Electric Grid Fragility Analysis - Briefing

An Applied Analysis of Grid Stress Using Public Operational Data

By Miles Wolf
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Full report available on my github -
https://github.com/miles-wolf/Electrical_Grid_Fragility_Analysis

1. Executive Summary

This report introduces a data-driven framework for comparing operational stress (grid fragility) across large electric power grids using publicly available EIA-930 hourly operational data from 2025. The analysis focuses on system behavior relative to each grid's historical norms, not physical outages or reliability.

The framework is applied to two distinct balancing authorities: **CAISO** (high renewables, variability-driven) and **PJM Interconnection** (high aggregate demand, scale-driven).

- A **normalized fragility score** is constructed from load ramp behavior and deviations from typical conditions, allowing for cross-system comparison.
- Grid fragility is **episodic** and concentrated in a few days.
- **CAISO** stress is primarily associated with abrupt, high-magnitude load ramps and rapid regime transitions (**variability-driven**).
- **PJM** stress is more often linked to sustained high-load conditions (**scale-driven**).

The framework provides a lens for identifying recurring fragility patterns (ramp-driven stress, high-load stress) to support deeper operational analysis. It does not yet predict failures. Future work will explore predictive mechanisms and additional balancing authorities.

2. Data and Scope

- **Data Sources:** U.S. Energy Information Administration (EIA) Form 930 consolidated hourly operational data.
- **Temporal Coverage:** Full calendar year 2025 (Jan 1 – Dec 31). Metrics are processed at **hourly resolution** and aggregated to the **daily level**. (Figure 1 - see section 9)
- **Geographic Scope:** Two large, distinct U.S. balancing authorities:
    - **CAISO** (*CISO* code) - California Independent System Operator
    - **PJM Interconnection** (*PJM* code) - Part of larger Eastern Interconnection Grid
- **Analytical Scope:** Focuses on **load-side operational stress** and relative stress, normalized within each balancing authority.

3. Measuring Grid Fragility

Grid fragility is a composite metric capturing how difficult a power system is to operate under normal conditions (magnitude, volatility, and persistence of demand stress).

The score is constructed from three standardized, demand-based stress indicators:

1. **Daily peak load** (demand magnitude)
2. **Daily maximum load ramp** (short-term volatility)
3. **Fraction of hours operating near peak demand** (stress persistence)

These components are summed after **z-score standardization** to ensure the score reflects *relative stress* within each grid, enabling comparison across systems with different absolute load scales (Figure 2 - equation for z-score displayed in Module 3 box)

- **Interpretation:** Values near zero are typical; positive values indicate above-normal stress; large positive values are rare, high-stress days. Fragility indicates **how hard the grid is being asked to work**, not reliability or outage probability.

4. Operational Regimes & Stress Mechanisms

Machine learning techniques, such as KMeans clustering, were performed to analyze the dataset. Daily operations cluster into a small number of **repeatable operational regimes**. Stress is **regime-dependent.** (Figure 3) (Figure 4)

- **CAISO Regimes:** Separation is driven by **ramp magnitude and short-term variability** (high-stress regimes extend vertically in feature space). This reflects a system constrained by flexibility.
- **PJM Regimes:** Separation is driven by **absolute load scale** (high-stress regimes extend horizontally). This reflects stress from sustained demand magnitude and capacity utilization.

Regime Frequency vs. Fragility Contribution:

- **CAISO:** The most fragile regime is **extremely rare**, but moderately stressed, variability-driven regimes dominate cumulative fragility exposure.
- **PJM:** Higher-fragility regimes occur **more regularly** at elevated load levels, accumulating stress through persistent scale-driven operation.

This leads to a **Controls Framing:** CAISO is limited by **variability-driven stress** (transient limitations/rapid ramps); PJM is limited by **scale-driven stress** (steady-state limitations/high absolute demand).

5. Extreme Fragility Events

Analysis of rare, upper-tail events reinforces the regime findings:

- **CAISO Event (Figure 5):** Characterized by a sharp, isolated spike in **ramp magnitude** coinciding with the fragility peak. Stress is dominated by **short-lived variability shocks** (control speed/flexibility limits).
- **PJM Event (Figure 6):** Characterized by smoothly evolving, elevated **peak load** over time. Fragility rises gradually, reflecting **sustained capacity and reserve pressure** over multiple days.

Extreme fragility is **mechanism-specific** and not universal across grids.

6. How Often Stress Occurs

The distribution of daily fragility is **strongly right-skewed**:

- Most days are low to moderate fragility.
- A small number of extreme events form a long upper tail.

Rarity–Severity Relationship: High-fragility events are rare but reach magnitudes far exceeding typical conditions. (Figure 7)

Why Averages Hide Risk: Traditional statistics (mean/median) understate the severity of critical events because low-stress days are much more frequent. System reliability is governed by tail behavior, not central tendencies.

7. Implications & Limitations

The Framework Enables:

- Systematic, quantitative assessment of grid stress using demand-side load behavior.
- Meaningful comparisons across systems of vastly different sizes and load profiles (due to internal normalization).
- Discovery of temporal structure (seasonal patterns, rare extreme events) and is suitable for downstream analysis (clustering, anomaly detection).

The Framework Does Not Claim To:

- Model the physical structure of the grid (topology, congestion).
- Identify causal drivers of stress (individual generators, market behavior, policy).
- Predict failures or outages.
- Explicitly incorporate supply-side dynamics.

Why it Scales:

- Built entirely on **publicly available, standardized EIA-930 data**.
- Computation scales linearly.
- Metrics are normalized relative to each system's own historical behavior, ensuring portability and comparability across regions and time

8. Conclusion

This project delivers a modular, reproducible framework for quantifying electric grid fragility. The analysis reveals systematic differences between PJM (scale-driven stress) and CAISO (variability-driven stress). The key takeaway is that rare, high-stress events dominate fragility signals and should be carefully treated. The framework provides a simple, controls-inspired approach to surface meaningful structure in grid behavior for future, more advanced modeling. Future work will also explore predictive mechanisms and additional balancing authorities.

9. Figures

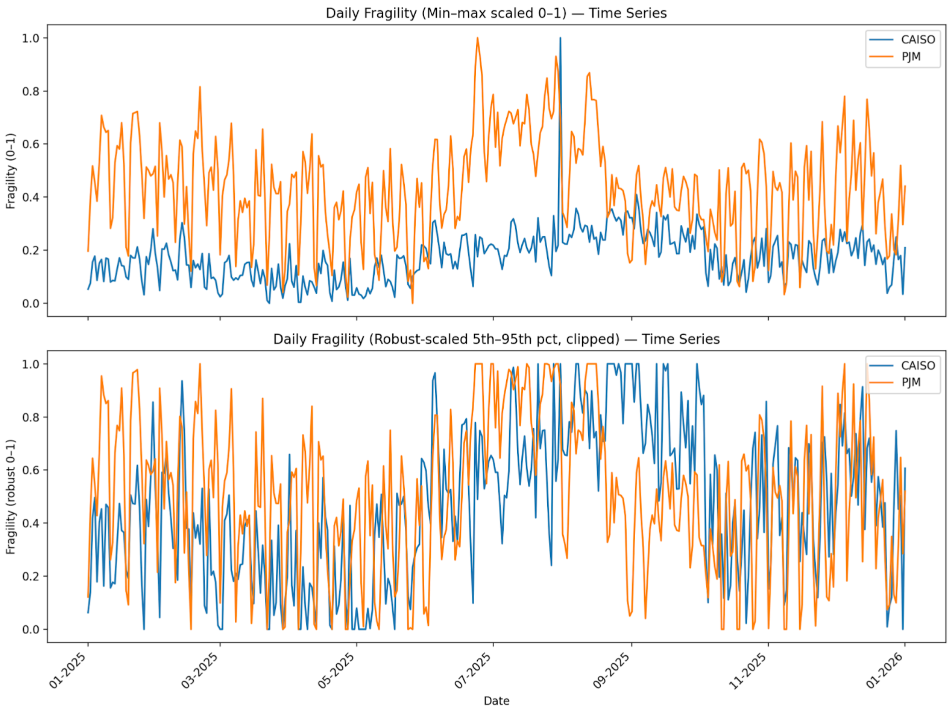

Figure 1. Daily Grid Fragility Time Series (Two Normalizations)

Daily fragility for CAISO and PJM over calendar year 2025 shown using two complementary normalizations: (a) min–max scaling, which emphasizes rare extreme stress days, and (b) robust scaling based on the 5th–95th percentile range, which emphasizes typical day-to-day variability. No observations are removed; scaling affects visualization only.

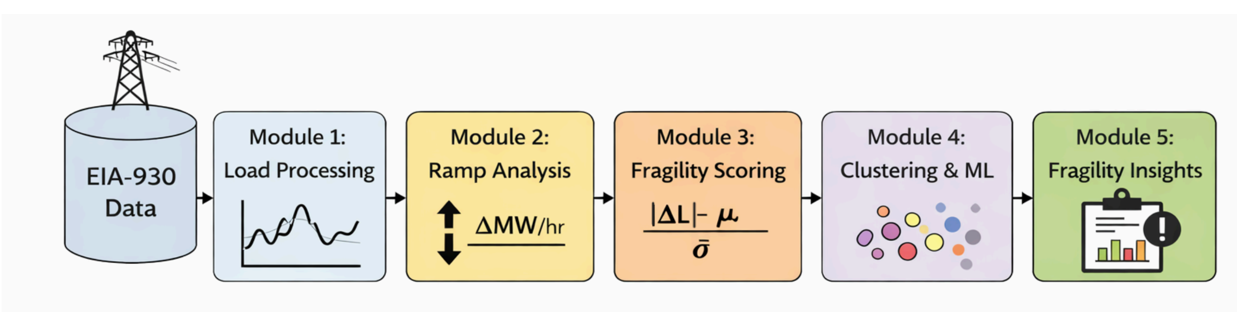

Figure 2 - Grid Fragility Analysis Process Flowchart

This flowchart illustrates the full analysis workflow, showing how raw EIA-930 demand data is transformed via successive modules into fragility scores and downstream modeling inputs.

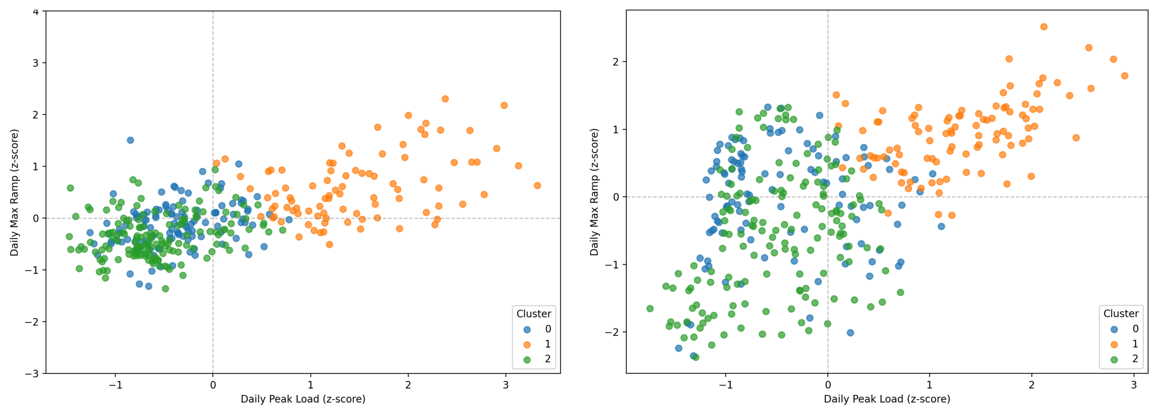

Figure 3. Operational regimes in normalized feature space

(a - left) CAISO *and* ***(b - right) PJM*** *daily operating regimes projected into normalized feature space defined by daily peak load (z-score) and daily maximum ramp magnitude (z-score). Points are colored by cluster assignment, representing operational regimes. Regime geometry differs by balancing authority: CAISO exhibits separation driven primarily by ramp magnitude and short-term variability, while PJM exhibits separation driven primarily by absolute load scale.* ***Note:*** *Rare extreme ramping regime omitted from view for readability.*

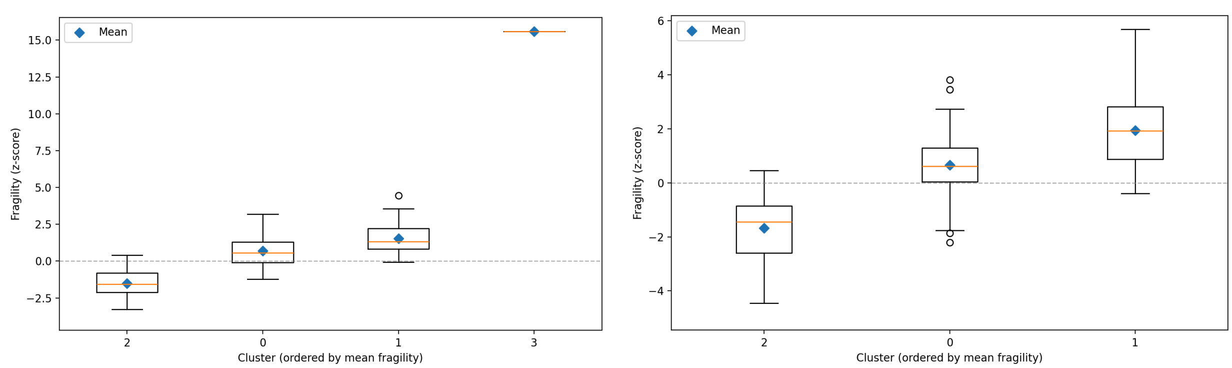

Figure 4. Regime frequency versus mean fragility

(a - left) CAISO (CISO) *and* ***(b - right) PJM*** *relationship between regime frequency (percentage of operating days) and mean fragility (z-score). Each point represents a distinct operational regime, illustrating the tradeoff between how often a regime occurs and the level of stress it imposes. In CAISO, the most fragile regime is rare, while moderately stressed regimes dominate cumulative exposure. In PJM, higher fragility is associated with more frequently occurring, scale-driven regimes.*

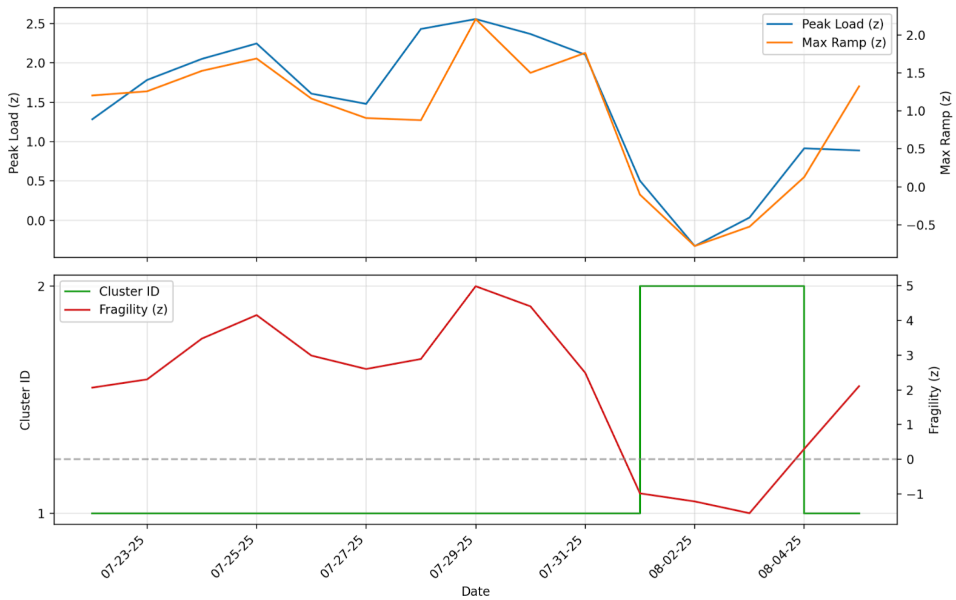

Figure 5. CAISO extreme fragility event — combined temporal trajectory

Daily peak load and maximum ramp magnitude (top), and cluster assignment and fragility (bottom) for a representative high-fragility event in CAISO. Fragility peaks during a brief, isolated ramping spike while peak load remains smooth, indicating stress driven by short-lived net-load variability rather than sustained demand. The cluster transition shows a transient excursion into a rare high-stress regime.

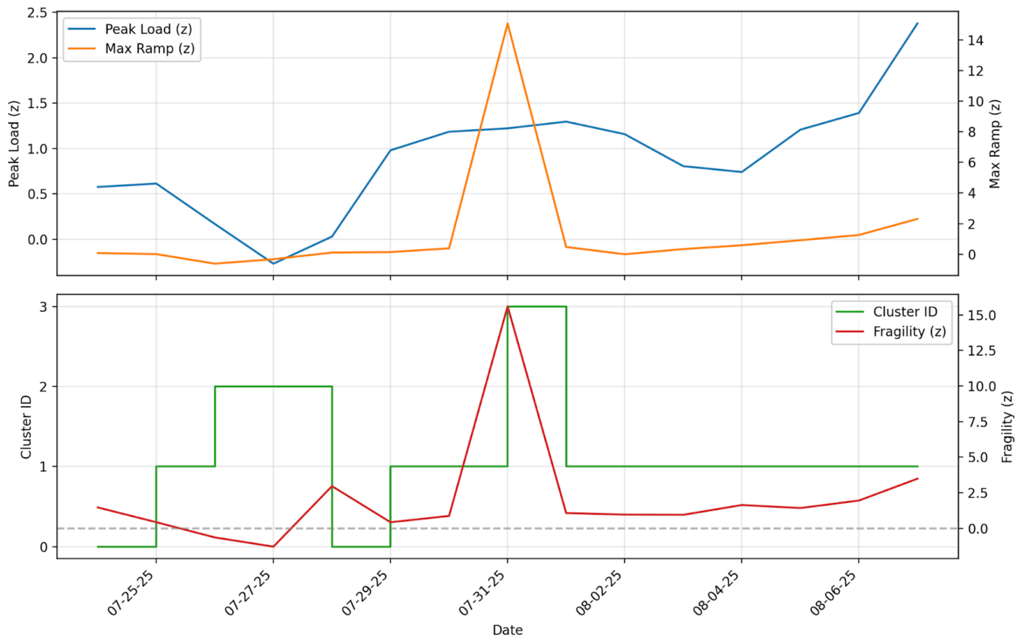

Figure 6. PJM extreme fragility event — combined temporal trajectory

Daily peak load and maximum ramp magnitude (top), and cluster assignment and fragility (bottom) for a representative high-fragility event in PJM. Fragility evolves gradually with elevated load and without sharp ramping spikes, reflecting sustained capacity and reserve pressure. Limited cluster transitions indicate prolonged operation within a high-load regime.

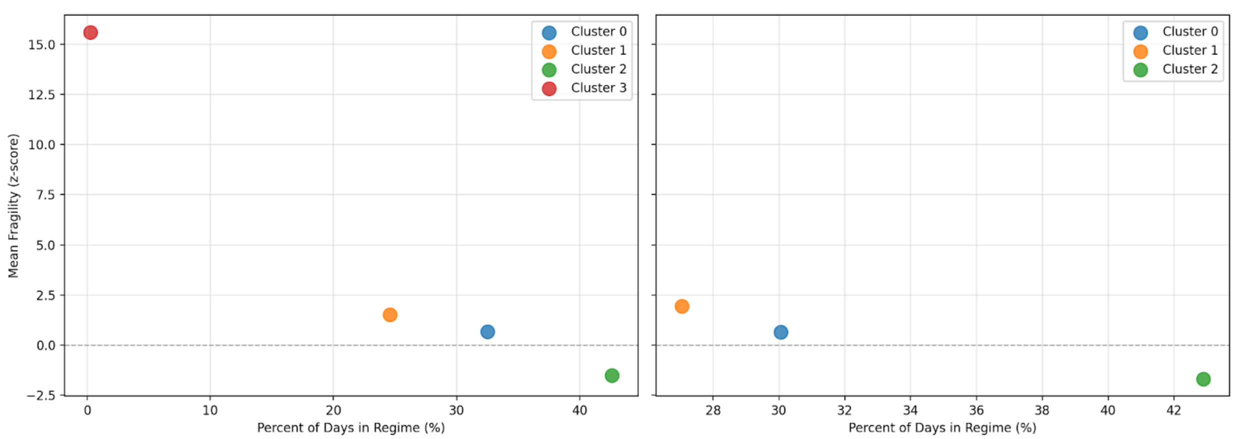

Figure 7. Distribution of daily fragility values

Plot of daily fragility for CAISO and PJM, illustrating the relative frequency of low, moderate, and high-stress conditions. The distributions are strongly right-skewed, with most days clustered at low fragility and a small number of extreme events forming a long upper tail.