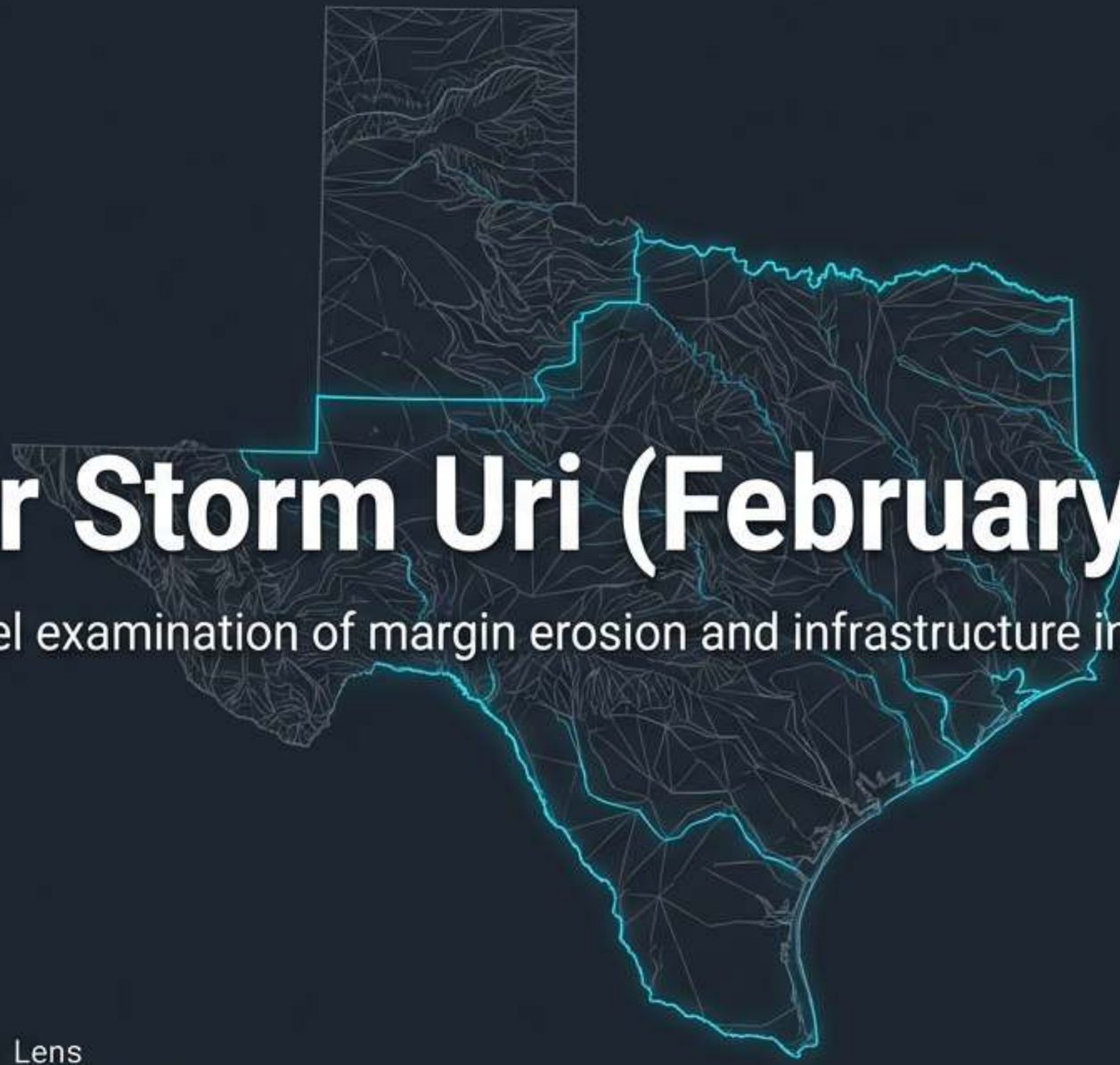


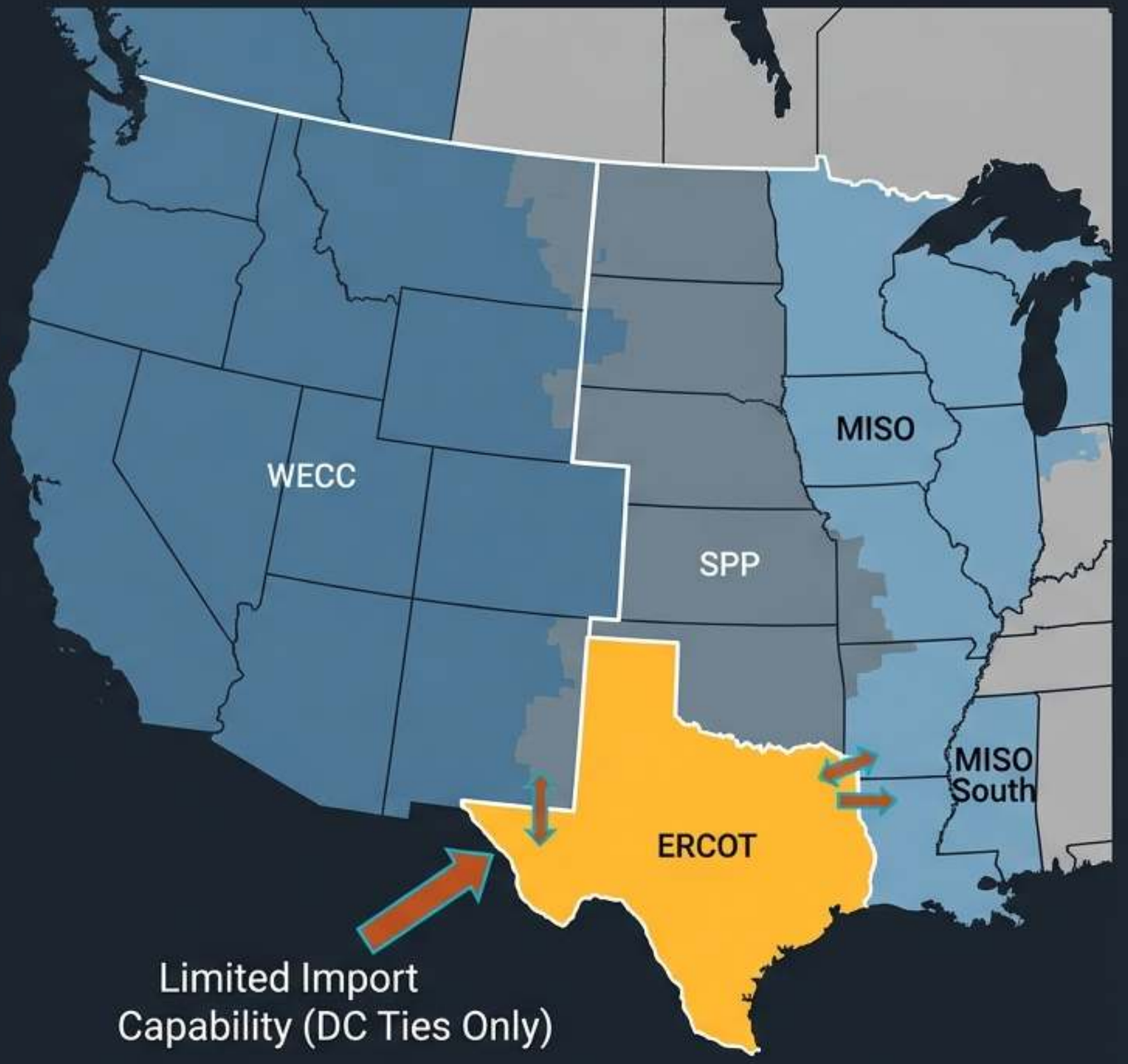
Winter Storm Uri (February 2021)

A system-level examination of margin erosion and infrastructure interdependency

Roboto Mono
Focus: Reliability Engineering Lens
Scope: Gas-Electric Coupling & Margin Loss
Outcome: Controlled Load Shedding

The Texas Grid: System Boundaries

- **Asynchronous Interconnection:** ERCOT manages 90% of Texas load.
- **Islanded Operations:** Limited DC ties (820 MW capacity) to Eastern Interconnection.
- **Fuel Mix Dependency:** 51% Natural Gas, 25% Wind.
- **Just-in-Time Fueling:** No significant on-site gas storage; pipeline dependent.
- **Summer-Peaking Design:** Optimized for heat rejection, not heat retention.



Design Assumptions and Operating Envelope

Resource Adequacy

Based on “50/50” seasonal load forecasts (average historical weather). Excluded extreme tail-risk scenarios.

Reserve Margins

2020/2021 Winter SARA projected adequate reserves based on typical winter demand patterns.

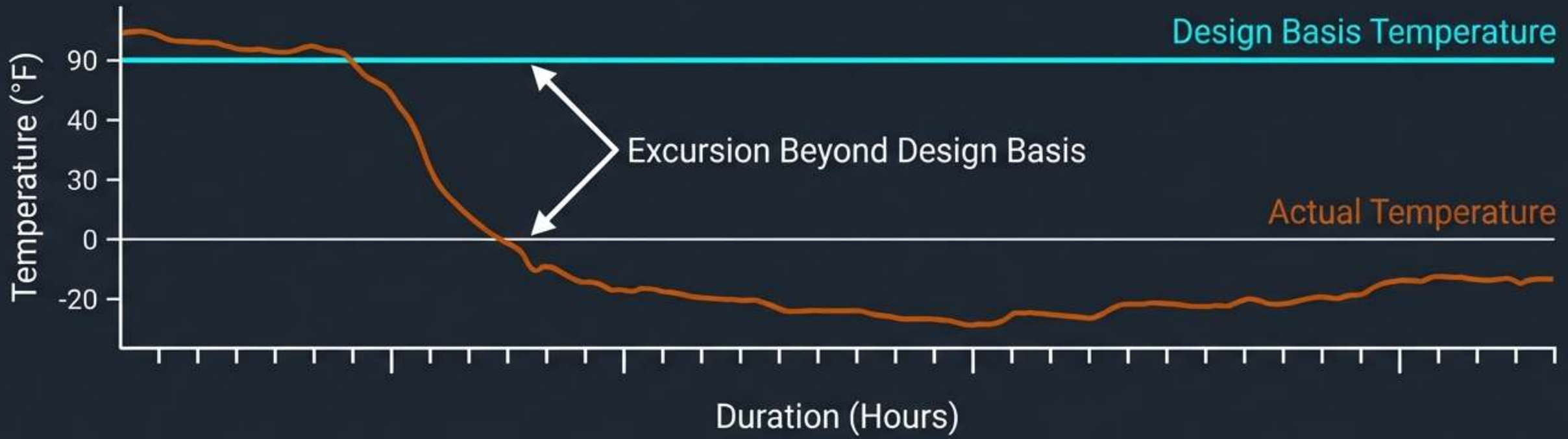
Winterization Standards

Voluntary or spot-checked weatherization. No mandatory retrofits for extreme cold were enforced.

Fuel Assumptions

Modeled assumption: Natural gas supply remains liquid and available during high-demand electric events.

Operating Context Shift: The Excursion



Temperature Deviation

40–50°F below average. >100 consecutive hours below freezing.

Common Mode Failure

Storm covered entire ERCOT footprint simultaneously. No regional redundancy.

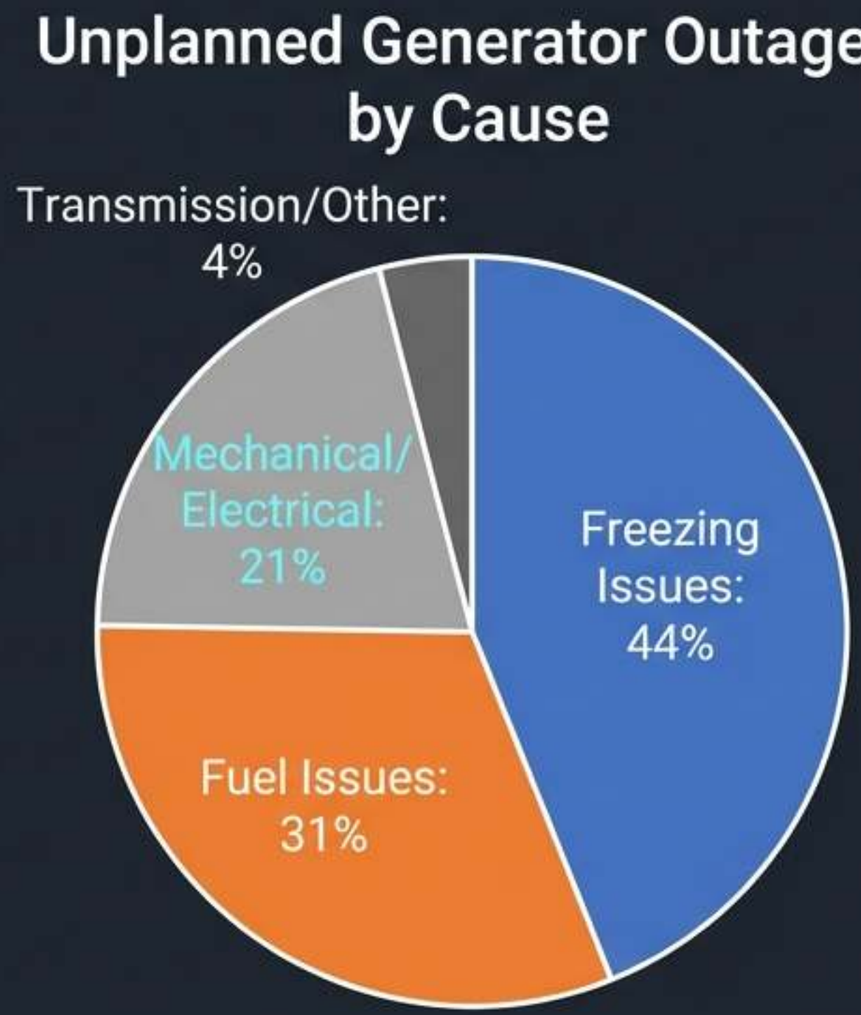
Demand Surge

Electric heating spiked demand beyond ‘extreme’ planning models.

Physical Environment

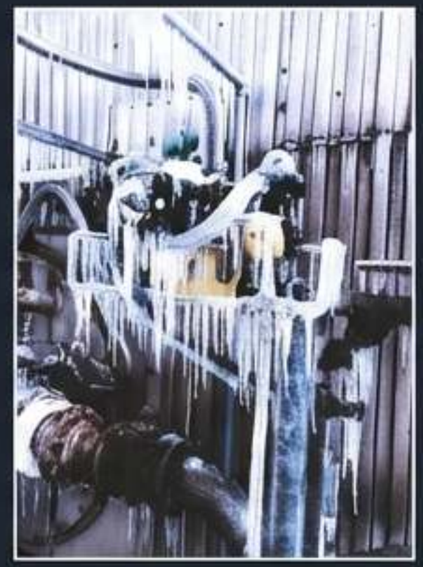
Ambient conditions exceeded hardware ratings.

Compound Stress: Supply Side Failures



Failure Mechanisms

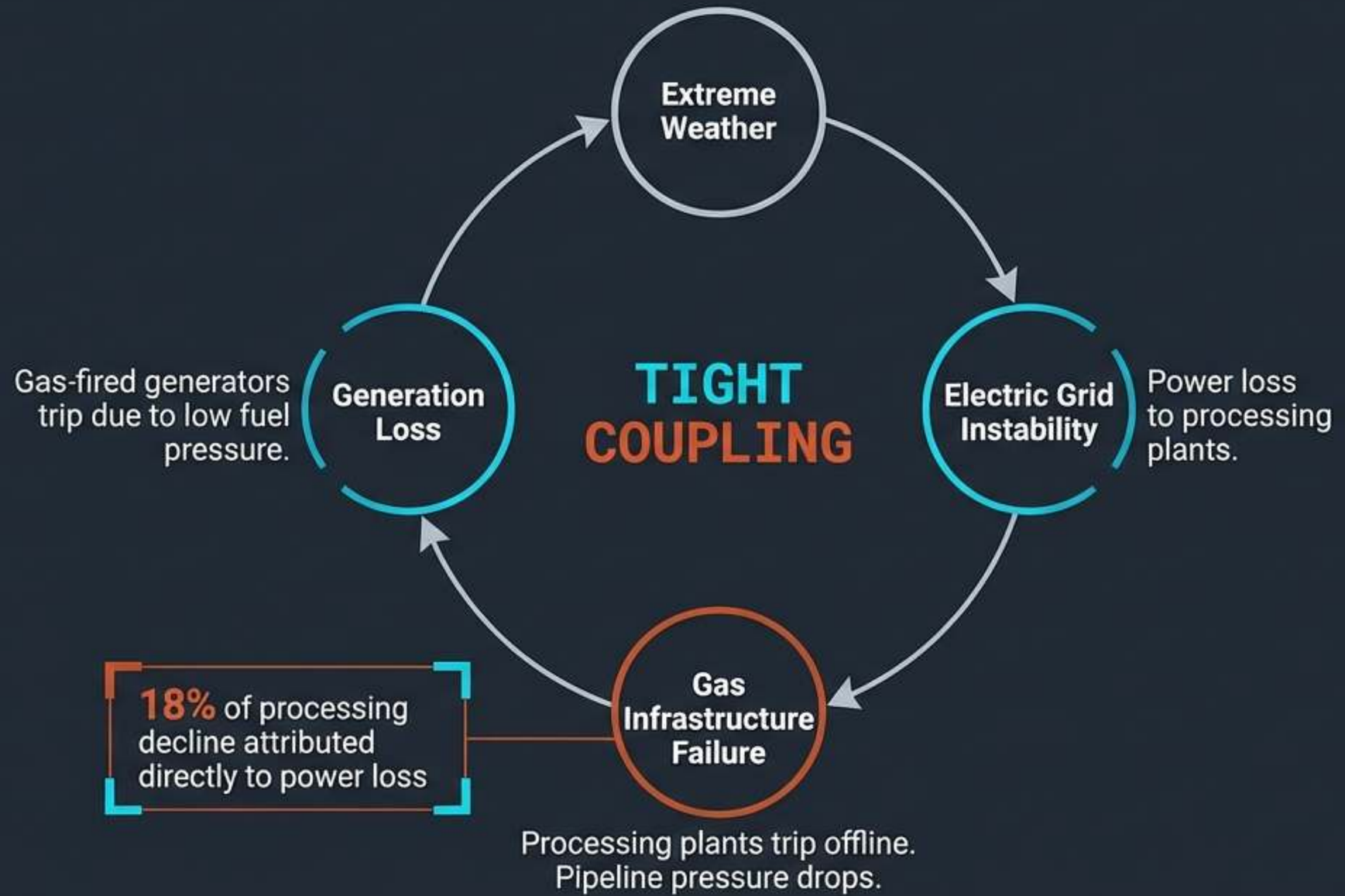
Generator Freezing:
1,045 units impacted. Frozen instrumentation lines and water valves.



Wind Blade Icing:
Aerodynamic icing reduced output.

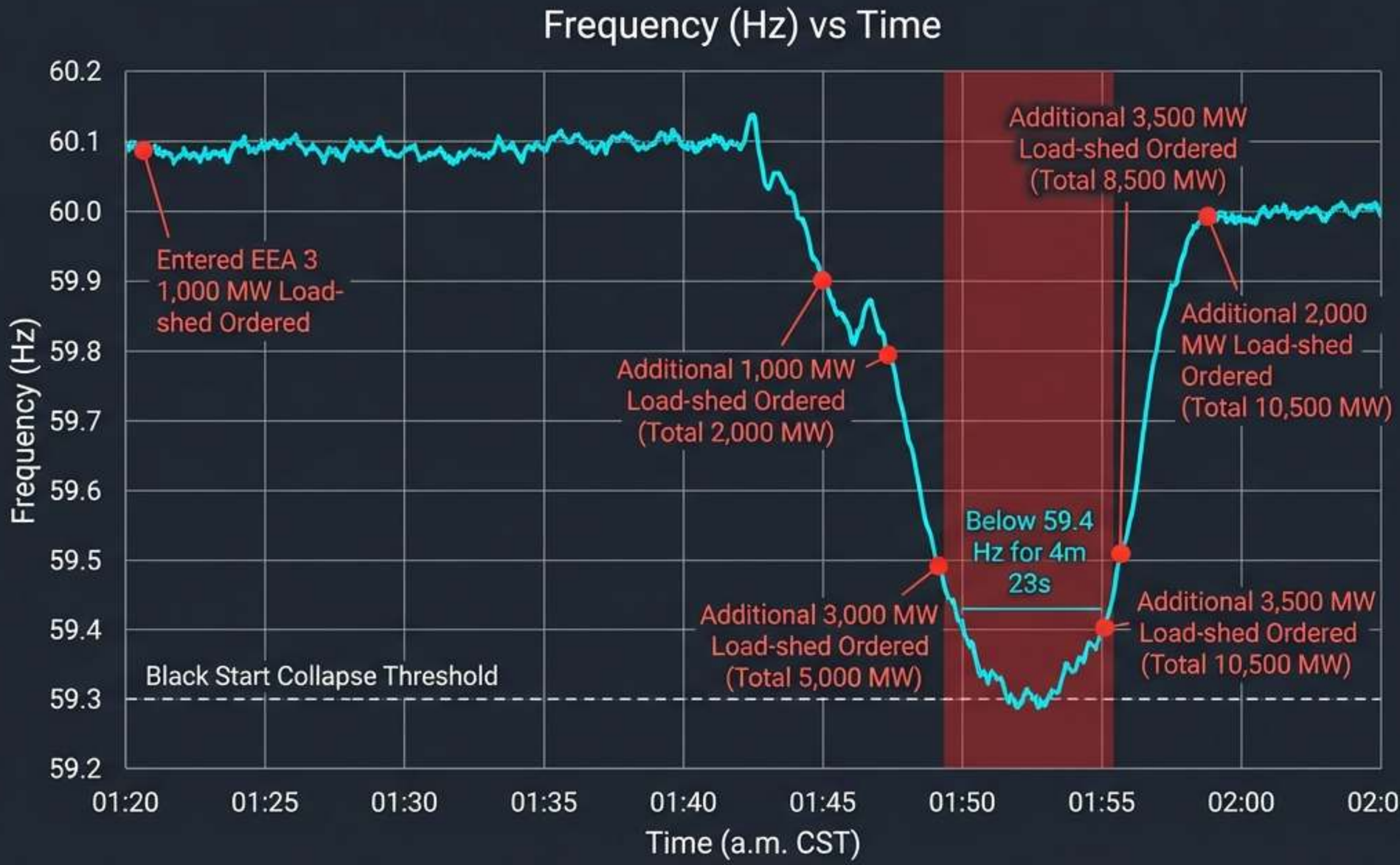
Wellhead Freeze-offs:
Liquid in gas gathering lines froze, cutting production ~50%.

The Vicious Cycle: Gas-Electric Coupling



Critical Load Designation: Many gas facilities were not mapped as "Critical Load" and were subject to rolling blackouts, feeding the cycle.

Rapid Margin Erosion: The Frequency Dip



The 9-Minute Threshold

Operators had <9 minutes to shed load before automatic relays would trip major generation units to protect hardware, causing total collapse.

Load Shedding as Stabilization

The Mechanism: Manual removal of customer power to mechanically balance supply/demand.

The Objective: Sacrifice service continuity to preserve 60 Hz frequency and preventing physical damage.

Inequity: Burden fell on non-critical circuits. Critical load (hospitals/police) protection concentrated outages on remaining residential circuits.

Downstream Consequences

Water Infrastructure

- Power loss at treatment plants/boosters.
- Pipe bursts in unheated structures.

Result: Boil water notices for millions.

Public Health & Safety

- Hypothermia risk.
- Carbon monoxide poisoning.
- Medical device failure.
- Loss of residential heating.

Industrial Impact

- Refinery and petrochemical shutdowns due to feedstock/power loss.
- Disruption of national supply chains.

Functional Failure Analysis

Category: RELIABILITY	Failed to maintain adequate reserve margins under foncast-exceeding conditions.
Category: RESILIENCE	Lacked physical hardening (insulation, heat tracing, enclosures) to withstand environmental stress.
Category: INDEPENDENCE	Failed to maintain operational separation between fuel supply (Gas) and generation (Electric).
Category: SERVICE CONTINUITY	Failed to deliver power to ~4.5 million customers during life-threatening weather.

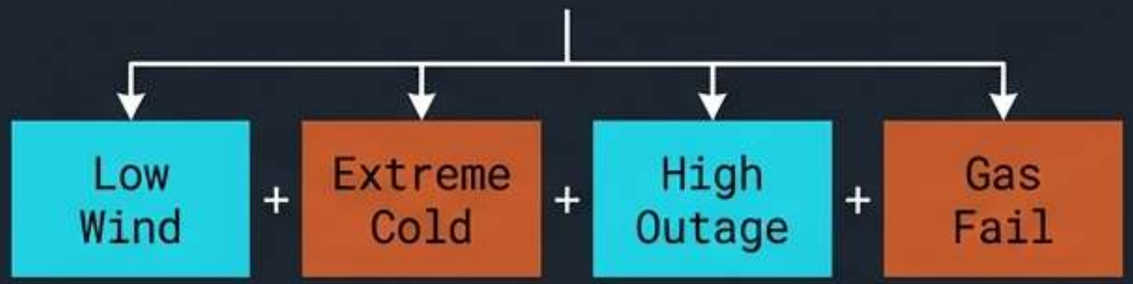
Missed Opportunities for Margin Preservation

1989 — 2011 — 2021

Precedent Events
Similar vulnerabilities exposed (frozen instrumentation, gas curtailment). Winterization remained voluntary.

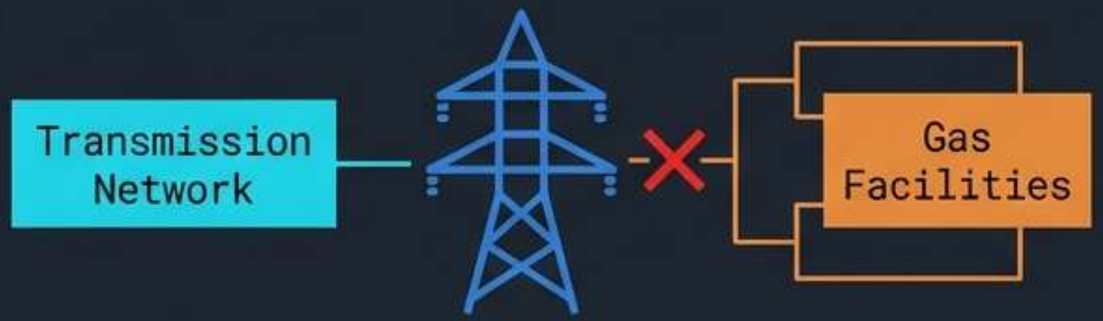
Stress Testing Gap

Models treated variables as independent. Did not simulate Compound Event: **Low Wind** + **Extreme Cold** + **High Outage** + **Gas Fail**.



Mapping Gap

Gas facilities were not integrated into transmission maps as "**Critical Electric Loads**," preventing prioritization.



Transferable Engineering Insights

Correlated Failure Modes

Redundancy is defeated if all systems share a common environmental vulnerability (e.g., Temperature).

Tight Coupling Risks

Efficiency (Just-in-Time) removes buffers. One failure immediately triggers the next in a tightly coupled system.

Stationarity is Dead

Designing infrastructure based solely on historical weather averages is insufficient for future climate extremes.

Interdependency Mapping

System security cannot be assured without mapping dependencies on external inputs (Fuel, Comms, Water).

The grid held, but the service failed.

Efficiency was prioritized, but resilience was consumed.

Which of our critical systems depend on another system that could fail at the exact same time?