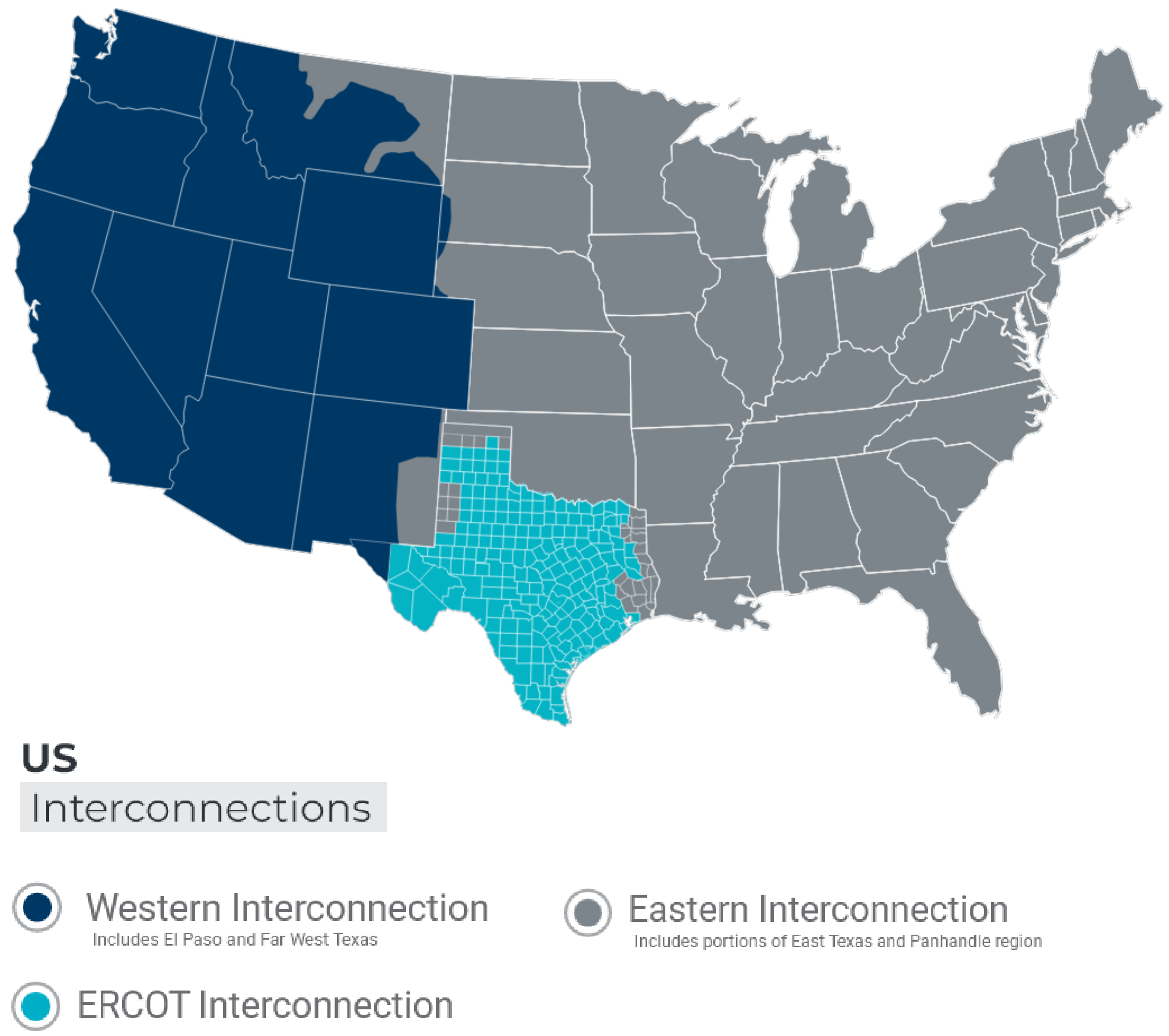
CIGRE/IEEE Webinar – Large Loads and Their Impact on the Grid

An Emerging Reliability Risk

Eric Meier
ERCOT Supervisor – Planning Modeling

May 21, 2025

The ERCOT Region



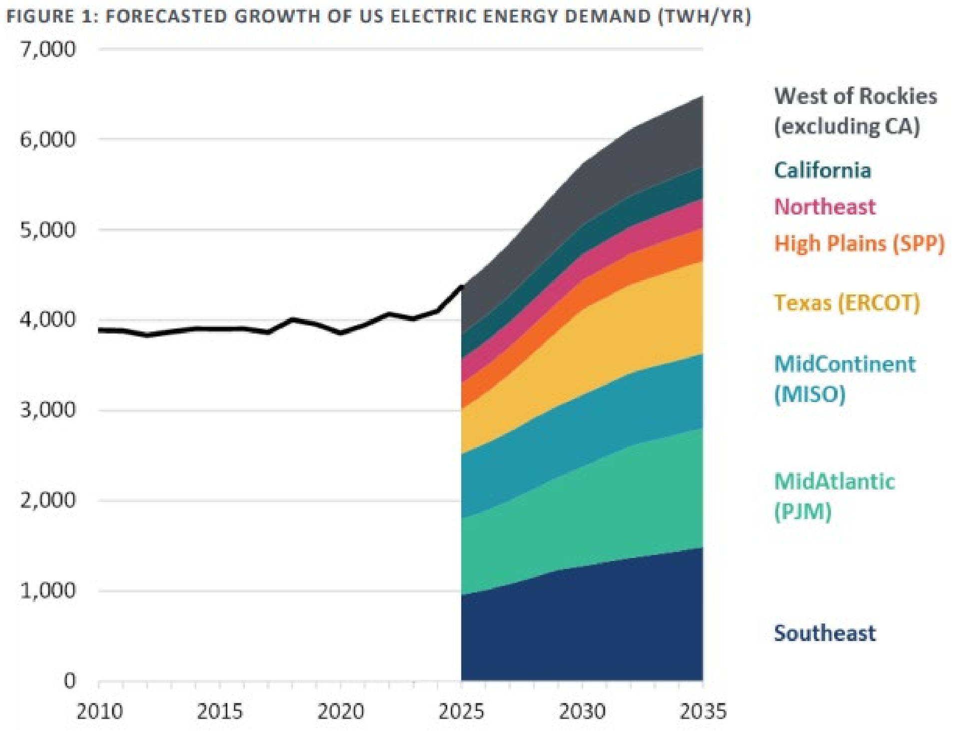
The ERCOT grid is the interconnected electrical system serving most of Texas with limited external connections.

ERCOT highlights include:

- 90% of Texas electric load
- 75% of Texas land
- More than 54,100 miles of transmission lines
- 1,250+ generation units (including PUNs)
- 85,508 MW peak demand
- 103,105+ MW of peak generation capacity

A New Era of Load Growth

- Across the United States and the world, we're seeing large load growth forecasts after decades of little load growth.
- Demand growth is from data centers, cryptomining, manufacturing, electrification, and hydrogen.

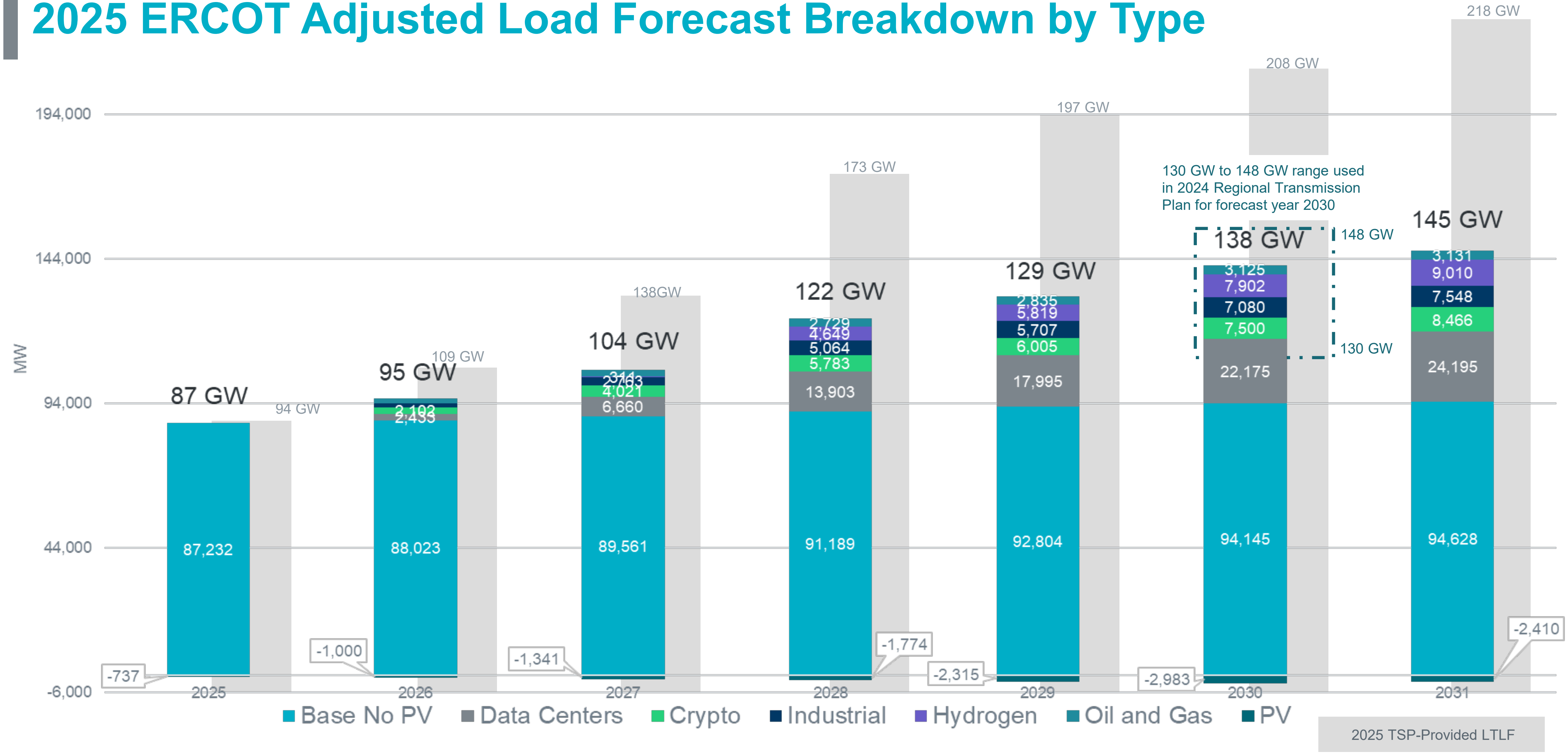


Source: The Brattle Group - Meeting Unprecedented Load Growth: Challenges & Opportunities

Near-Term Load Drivers	Data Centers	Manufacturing	Electrification
Arizona Public Service	●		
CAISO	●		●
Duke	●	●	
ERCOT	●	●	
Georgia Power	●	●	
ISO-NE			●
MISO	●		●
NYISO	●	●	●
Pacific Northwest	●	●	
PJM	●	●	●
SPP	●		

Source: Grid Strategies - Strategic Industries Surging: Driving US Power Demand Report

2025 ERCOT Adjusted Load Forecast Breakdown by Type



Key Takeaway: After adjustments, Data Center Load remains the largest growth by type.

Data Centers

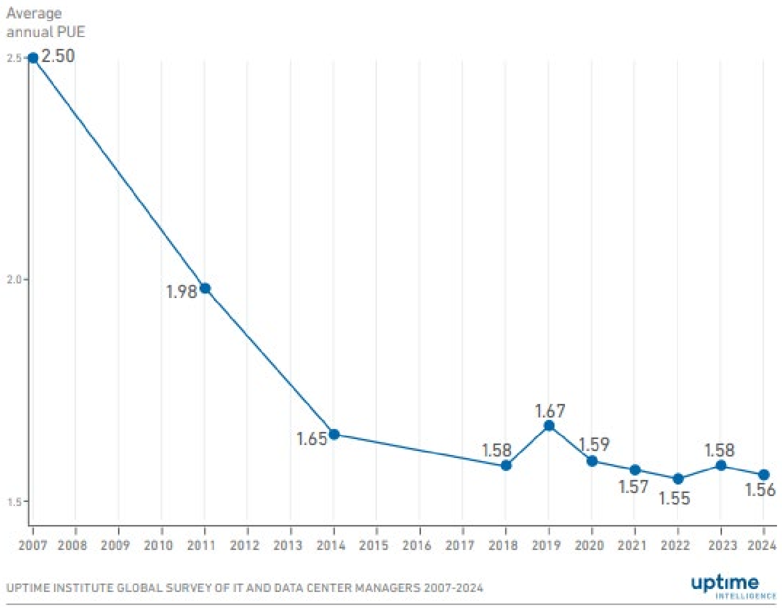
- Much of the current load growth is being driven by increasing data center and cryptocurrency mining demand.
- Data centers can serve cloud usage, AI, enterprise users, and have many use cases.
- Main data center components:
  - Servers/Compute: Devices like CPUs/GPUs/TPUs that process data ~ 60% of power consumption
  - Storage: Devices that store information ~ 5% of power consumption
  - Networking: Equipment that connects servers within the data center ~ 5% of power consumption
  - Cooling and Environmental Controls: Equipment that manages temperature and humidity ~ 5% to 30% of power consumption
  - Uninterruptible power supply (UPS) batteries and backup power generators: Supply power during outages
  - Other Infrastructure: Lighting, office equipment, etc.
- A single generative AI query to create an AI image takes 0.011 kWh's of energy.
  - Power Hungry Processing: Watts Driving the Cost of AI Deployment? - Hugging Face and Carnegie Mellon.

Source: International Energy Agency – Energy and AI Report

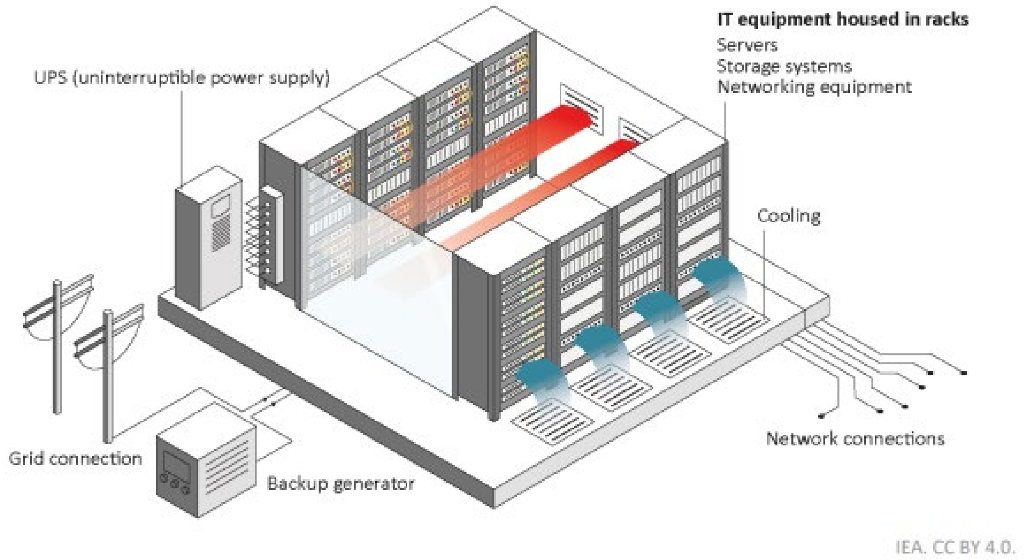
Data Center Efficiency

- Data center efficiency is measured in Power Usage Effectiveness or PUE. It's a ratio that describes how much energy is used computing equipment versus all other equipment, such as cooling, lighting, etc.
- The industry average for PUE is current around 1.56 and has not improved since 2020.

$$\text{PUE} = \frac{Total\ Facility\ Energy}{IT\ Equipment\ Energy} = 1 + \frac{Non{-}IT\ Facility\ Energy}{IT\ Equipment\ Energy}$$



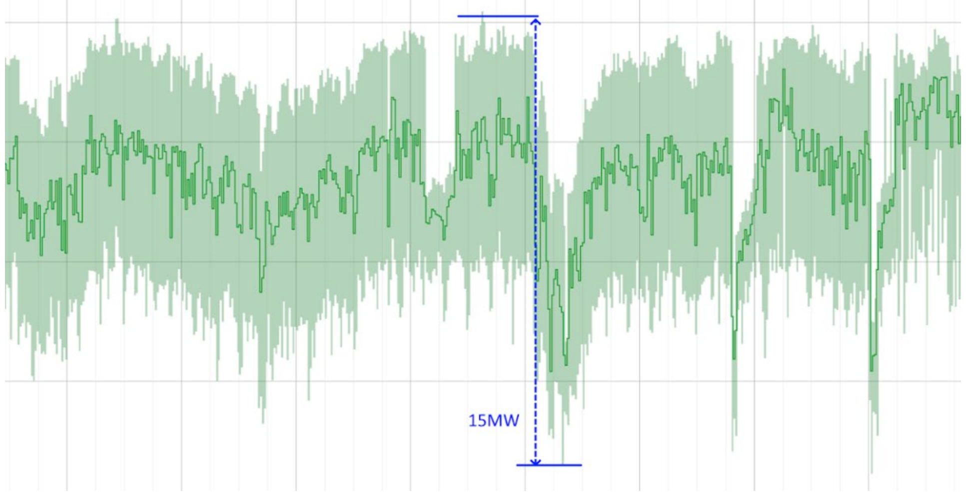
Source: Uptime Institute, Global Data Center Survey 2024 (July 2024)



Source: International Energy Agency – Energy and AI Report

Data Center Load Profiles

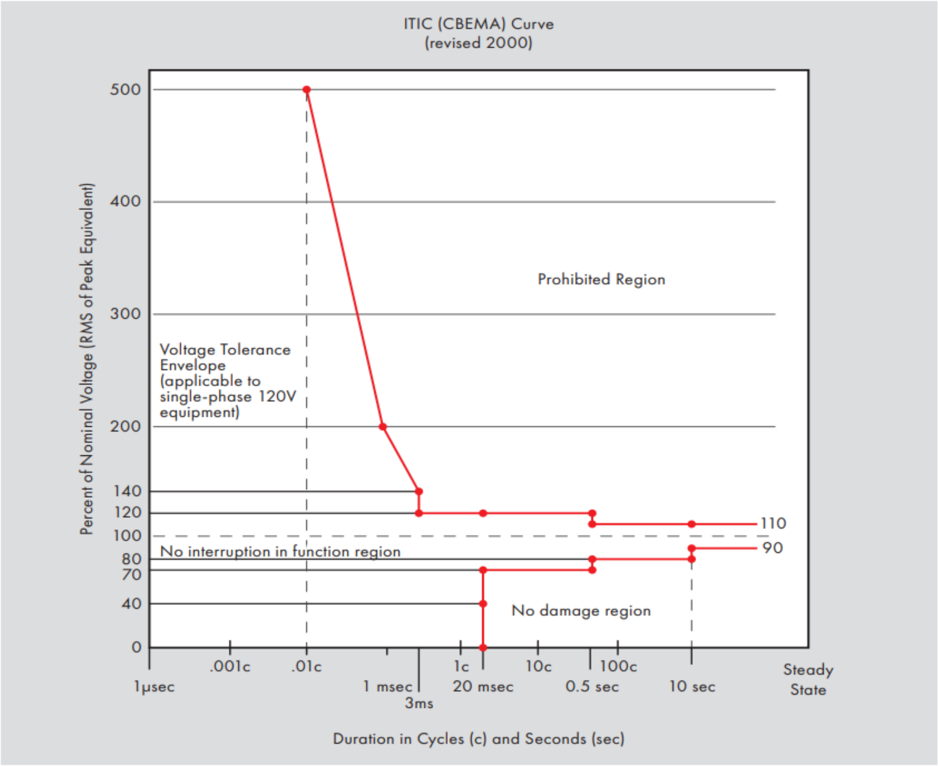
- In a cloud or traditional data center the load profile is typically constant as the facility has high availability requirements to meet.
- For data centers focused on AI training, they can have a highly variable load profile.
- This fluctuating load demand is due to giving the AI model examples and grading it on its output. Here software programs are driving power demand.
  - The data center owner may not know the size of the model unless its their model being trained.
  - Load demand can be impacted by changes to code, firmware, and compilers.
- For data centers focused on AI inference aka the using of the AI model, the load profile is less variable.



Source: https://cloud.google.com/blog/topics/systems/mitigating-power-and-thermal-fluctuations-in-ml-infrastructure

Data Center Power Architecture

- There are numerous configurations for server power architecture with centralized and distributed UPSs, AC vs DC server buses, and centralized power distribution vs rack PDUs.
- Primarily it is the UPS or rectifier that we need to be concerned with. They are typically designed to conform to the ITIC curve with respect to to voltage ride-through although server loading matters. Better ride-through performance would require bigger on-board capacitors which costs more.

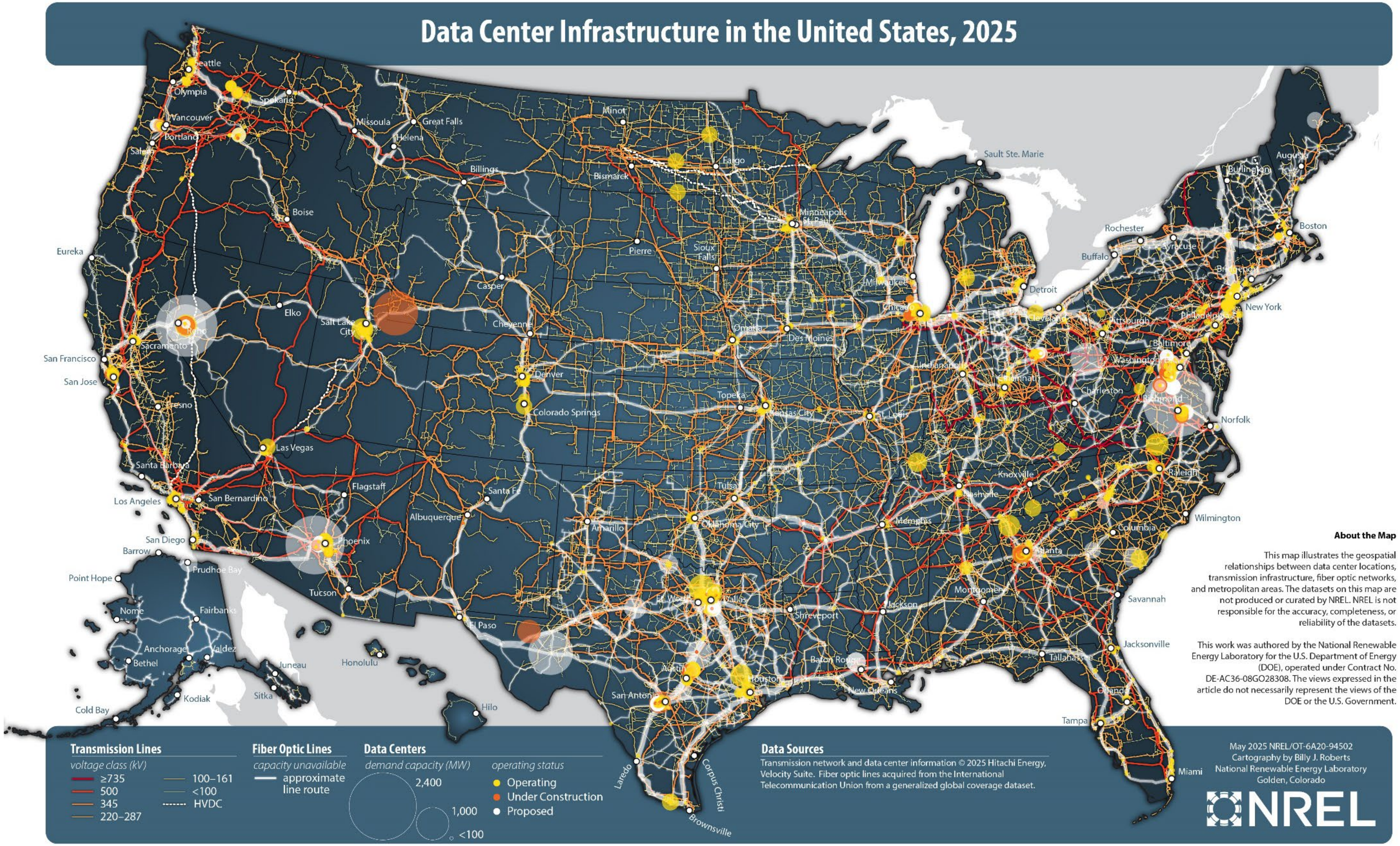


Mains Power → UPS → Power Supply → Rack PDU → Compute: GPU/CPU

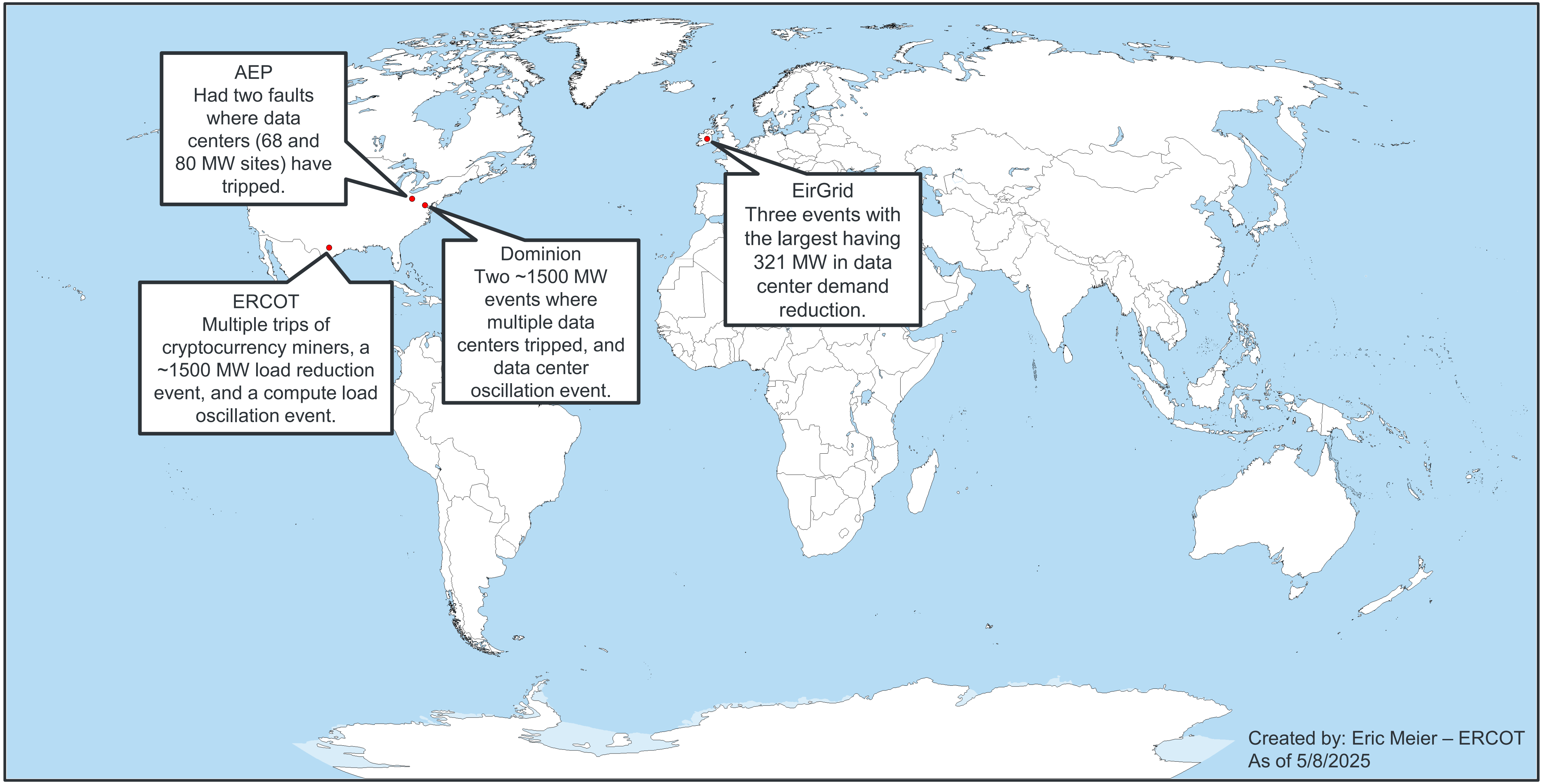
Cryptocurrency Mining

- Cryptocurrency such as Bitcoin is a decentralized cryptocurrency on a blockchain where a peer-to-peer network maintains a record of transactions. New coins can be unlocked through cryptocurrency mining.
- In Bitcoin mining, computers solve mathematical problems to unlock new coins. The first miner to solve the problem obtains the bitcoin. This is known as Proof of Work.
- Proof of Stake is the other mining method where users stake coins which then lets them validate transactions across the network. This is less energy intensive.
- Cryptocurrency mining is a pure arbitrage play where miners are turning energy into money. As such they are typically price responsive and there's little demand variability during normal operations.
- Miners typically use specialized ASIC miners which are designed to UL specs. They can be run in a server farm or at home. They have no special ride-through capabilities, backup generation, or UPSs.

Where Will Data Centers Go?

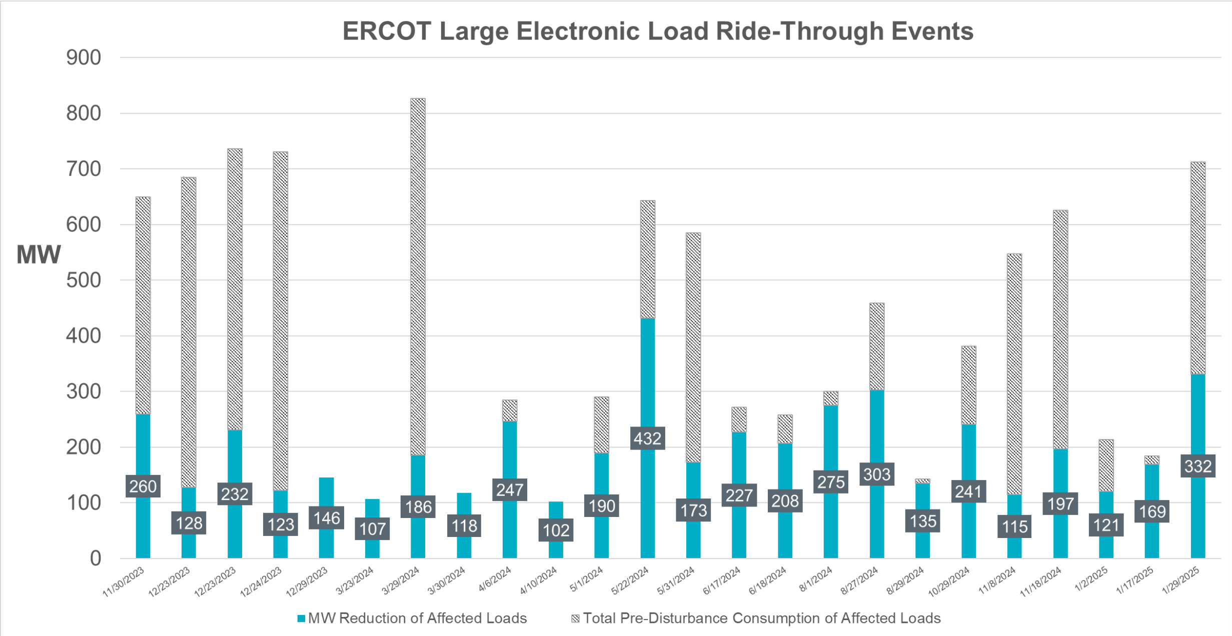


Large Scale Load Reduction Events, Trips, and Oscillations



ERCOT Load Ride-Through Events

- ERCOT continues to see load reduction for even shallow voltage dip events with power electronic load.
  - Large variance in the percent of reduction with similar voltage dips at the point of interconnection.
  - Some power electronic loads are more sensitive to voltage disturbances than others.
- Current models do not capture this behavior, making accurate studies to identify transmission improvements difficult.
  - There are possible facility protection systems not visible to ERCOT nor included in dynamic models.
- Single line to ground faults are causing significant reductions for shallow positive sequence voltage dips. These are the most common, however, 3 line-to-ground faults will have an even bigger impact on load reduction.
  - Faulted phase likely reducing below ~0.7pu causing load reductions.
  - Single-phase high-resolution data is required for analysis and data from facility (low side) would aid in event analysis.

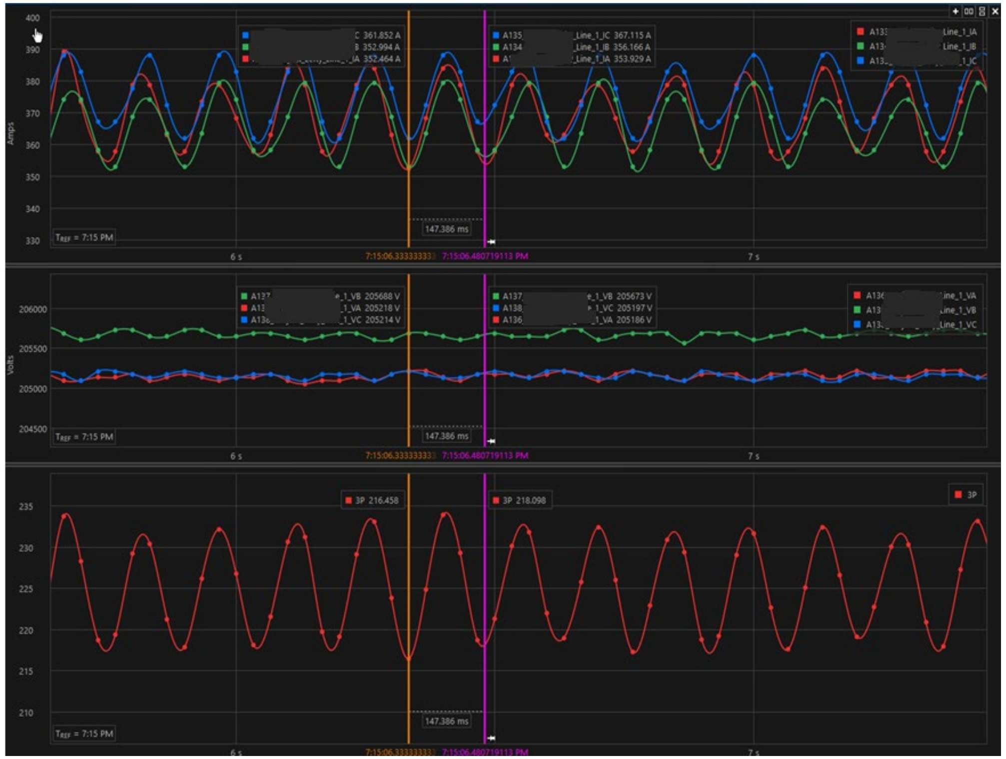


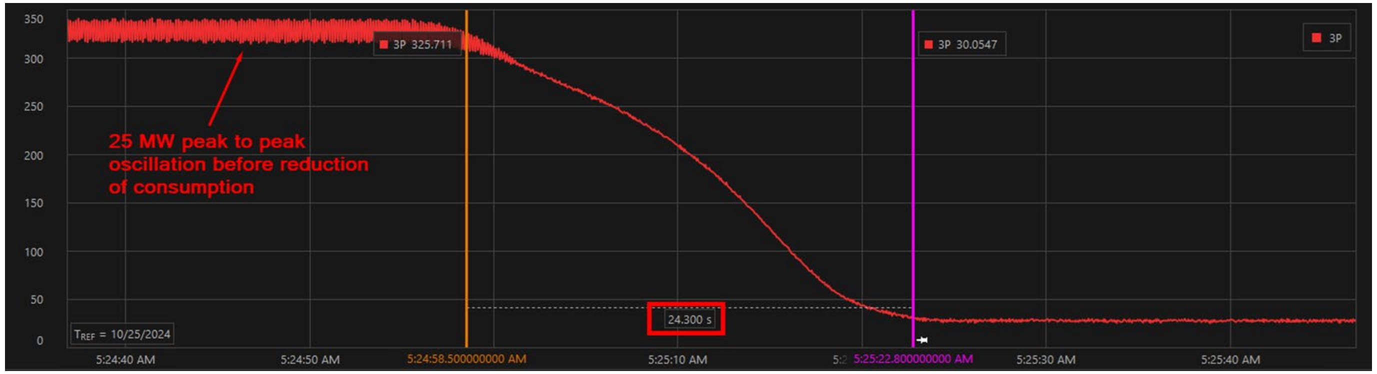
Source: ERCOT Large Load Events_LFLTF_March2025.pptx - https://www.ercot.com/calendar/03042025-LFLTF-Meeting

ERCOT Large Load Oscillation

- In September 2024, ERCOT observed a ~40 MW oscillation from a large load when consumption was above 300 MW.
- High resolution data (20 samples/cycle) showed a ~23 Hz oscillation with ~50 MW peak to peak magnitude on Oct. 28.
- Root cause was determined to be old firmware on some equipment. Load was limited until firmware was updated.

- **Key Observations**
  - Oscillation was sub-synchronous and could damage nearby generation.
  - High resolution measurements were needed to see the oscillations – SCADA was not fast enough.
  - ERCOT is concerned AI data centers may exhibit similar oscillations.
  - Load models failed to capture this behavior.

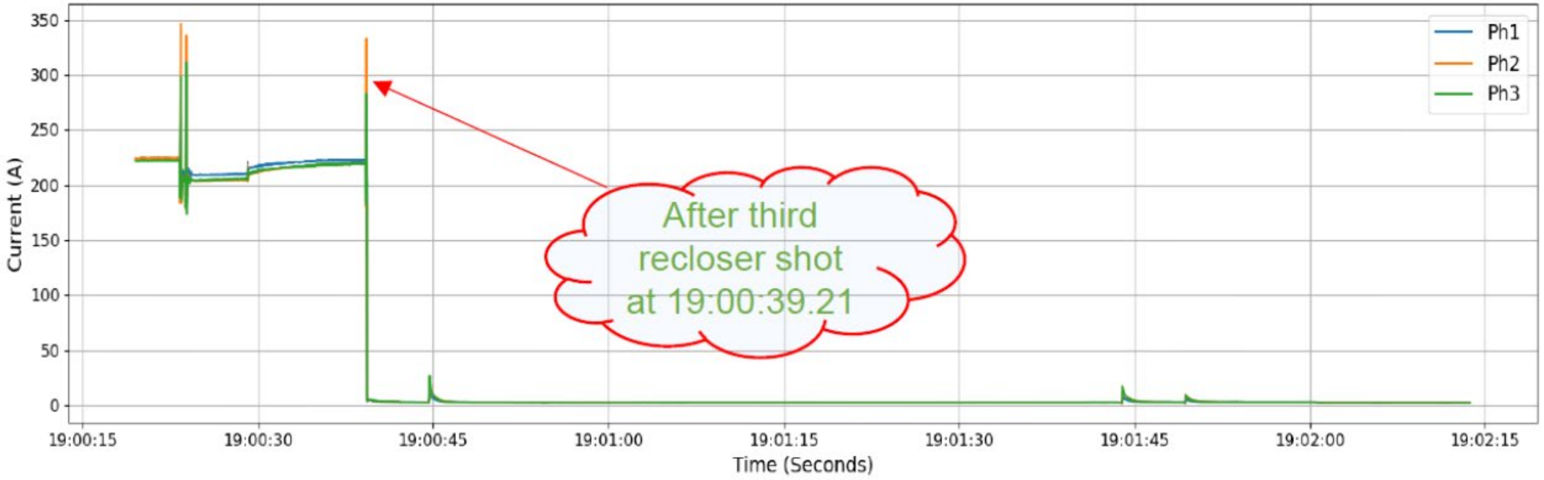




Source: LL_Oscillation_LFLTF_Mar2025_Final.pptx - https://www.ercot.com/calendar/03042025-LFLTF-Meeting

Dominion Events

- In Dominion, a 230-kV transmission line fault led to customer-initiated simultaneous loss of approximately 1,500 MW of voltage-sensitive load.
- The fault was caused by a lightning arrestor failure on a 230-kV transmission line, resulting in a permanent fault that eventually “locked out” the transmission line. The auto-reclosing control on the transmission line was configured for three auto-reclose attempts staggered at each end of the line.
- This configuration resulted in six successive system faults in an 82-second period. The protection system detected these faults and cleared them properly.
- Most of the sustained load reduction occurred simultaneously with the third voltage depression, which coincided with the third automatic reclosing attempt. This can be attributed to the interaction between the automatic reclosing sequence on the faulted line and the data center’s protection/control scheme that counts the number of voltage disturbances within a specified period.
  - Most data center protection schemes utilize a “3 strikes” rule before switching to backup power.



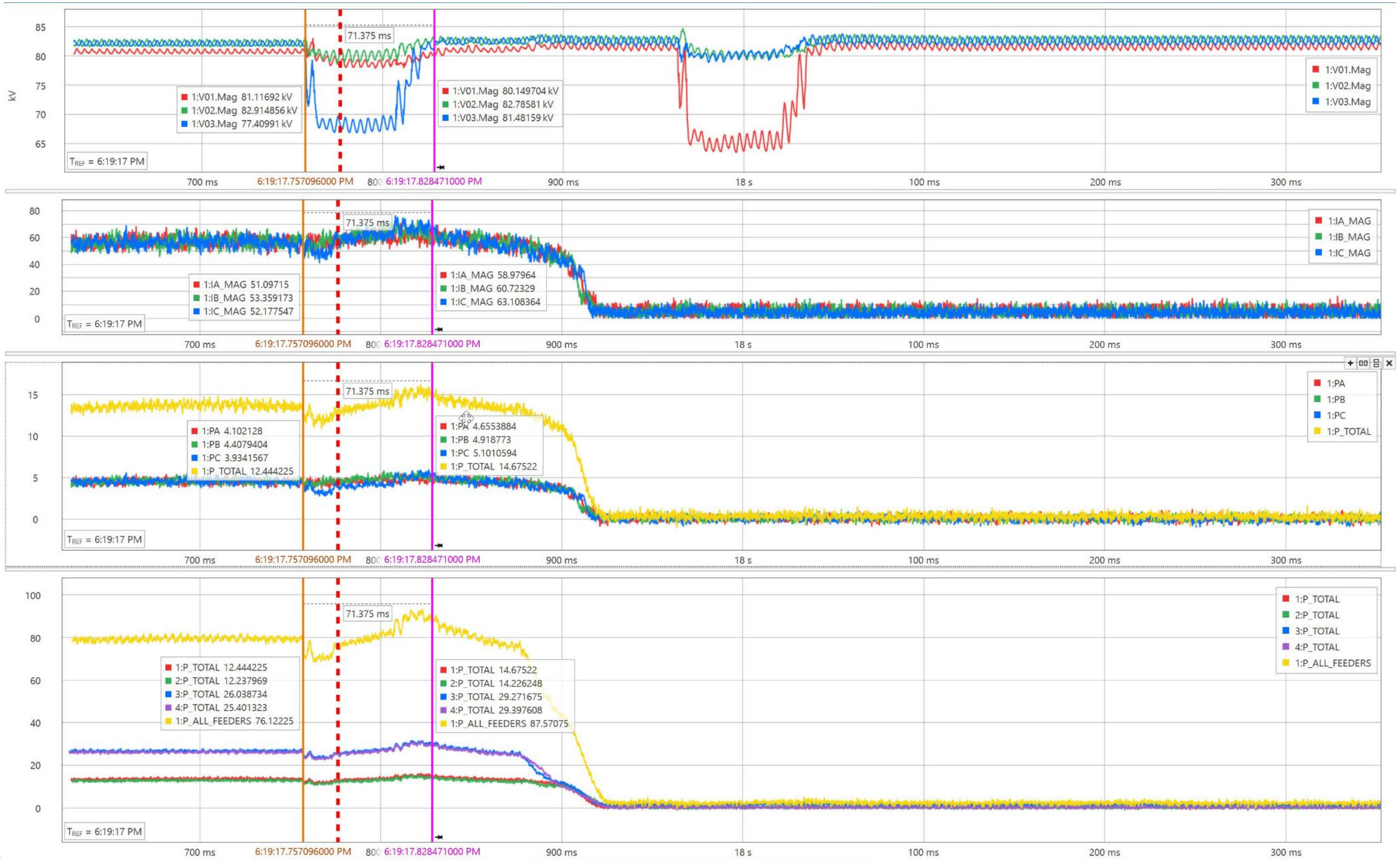
Source: NERC Incident Review - Considering Simultaneous Voltage-Sensitive Load Reductions

AEP Events

- Two recent normally cleared 138-kV phase-to-ground faults.
  - February 9, 2025 – crane strikes line
  - March 12, 2025 – oversized train strikes distribution line causing distribution wires to hit transmission line on same ROW
- Several data centers with different owners were in area located within reach of the faults.
- In these events, several data centers and crypto miners rode through, while some data centers tripped following attempted transmission system reclosing.
- High-speed reclosing (HSR) / timed auto-reclosing of lines a common practice.
  - HSR typically follows initial fault in 20-30 cycles range
  - Then 1-3 timed reclosing attempts follow HSR typically between 5 to 20 seconds
  - Normal fault clearing typically 3-6 cycles

Source: Data Center Fault Event Records – NERC LLTF 4/10/2025 Presentations

AEP March 11, 2025 Event - Data Center 80 MW: Trips after 2nd Reclose Attempt

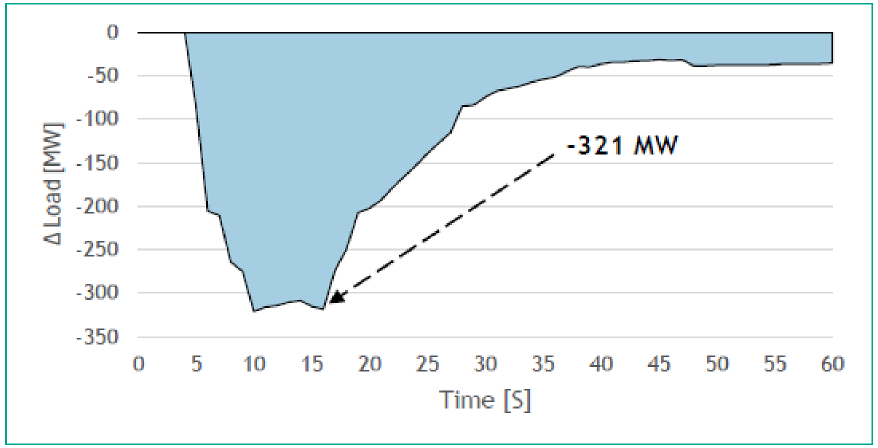


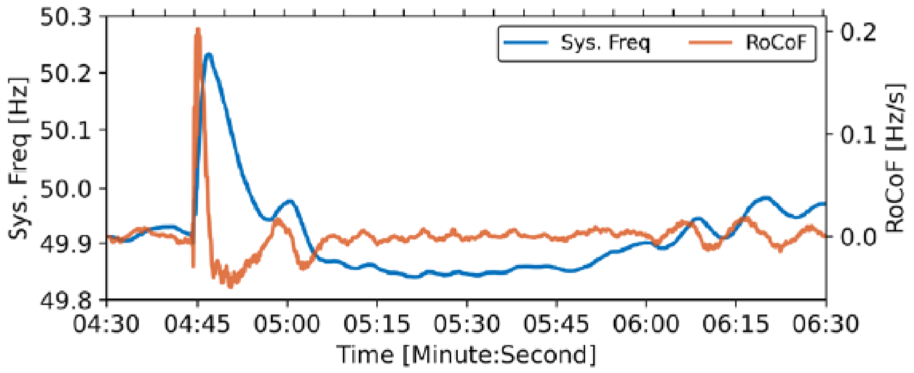
EirGrid Events

- In EirGrid, there have been three transmission faults that caused a transient voltage dip leading to data center demand reduction.
- The reduction was triggered by data center transferring load to UPSs due to voltage protection settings.
- This demand reduction caused the system frequency to rise because of a generation and load imbalance.
- Reconnection of load also posed a challenge to system frequency.

Date	Transmission System Contingency	Data Centre Demand Reduction
7 Jan 2022	Limerick: Killonan-Kilpaddoge 220 kV Fault	74 MW
13 Dec 2022	Dublin: Kellystown-Woodland 220 kV Fault	204 MW
26 Jan 2025	Dublin: Poolbeg 220 kV Reactor Fault	321 MW

January 26th, 2025 Event





An Emerging Reliability Risk

- Large loads are seeking to interconnect faster than ever before, and the newest load complexes are reaching five gigawatts in scale.
- These loads present an emerging reliability risk to the power system as demonstrated by the load trips. There are no regulations on registration requirements, operational rules, or models for many of these facilities.
- In our current state, unmodeled, unsimulated, and unpredicted load behaviors exacerbate the risk of blackouts.
- We don’t need to wait for SkyNet for AI to threaten our grid, the risk is here now.
- However, we have a chance to work with load developers and owners to optimize their facilities to both support the grid and to ensure that grid behavior is supporting the reliability of their facilities.

Industry Efforts Around Large Loads

North American Electric Reliability Corporation Large Load Task Force

- Focused on the reliability of the bulk power system
- Producing two whitepapers and a reliability guideline
- May lead to standards authorization requests for new regulations
- Cannot propose solutions beyond changes to standards and practices and does not have much participation from large loads themselves

Energy Systems Integration Group Large Load Task Force

- Focused on a holistic power systems view covering data collection, interconnection, forecasting, performance requirements, modeling, markets, and resource adequacy
- Producing a whitepaper
- Has participation from load developers
- Trying to find mutually beneficial solutions
- Looking beyond standards and practices with specific engineering solutions

ERCOT Large Load Working Group

- Focused on the reliability of the ERCOT system
- Responsible for developing and recommending policies to facilitate the reliable and efficient integration of Large Loads into the ERCOT system
- Covers technical and market issues, including planning, operations, and market-related processes for Large Load interconnection and management

Path Forward

- Moving forward we need to fully understand how the load facilities operate, characterize them, and develop good models of them – both electrically and behaviorally.
  - For example, we need to understand the interaction between power electronic load and transmission system protection. The tripping on the "3 strikes" setting is causing loads to trip.
- Ultimately, we need to build and foster partnerships between grid operators and load developers/owners to accomplish this.
- The industry needs to continue with the efforts underway in various task forces and working groups doing this work. However, this work will evolve into requirements and changes that grid operators will need to implement.
- Certain loads may need to become registered entities and have regulations and performance requirements applied to them.
- We have a rare opportunity to take on a generationally defining challenge for the industry. We're in the early stages now, but when this work is done, the grid will not be the same. The longer we wait however, the greater the risk to the grid and society.

Questions?

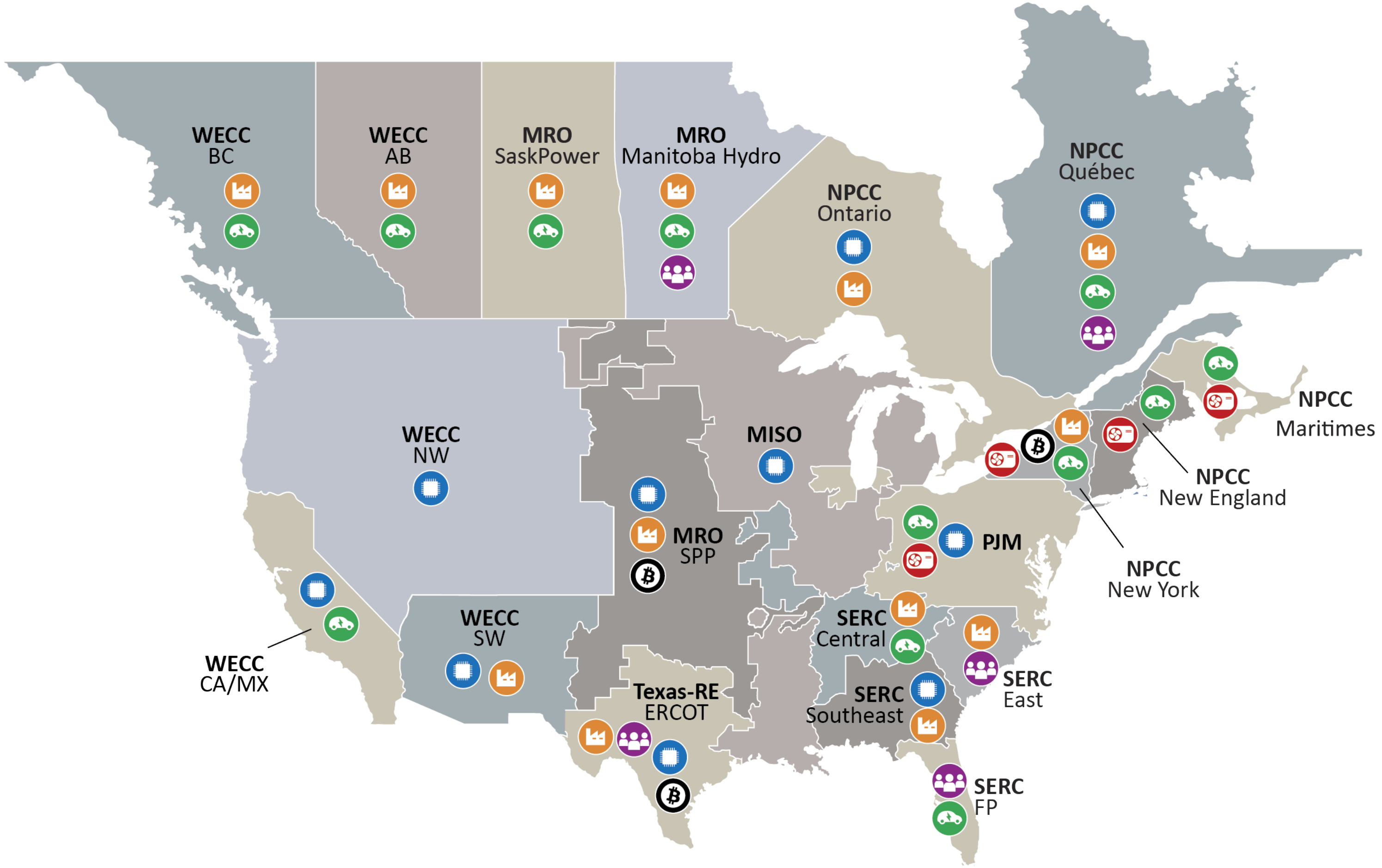
Large Loads and Their Impact on the Grid

NGN Webinar: Large Loads and Their Impact on the Grid

Evan Mickelson, Engineer, NERC

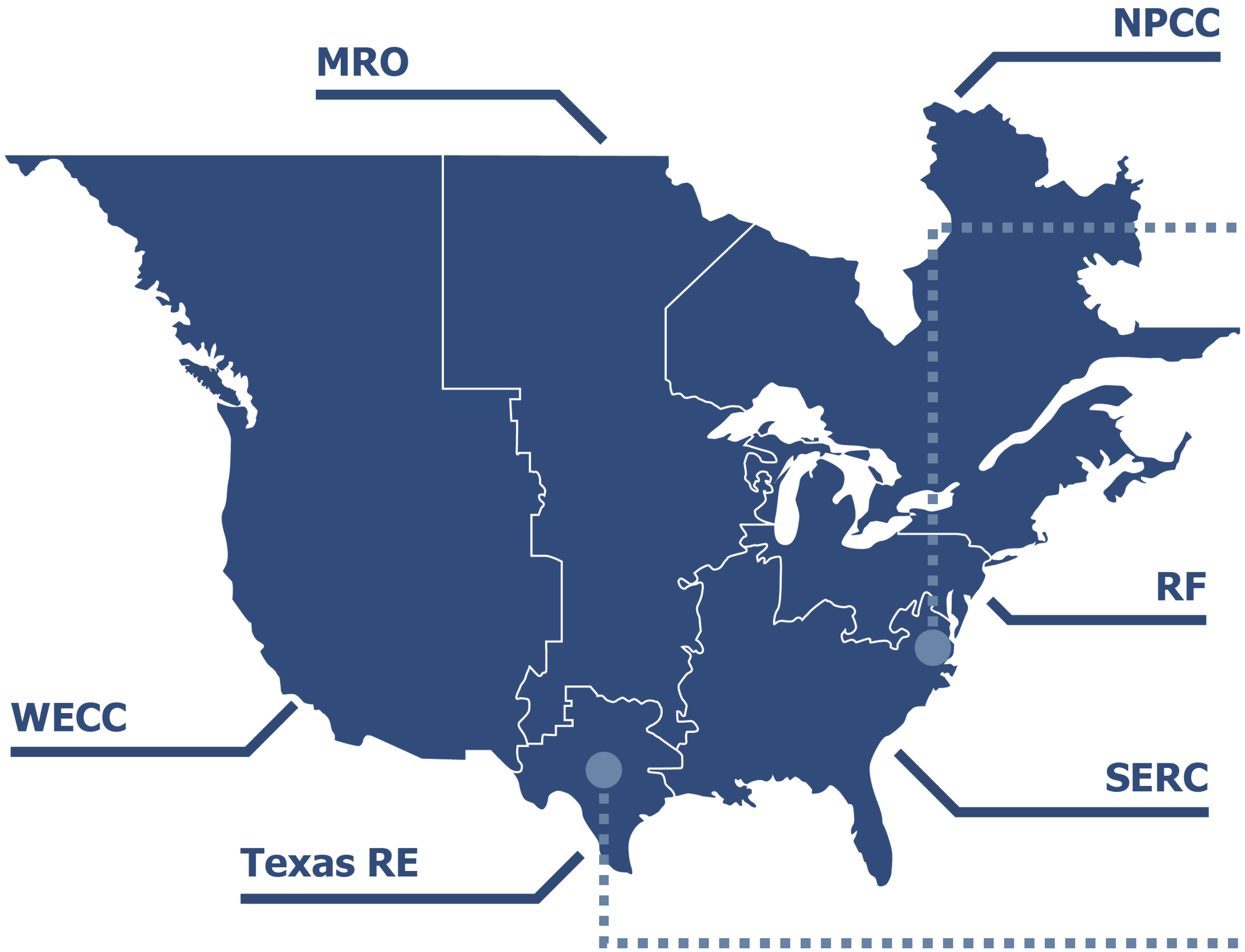
May 21, 2025

Primary Demand Drivers by Assessment Area



- **DATA CENTERS**
- **LARGE INDUSTRIAL LOADS**
- **TRANSPORTATION ELECTRIFICATION**
- **CRYPTO**
- **HEAT PUMPS**
- **DEMOGRAPHIC CHANGES**

Voltage Sensitive Load Loss Events



EI Data Center Load Loss Events

- 1500 MW Load Loss (July 2024)
- 1800 MW Load Loss (February 2025)

ERCOT Crypto Mining Load Loss Events

- 25 Loss Events (November 2023–January 2025)
- 100–400 MW Load Loss

Data Center Load Loss Event

NERC
NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

Incident Review

Considering Simultaneous Voltage-Sensitive Load Reductions

Primary Takeaways

Operators and planners of the Bulk Electric System (BES) should be aware of the risks and challenges associated with voltage-sensitive large loads that are rapidly being connected to the power system. Specifically, when considering data centers and cryptocurrency mining facilities, entities should be aware of the potential for large amounts of voltage-sensitive load loss during normally cleared faults on the BES. Voltage-sensitive data center-type loads have increased on the system and are predicted to continue growing rapidly. The 2024 NERC *Long-Term Reliability Assessment* (LTRA) documents and discusses this potential growth of data center-type loads. This vignette highlights this load-loss potential based on analysis of a recent event in the Eastern Interconnection and offers some considerations for BES operators, planners, and regulators concerning identifying and mitigating the potential reliability effects and risks presented by these large voltage-sensitive load losses for future operations.

Summary of Incident

A 230 kV transmission line fault led to customer-initiated simultaneous loss of approximately 1,500 MW of voltage-sensitive load that was not anticipated by the BES operators. The electric grid has not historically experienced simultaneous load losses of this magnitude in response to a fault on the system, which has historically been planned for large generation losses but not for such significant simultaneous load losses. Simultaneous large load losses have two effects on the electric system: First, frequency rises on the system as a result of the imbalance between load and generation; second, voltage rises rapidly because less power is flowing through the system. In this incident, the frequency did not rise to a level high enough to cause concern. The voltage also did not rise to levels that posed a reliability risk, but operators did have to take action to reduce the voltage to within normal operating levels. However, as the potential for this type of load loss increases, the risk for frequency and voltage issues also increases. Operators and planners should be aware of this reliability risk and ensure that these load losses do not reach intolerable levels.

Incident Details

At approximately 7:00 p.m. Eastern on July 10, 2024, a lightning arrestor failed on a 230 kV transmission line in the Eastern Interconnection, resulting in a permanent fault that eventually "locked out" the transmission line. The auto-reclosing control on the transmission line was configured for three auto-reclose attempts staggered at each end of the line. This configuration resulted in 6 successive system faults in an 82-second period. The protection system detected these faults and cleared them properly. The shortest fault duration was the initial fault at 42 milliseconds, and the longest fault duration was 66 milliseconds. The voltage magnitudes during the fault ranged from .25 to .40 per unit in the load-loss area.

RELIABILITY | RESILIENCE | SECURITY

EVENT:

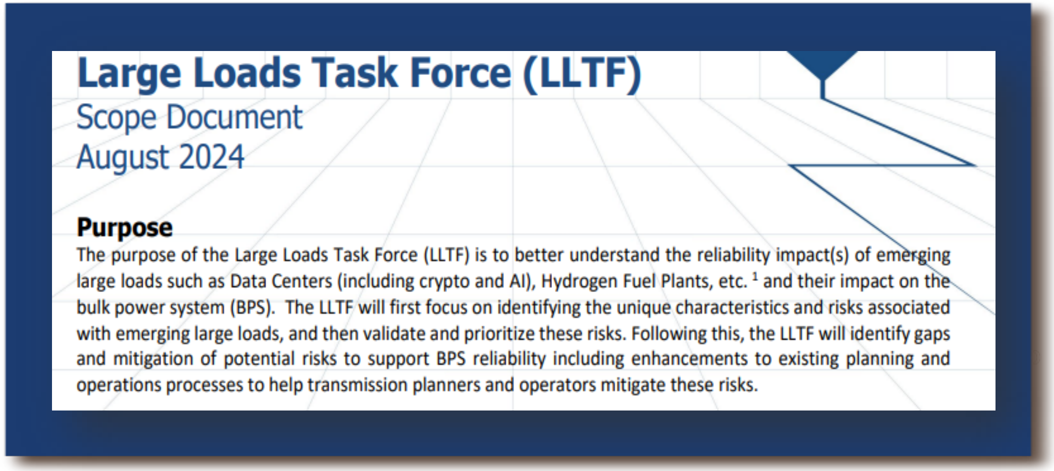
- 1,500 MW Load Loss (exclusively data center load)
- Coincident with 230 kV normal line fault clearing
- Widespread: 60 different load points, 25 substations

CONCLUSIONS:

- Require models for large loads to determine Bulk Electric System risk from coincident large load losses
- Assess need for new or modified standards and if large loads should be registered with NERC

Background

- NERC LLTF formed August 2024
- To **understand the reliability impact(s) of emerging large loads on the BPS**
  - Data centers (including crypto and AI)
  - Hydrogen fuel plants
  - Other emerging industrial loads
- Via the **Framework to Address Known and Emerging Reliability and Security Risks**



Large Loads Task Force (LLTF)

Scope Document
August 2024

Purpose

The purpose of the Large Loads Task Force (LLTF) is to better understand the reliability impact(s) of emerging large loads such as Data Centers (including crypto and AI), Hydrogen Fuel Plants, etc. [1] and their impact on the bulk power system (BPS). The LLTF will first focus on identifying the unique characteristics and risks associated with emerging large loads, and then validate and prioritize these risks. Following this, the LLTF will identify gaps and mitigation of potential risks to support BPS reliability including enhancements to existing planning and operations processes to help transmission planners and operators mitigate these risks.

Large Load Task Force Framework to Address Reliability and Security Risks

Risk Identification, Validation, and Prioritization

White Paper (July 2025):
Characteristics and Risks of Emerging Large Loads

Gap Analysis

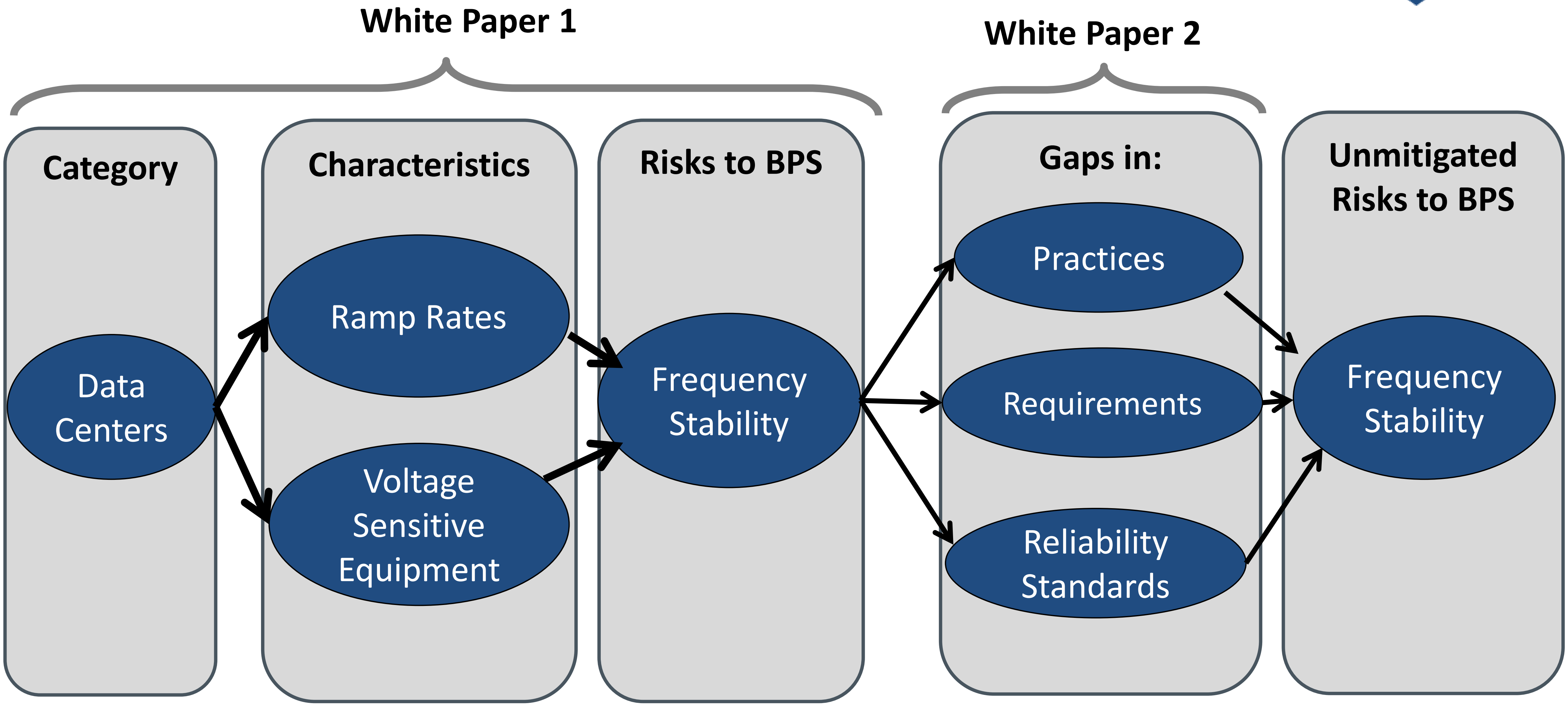
White Paper (Q3 2025):
Assessment of Gaps in Existing Practices, Requirements, and Reliability Standards for Emerging Large Loads

Risk Mitigation

Reliability Guideline (Q1 2026):
Risk Mitigation for Emerging Large Loads

Standard Authorization Request(s):
Update Reliability Standards as needed

White Paper 2: Gap Analysis



This is only one example to demonstrate the structure.

Large Load Categories

Compute Load

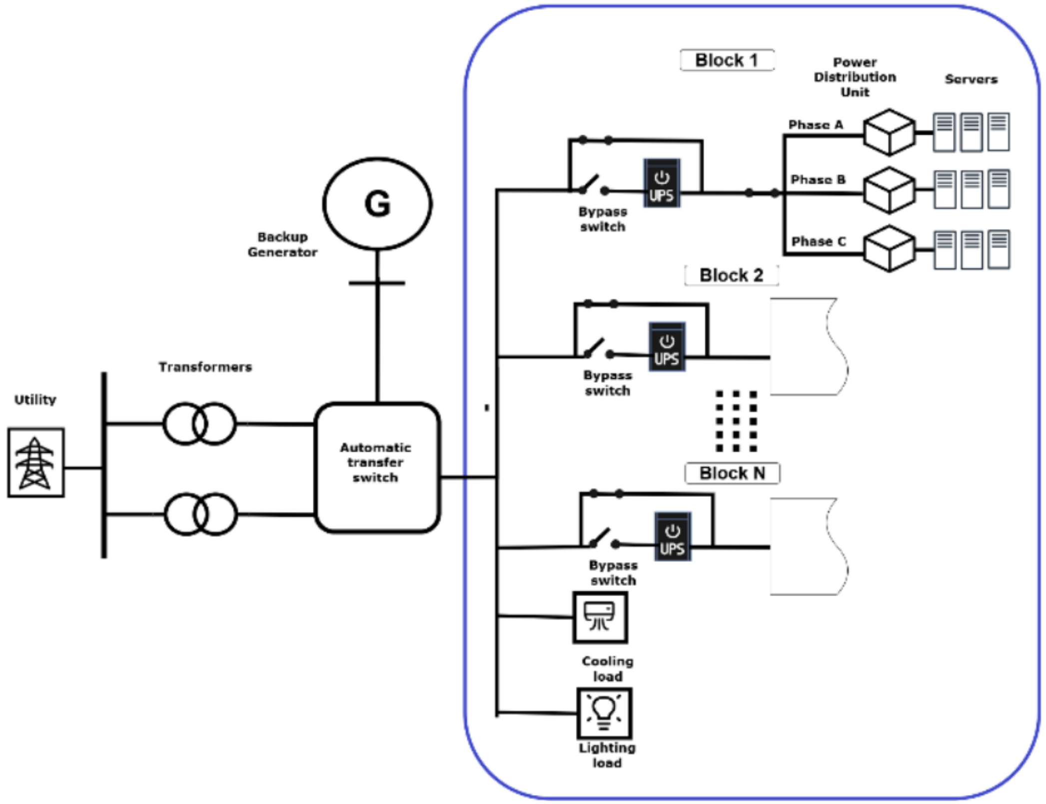
- Data Center Facilities
- Crypto Mining
- Artificial Intelligence

Industrial Load

- Mining and Mineral Processing
- Metals and Heavy Manufacturing
- Heavy Intensity Electrical Processing (e.g., arc furnaces)
- Semiconductors and Electronics Manufacturing
- Chemical and Petrochemical Processing
- Water and Waste Processing

Hydrogen

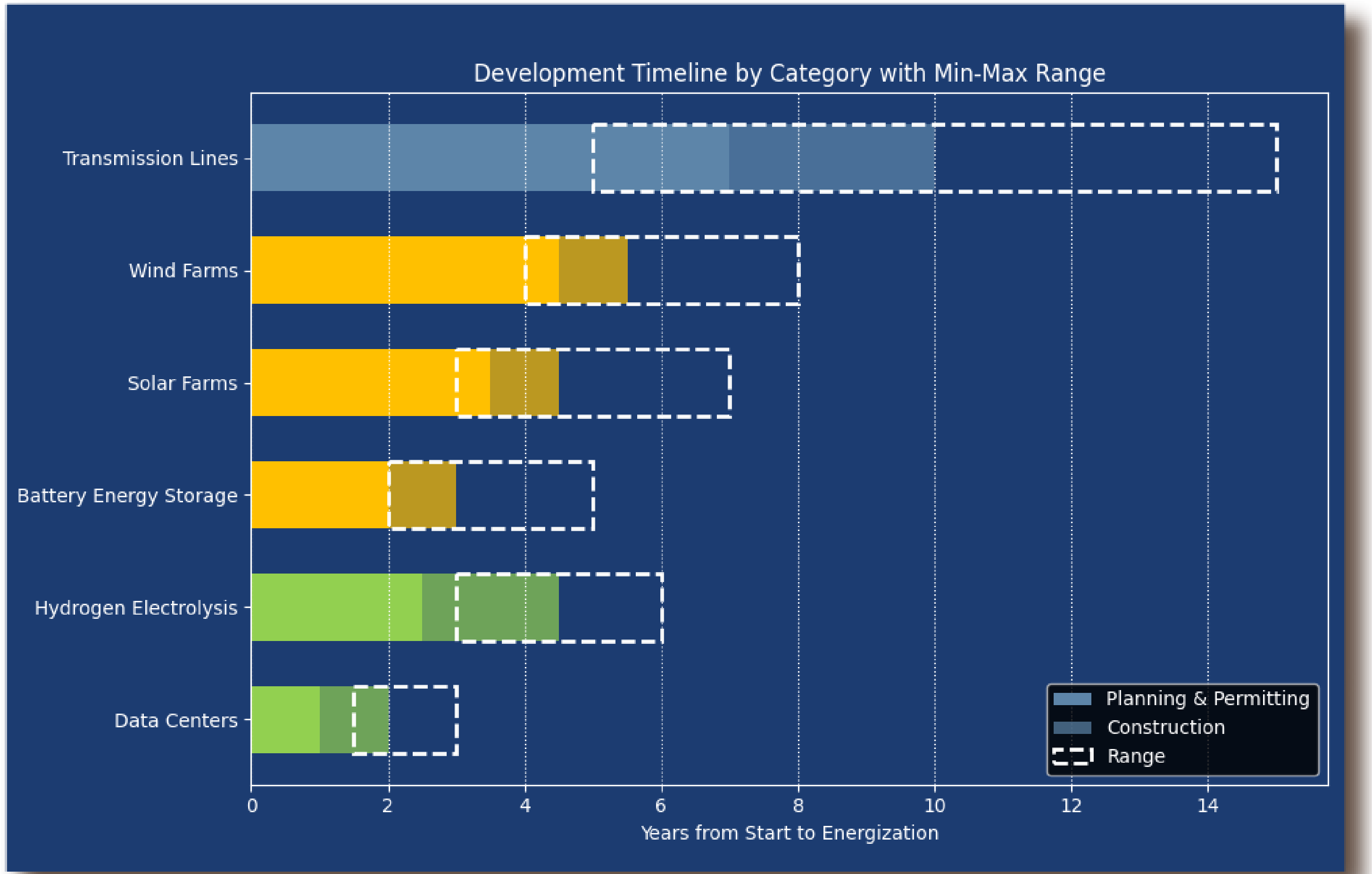
Example Data Center One-Line



Source: EPRI

Characteristics

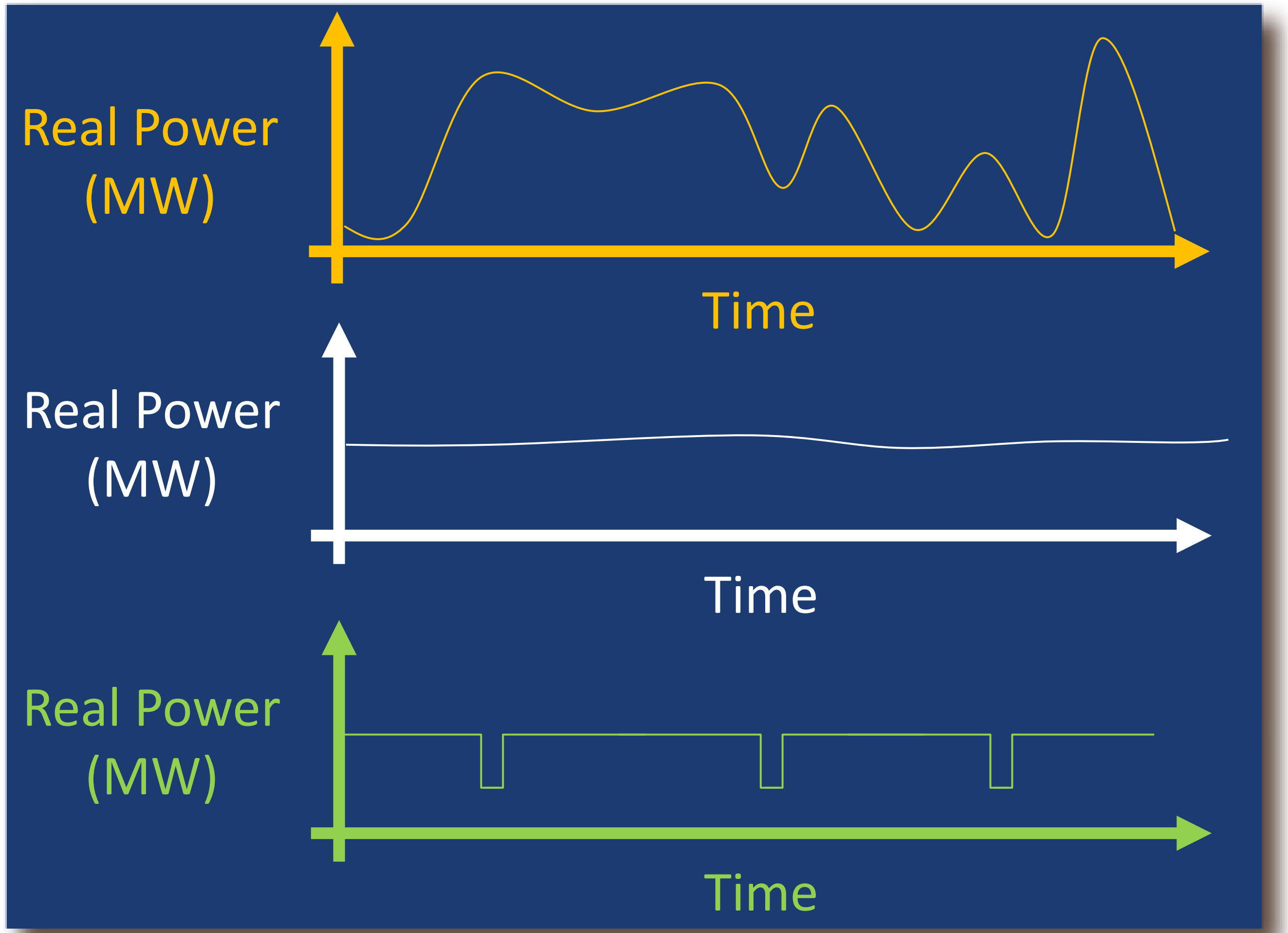
- Peak Demand
- **Fast Interconnection Timeline**
- Demand Profile
- Load Predictability
- Ramp Rate
- Load Type (PEL/Motors/etc.)
- Voltage Sensitivity
- Inaccurate Dynamic Models
- Internal Segmentation



Sources:
https://www.2035report.com/wp-content/uploads/2024/04/GridLab_2035-Reconductoring-Technical-Report.pdf
https://emp.lbl.gov/sites/default/files/2024-04/Queued%20Up%202024%20Edition_R2.pdf

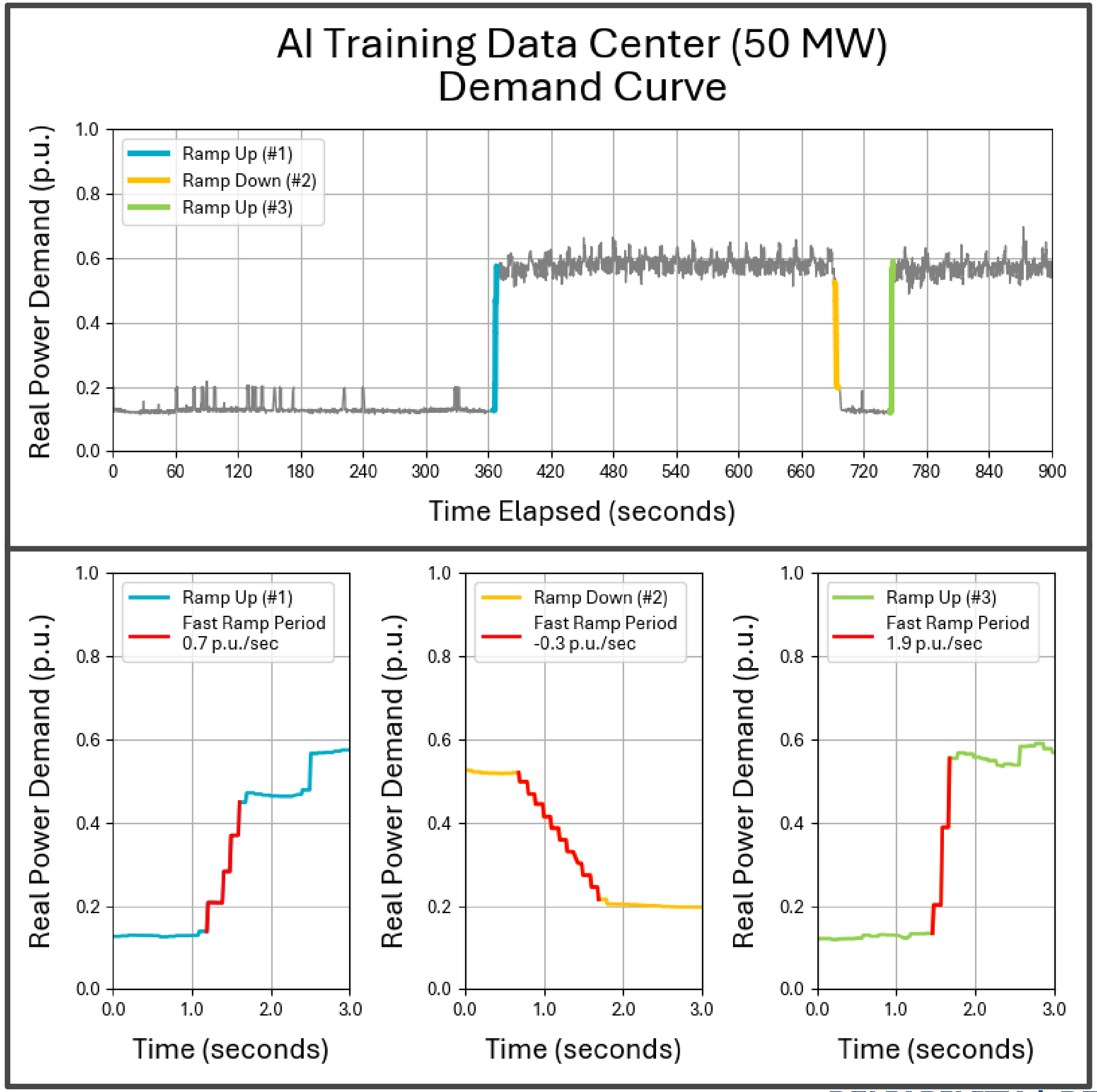
Characteristics

- Peak Demand
- Fast Interconnection Timeline
- **Demand Profile**
- Load Predictability
- Ramp Rate
- Load Type (PEL/Motors/etc.)
- Voltage Sensitivity
- Inaccurate Dynamic Models
- Internal Segmentation



Characteristics

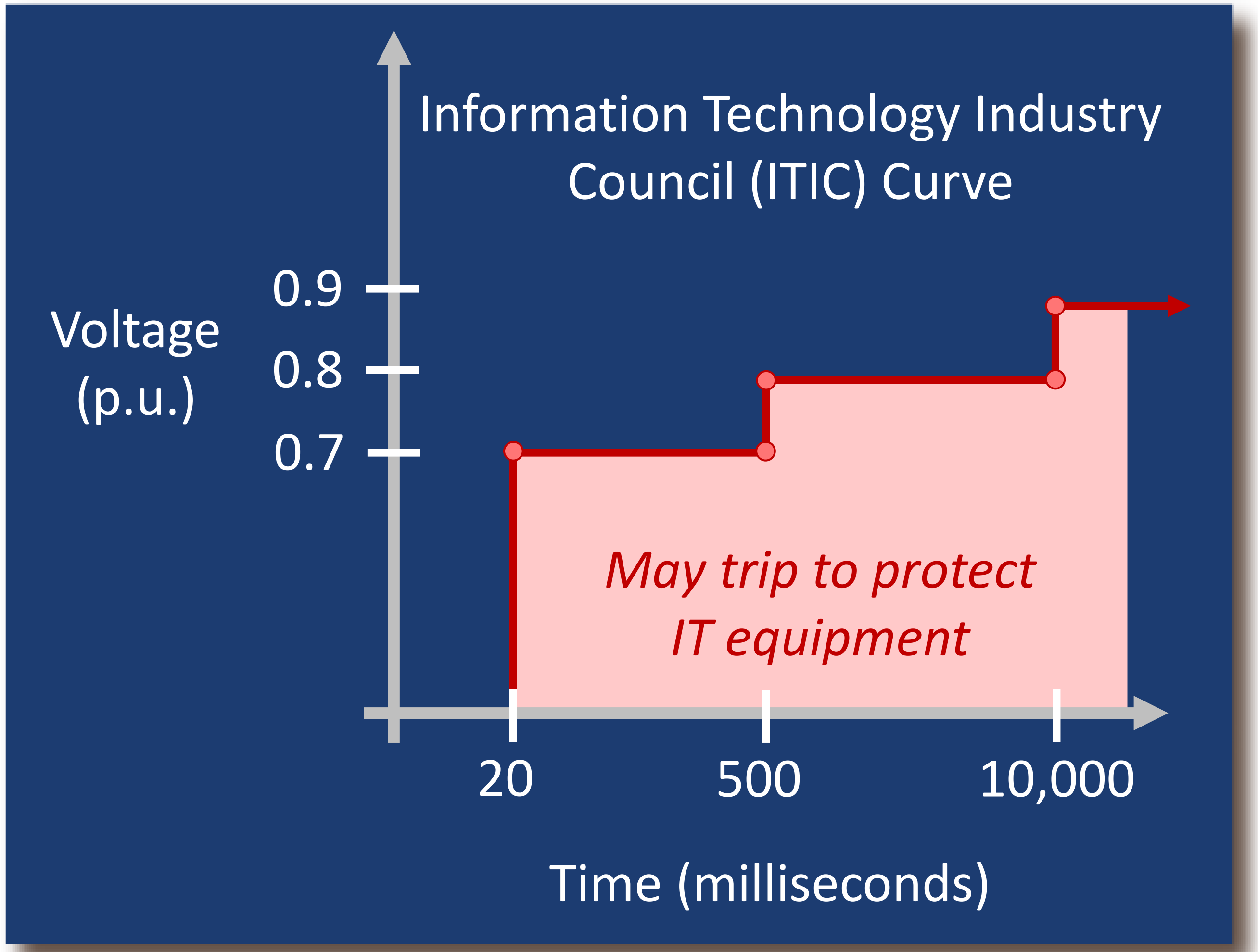
- Peak Demand
- Fast Interconnection Timeline
- Demand Profile
- Load Predictability
- **Ramp Rate**
- Load Type (PEL/Motors/etc.)
- Voltage Sensitivity
- Inaccurate Dynamic Models
- Internal Segmentation



Source: EdgeTunePower

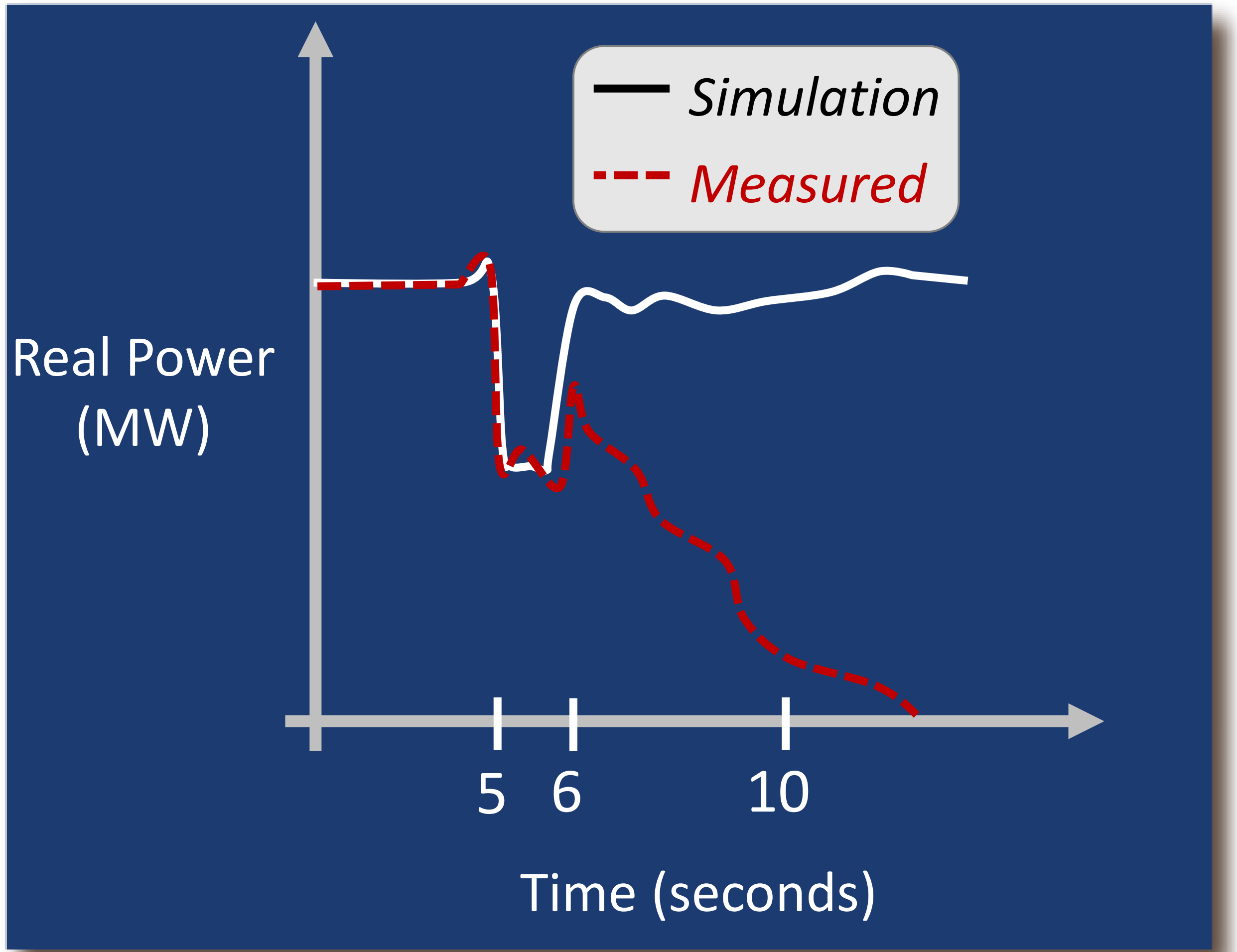
Characteristics

- Peak Demand
- Fast Interconnection Timeline
- Demand Profile
- Load Predictability
- Ramp Rate
- Load Type (PEL/Motors/etc.)
- **Voltage Sensitivity**
- Inaccurate Dynamic Models
- Internal Segmentation



Characteristics

- Peak Demand
- Fast Interconnection Timeline
- Demand Profile
- Load Predictability
- Ramp Rate
- Load Type (PEL/Motors/etc.)
- Voltage Sensitivity
- **Inaccurate Dynamic Models**
- Internal Segmentation



Draft LLTF First White Paper: Prioritization of Risks

HIGH

Long-Term Planning
- Resource Adequacy

Operations/Balancing
- Balancing and Reserves

Resilience
- Automatic UFLS Programs

Stability
- Dynamic Modeling
- Frequency Stability
- Oscillations
- Ride-through
- Voltage Stability

MEDIUM

Long-Term Planning
- Demand Forecasting
- Transmission Adequacy

Operations/Balancing
- Lack of Real-Time Coordination
- Short-Term Demand Forecasting

Resilience
- Load-Shed Obligation Impacts

LOW

Power Quality
- Harmonics
- Voltage Fluctuations

Resilience
- System Restoration

Security Risks
- Cyber Security

Draft LLTF First White Paper: Prioritization of Risks

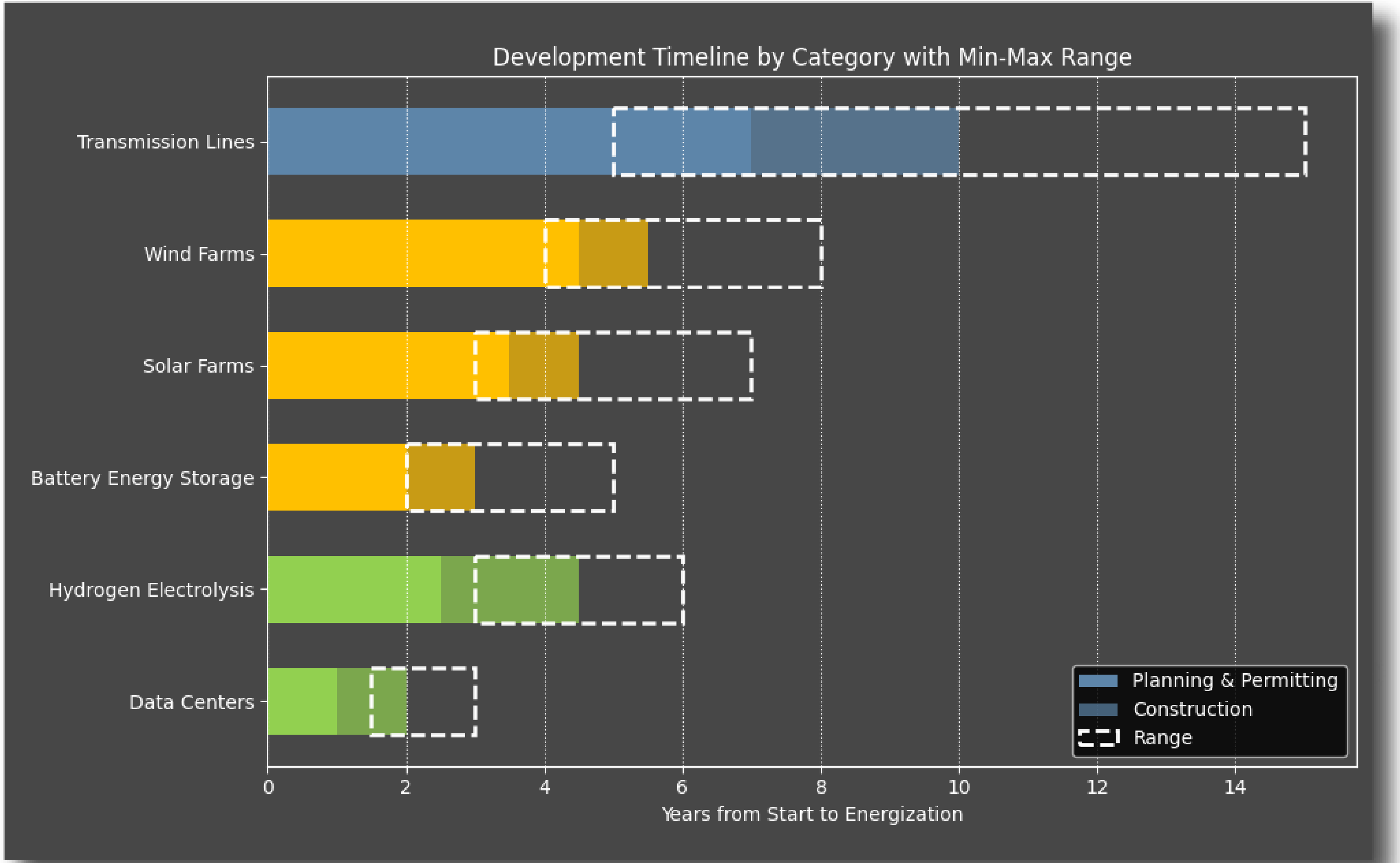
HIGH

Long-Term Planning
- Resource Adequacy

Operations/Balancing
- Balancing and Reserves

Resilience
- Automatic UFLS Programs

Stability
- Dynamic Modeling
- Frequency Stability
- Oscillations
- Ride-through
- Voltage Stability



Sources:
https://www.2035report.com/wp-content/uploads/2024/04/GridLab_2035-Reconductoring-Technical-Report.pdf
https://emp.lbl.gov/sites/default/files/2024-04/Queued%20Up%202024%20Edition_R2.pdf

Draft LLTF First White Paper: Prioritization of Risks

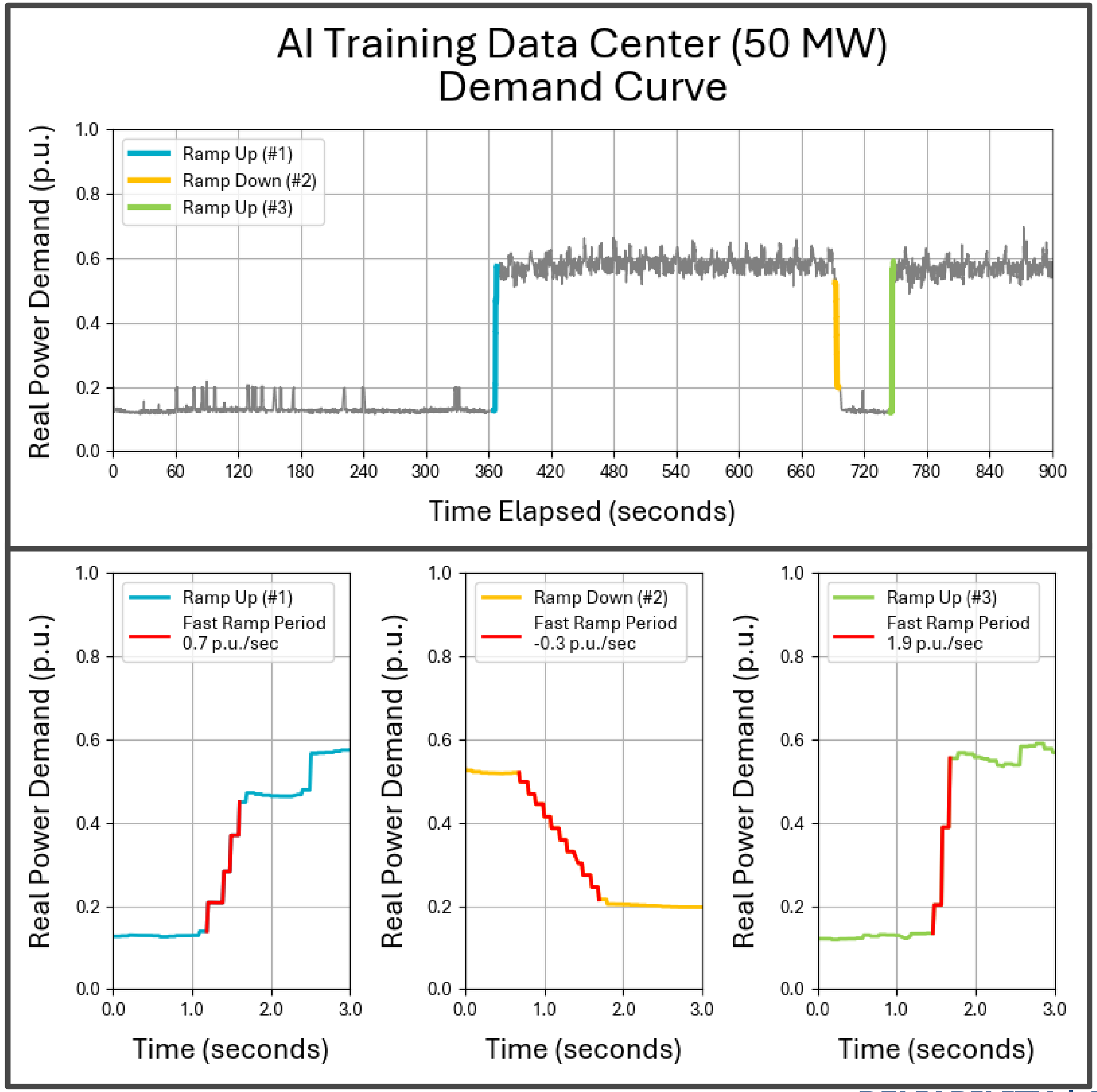
HIGH

Long-Term Planning
- Resource Adequacy

Operations/Balancing
- Balancing and Reserves

Resilience
- Automatic UFLS Programs

Stability
- Dynamic Modeling
- Frequency Stability
- Oscillations
- Ride-through
- Voltage Stability



Source: EdgeTunePower

Draft LLTF First White Paper: Prioritization of Risks

HIGH

Long-Term Planning
- Resource Adequacy

Operations/Balancing
- Balancing and Reserves

Resilience
- Automatic UFLS Programs

Stability
- Dynamic Modeling
- Frequency Stability
- Oscillations
- Ride-through
- Voltage Stability

PRC-006-5 — Automatic Underfrequency Load Shedding

A. Introduction

1. **Title:** **Automatic Underfrequency Load Shedding**
2. **Number:** PRC-006-5
3. **Purpose:** To establish design and documentation requirements for automatic underfrequency load shedding (UFLS) programs to arrest declining frequency, assist recovery of frequency following underfrequency events and provide last resort system preservation measures.

Source: https://www.nerc.com/pa/Stand/Reliability%20Standards/PRC-006-5.pdf

UFLS design assessment frequency: every 5 years
Emerging large load time to connection: <2 years

Draft LLTF First White Paper: Prioritization of Risks

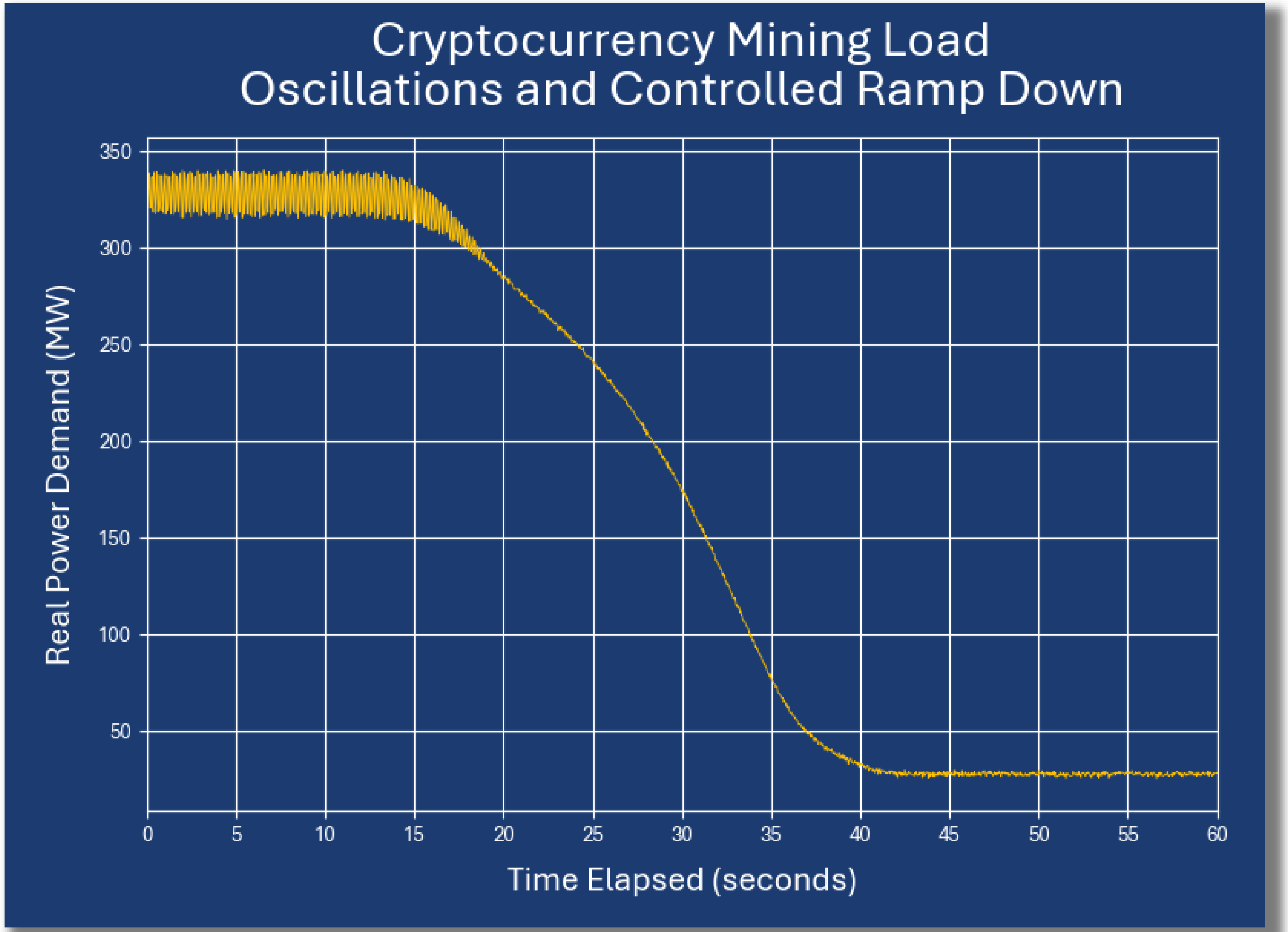
HIGH

Long-Term Planning
- Resource Adequacy

Operations/Balancing
- Balancing and Reserves

Resilience
- Automatic UFLS Programs

Stability
- Dynamic Modeling
- Frequency Stability
- Oscillations
- Ride-through
- Voltage Stability



Source: ERCOT

Draft LLTF First White Paper: Characteristics and Risks of Emerging Large Loads

Recommendations for Large Load Task Force (#1-3)

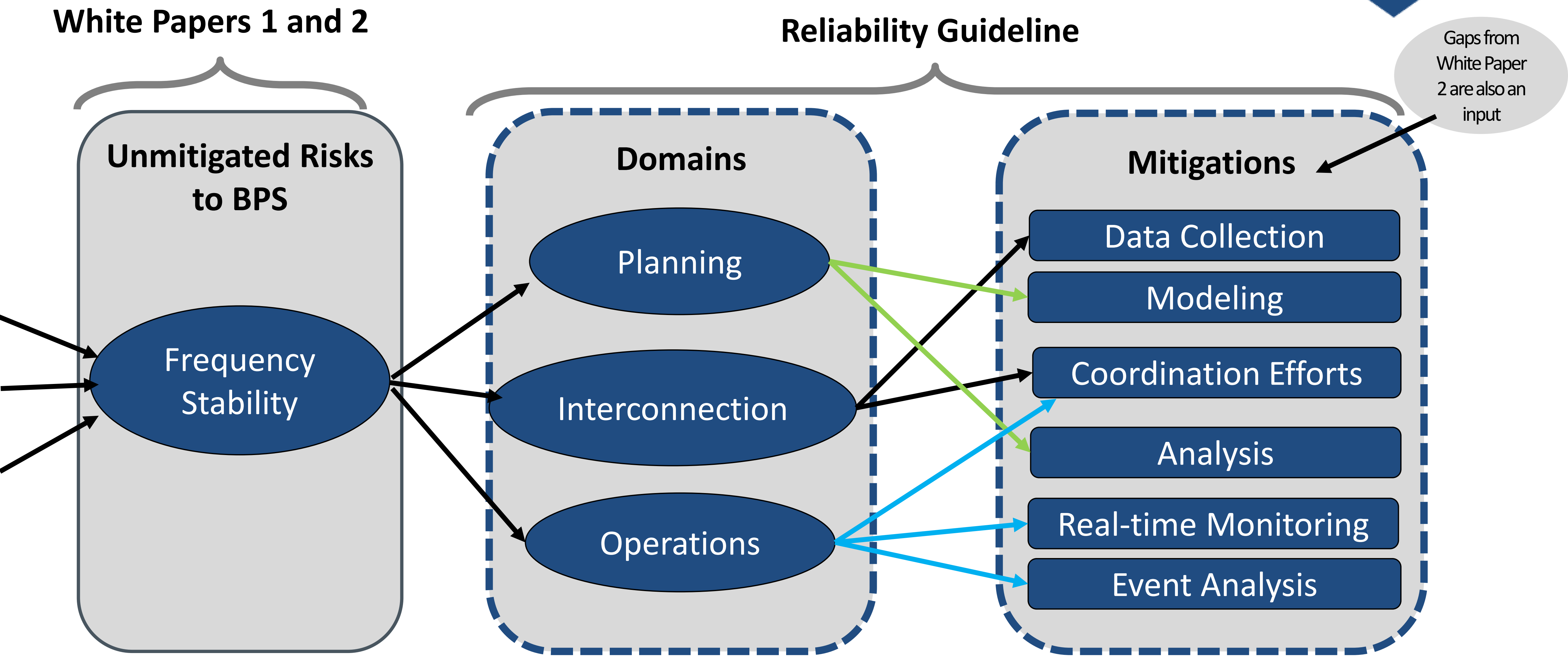
- Process and Standard Gap Identification
- Risk Mitigation
- Characteristic Definition and Categorization

Recommendations for Reliability Security Technical Committee (RSTC) Working Groups (#4-6)

- Model Development and Refinement for Large Loads
- Assess Possible Protection System Impacts
- Investigate risks posed to resource adequacy

Recommendation to Utilities (#7)

- Industry should collect data to understand the unique risks associated with connecting a large load.



This is only one example to demonstrate the structure.

Questions and Answers