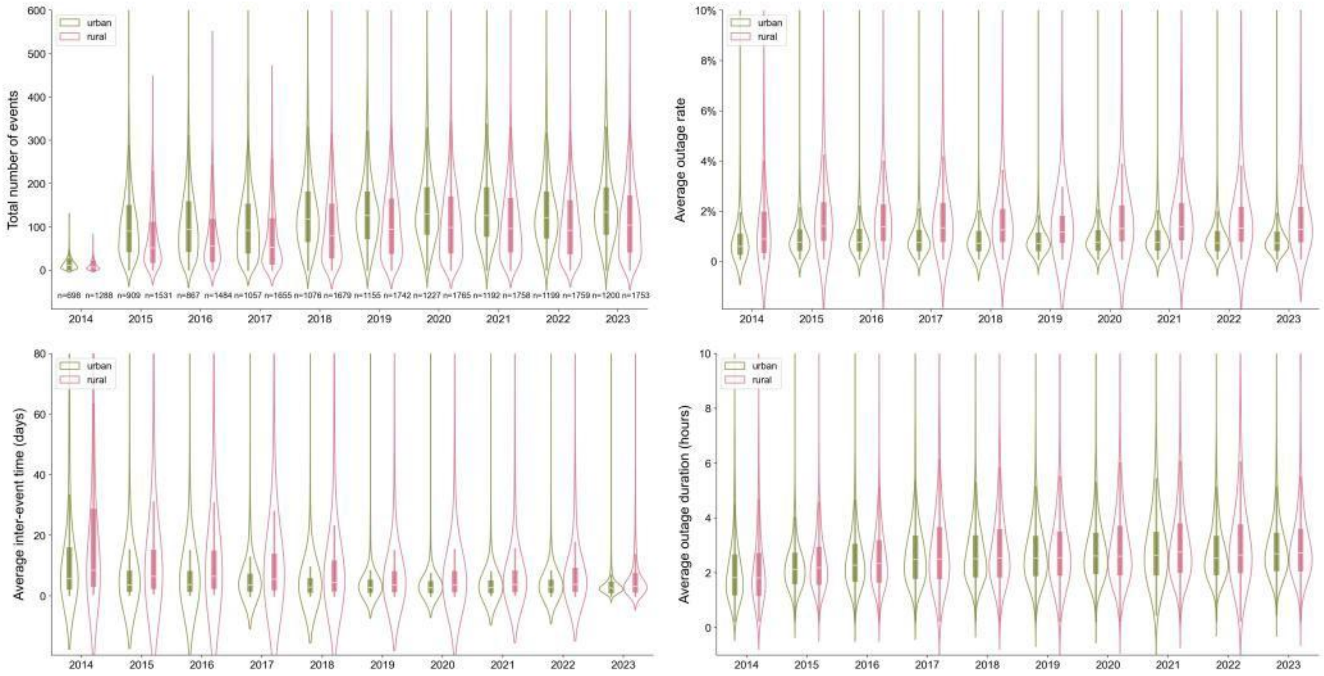

Figure 10: Comparison of outage metrics between urban and rural areas. (a) Duration; (b) Frequency; (c) Intensity. (Source: Li et al., 2025)

The Past Decade Reveals a Power System Under Increasing Stress Across All Dimensions

Summary of Part 1: The escalating crisis in U.S. grid reliability

Temporal Acceleration

- Systematic deterioration across all six vulnerability metrics.
- Sharp 30% surge in outage events observed after 2017.
- Prolonged outages (>12 hours) are becoming the new normal.

Spatial Expansion

- Hotspots of vulnerability are expanding from coastal areas to inland.
- Urban areas face high-frequency disruptions.
- Rural areas suffer from disproportionately long durations.

Social Disparity

- "Dual Burden" confirms vulnerable communities face worse outages.
- The gap between advantaged and disadvantaged counties is widening.
- Inequity is structural and worsening over time.

The Challenge: The crisis is too complex for traditional metrics alone.
The Solution: We need predictive intelligence to anticipate risks. →

Part 02

From Understanding the Problem to Predicting and Preventing

Introducing the Power System Vulnerability Index (PSVI)

Methodology

XGBoost & SHAP Analysis

Assessment

Nationwide Vulnerability Mapping

Insights

Key Drivers & Risk Factors

An Interpretable Machine Learning Approach Transforms 179 Million Outage Records Into Actionable Assessments

The PSVI framework integrates big data processing with advanced predictive modeling

179 Million Records

3,022 Counties

10-Year Period (2014-2023)

15-Minute Resolution

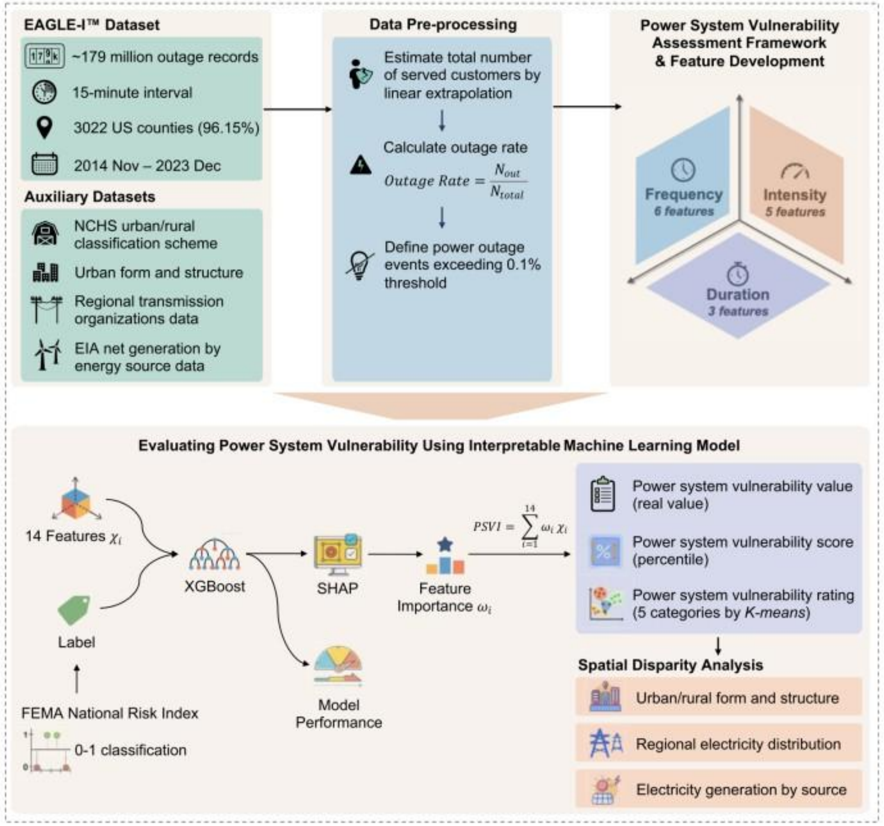

Figure 1: The PSVI Framework Workflow: From raw EAGLE-I data to county-level vulnerability scores. (Source: Ma et al., 2025)

1. Data Processing

Rigorous cleaning of raw outage data, handling missing values, and integrating with county-level geospatial boundaries.

2. Feature Engineering

Construction of 14 distinct features across Frequency, Duration, and Intensity dimensions to capture holistic vulnerability.

3. Modeling & Explainability

Application of XGBoost for robust prediction, coupled with SHAP (SHapley Additive exPlanations) to ensure model transparency.

4. Vulnerability Scoring

Outputting a normalized POVI score (0-100) and classifying counties into five risk levels: Negligible to Extreme.

The POVI Framework Captures Power System Vulnerability Through Frequency, Intensity, and Duration

14 statistical features derived from outage time series data drive the predictive model

Frequency (2)

Total Events	Avg Inter-arrival Time

Duration (6)

Sum	Mean
Median	Std Dev
Skewness	Kurtosis

Intensity (6)

Sum (Cust-Hrs)	Mean
Median	Std Dev
Skewness	Kurtosis

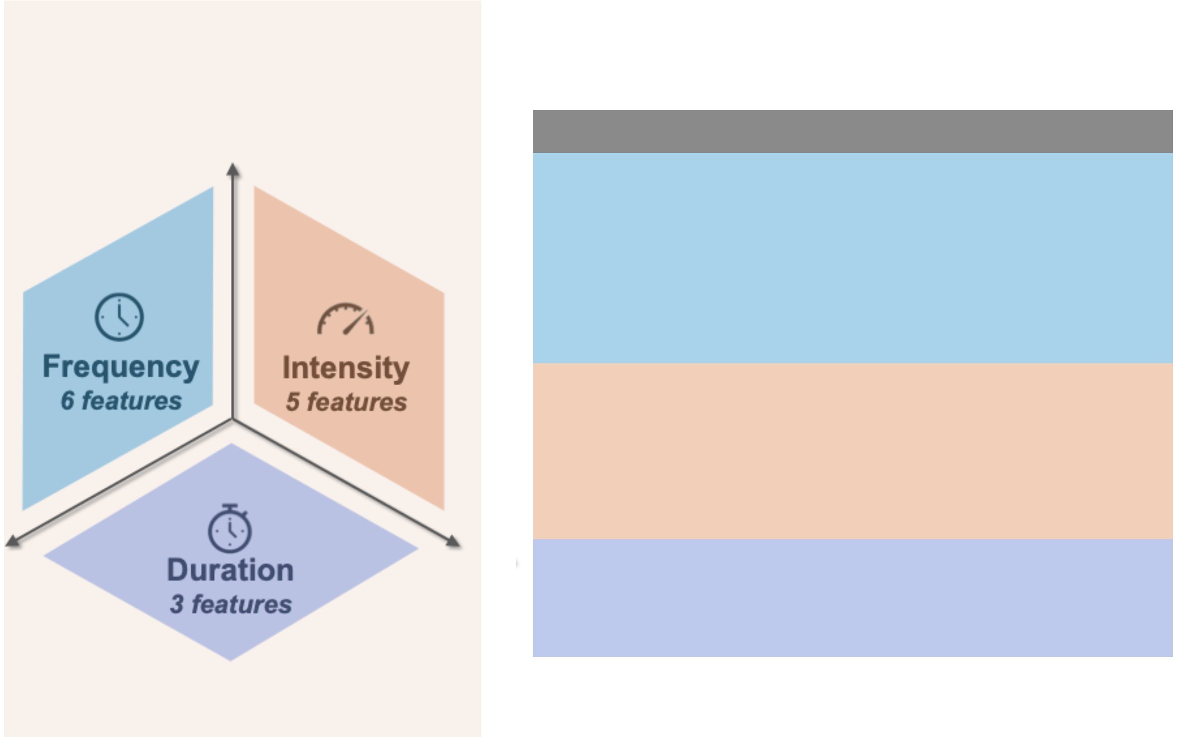

Figure 2: The PSVI workflow transforms raw outage data into statistical features across three dimensions to train the XGBoost model. (Source: Ma et al., 2025)

XGBoost Achieves Strong Predictive Performance, With Intensity Features Driving Vulnerability Assessments

Model validation and feature importance analysis (SHAP)

Model Superiority

XGBoost outperformed Random Forest and Decision Tree models, achieving robust predictive capability across all validation folds.

0.93
Accuracy

0.93
Precision

0.93
Recall

0.93
F1-Score

Key Drivers

Intensity features (e.g., Average Outage Rate, Peak Customers Affected) are the most critical predictors, followed by Duration metrics.

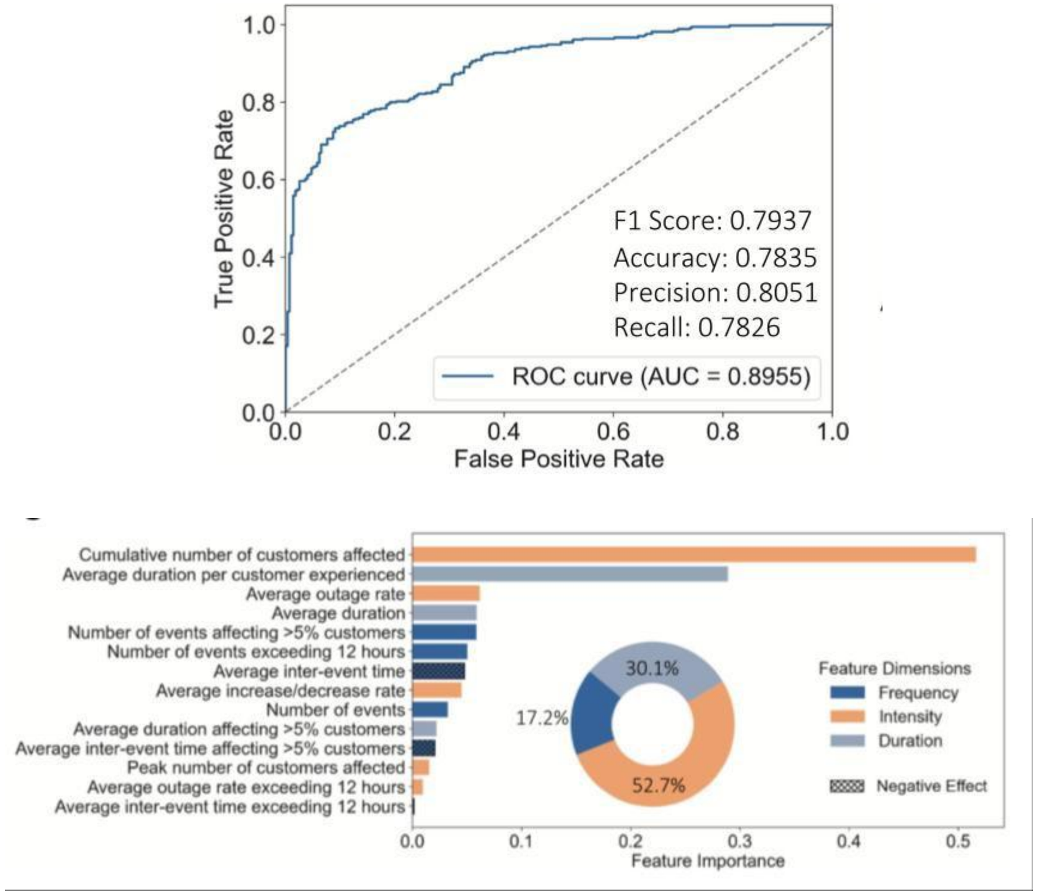

Figure 3: (a) ROC curve of the XGBoost model; (b) SHAP summary plot showing feature importance and impact on model output. (Source: Ma et al., 2025)

Most Counties Exhibit Minor to Moderate Vulnerability, But 318 High-Risk Counties Require Immediate Attention

Nationwide assessment identifies critical hotspots of g

318

High-Risk Counties

Classified as Major or Extreme Vulnerability

Vulnerability Distribution

Minor (Level I)	**~45%**
Moderate (Level II)	**~44%**
Major (Level III)	**~8%**
Extreme (Level IV)	**~2.5%**

Insight: While the majority of the U.S. grid shows manageable vulnerability, the "long tail" of high-risk counties represents a significant concentration of instability.

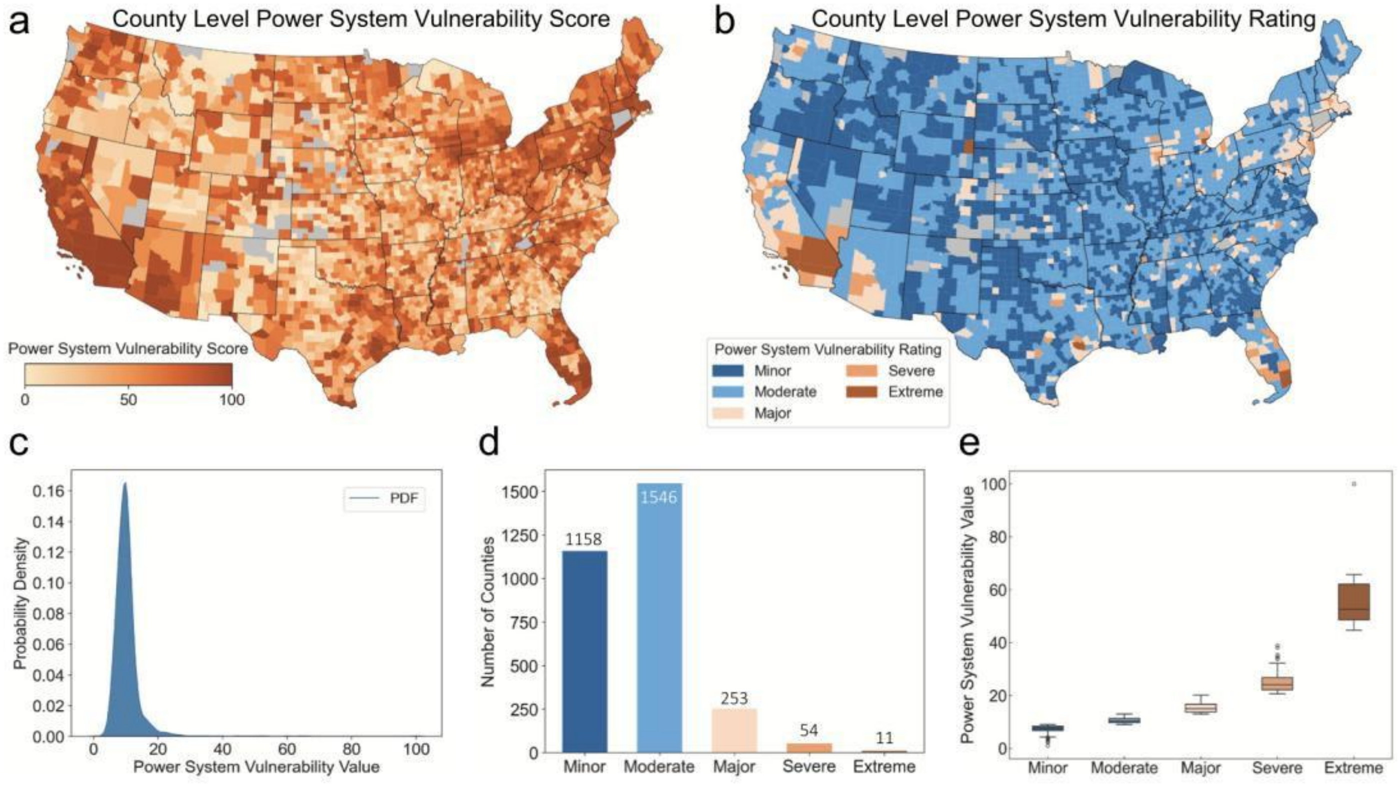

Figure 4: Nationwide distribution of Power System Vulnerability Index (PSVI). (a-b) Spatial map of vulnerability levels; (c-e) Distribution of PSVI scores. (Source: Ma et al., 2025)

Six States Contain Extreme-Level Vulnerability Counties, With California Leading in High-Risk Areas

State-level analysis reveals concentrated pockets of extreme grid instability

Extreme Vulnerability Counties

California	41
Michigan	11
Louisiana	10
Arkansas	6
Maine	5
Florida	3

California's Crisis

California accounts for **over 50%** of all extreme-vulnerability counties nationwide, driven by wildfire risks and aging infrastructure.

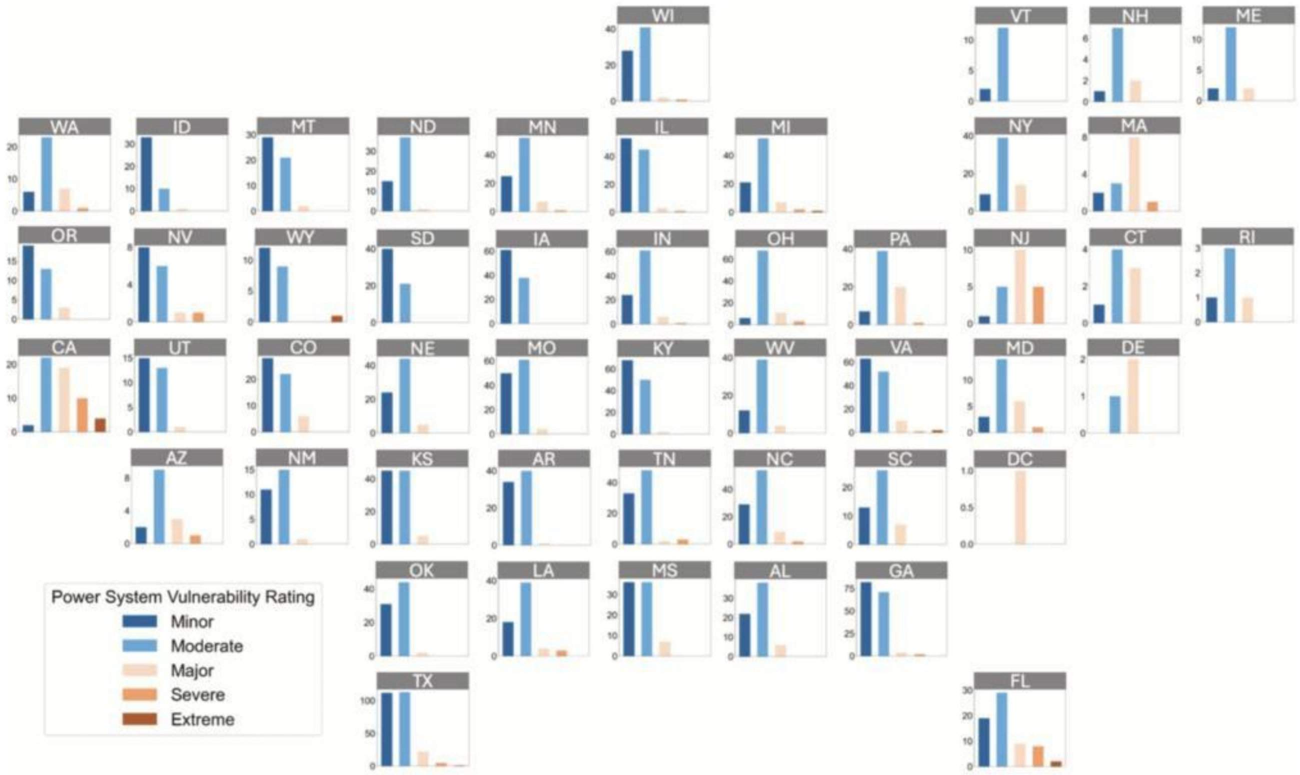

Figure 5: State-level distribution of PSVI scores. Bar plots show count of counties in each vulnerability level by state. (Source: Ma et al., 2025)

Power System Vulnerability Has Increased Steadily Since 2014, With Sharp Acceleration in Recent Years

Temporal analysis confirms the grid is becoming less resilient over time

2014-2018

Gradual Decline

Initial period showed a slow but steady increase in vulnerability scores, primarily driven by aging infrastructure.

Post-2019 Surge

A distinct inflection point appears around 2019, where the rate of vulnerability growth **doubles**. This acceleration correlates with increased frequency of extreme weather events.

Statistical Note: The Mann-Kendall trend test confirms the upward trajectory is statistically significant ($p < 0.01$) across the continental U.S.

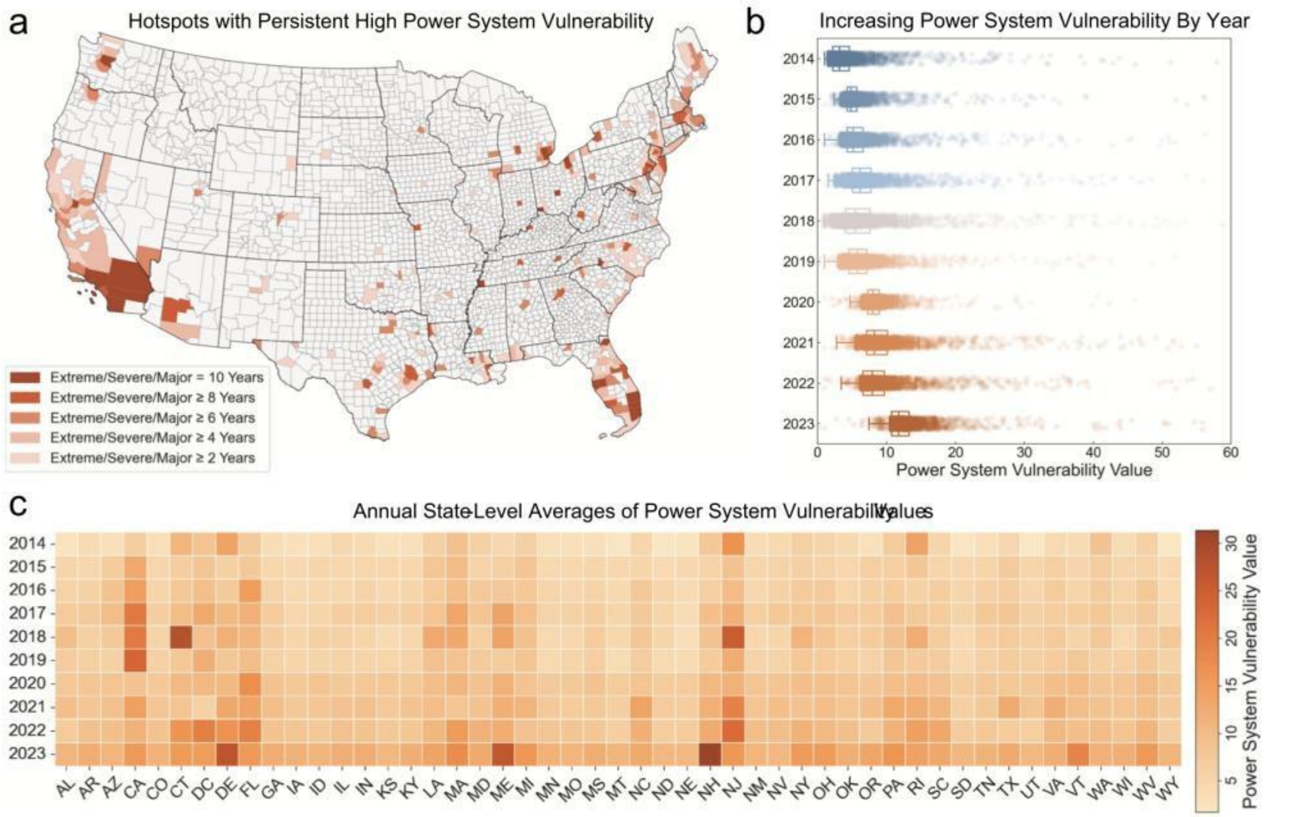

Figure 6: Spatiotemporal distribution of the annual power system vulnerability index (Source: Ma et al., 2025)

Urban Areas Exhibit Exponentially Greater Power System Vulnerability Compared to Rural Counties

Disparity analysis reveals a strong correlation between development density and grid risk

Exponential Growth

Vulnerability scores do not increase linearly; they rise **exponentially** as land development intensity increases, making highly developed urban centers significantly more fragile.

The Urban Penalty

High Intensity Developed areas show the highest median POVI scores, reflecting the complexity and cascading failure risks inherent in dense urban grids.

Rural Baseline

Open Space and **Low Intensity** areas maintain consistently lower vulnerability scores, serving as a baseline for comparison.

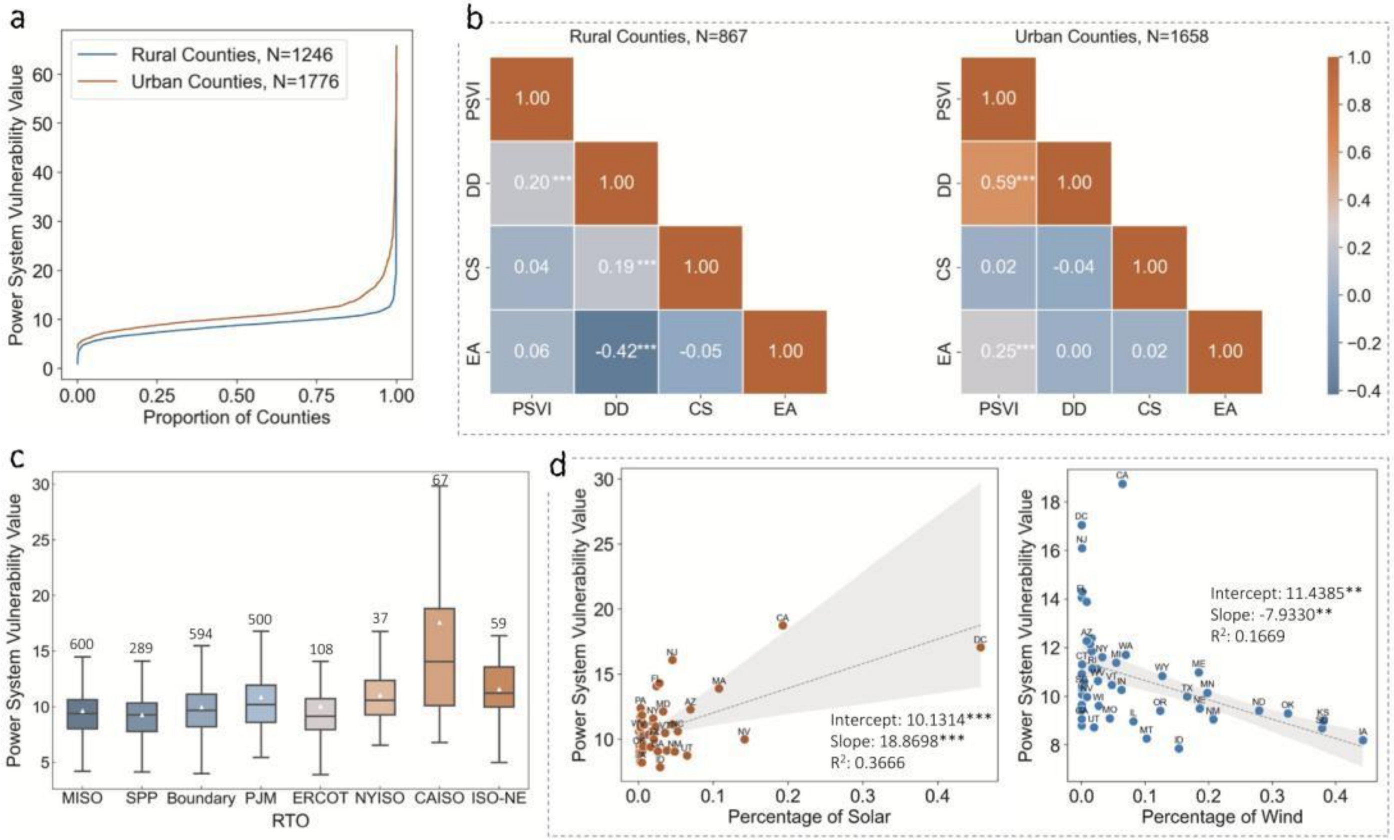

Figure 7: Disparity in the power system vulnerability index.
(Source: Ma et al., 2025)

CAISO Exhibits Highest Vulnerability Among RTOs, While Boundary Counties Face Elevated Risks

Regional transmission analysis highlights disparities in grid resilience

CAISO Outlier

The California Independent System Operator (CAISO) shows a significantly higher median POVI score compared to all other RTOs, reflecting the state's systemic challenges.

- **Stable Core:** PJM, MISO, and SPP demonstrate relatively lower and consistent vulnerability levels across their territories.
- **ERCOT Variance:** While generally stable, ERCOT shows high variance, indicating pockets of extreme risk within Texas.

The "Boundary Effect"

Counties located at the geographic boundaries of RTOs often exhibit higher vulnerability scores, suggesting challenges in cross-border coordination and infrastructure maintenance at the grid's edge.

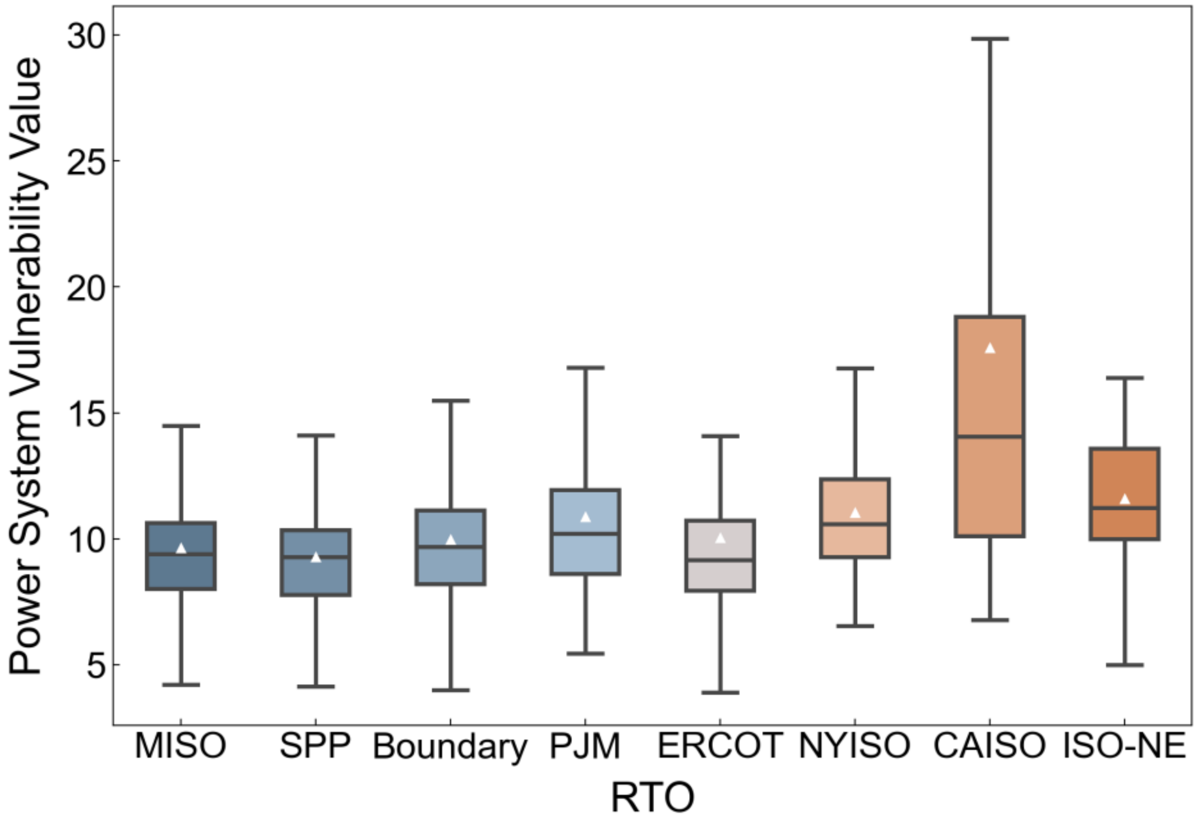

Figure 8: Box plots of PSVI scores for each RTO, highlighting CAISO's elevated risk profile. (Source: Ma et al., 2025)

Solar Energy Shows Positive Correlation with Vulnerability, While Wind Energy Exhibits Weak Inverse Relationship

Renewable integration presents distinct challenges and opportunities for grid stability

Solar Energy

Positive Correlation

Counties with higher solar generation tend to have higher POVI scores. This reflects the challenge of managing intermittency and the "Duck Curve" in regions with aggressive solar adoption (e.g., California).

Wind Energy

Weak Inverse Correlation

Wind generation shows a slight negative association with vulnerability. Utility-scale wind farms are often integrated into high-voltage transmission networks, potentially offering greater stability than distributed solar.

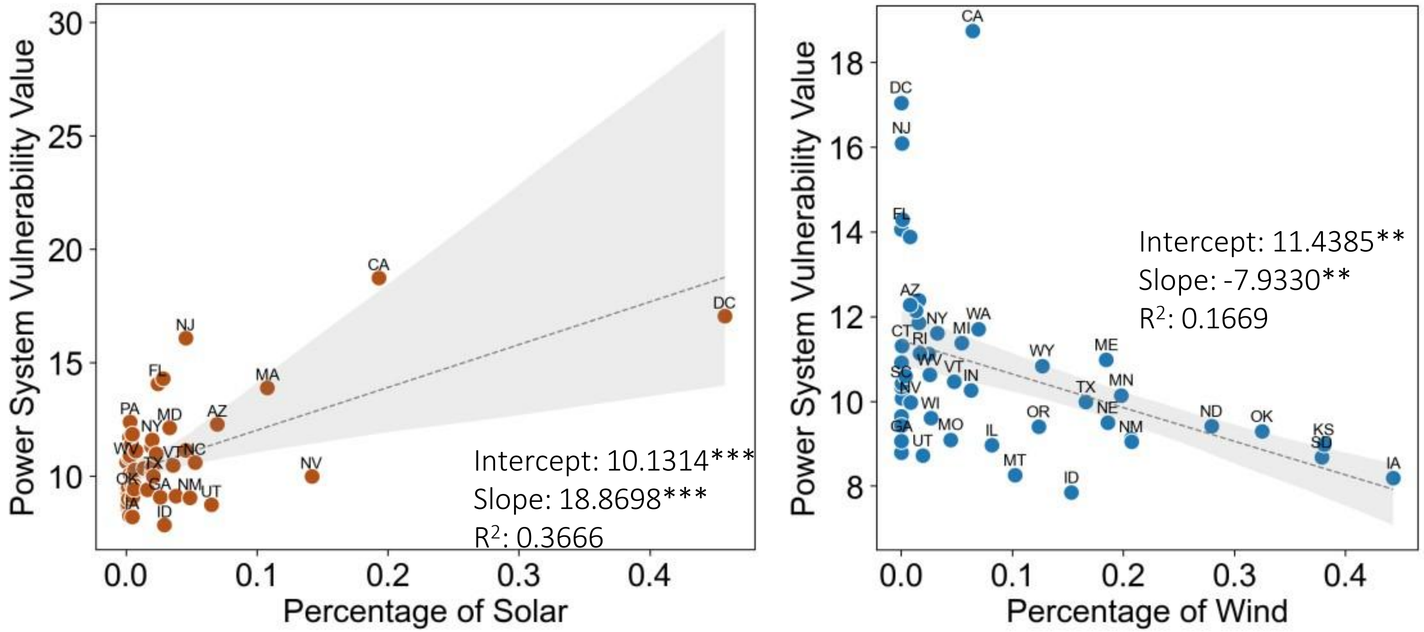

Figure 9: OLS regression plots between the power system vulnerability values and the percentage of solar/wind energy used for generation (Source: Ma et al., 2025)

The Power System Vulnerability Index Provides the First Comprehensive, Data-Driven Assessment of U.S. Power System Vulnerability

Summary of Part 2: A scalable framework for predictive grid intelligence

The Engine

By processing **179 million records** through an interpretable XGBoost model, POVI transforms raw data into a standardized 0-100 vulnerability score with 93% predictive accuracy.

The Diagnosis

While most of the grid is stable, **318 counties** are in critical condition. The "long tail" of risk is concentrated in California, the South, and urban centers.

The Insight

Vulnerability is **accelerating**. Intensity metrics (scale of impact) are now the primary drivers of risk, overtaking simple frequency or duration measures.

The Question: We now know *where* and *why* the grid is vulnerable.
The Next Step: How can utilities use this intelligence to act? →

Part 03

From Prediction to Action

Translating PSVI Insights Into Utility Resilience Strategies

Strategy 1

Investment Prioritization

Strategy 2

Emergency Preparedness

Strategy 3

Regulatory Planning

Use PSVI to Prioritize Grid Modernization Investments in High-Vulnerability Counties

Data-driven capital allocation maximizes resilience ROI where it matters most

1 Identify Hotspots

Focus capital expenditure on the **318 counties** identified as Major or Extreme vulnerability (PSVI Levels III & IV).

2 Overlay Asset Data

Integrate PSVI scores with internal asset health records to pinpoint where grid fragility meets physical degradation.

3 Deploy Solutions

Urban: Prioritize automation and redundancy.

Rural: Invest in vegetation management and microgrids.

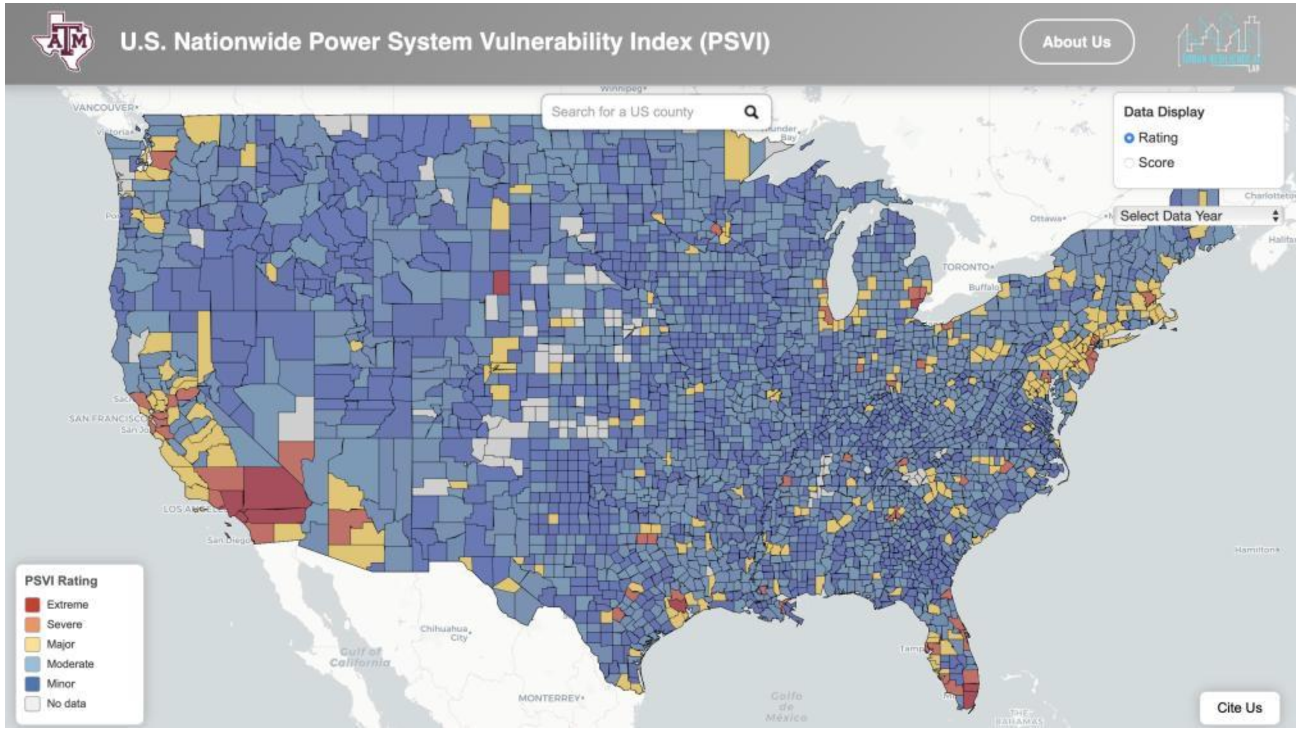

Figure 3 (Reprise): The POVI map serves as a strategic blueprint for investment, highlighting the geographic clusters requiring immediate modernization. (Source: Ma et al., 2025)

Leverage PSVI to Pre-Position Crews and Equipment Before Extreme Weather Events

Transforming emergency response from reactive mobilization to proactive readiness

Traditional response models wait for outages to occur before dispatching crews. POVI enables utilities to anticipate where the grid is most likely to fail under stress.

01

Monitor Threat

Identify the projected path and intensity of incoming weather events (e.g., storms, heatwaves).

02

Overlay PSVI

Map the threat against POVI scores to identify **high-vulnerability counties** within the impact zone.

03

Deploy Assets

Pre-position repair crews and spare parts in these specific high-risk areas **24-48 hours** in advance.

✓ Operational Impact: Significantly reduces travel time for crews, lowers SAIDI (duration) metrics, and ensures faster restoration for the most fragile communities.

Use PSVI as a Transparent, Data-Driven Metric for Regulatory Filings and Stakeholder Engagement

Building trust and justifying investments through objective vulnerability assessment

Rate Case Justification

Move beyond traditional reliability indices (SAIDI/SAIFI) by using PSVI to empirically demonstrate the need for resilience investments in specific, high-risk geographies.

ESG & Equity Reporting

Quantify the "Social" impact of grid modernization. Show regulators and investors how targeted investments are reducing the "Dual Burden" on disadvantaged communities.

Stakeholder Trust

Replace anecdotal evidence with a reproducible, interpretable score. PSVI provides a common language for utilities, regulators, and consumer advocates to discuss grid health.

The Regulatory Advantage

Data-driven transparency reduces regulatory lag and accelerates approval for critical infrastructure projects by clearly linking capital expenditure to vulnerability reduction.

Advancing Power System Resilience Requires Continued Innovation and Cross-Sector Collaboration

The roadmap for evolving POVI into a dynamic, real-time grid intelligence platform

Enhanced Granularity

Moving beyond county-level aggregates to **substation and feeder-level analysis**. This high-resolution view will pinpoint specific infrastructure weaknesses and enable hyper-localized interventions.

Real-Time Monitoring

Transitioning from historical retrospective analysis to **live predictive monitoring**. Integrating real-time sensor data will allow operators to anticipate vulnerability spikes during unfolding events.

Climate Integration

Incorporating long-term **climate projection models** to stress-test the grid against future extreme weather scenarios, ensuring infrastructure built today survives the climate of tomorrow.

Three Critical Messages for Utility Leaders

Synthesizing the findings: From diagnosis to solution

01

⚠

The Crisis Is Real

Grid reliability is deteriorating systematically. The "Dual Burden" is widening the gap between resilient and vulnerable communities, creating a structural equity crisis that cannot be ignored.

02

Prediction Is Possible

We are no longer flying blind. The POVI framework proves that machine learning can transform raw outage data into precise, actionable intelligence with 93% predictive accuracy.

03

⚡

Action Is Urgent

The window for proactive hardening is closing. Utilities must immediately leverage these insights to prioritize investments, pre-position assets, and protect the most vulnerable.

Thank You

Questions and Collaboration Opportunities

contact@research-team.edu

www.grid-resilience-lab.org

Department of Geography, Texas A&M University

Key References

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