ESIG Perspective on Large Loads and EMT Modeling

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Energy Systems Integration Group (ESIG)

- ESIG is a **member-driven** educational non-profit
- **~300 member organizations worldwide** broadly focused on decarbonization and integration of energy systems
- **Workshops, webinars, reports** available on our website (https://www.esig.energy/) and on YouTube (@EnergySystemsIntegrationGroup)
- We convene **task forces** to address critical industry problems and propose practical solutions

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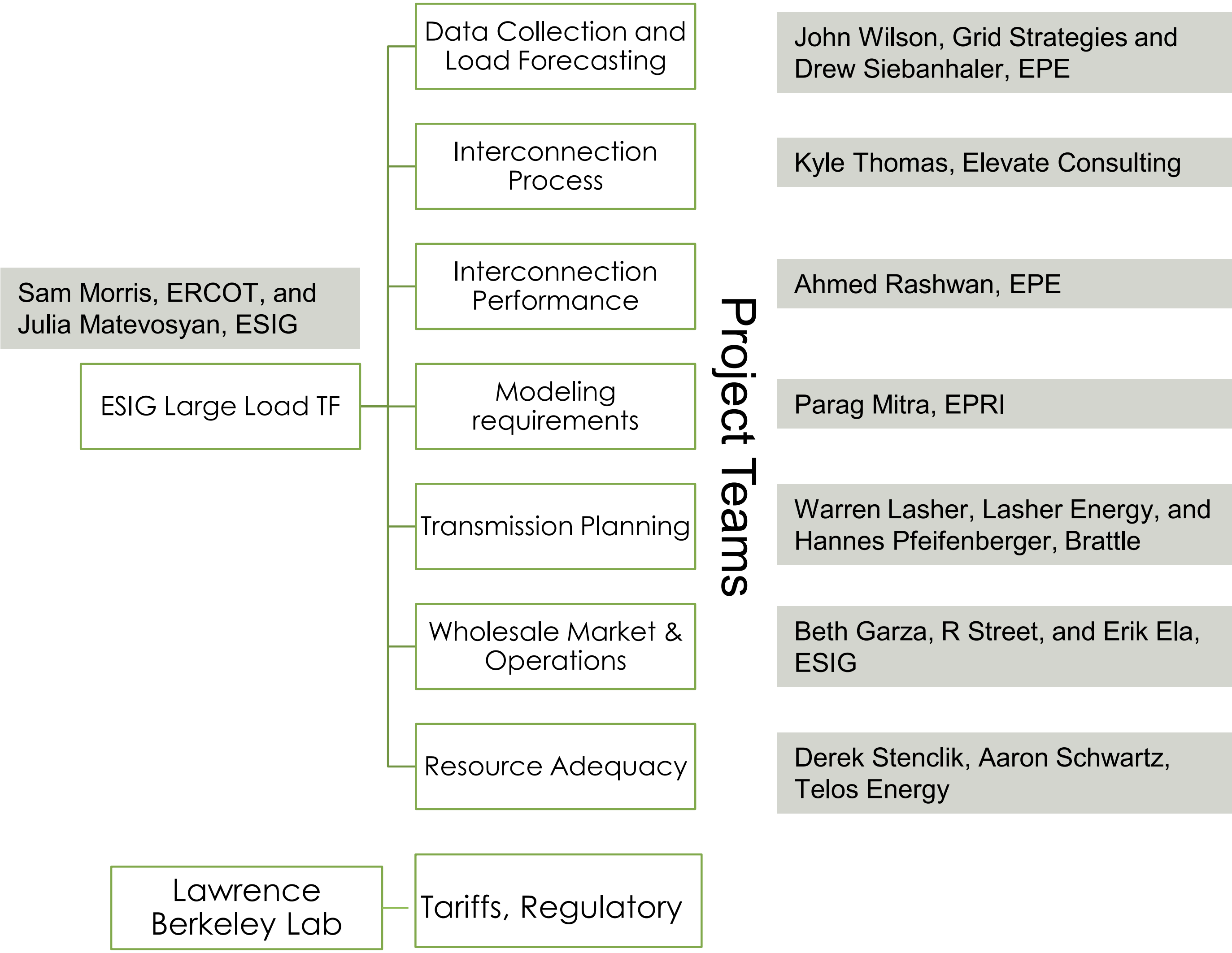
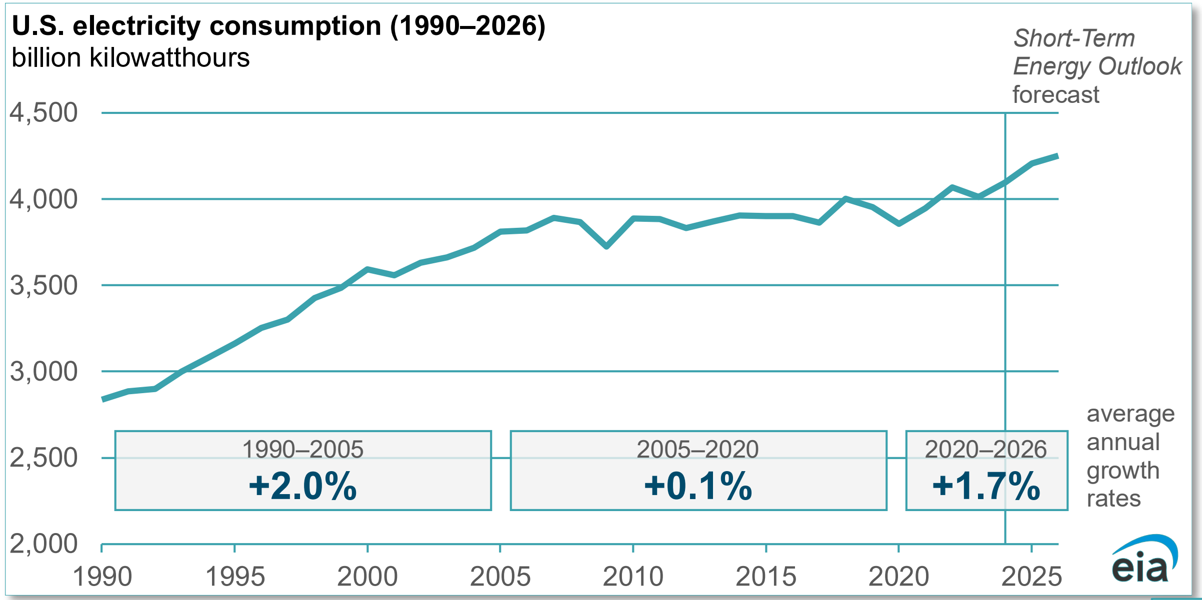
ESIG's Large Load Task Force

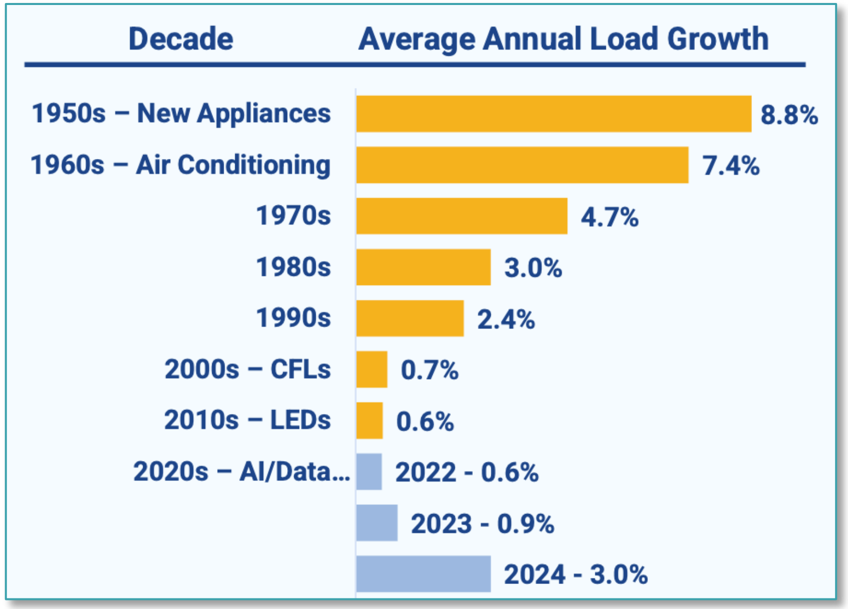
- The goal is to bring together Industry members to:
  - Share perspectives
  - Summarize the state-of-the-art
  - Identify existing or potential gaps
  - Identify pragmatic solutions



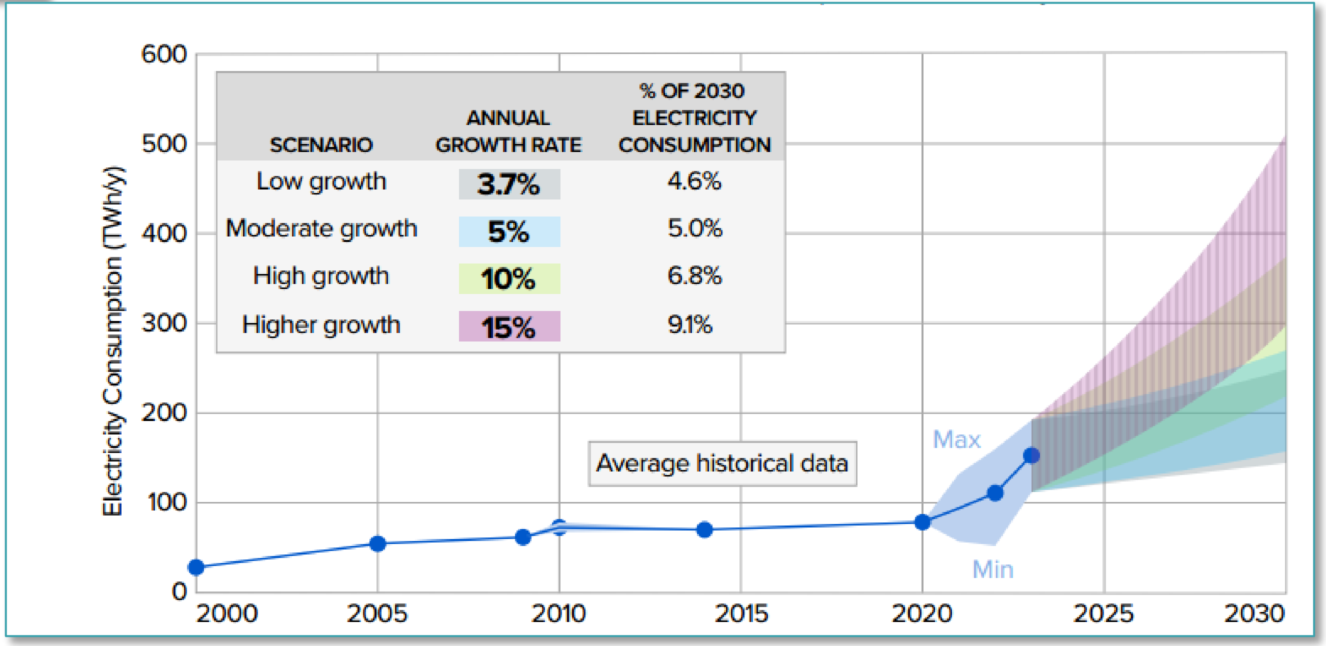
Acknowledgement: The U.S. Department of Energy Office of Energy Efficiency and Renewable Energy and Meta are supporting this effort along with ESIG members

Load is Growing After Years of Flat Forecasts





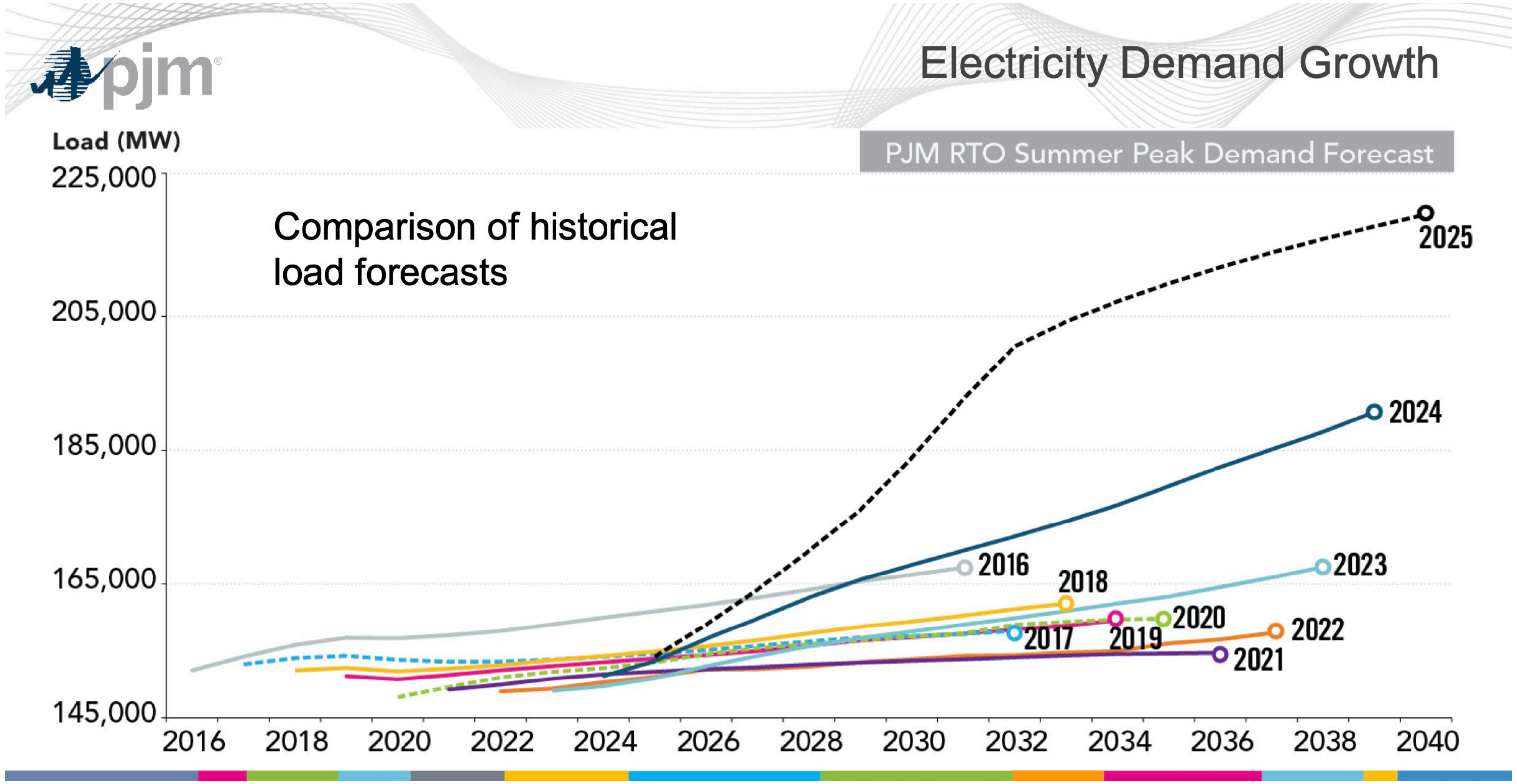
- Primarily driven by large load interconnections
  - AI, data centers, crypto



Source: EPRI, Powering Data Centers 2024; https://www.eia.gov/todayinenergy/detail.php?id=65264; Grid Strategies, National Load Growth Report, 2024

Uncertainty in Load Forecasts

- Driven by **non-public** large load interconnection information
- **Experience** from IBR interconnections is key
- Efforts need to be made to **classify large loads appropriately** to allow for necessary performance and data requirements

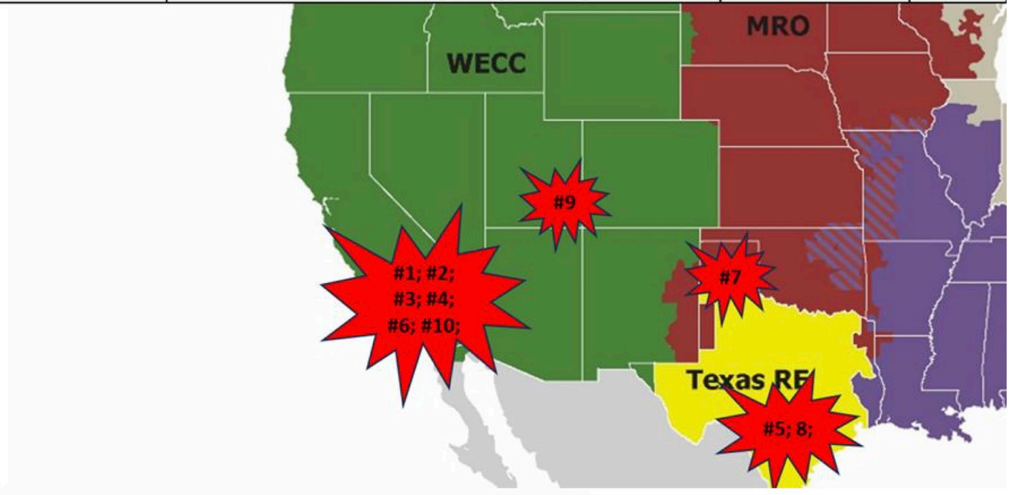


Source: Large Load Additions Workshop, May 9, 2025

How to Start: Learn From the Past

- Large Loads and Inverter-based Resources (IBR) share **significant similarities** in performance and reliability
  - Power electronic interface
  - Software-based performance
  - Immature technology
  - Lack of specificity in the regulatory space
- The bulk power system **cannot afford** to repeat IBR mistakes

Reference Number	Disturbance	IBR Reduced (MW)	Year
#1	Blue Cut Fire	1,753	2016
#2	Canyon 2 Fire	1,619	2017
#3	Angeles Forest & Palmdale Roost	1,588	2018
#4	San Fernando	1,205	2020
#5	2021 Odessa	1,112	2021
#6	Victorville & Tumbleweed & Windhub & Lytle Creek Fire	2,464	2021
#7	Panhandle Wind	1,222	2022
#8	2022 Odessa	1,711	2022
#9	Southwest Utah	921	2022
#10	California Battery Energy Storage	906	2023



Adapted from NERC Ridethrough Technical Conference, Sep. 4 2024

None of the affected facilities in **any** of these published reports had models which accurately reflected actual performance

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Lessons (Maybe) Learned From the Past

- Large loads need a **specific regulatory category**
  - Allows for technology specific:
    - Requirement discussion and balloting
    - Interconnection processes
    - Performance and data requirements
    - Modeling requirements
- Advanced controls and performance characteristics must be **transparent** now and **enabled** through **stringent modeling requirements and practices**

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First Step for Large Loads: A Definition

- At present, no industry consensus on the definition of a Large Load (LL)
- North American Reliability Corporation's (NERC's) Large Load Task Force (LLTF), conducted a survey on size thresholds for "Large Load" for the purposes of development and enforcement of future NERC reliability standards
  - Most of the 384 respondents suggested > 50 MW, and the single size most commonly suggested was 75 MW
  - However, NERC LLTF could not reach consensus on a threshold and settled on a high-level definition:

    Commercial or industrial facilities (or aggregations) that can pose BPS reliability risks due to their size, operational behavior, or control systems, e.g., data centers, crypto mining, hydrogen electrolyzers, industrial manufacturing
- A similar definition is adopted for a new CIGRE Role and Requirements for Large, Inverter Based Loads TF:
  - *Large demand facilities that are interfaced with power electronics and have the capacity, on an individual or aggregated basis, to have material impact on the host grid*
- The definition adopted by ESIG LLTF:
  - ***A large load is a load that the connecting utility/ISO/RTO identifies as having a material impact on its system either due to its individual size and/or characteristics or on aggregate basis***

How do Modern Large Loads Differ?

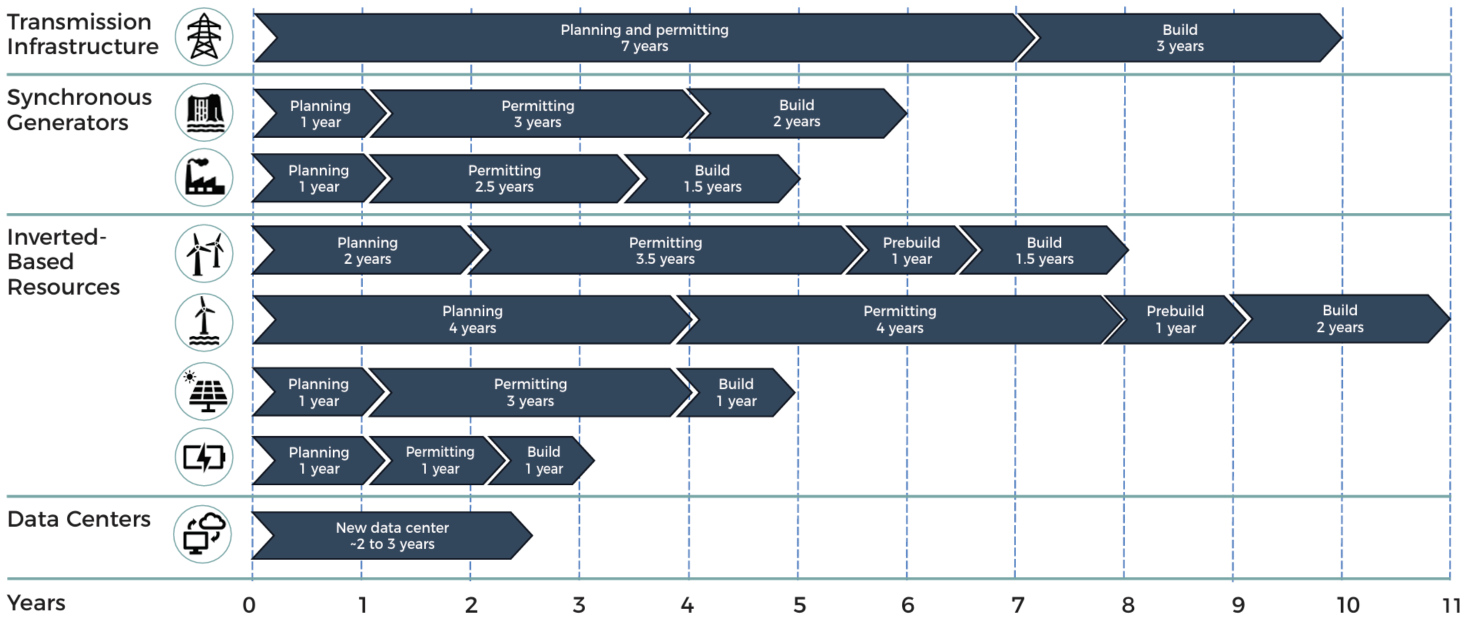
- **Scale** – Individual facilities (e.g., hyperscale data centers, hydrogen plants) now reach 100s of MW to GW scale, far beyond past industrial loads.
- **Interconnection** – Connect at transmission level (instead of distribution) due to size/reliability needs
- **Clustering** – Concentrated in grid-constrained regions (e.g., Northern Virginia, Texas industrial corridors) creating local demand spikes.
- **Power electronics** – Converter-dominated interfaces bring new challenges: power quality, protection, and sensitivity to disturbances.
- **Fault behavior** – Many switch-over to backup during routine faults, risking cascading grid impacts from simultaneous large load losses.
- **Dynamic profiles** – AI clusters, electrolyzers, EV charging, and heat pumps cause rapid swings and new peak risks.
- **Opaque to operators** – Private developers often limit data sharing, complicating forecasting and operational planning.
- **Growth vs. infrastructure** – Loads materialize in 2–3 years; new grid build-out takes 7–10 years, causing backlog and bottlenecks.

System-Level Implications

- **Planning:** Load growth far outpaces connection request processing ability, transmission & generation buildout; forecasts highly uncertain.
- **Operations:** Short-term forecast errors drive inefficient unit commitment & higher reserve needs.
- **Reliability:** Risks to stability, load-shedding, and restoration from large, concentrated loads.
- **Power Quality:** Harmonics, flicker, and reactive swings from converter-based systems.
- **Observability:** Need for PMUs/DFRs as loads now require high-speed monitoring.
- **Markets:** Drive congestion, price impacts, and incentive shifts.
- **Transmission:** Load siting often mismatched with available transmission capacity.

Planning Generation and Transmission

- Today, large loads want to interconnect faster and they are unprecedentedly large
- Significant, fast load growth puts pressure on generation capacity prices.
- Generation may take longer to build and the generation interconnection queues are slow and backlogged.
- Transmission requires even more time to build.
- **Modeling and study practices must improve quickly**



Timelines for grid infrastructure are not aligned with those for large load development, creating bottlenecks for grid supply of electricity. SOURCE: ADAPTED FROM S&P GLOBAL.

Source: Practical Guidance and Considerations for Large Load Interconnections GridLab and Elevate Energy, May 2025

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Modeling Large Loads Difficult

- Large loads must be accurately modeled and studied before interconnection to limit adverse grid impacts
- Modeling inverter-based resources is hard enough, modeling large loads is **more difficult**
  - One large load facility may operate with multiple performance profiles from different customers (AI use, AI training, compute, cryptocurrency, etc.)
    - These performance profiles may be wildly different and not known at the time of interconnection
  - Large loads tend to include ”more complex” components
    - Multiple controllers, hybrid facilities, backup generator schemes, etc.
  - All of the modeling challenges observed with IBR exist with large loads
- Accurately modeling large loads will require detailed communication between large load developers, planners, regulators; and the usage of models in all simulation domains, particularly the electromagnetic transient (EMT) domain

Which Simulation Domain Should be Prioritized?

- Planning a **reliable power** system depends on **accurate modeling** of the system and resources connected to it. This includes accurate modeling of **large load performance**, as well as **protections or other functions** that may take the large load offline

Table 3.1: Solar PV Tripping and Modeling Capabilities and Practices

Cause of Reduction	Can Be Accurately Modeled in Positive Sequence Simulations?	Can Be Accurately Modeled in EMT Simulations?
Inverter Instantaneous AC Overcurrent	No	Yes
Passive Anti-Islanding (Phase Jump)	Yes[a]	Yes
Inverter Instantaneous AC Overvoltage	No	Yes
Inverter DC Bus Voltage Unbalance	No	Yes
Feeder Underfrequency	No[b]	No[c]
Incorrect Ride-Through Configuration	Yes	Yes

Table 3.1: Solar PV Tripping and Modeling Capabilities and Practices

Cause of Reduction	Can Be Accurately Modeled in Positive Sequence Simulations?	Can Be Accurately Modeled in EMT Simulations?
Plant Controller Interactions	Yes[d]	Yes[e]
Momentary Cessation	Yes	Yes
Inverter Overfrequency	No[b]	Yes
PLL Loss of Synchronism	No	Yes
Feeder AC Overvoltage	Yes[f]	Yes
Inverter Underfrequency	No[b]	Yes

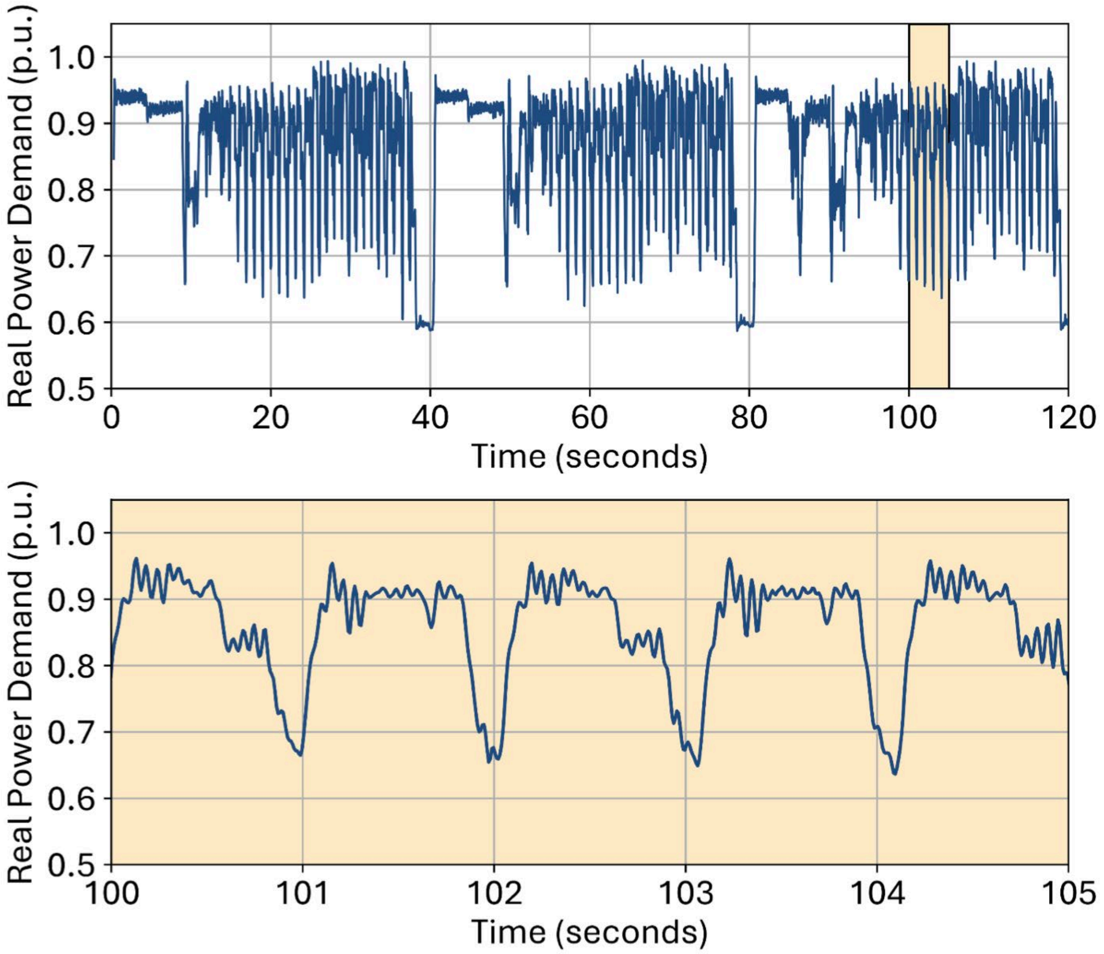
Adapted from: NERC 2022 Odessa Disturbance Report

Which Simulation Domain Should be Prioritized?

- **Phasor domain** modeling and simulation is not going away
  - Large system studies
  - Information sharing
  - Forward looking research studies
- **Electromagnetic transient** modeling provides significant benefit when representing large loads
  - Fast transient behavior
  - Communications between multiple controllers
  - Integrating vendor-specific code and performance
  - Representing complex configurations

Accurate EMT Modeling Enables More Reliable Interconnection

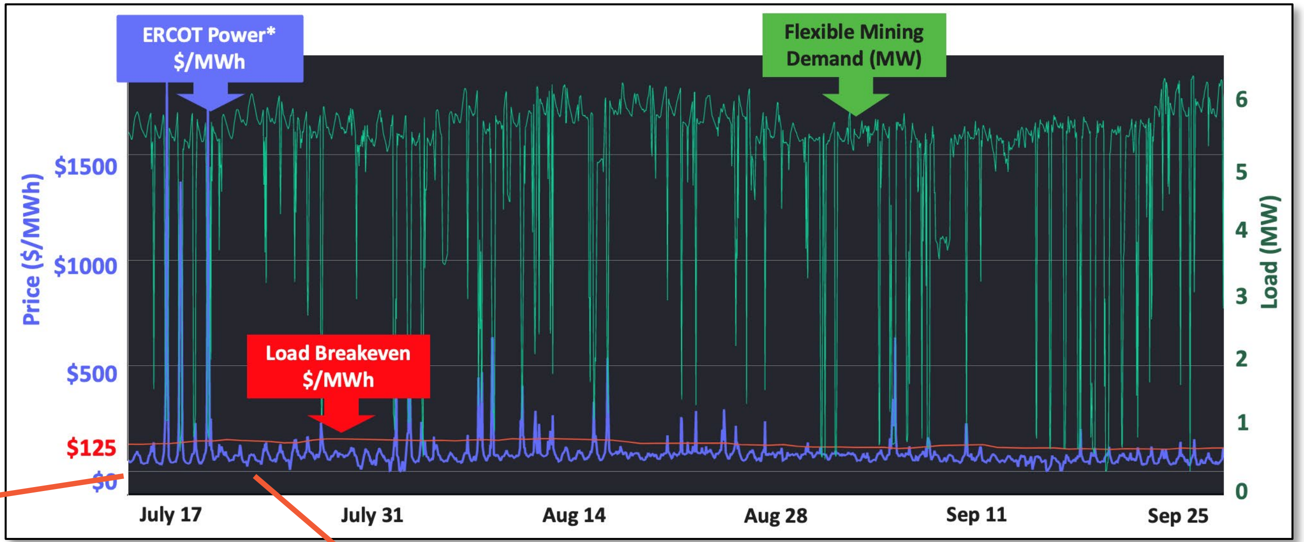
- Extremely fast ramps
- Technology dependent
  - Similar to IBR but potentially worse
- Multiple systems communicating
- Highly dependent on source code and software

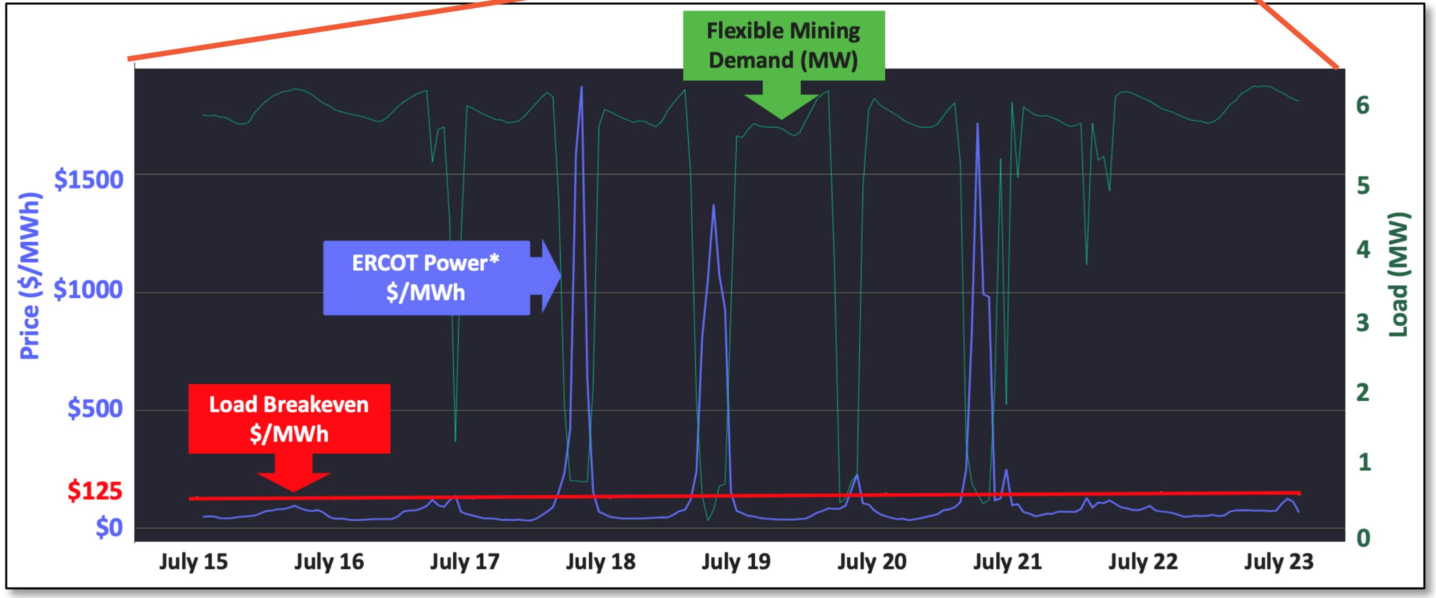


Source: [Characteristics and Risks of Emerging Large Loads](#) July, 2025

Some Loads are Naturally Flexible - Cryptocurrency

- **More flexibility is possible** but needs incentive or requirement to unlock



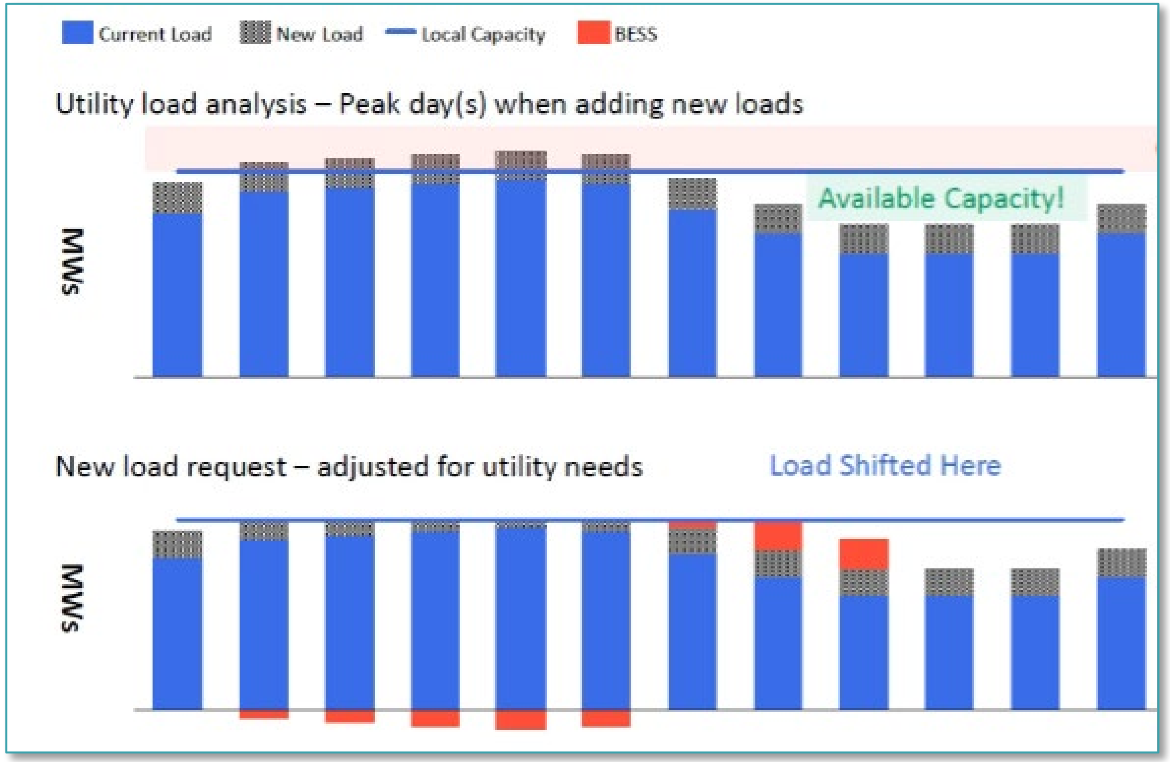


- **Collaborative discussion** between system operators, developers, and manufacturers is needed

Shaun Connell, Lancium, 2023

Complex Facilities Need Complex Models: Co-location

- Black Hills Energy and Microsoft designed Large Power Contract Service Tariff that allows utility to tap into Microsoft's backup generation during high demand periods.
- Defers need to build new power plant
- Utility purchases power, including renewables, in the market to serve the data center
- Microsoft gets lower cost market energy and ratepayers do not need to cover cost of a new power plant
- Note that flexible generation to be designed from the start. Gas turbines, batteries, reciprocating engines can likely do this. Diesels may not be able to.



https://datacenters.blackhillsenergy.com/resources/energy-solutions-data-centers; Sean Jones, Tesla, NERC LLTF 4/10/25

To unlock a future where data centers can be grid assets, detailed EMT modeling is necessary

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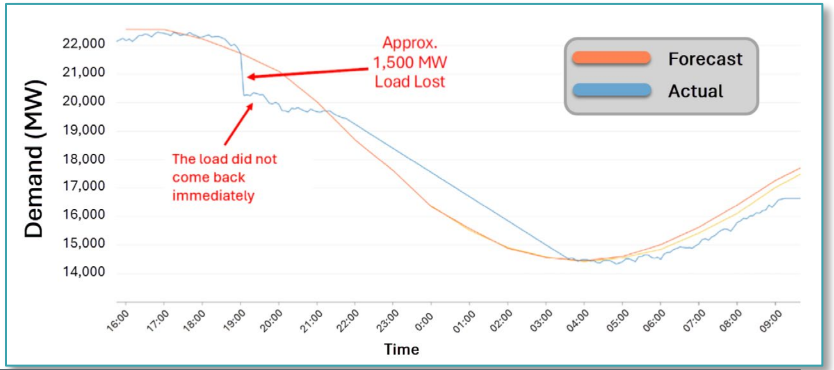
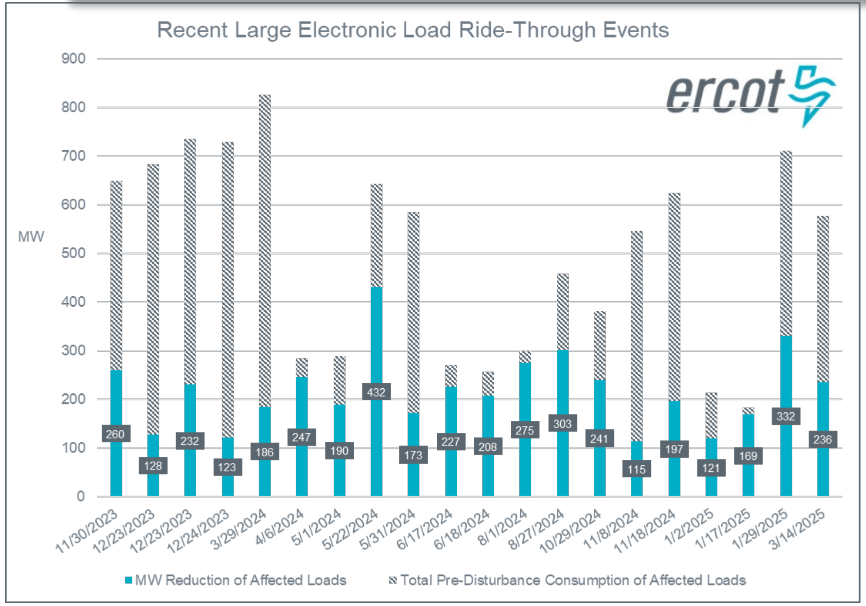
Complex Facilities Need Complex Models: “Ridethrough”

- Power electronic-connected devices may trip offline for numerous reasons detailed in NERC Major Event Reports. Large loads may trip offline these reasons and additional:
  - Price sensitivity
  - Power quality
  - Equipment failure
- Some large load performance is common, but “looks” like ridethrough failure:
  - Changes in AI learning
  - End-user demand changes
  - Transfer of AI learning, compute, and other functions



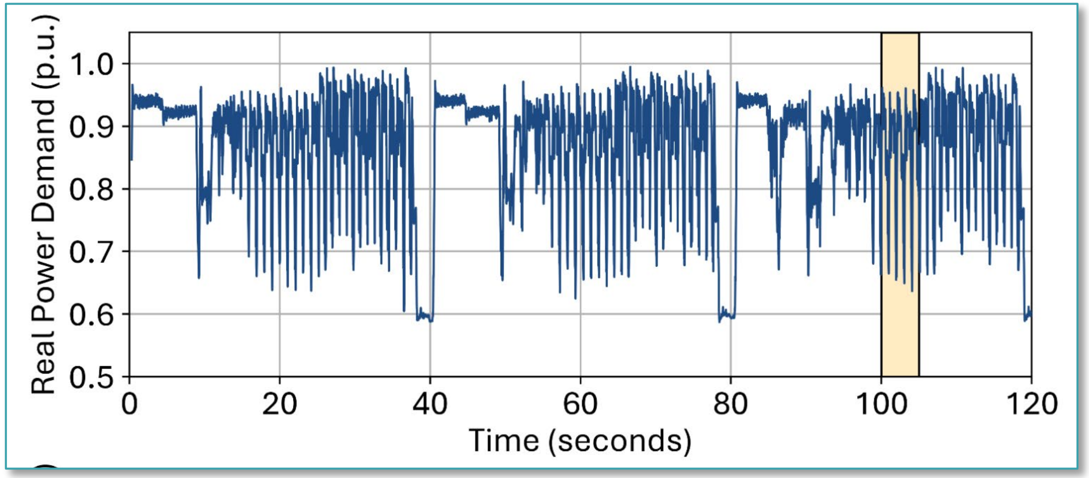


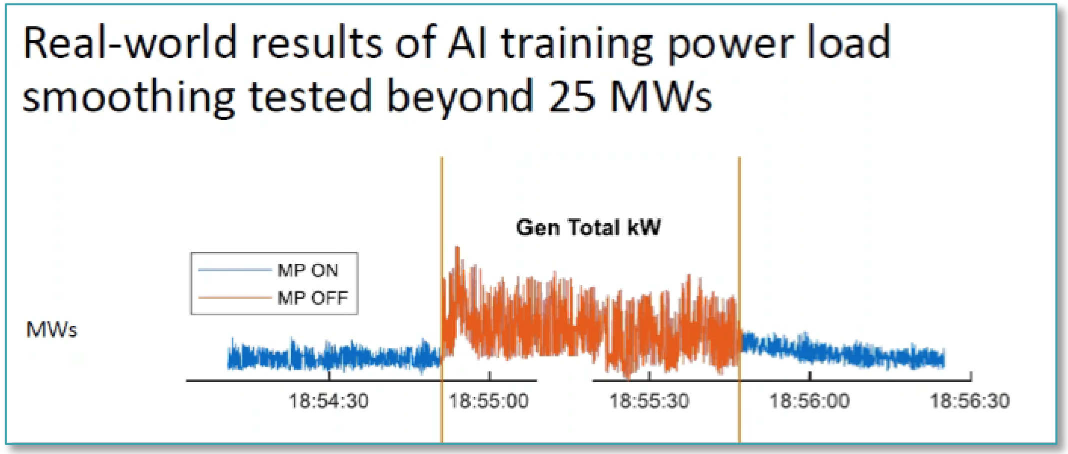
Source: ERCOT Large Load Workshop, June 2025

EMT modeling is necessary to represent the complex controls, communications, and interactions

Complex Facilities Need Complex Models: “Oscillations”

- Power system oscillations primarily driven by:
  - Controller interaction
  - Sub-synchronous phenomenon
  - Improper control tuning
- Some large load performance is common, but “looks” like an oscillation
- Large load fluctuations need to be mitigated to support grid reliability
  - EMT studies must be utilized to test and tune solutions to protect both the grid and the large load equipment





NERC LLTF 6/18/25; Sean Jones, Tesla, NERC LLTF 4/10/25

EMT modeling is necessary to represent the complex controls, communications, and interactions

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Enabling EMT Modeling of Large Loads

- EMT modeling needs to be subject to mandatory enforcement through NERC, Transmission Planner/Owner, Planning Coordinator Requirements
  - **"This report shows that the voluntary recommendations set forth in NERC Guidelines and other publications are not being implemented." - Inverter-Based Resource Performance Issues Report, NERC, November 2023**
- Standardized interconnection requirements help enable better practice
  - Standardized performance requirements
  - Standardized model quality, submission, and usability requirements
  - The current technical minimum is insufficient
- Collaborative discussions amongst stakeholders is necessary to understand performance and flexibility
  - EMT modeling of large loads can provide detailed study results to inform both better interconnection practices from the Developers and higher technical minimum requirements

Conclusions

- Promoting detailed EMT modeling of large loads TODAY is paramount to ensuring grid reliability
- Every day of delay increases opportunity cost
- EMT modeling is essential in representing the high complexity of large load facilities, controls, and performance
- Regulatory enhancements are necessary to enable technical experts to utilize detailed, site-specific EMT modeling