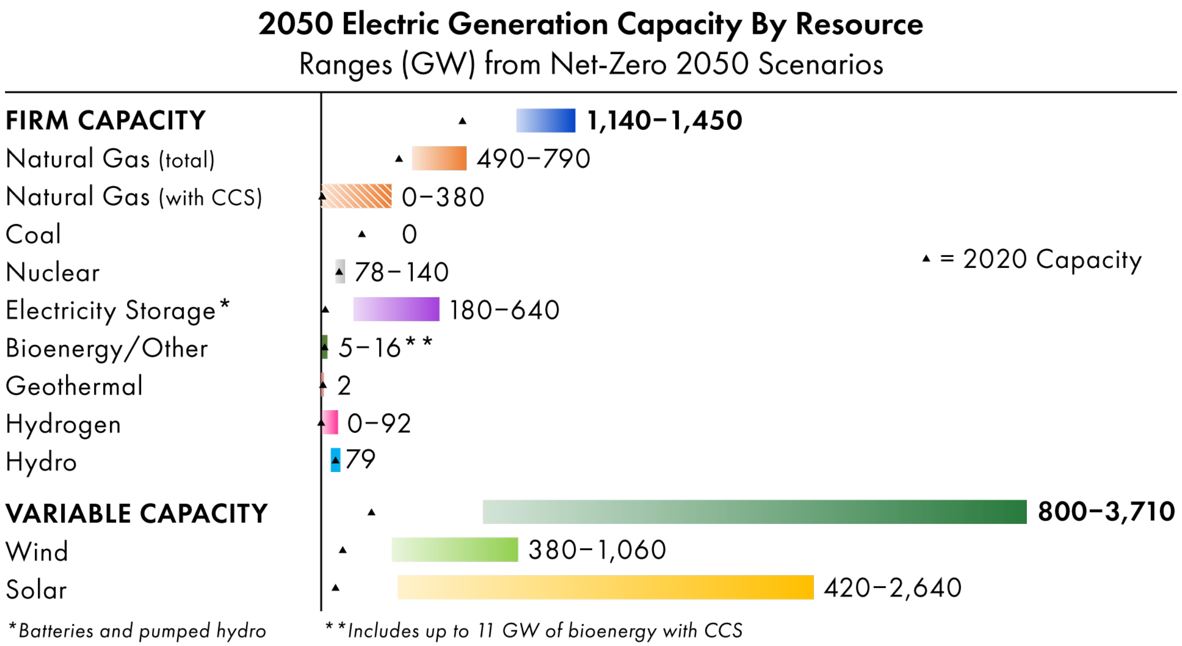
Reliability and resilience as the energy system evolves

Overview of latest EPRI R&D

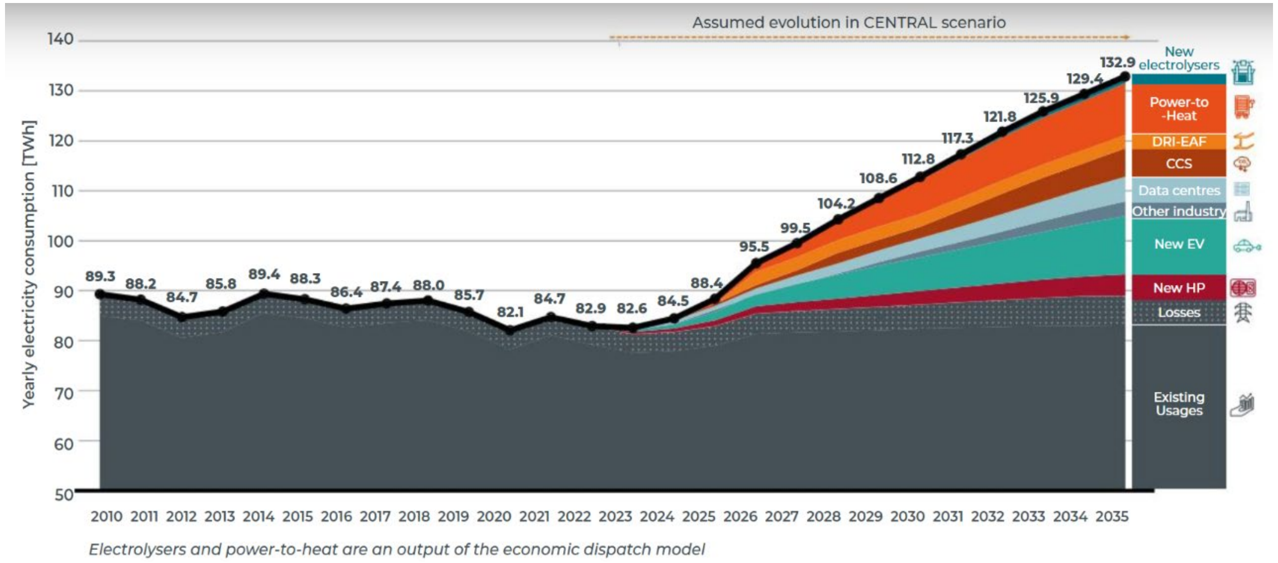
Aidan Tuohy, PhD
Director, Transmission Operations and Planning
UTK-CURENT 2025 Industry Conference
April 2025

Supply and demand changes are happening and are impacting how we plan and operate the system!



From EPRI LCRI Net-Zero 2050: U.S. Economy-Wide Deep Decarbonization Scenario Analysis (link)

Example from Belgium:



Source: Adequacy studies (elia.be)

Increased shares of variable renewables

- Energy storage, demand flexibility and thermal plant needed to balance periods of low wind/solar
- Transmission, T&D interaction and other energy system interactions will all impact needs

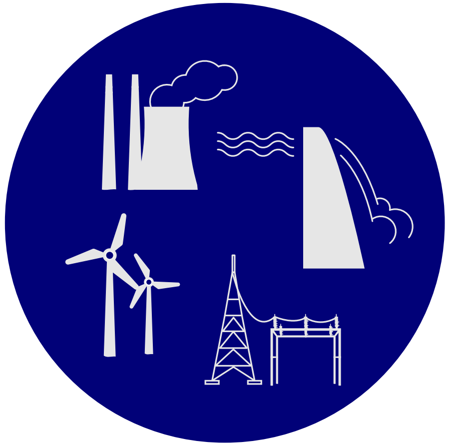
Increased reliance on electricity

- Often best way to decarbonize society's energy needs
- Increases in demand coming unseen in decades
- Energy growth in developing world needs to be clean

Reliability and Resiliency Must Increase Through Transition

Additional Grid Investment and Innovation Are Required to Decarbonize the Economy

Resource Adequacy



Additional resources to meet energy needs for resiliency to extreme future scenarios

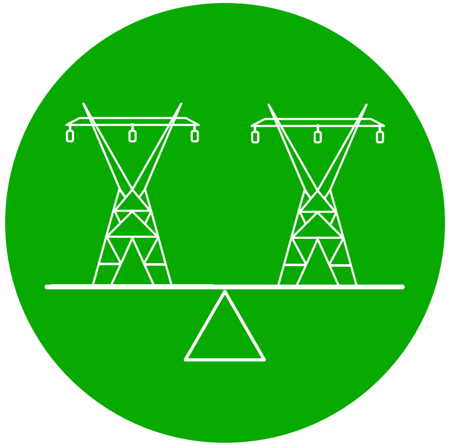
Delivery Adequacy

Regional T&D capacity to integrate renewables and DER and serve increased electrification demand

Balancing & Flexibility

Flexibility resources and operating reserves to manage variability and uncertainty

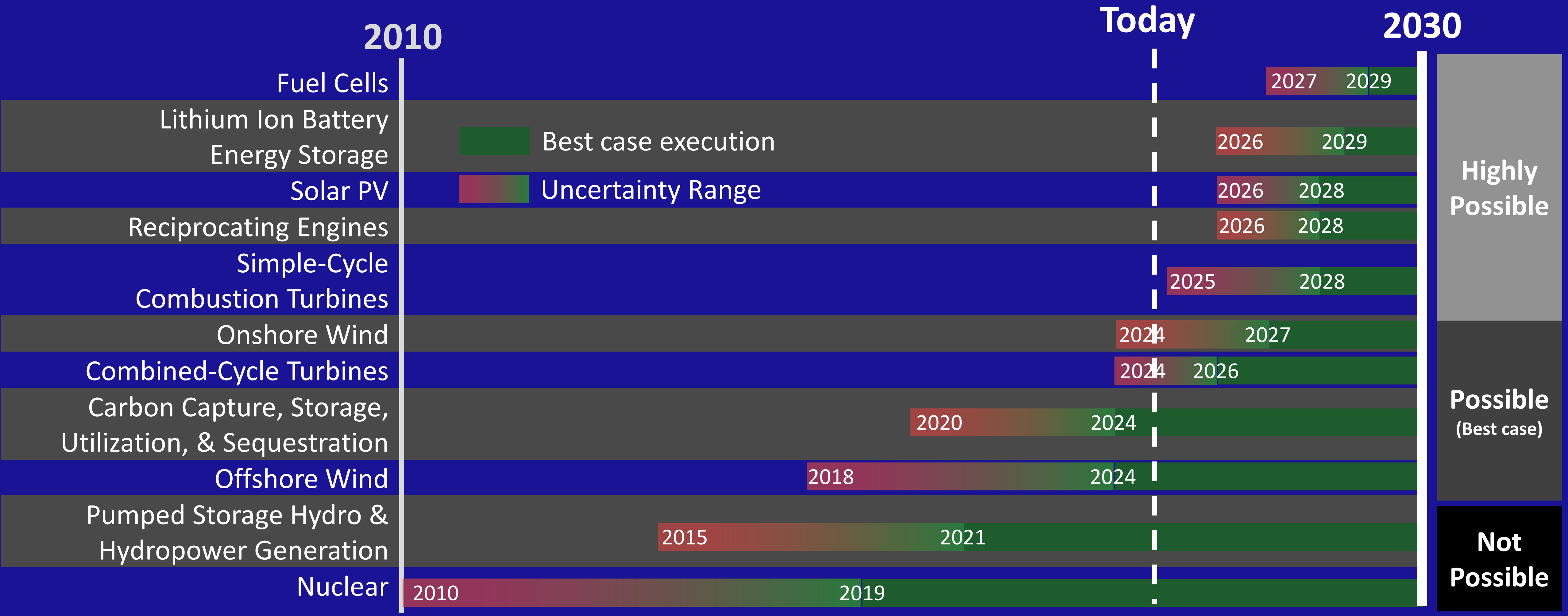
Grid Stability



Resources and controls to maintain frequency and voltage for much faster dynamic system

EPRI tools and models to ensure reliability in every hour of every day through the transition

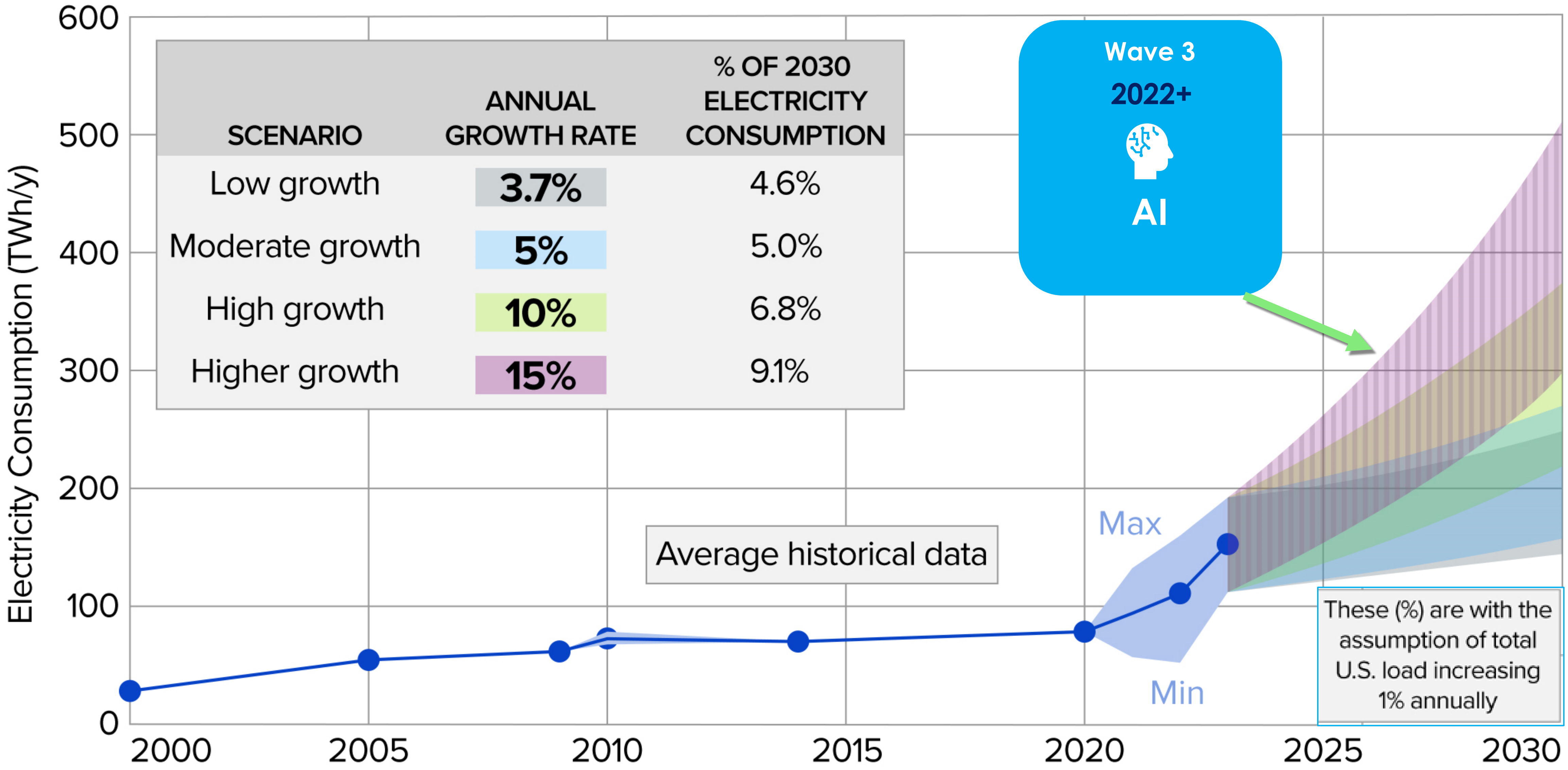
To be operating by 2030, investment decisions need to be taken by...



Reaching critical decision point for post-2030 dispatchable resources

Large Load Integration and Forecasting

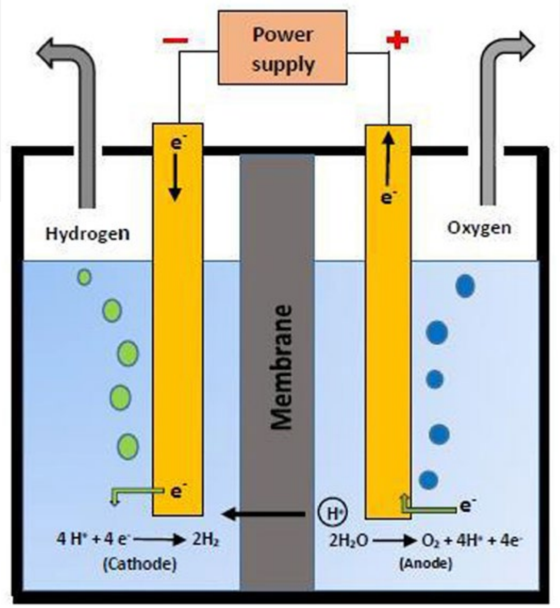
AI is Driving a Third Wave of Data Center Growth



SCENARIO	ANNUAL GROWTH RATE	% OF 2030 ELECTRICITY CONSUMPTION
Low growth	3.7%	4.6%
Moderate growth	5%	5.0%
High growth	10%	6.8%
Higher growth	15%	9.1%

Not just data centers…

Hydrogen Electrolyzers



In 1000s of MW

Crypto Mining

Few kW to ~1000s MW

Data Centers

Few kW to ~1000s MW

EV Charging

Up to 50 MW

Solutions through Collaborative Research

Challenges

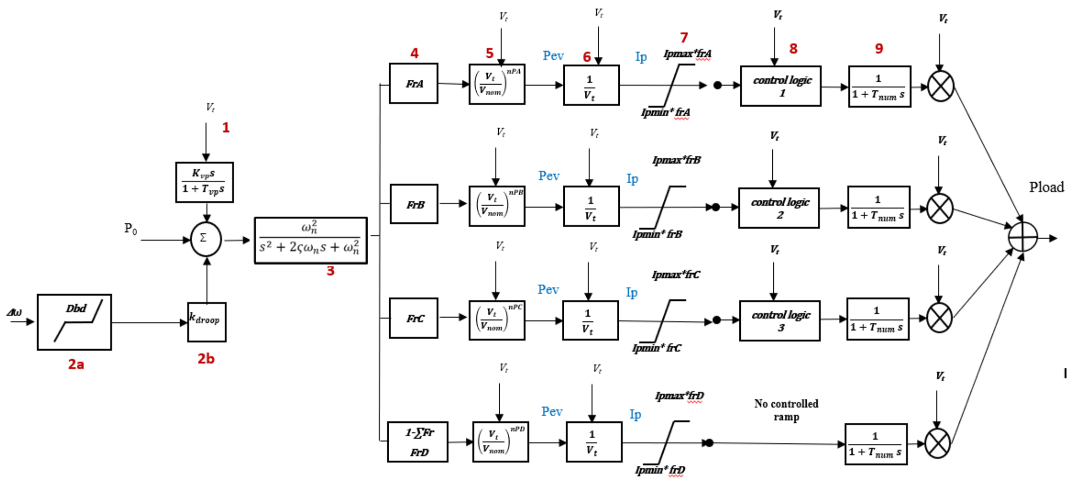
- Large MW size and quick operational requirements
- Transmission and generation adequacy will be challenged to meet the growing needs
- Increased loads with variable generation presents a challenge
- Effect on grid stability and reliability

Solutions

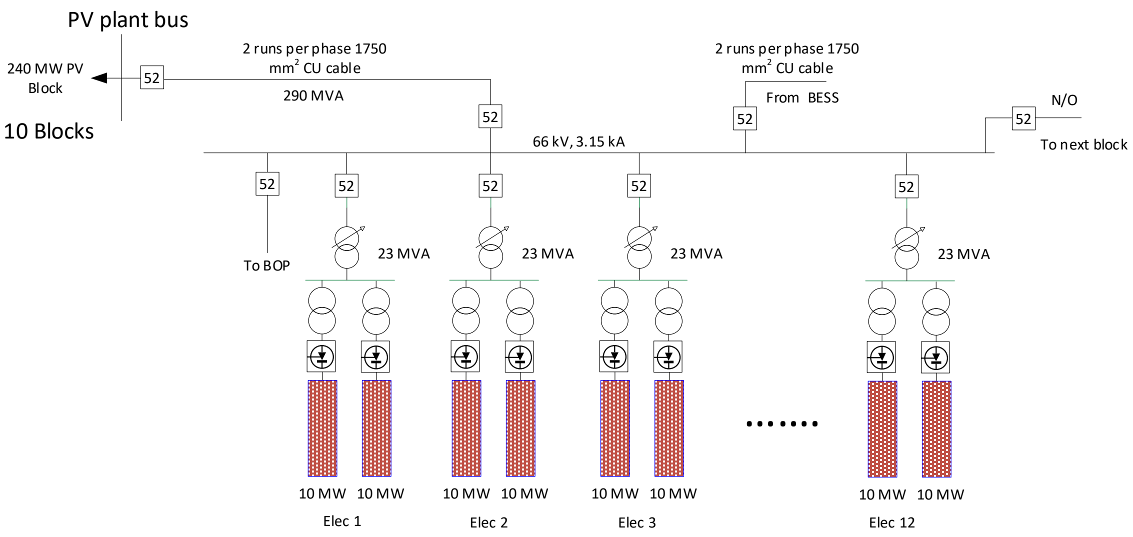
- **Improved forecasting** of large loads including considerations of flexibility in forecasting.
- Understanding how **load flexibility can affect system adequacy**
- Understanding how **collocated generation** can support the grid
- Leveraging **load flexibility** to mitigate impacts of generation variability
- Identifying the role of **energy storage**
- Improve **modeling** of large loads and understanding their **frequency and voltage support** capabilities
- Understand the role of **energy storage** and new **grid forming** capabilities

EPRI

Highlights of Load Modeling Work



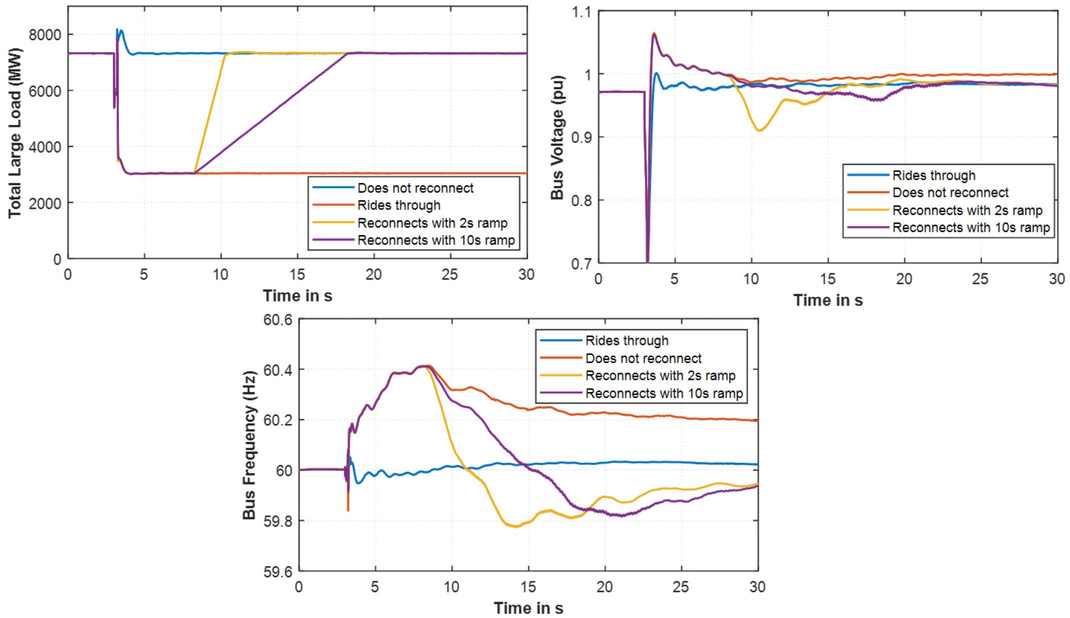
Positive Sequence Model for Large Electronic Loads



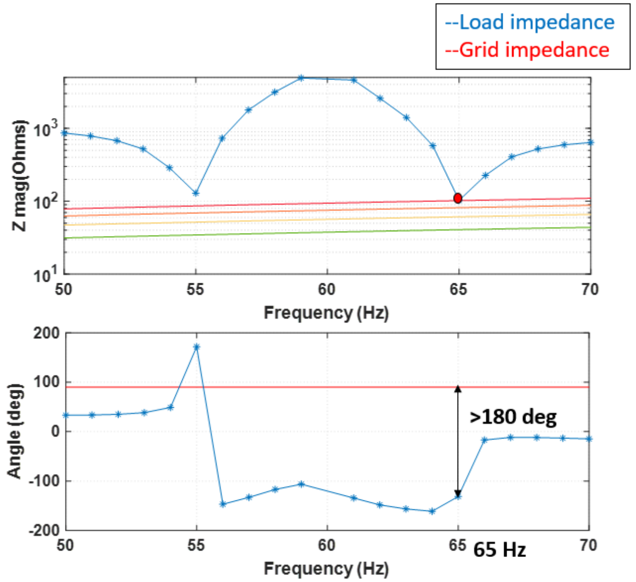
EMT models for Large Load Facilities

- Positive sequence models to help us capture bulk system reliability impacts. Few utilities are already evaluating data center drop out effect using the positive sequence model we developed
- EMT models are more experimental and help us identify improvements needed in positive sequence models as well as any stability related vulnerabilities due to a certain control philosophy
- Models are still evolving, and new features are being added

Highlights of Impact Assessment Work



Bulk System Impact due to Large Load Loss

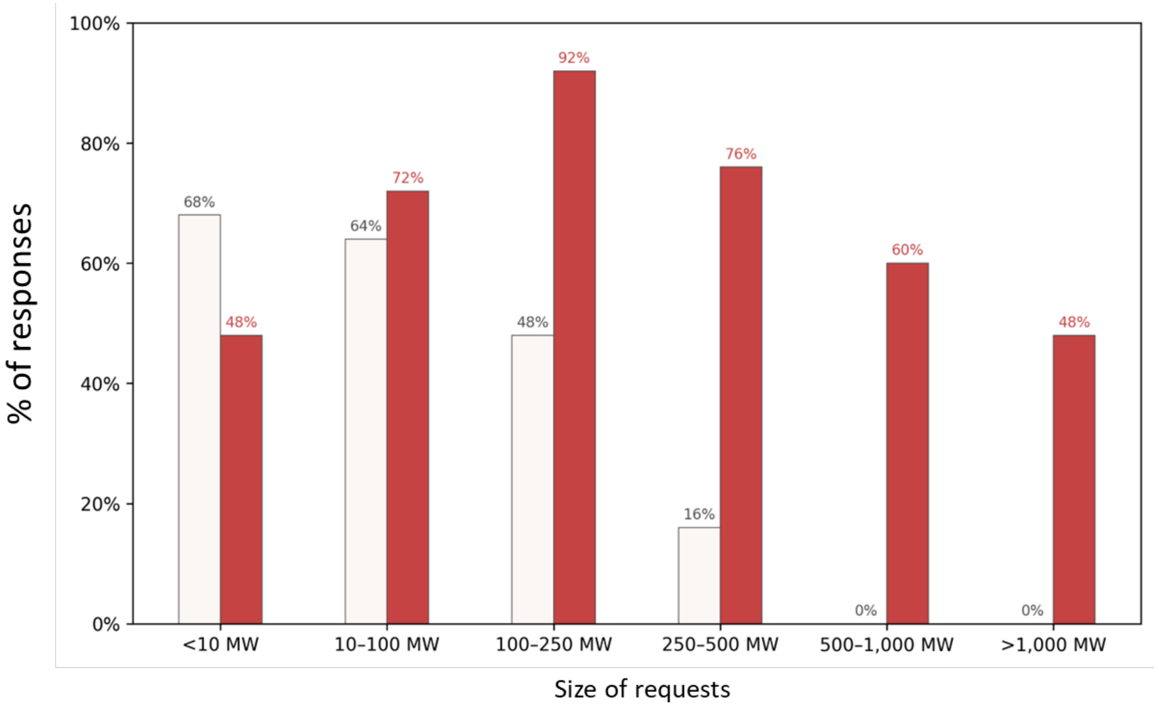


Impedance Analysis and EMT assessment for Stability Risk Screening

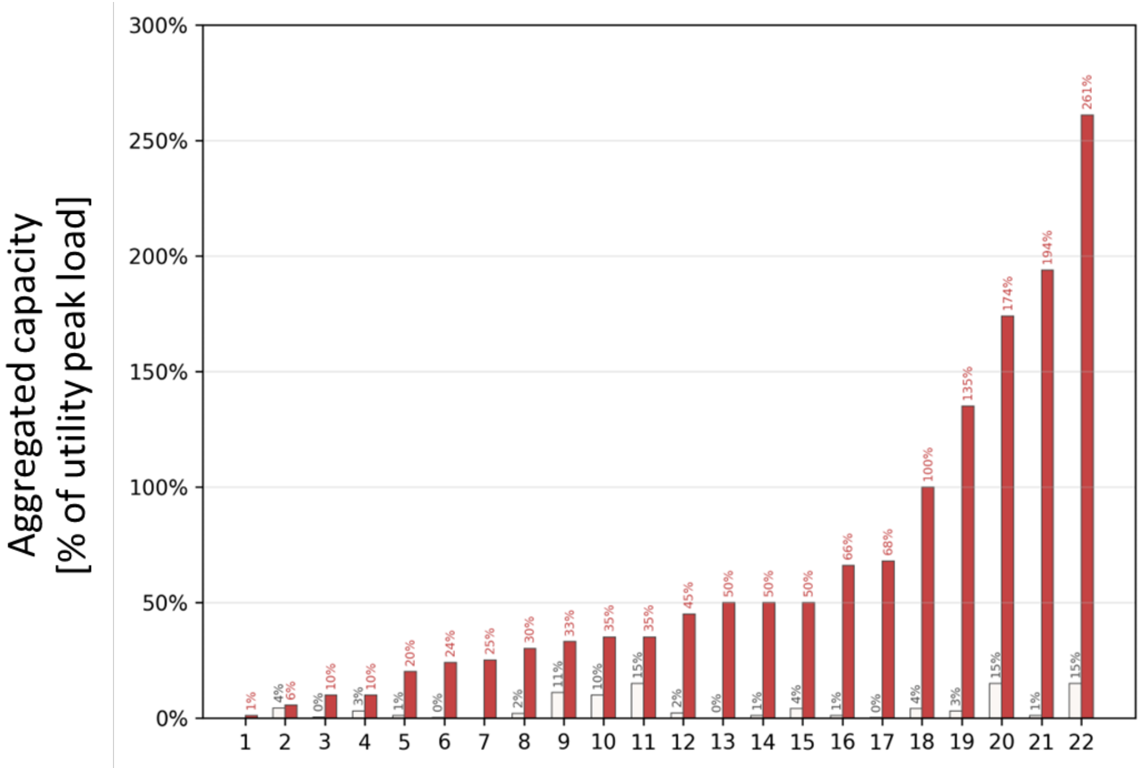
- ❑ Identify bulk system risks related to large load loss. Presented initial findings are different forums
- ❑ Impedance analysis and EMT assessments to screen for instability modes and develop an understanding of fundamental instability drivers
- ❑ Provide guidance to planners on assessing risks related to large load
- ❑ Power quality risks being investigated as well.

Experiences and Trends for Data Center Forecasting

Data Center Sizes Getting Larger



Requests are now large portion of load



Forthcoming Sept 2024: *Utility Experiences and Trends Regarding Data Centers: 2024 Survey*. EPRI, Palo Alto, CA: 2024. 3002030643.

Demonstrate how data centers can support and stabilize the electric grid while improving interconnection and efficiency.

Drive a cultural, taxonomic, and operational shift, creating a blueprint for data center stakeholders, utilities, market operators, technology innovators, and policymakers to adopt.

Flexible Data Center Designs

Enabling future data centers to become grid resources through flexible & efficient designs and operational practices

Transformational Utility Programs

Explore market and program structures that advance data center flexibility

Grid Planning for Operational Flexibility

Equip the utility industry planning practices to embrace large flexible loads

Load Forecasting Initiative

LOAD FORECASTING

Improved load forecasts at operational and planning timescales* will drive more efficient investment decisions and better grid performance.

EPRI launched a 24-month initiative (ending in Q4 2025) to address critical needs in load forecasting that will work across three areas:

01 Industry Coordination
Enable knowledge-sharing and collaboration among utilities, ISOs/RTOs, etc.

02 Long-Term Forecasting (Planning)
Develop methodologies and guidance to incorporate new load drivers

03 Short-Term Forecasting (Operations)
Develop methodologies and guidance to mitigate changes in forecast accuracy

Website: msites.epri.com/LFI

*we are defining “planning timescales” as >1-year ahead

Integrating Inverter Based Resources

Challenges utilities may face with increased percentage of inverter-based resources (IBRs)

Grid Forming Inverters	Changing System Strength	Locational Aspect of Services	Accurate Simulation Models	Reliable Protection Studies
How to define specifications for vendors?	Minimum number of rotational machines?	Can IBRs provide system services?	Can models be robust in low system strength scenarios?	How to accurately represent IBR contribution?
What impact will be there on the grid?	Can IBR dynamic behavior be robust under network change?	Should IBRs be located/hosted at critical nodes?	Can new forms of instability be captured and analyzed?	Would existing protection be impacted?

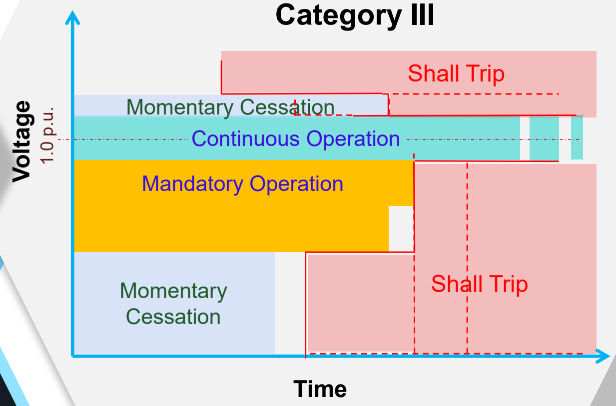
Grid Stability with Inverter-Based Resource (IBR) Grids

Grid-Forming Inverters

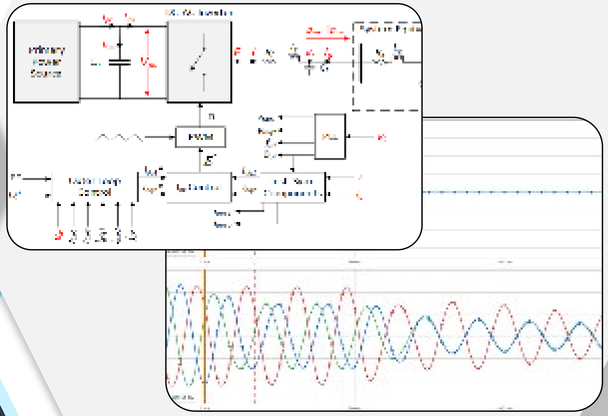
universal interoperability for grid-forming inverters
unifi consortium

U.S. DEPARTMENT OF ENERGY

Interconnection Standards



Modeling/Analysis of Weak Grid Systems



Modeling, Controls, & Integration

Demos, Commercialization, & Standards

IEEE 1547 – DER Interconnection

IEEE 2800 – Bulk System IBR

DOE PVMOD Project

TI: Operating with 100% Inverters

Tools for reliably operating future grids

EPRI

Relative Reliability Contributions for Various Resources

- **Must ensure reliability when considering new resource mix**
- **Not all resources are equal in “Reliability Capability”**
- **Synchronous resources broader & deeper ability to support reliability**
- **Reliability is not only consideration: Sustainability, Diversity, Economics, Emissions, among others**

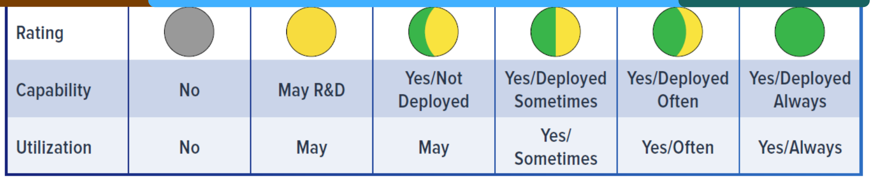
EPRI whitepaper (2025 update): Contributions of Supply & Demand Resources to Required System Reliability Services (3002031456)

Table 4. *Relative Reliability Contributions*

WARNING: Relative rankings in table based on specific assumptions and disclaimers documented in white paper—do not use in isolation.

Relative scores are based on “typical” capabilities of resources presently being installed.

Reliable system operation requires online resources aggregately capable of providing the full range of required reliability services.
Synchronous Interconnection resources provide the highest contribution across the broadest range of reliability services.



Grid Enhancing Technologies

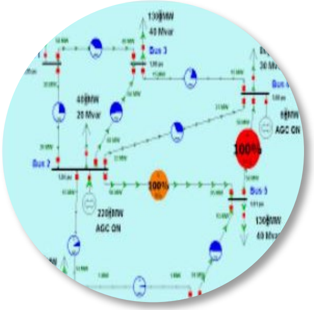
GETs Technologies could unlock system capacity quickly

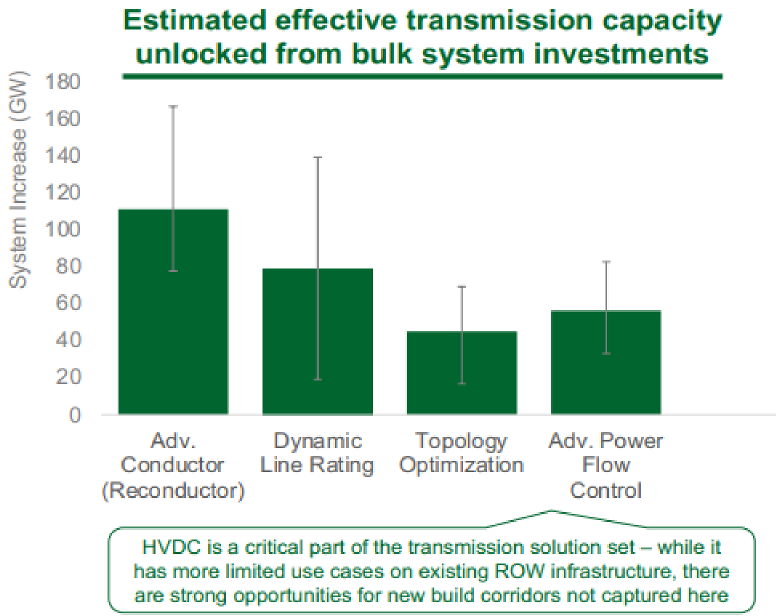
Advanced Conductors

Dynamic Line Ratings

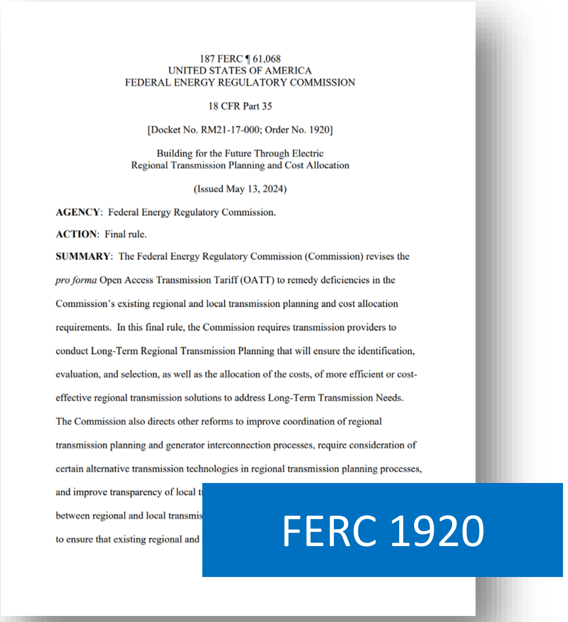
Advanced Power Flow Controllers

Topology Optimization





Source: DOE Innovative Grid Deployment Lift-Off Report



187 FERC ¶ 61,068
UNITED STATES OF AMERICA
FEDERAL ENERGY REGULATORY COMMISSION

18 CFR Part 35

[Docket No. RM21-17-000; Order No. 1920]

Building for the Future Through Electric
Regional Transmission Planning and Cost Allocation

(Issued May 13, 2024)

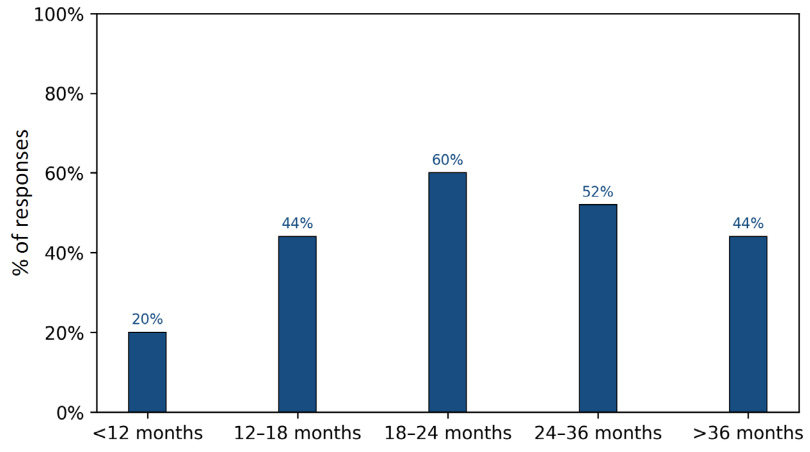
AGENCY: Federal Energy Regulatory Commission.

ACTION: Final rule.

SUMMARY: The Federal Energy Regulatory Commission (Commission) revises the *pro forma* Open Access Transmission Tariff (OATT) to remedy deficiencies in the Commission's existing regional and local transmission planning and cost allocation requirements. In this final rule, the Commission requires transmission providers to conduct Long-Term Regional Transmission Planning that will ensure the identification, evaluation, and selection, as well as the allocation of the costs, of more efficient or cost-effective regional transmission solutions to address Long-Term Transmission Needs. The Commission also directs other reforms to improve coordination of regional transmission planning and generator interconnection processes, require consideration of certain alternative transmission technologies in regional transmission planning processes, and improve transparency of local t... between regional and local transmis... to ensure that existing regional and...

FERC 1920

Data Center Lead Time Requests



Utility Experiences and Trends Regarding Data Centers (3002030643)

GET SET

Grid-Enhancing Technologies for a Smart Energy Transition

Accelerating the transition

Advanced Conductors

Dynamic Line Ratings

Advanced Power Flow Controllers

Planning

Operations

ACCELERATION IN ACTION

CONDUCT Unbiased third-party testing in labs & field

SIMULATE use of GETs in planning and operations

COMPILE experiences from pilots and implementations across the globe

COMMUNICATE findings & guidance in a one-stop shop for all technologies and users

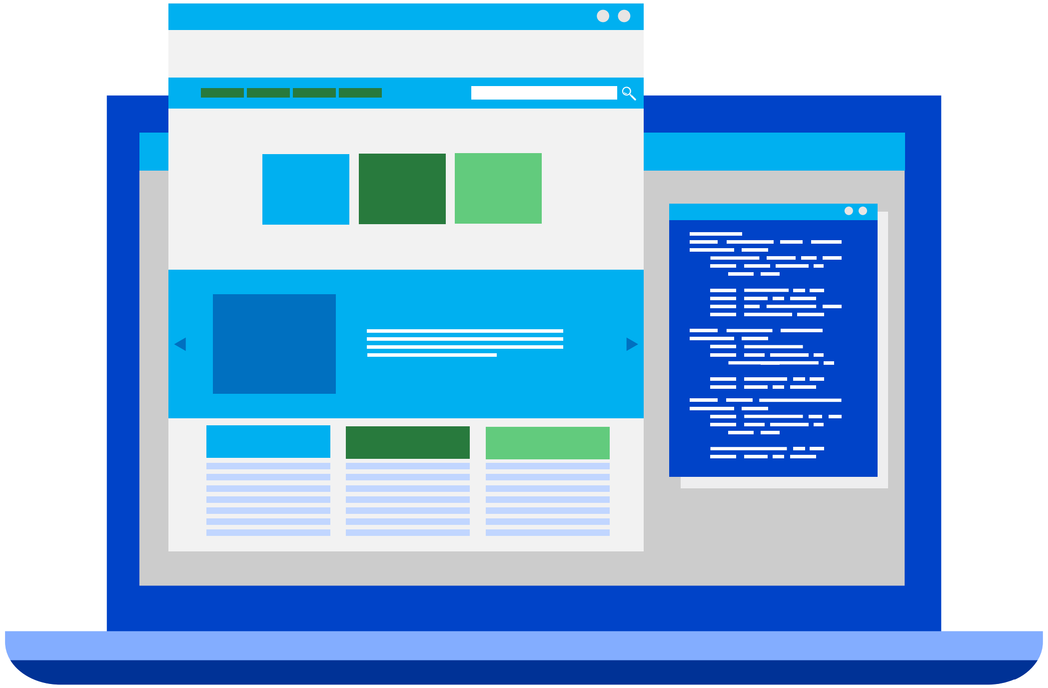
COLLABORATE with utilities, and stakeholders through webinars, workshops and user groups

EPRI

AI in operations and planning

Current State of AI in the Global Energy Sector

Massive potential, limited progress



Digital Revolution

AI (Artificial Intelligence) / ML (Machine Learning) / LLM (Large Language Models) are making tremendous advances and proliferating in all aspects of life.

Data-Rich Environment

Utilities have: **Lots of data**: structured, unstructured, time series, images, documents, simulation results. **Lots of use cases** to be solved to automate processes and gain insights. **Rapidly changing industry**: regulations, markets, resources, assets, climate, behaviours.

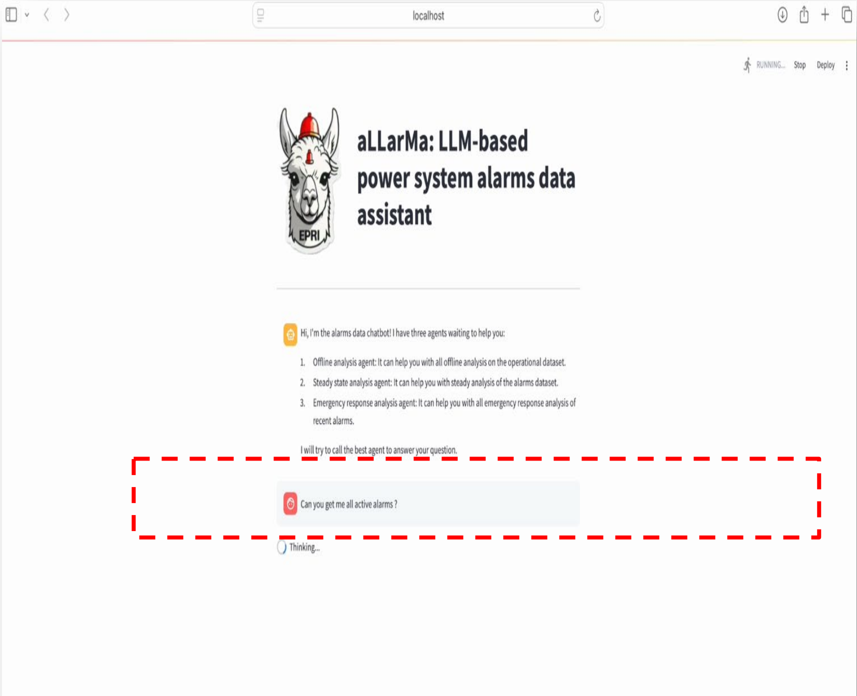
Early-Stage Prototypes

Some limited successful applications of AI in utilities for narrow sets of use cases (mostly forecasting) and early stage LLM prototypes, mostly on document search and summarization.

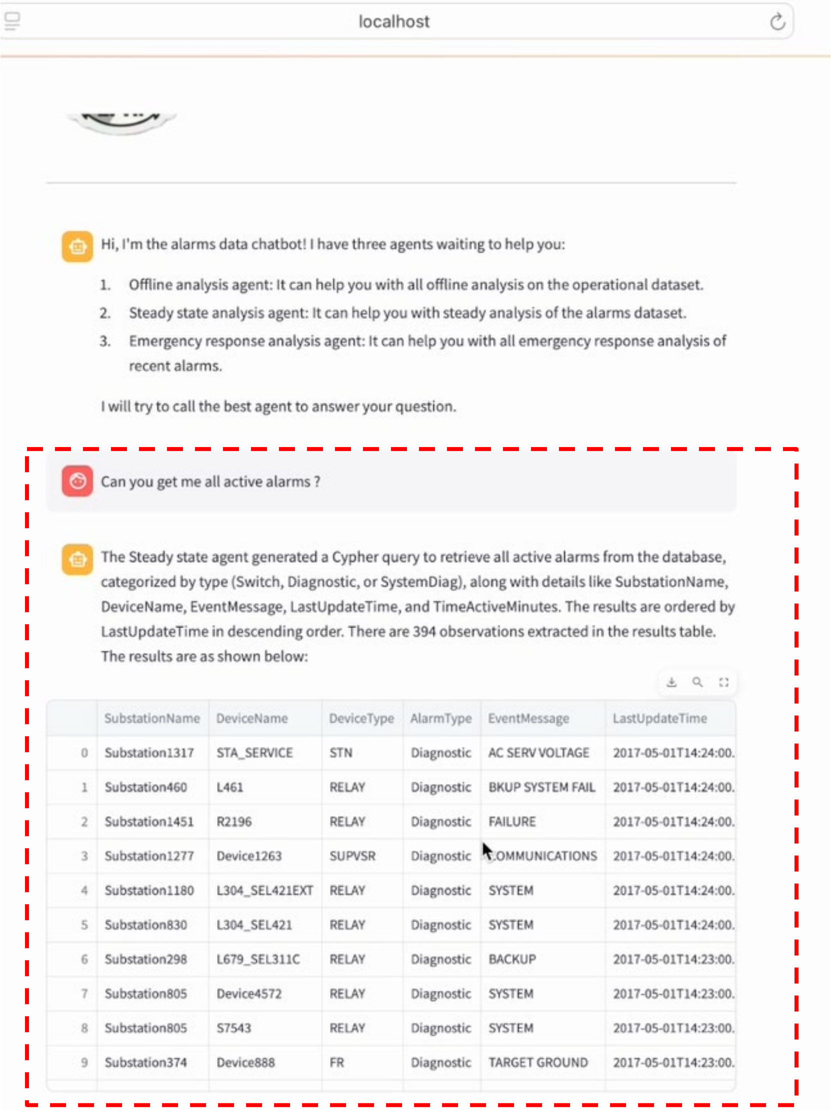
AI Application Opportunities Across the Energy Industry…

Use Case: Alarm Data Mining

Screenshots of the first version of the aLLarMa application as it was developed in November 2024.



Operator prompt: 'Can you get me all active alarms?'

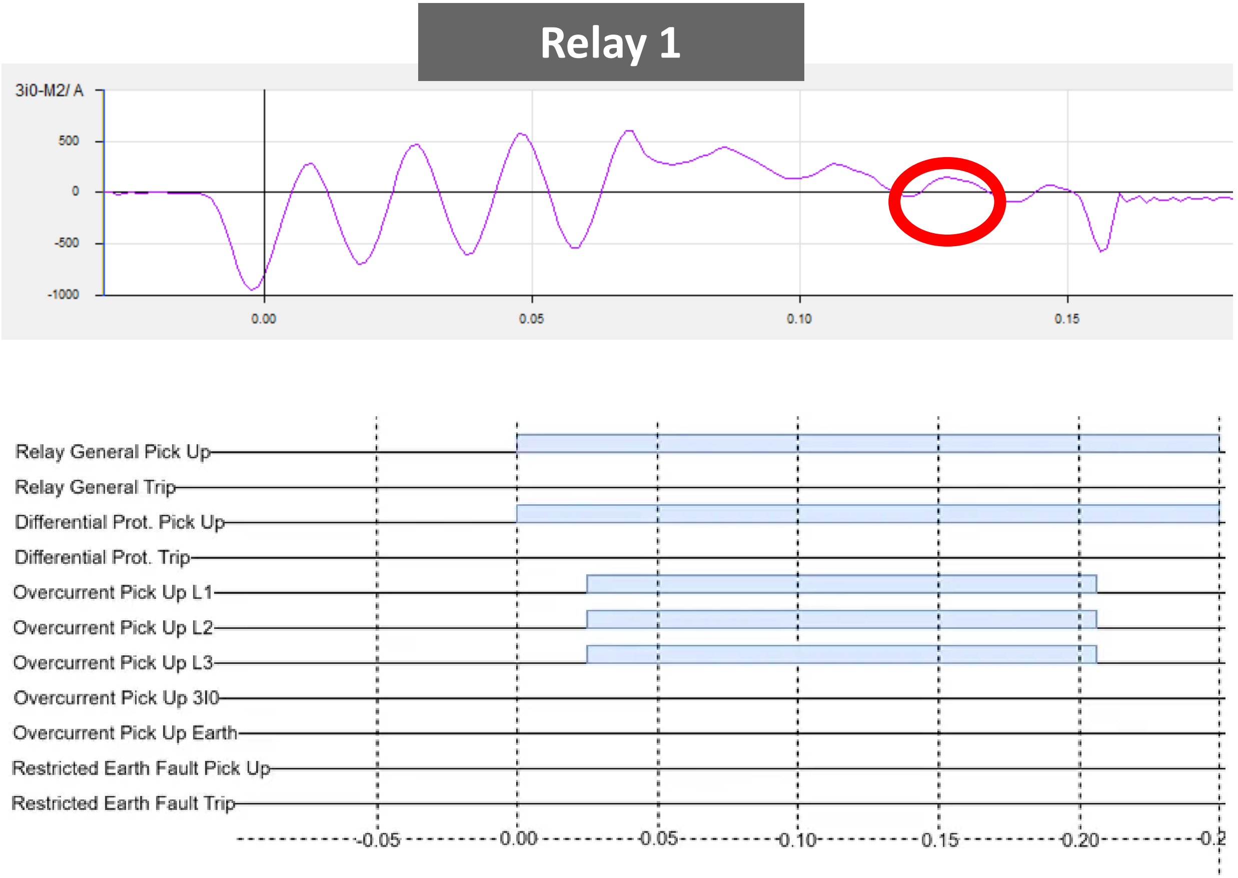


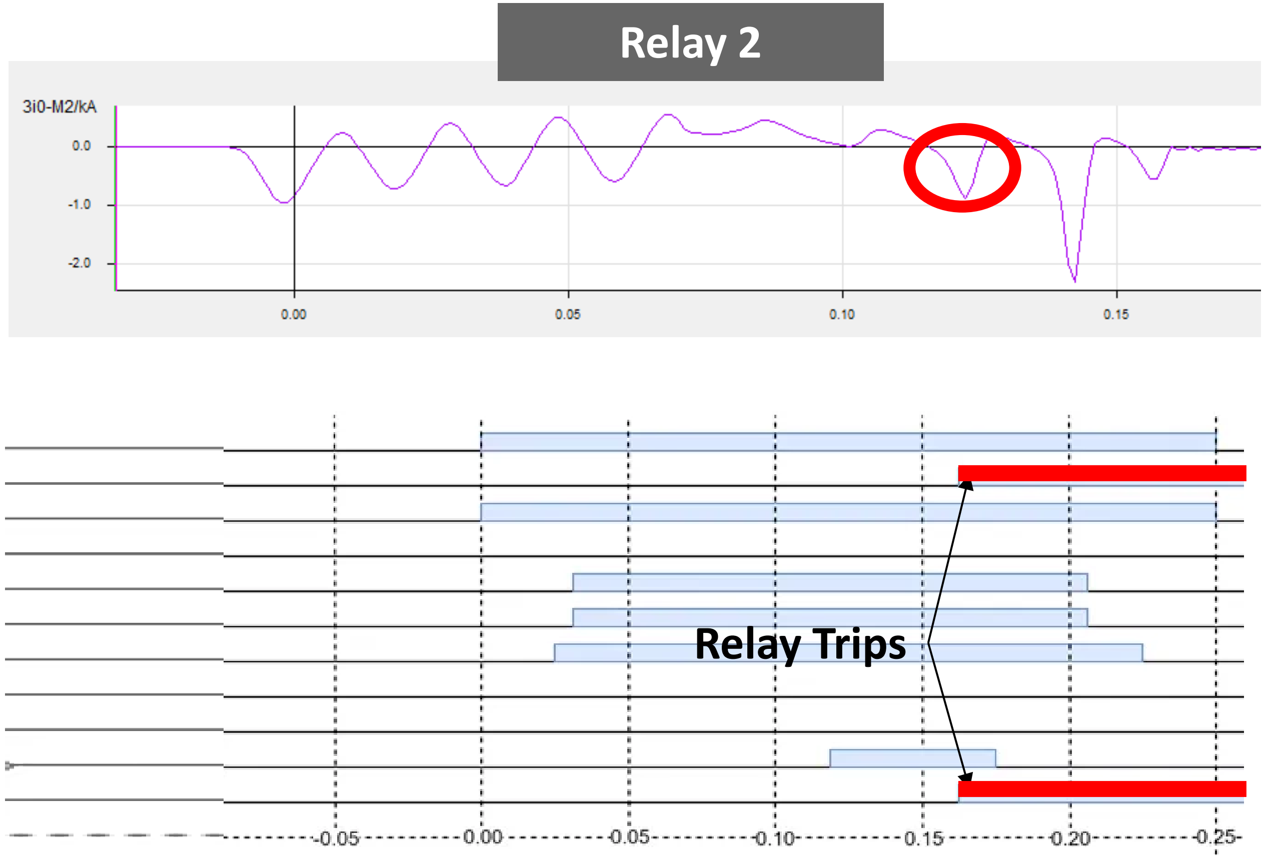
	SubstationName	DeviceName	DeviceType	AlarmType	EventMessage	LastUpdateTime
0	Substation1317	STA_SERVICE	STN	Diagnostic	AC SERV VOLTAGE	2017-05-01T14:24:00.
1	Substation460	L461	RELAY	Diagnostic	BKUP SYSTEM FAIL	2017-05-01T14:24:00.
2	Substation1451	R2196	RELAY	Diagnostic	FAILURE	2017-05-01T14:24:00.
3	Substation1277	Device1263	SUPVSR	Diagnostic	COMMUNICATIONS	2017-05-01T14:24:00.
4	Substation1180	L304_SEL421EXT	RELAY	Diagnostic	SYSTEM	2017-05-01T14:24:00.
5	Substation830	L304_SEL421	RELAY	Diagnostic	SYSTEM	2017-05-01T14:24:00.
6	Substation298	L679_SEL311C	RELAY	Diagnostic	BACKUP	2017-05-01T14:23:00.
7	Substation805	Device4572	RELAY	Diagnostic	SYSTEM	2017-05-01T14:23:00.
8	Substation805	S7543	RELAY	Diagnostic	SYSTEM	2017-05-01T14:23:00.
9	Substation374	Device888	FR	Diagnostic	TARGET GROUND	2017-05-01T14:23:00.

This is summarised in text and a table of the results is presented to the user.

Use Case: Misoperation Investigation

Transformer Differential records from an external fault pasted into the LLM
Relays connected to the same CTs, but different CT cores



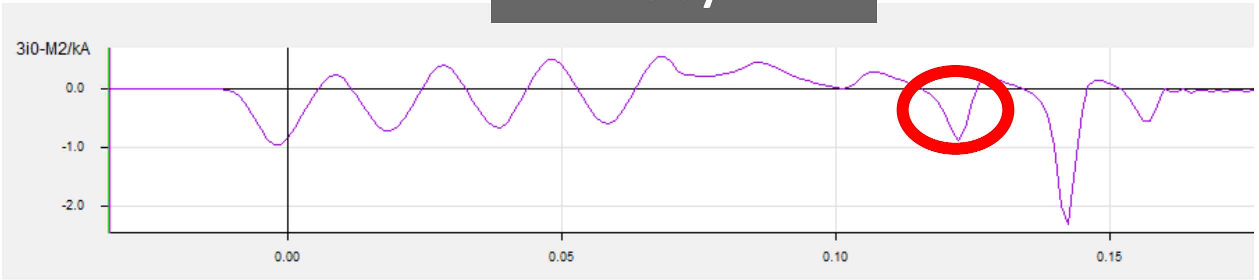


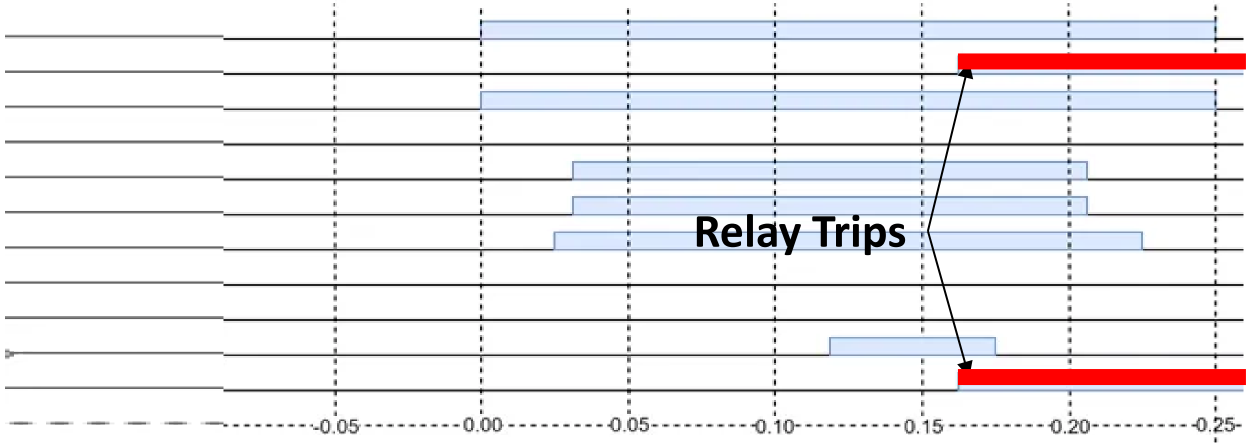
Use Case: Misoperation Investigation

Transformer Differential records from an external fault pasted into the LLM
Relays connected to the same CTs, but different CT cores

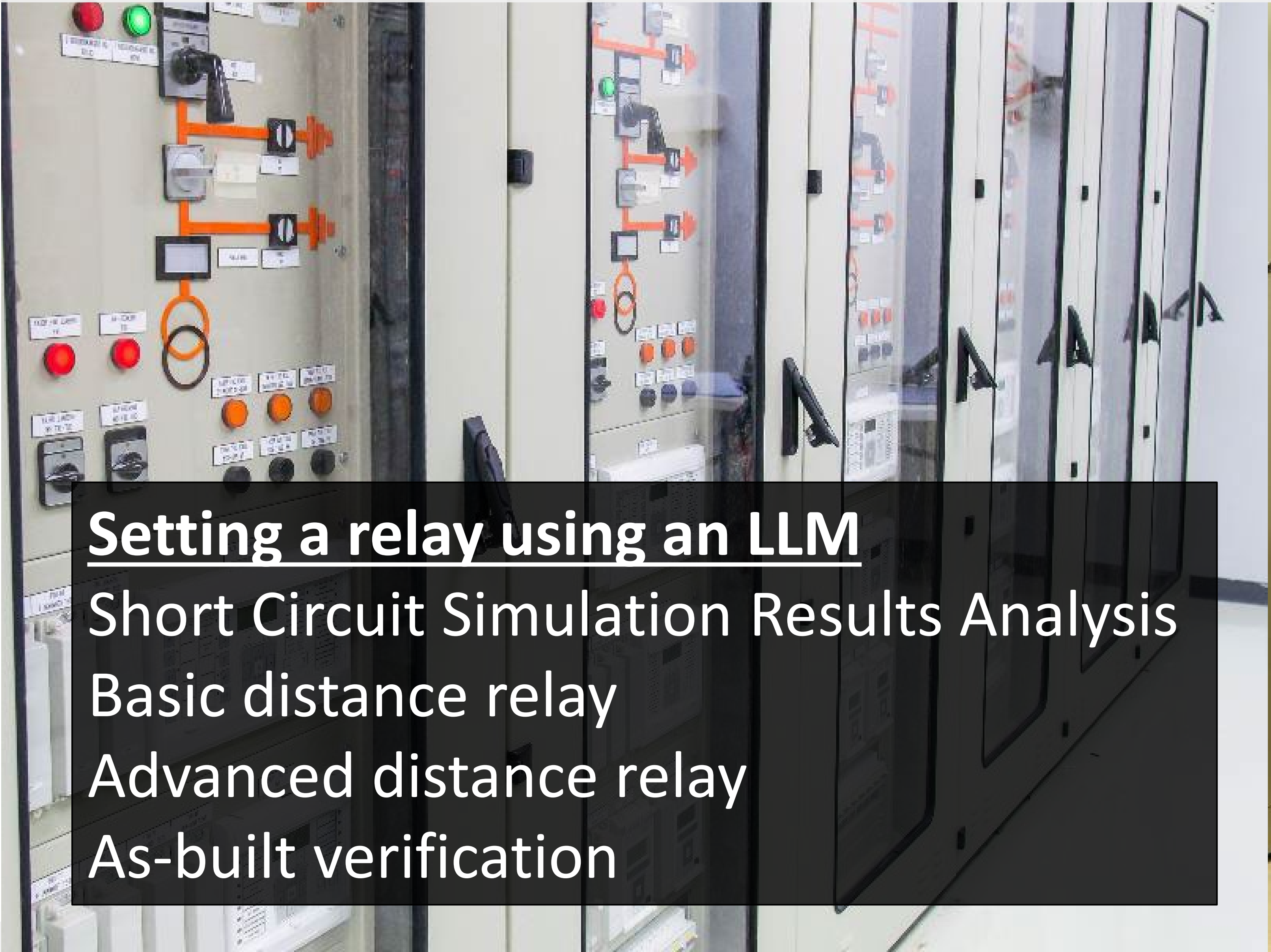
- Correctly identified the situation from the image
- Correctly identified CT core saturation as the likely cause
- Correctly recommended relay and CT checks and tests
- With additional information, executed a calculation to correctly verify the CT design

Relay 2





Thinking beyond Knowledge Retrieval Benchmarks to Assessing Complex, Agentic Task Performance



Setting a relay using an LLM

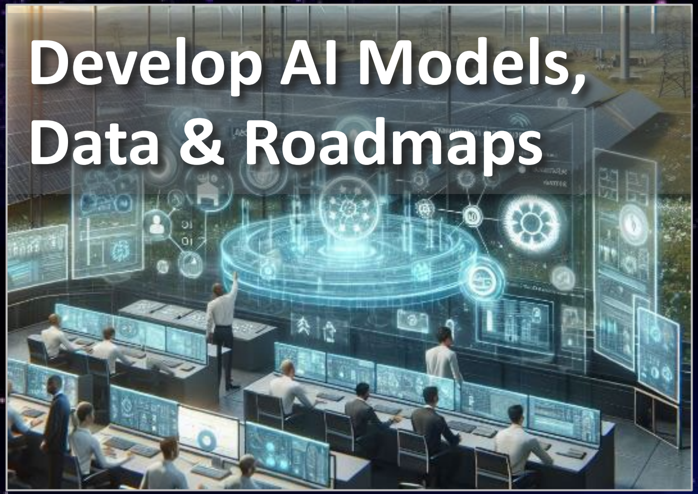
Short Circuit Simulation Results Analysis

Basic distance relay

Advanced distance relay

As-built verification

Open Power AI Consortium – Key Objectives



Create an ecosystem for stakeholders to identify, develop, validate and deploy AI solutions to transform the electric sector

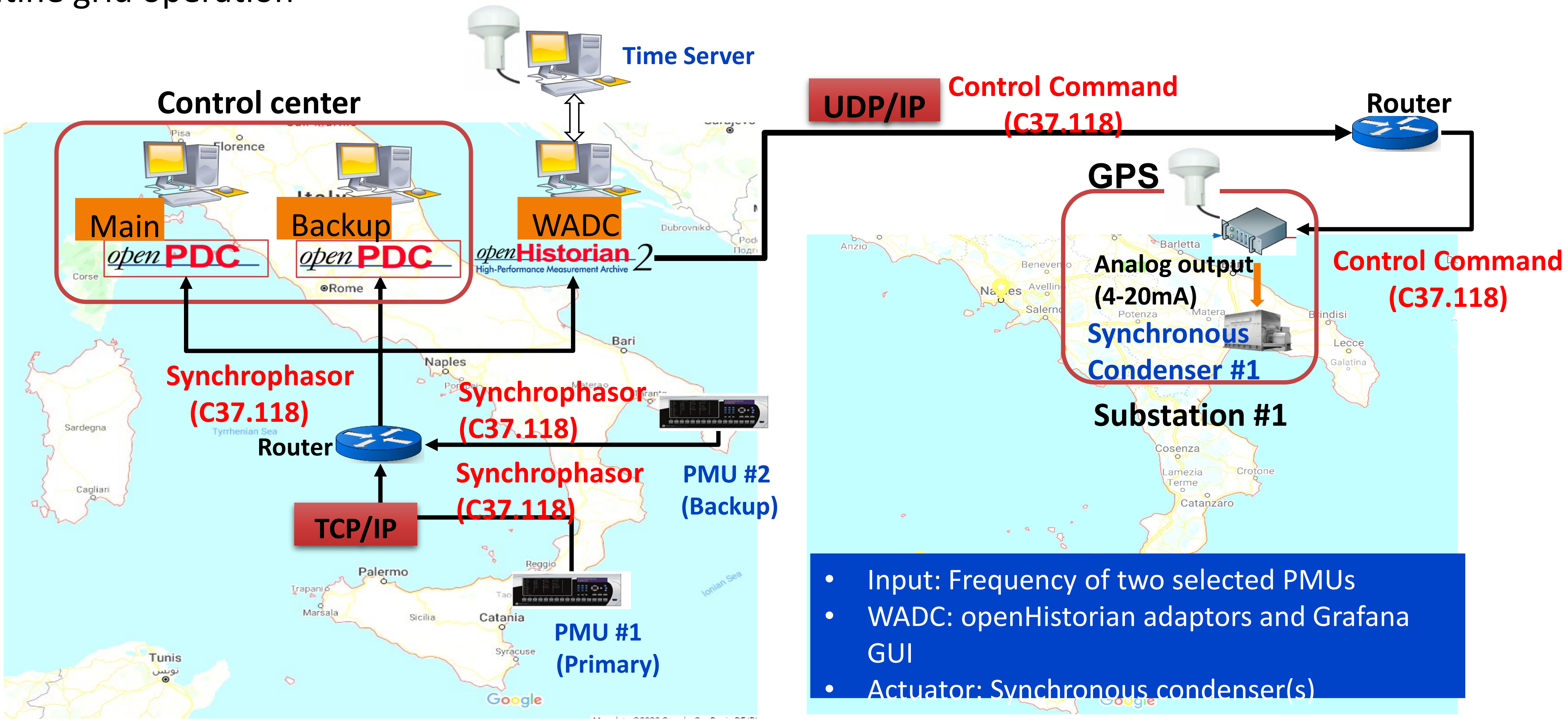
Images created with Copilot

TOGETHER…SHAPING THE FUTURE OF ENERGY®

www.epri.com

Wide-Area Oscillations Damping Control for Italian Power Grid

- WADC field deployed at Terna control center and substation
- Operating as a novel automated wide-area monitoring protection and control (WAMPAC) tool in Terna’s routine grid operation

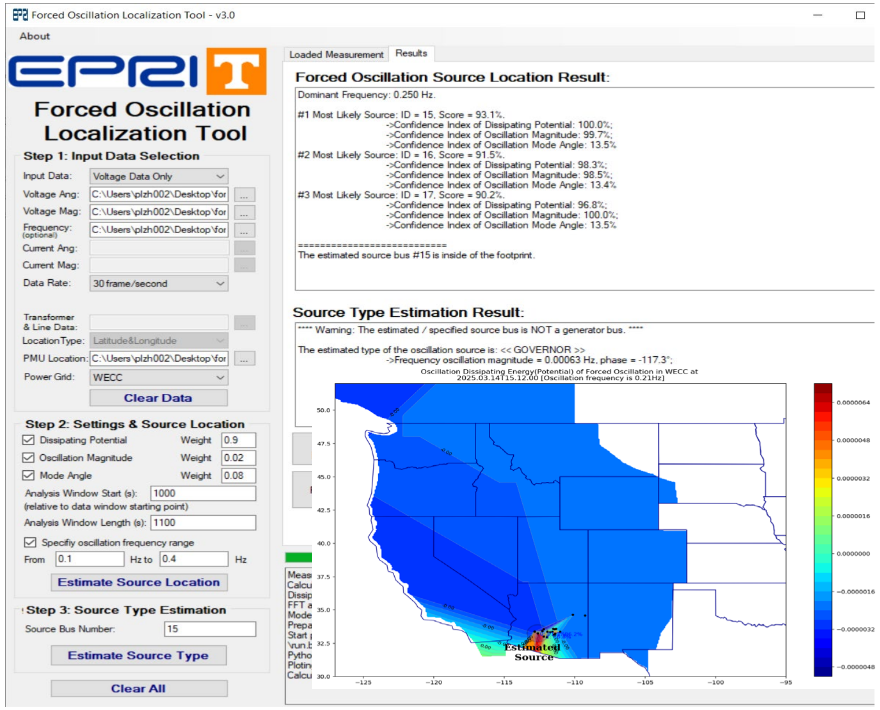


- Input: Frequency of two selected PMUs
- WADC: openHistorian adaptors and Grafana GUI
- Actuator: Synchronous condenser(s)

Forced Oscillation Localization Tool (FOLT)

In Collaborations with UTK/CURENT

- Performance verified by simulated and actual event data
  - EI forced oscillation event (01/11/2019), SRP BESS-induced forced oscillation event (09/20/2023, 11/03/2023), and Dominion data center 11 Hz oscillation event
- Online version ready for field deployment



FOLT Offline

FOLT Online v1.0

- **Forced oscillation detection**
- **Source location estimation**
- **Source type estimation**
- **Inside/Outside identification**

Streaming synchrophasor data → openPDC

FOLT Online: Implemented as an openPDC adaptor + GUI