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AI FOR GRID AND ENERGY OVERVIEW

Matthew Reno

Sandia ML/DL Workshop

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U.S. DEPARTMENT OF ENERGY NNSA National Nuclear Security Administration

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MACHINE LEARNING IN POWER SYSTEMS

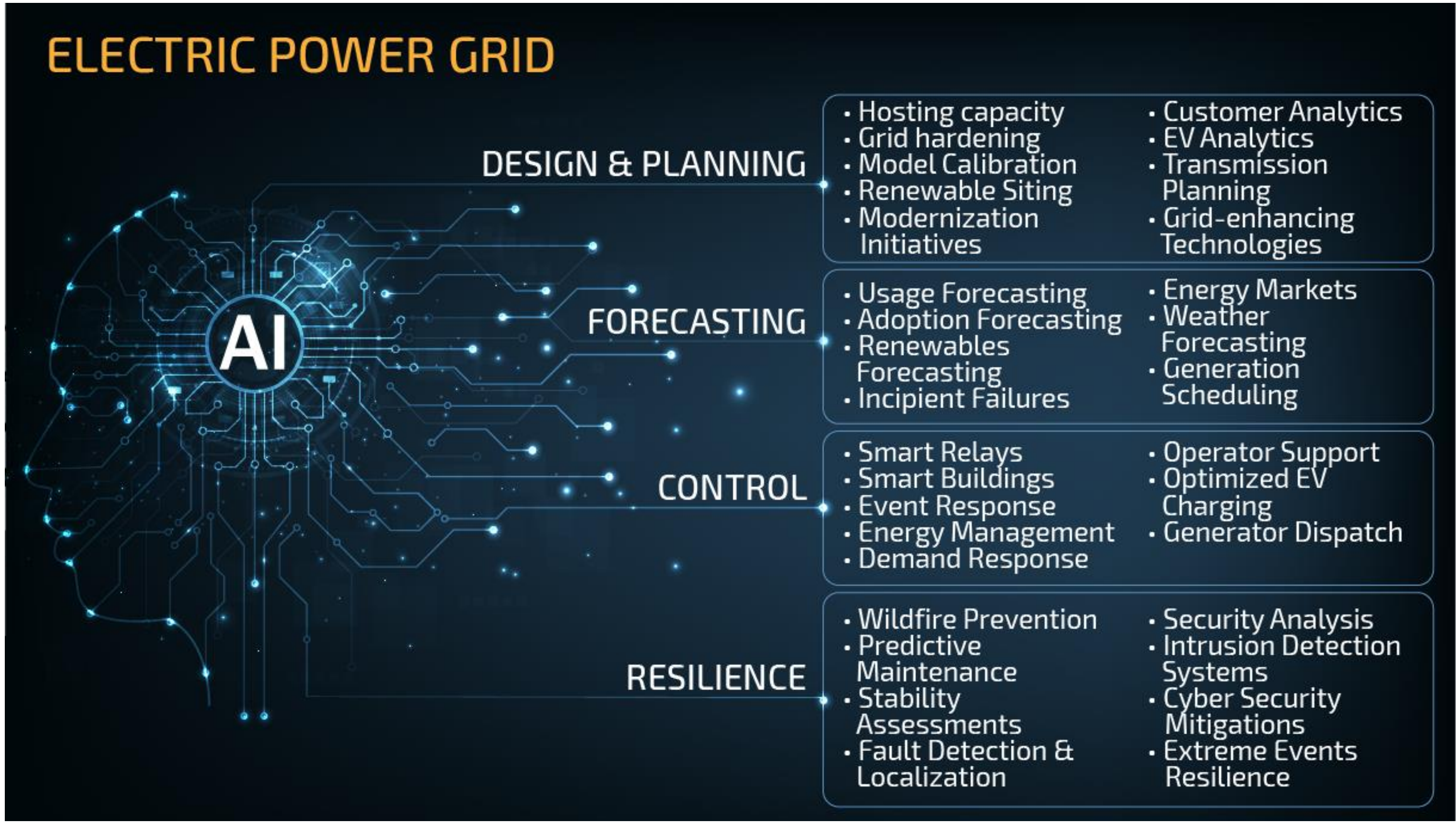
- Power Systems is a perfect application for AI/ML due to the complex systems and large amounts of data. This is made possible recently due to:
  - Advances in computing power for real-time learning and decision making
  - Additions of new sensing equipment such as smart meters
  - New Artificial Intelligence algorithms to handle large datasets, transferable learning, and physics-based algorithms
- With the increasing number of sensors in the system, utility processes and analytics can't keep up with all the new data coming in. There are many potential applications for this data that can be developed to use machine learning (ML) algorithms for improved system control, planning, and resilience.

SANDIA'S AI FOR THE ELECTRIC GRID PROGRAM

Revolutionize the electric power grid through innovative AI/ML research to provide unprecedented efficiency, resilience, and sustainability

Develop and implement cutting edge AI/ML algorithms for grid planning, control, optimization, protection, and resilience

- Reinforcement learning for grid optimization, control, and utilization of renewable sources
- Predictive analytics to anticipate and mitigate potential disruptions, ensuring a reliable and resilient grid capable of withstanding adverse events and minimizing downtime.
- Real-time monitoring, grid edge visibility, and intelligent decision-making
- Customer pattern learning for advanced load control and responding to individual customer needs
- Physics-informed algorithms that are adaptable to different grid architectures and operational contexts
- Enhanced cybersecurity through AI-based threat detection and response systems



AI OPPORTUNITIES FOR A CLEAN POWER GRID

U.S. Department of Energy, "AI for Energy: Opportunities for a Modern Grid and Clean Energy Economy", 2024.

Planning	• Completing, correcting, and harmonizing sparse data on grid infrastructure to inform predictive asset replacement • Assessing dynamic system conditions to inform upgrades, maintenance, and new resource needs, as well as dynamic assessments of available grid capacity • Preventing avoidable losses through predictive maintenance • Detecting faults in solar panels, dams, wind turbine blades, generators, etc. • Processing aerial images for remote job-site inspections • Informing adoption of grid-enhancing technologies (e.g.., Dynamic Line Rating to provide real-time transmission and distribution conditions; Topology Optimization to reroute power flow to reduce congestion) and accelerating interconnection queues to get projects connected to the grid • Enabling modelling for distributed energy resource adoption to anticipate distribution system upgrades and implications for load, and load shape
Permitting and Siting	• Organizing, extracting, consolidating information across Federal, state, and/or local regulations to improve the efficiency of administrative processes • Accelerating environmental review process, e.g., for comment processing, information extraction, drafting documents, automating compliance checks, etc. • Optimizing placement of renewable energy and transmission projects to facilitate effective and efficient siting and permitting • Generating size/location data for rooftop solar panels, optimal placement of wind turbines, etc. • Identifying and managing sites for geothermal energy, using satellite imagery and seismic data • Placing hydropower dams in a way that satisfies energy and ecological objectives
Operations and Reliability	• Improving variable renewable energy forecasting (solar, wind, run of river hydro) • Improving demand forecasting using AI trained on historical data, including weather, climate, economic and load • Improving power system optimization; reducing the computational intensity of modeling • Setting real-time pricing to optimize the operation and/or economics of distributed energy resources, storage, etc. • Anticipating system anomalies to avoid disruption
Resilience	• Enabling proactive monitoring to make critical infrastructure more resilient to severe weather • Monitoring, detecting, and diagnosing anomalous events (e.g., extreme weather events, cyber-attack) • Improving coordination with other interdependent systems (e.g., natural gas, water) to regain operation after disruption • Enhancing situational awareness across system with coupled AI and digital twins • Improving the accuracy and interpretability of landslide predictions, sea level rise, storm surge, etc. • Simulating disruption/disaster scenarios to inform resilience strategies • Enhancing system efficiency and coordination to restart the grid during full or partial blackouts • Optimizing the deployments of repair crews to accelerate response • Identifying the fastest path to system restoration

OVERVIEW OF SESSION

"Advanced Research Directions on AI for Energy", ANL-23/69, 2024.

Three grand challenges in the transition of the Energy System that AI can help solve over the next decade:

- Realizing proactive, real-time energy system operations
  - The growing complexity of the grid is making it increasingly difficult to operate efficiently. Revolutionizing grid operation by providing support for the proactive operation and predictive online control of the power grid to achieve improved efficiency, reliability, and resilience will require new foundation models.
- Building cyber- and all-hazards resilient and secure energy systems
  - The nation's aging infrastructure, extreme weather events, and the grid's increasing complexity are impacting robust management of system reliability and resilience; meanwhile, our reliance on electricity has been increasing for everything from transportation to communication and home appliances
- Designing and planning a 100% clean electricity system
  - Achieving a 100% clean electrical grid by 2035 and all domestic energy use by 2050, while maintaining today's reliability and perhaps improving it considerably, will require multiple technological leaps.

CROSSCUTTING ASPECTS NEEDED IN ENERGY MISSION AREAS

The following must be pursued across the five energy areas of nuclear energy, power grid, carbon management, energy storage, and energy materials

High-Consequence

- High-Consequence Decisions and Critical Operations
- Accreditation of AI Methods
- Trustworthiness and Verification and Validation (V&V)
- Development and Maintenance of Talent to Respond to AI Implications

Urgency

- Move at Speed of Field; Micro-Revolutions vs. Incrementalism
- Mission Imperative

Complexity

- Inverse Problems
- Robustness to Changing Environments
- Multimodal and Scalable

AI FOR POWER GRID REQUIREMENTS

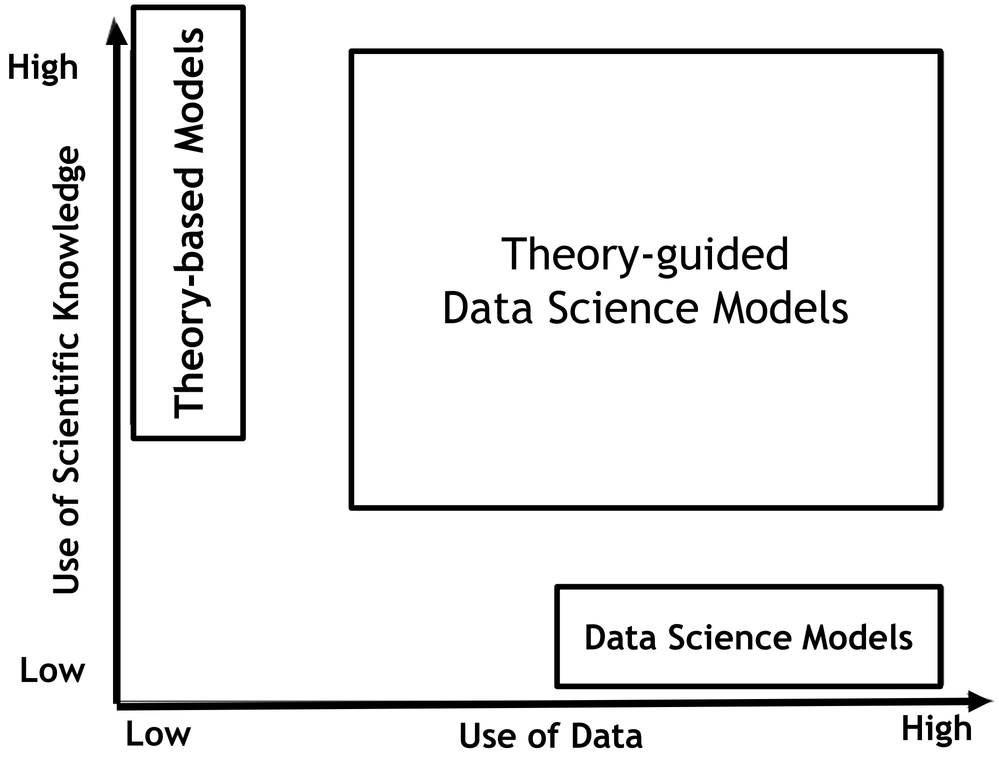
U.S. Department of Energy, "AI for Energy: Opportunities for a Modern Grid and Clean Energy Economy", 2024.

- Foundation models hold substantial promise for uses beyond text and image processing and generation featured in commercially available models.
- The application of foundation models within the power industry, however, must be approached with caution.
- The power grid is critical infrastructure - mistakes can cause significant economic damage, impact marginalized populations, and destroy long-built trust in grid operators.

Rigorously Validated Systems	The models and data sets used for AI training must be thoroughly validated for accuracy through extensive testing in simulated environments that replicate real-world scenarios. This validation is critical to ensure AI's reliability and safety when applied to power grid operations.
Physics-Informed and Explainable	AI outputs must be consistent with the fundamental laws of physics to provide realistic, explainable, and applicable solutions. Physics-informed AI models, such as those that accurately simulate the flow of electricity through the grid, can lead to more efficient and reliable energy distribution.
Human-in-the-Loop (HITL)	Human oversight should be an integral part of AI-driven processes to ensure ethical, practical, safe, secure, and innovative outcomes. Human-in-the-loop approaches involve human expertise and accountability in the decision-making loop, allowing operators to review and refine AI-generated recommendations.
Scalability and Performance	Considering the rapid expansion of edge devices (e.g. devices at the boundary between the utility equipment and the customerâ€™s equipment) and the increasing demand for electrification, AI needs to efficiently handle and process large volumes of data (or system of systems) in real-time or near-real-time to effectively inform operational decisions.
Ethics and Governance	AI systems in the power grid should comply with robust cybersecurity policies and standards due to the critical nature of electric infrastructure. Adherence to frame-works like the NERC Critical Infrastructure Protection standards is necessary to mitigate cyber threats and maintain the integrity of grid operations. AI systems should also consider the principles of Ethically Aligned Design.

PHYSICS-BASED CONSTRAINTS IN AI

- Given that we know many of the relationships in power systems (Ohms law, power flow equations, etc.), it is advantageous to use the known physics equations.
- Important to make the decisions explainable. Standard control theory methods need formula representations for demonstrating stability and stability margins.
- Challenges Integrating Physics-Based Constraints into AI
  - Much recent work in AI uses raw data input (image pixels, etc.) and ignores physics-based constraints
  - Areas such as power systems have large quantities of physics-based constraints and AI should be able to use that knowledge without starting from scratch
- Successful Integrations of Physics-Based Constraints into AI
  - AI for calibrating distribution system models (phase identification, topology parameter estimation, etc.)

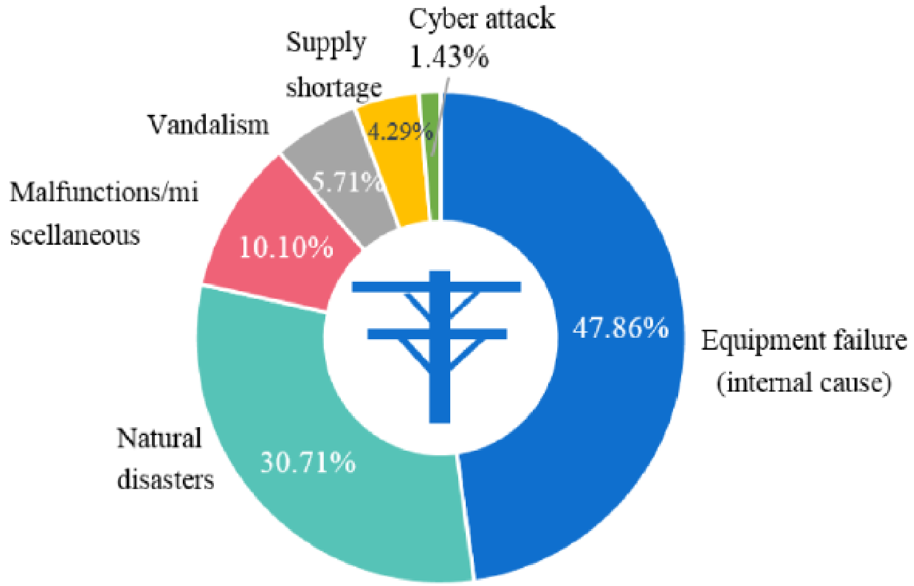


A. Karpatne *et al.*, "Theory-guided Data Science: A New Paradigm for Scientific Discovery from Data," *IEEE Trans. Knowl. Data Eng.*, vol. 29, no. 10, pp. 2318–2331, 2017.

ACCESS TO TRAINING DATA FOR AI

- Much of the recent success of AI is driven by access to large quantities of high-quality data. This is often difficult to obtain for real-world applications, especially for Critical Energy/Electric Infrastructure Information (CEII)
- Challenges with Training Data Availability and Quality for AI
  - Many real-world applications have either unlabeled data, incompletely labeled data, or few to no examples of critical event types
  - Some events (rare resiliency events, cyber attacks, etc.) have never occurred
- Successful Applications of AI with Limited Access to Training Data
  - Semi-supervised learning or transfer learning that uses some previous data and training to apply to a new application
  - Detection of incipient failures of devices like transformers
  - Power system protection, including fault classification and location

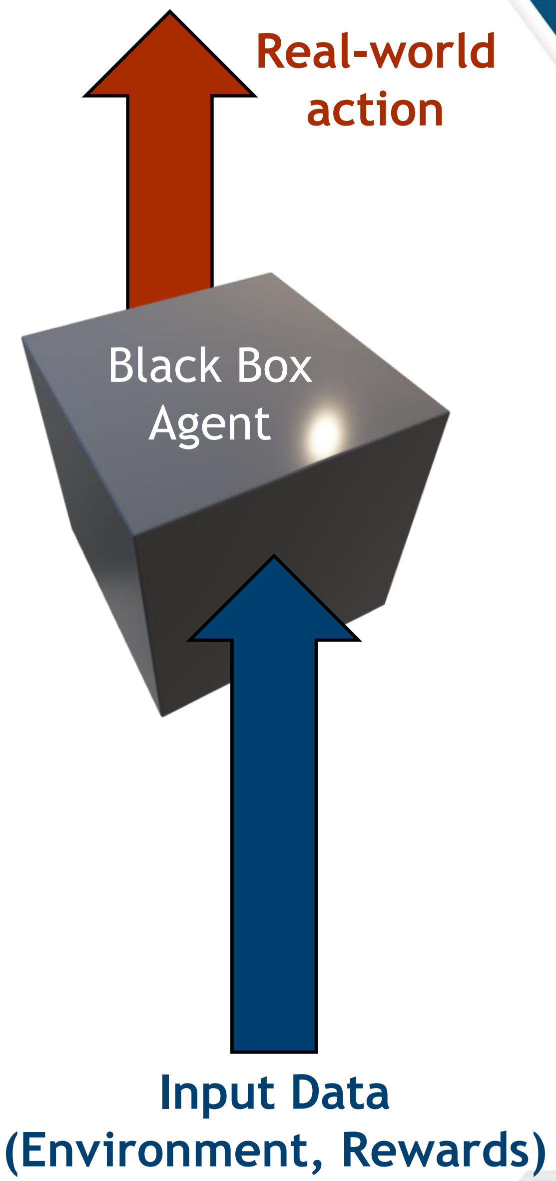
Causes of Outages Worldwide



Z. Bie, Y. Lin, G. Li, and Li Furong, “Battling the Extreme: A Study on the Power System Resilience,” *Proc. IEEE*, vol. 105, no. 7, pp. 1253–1266.

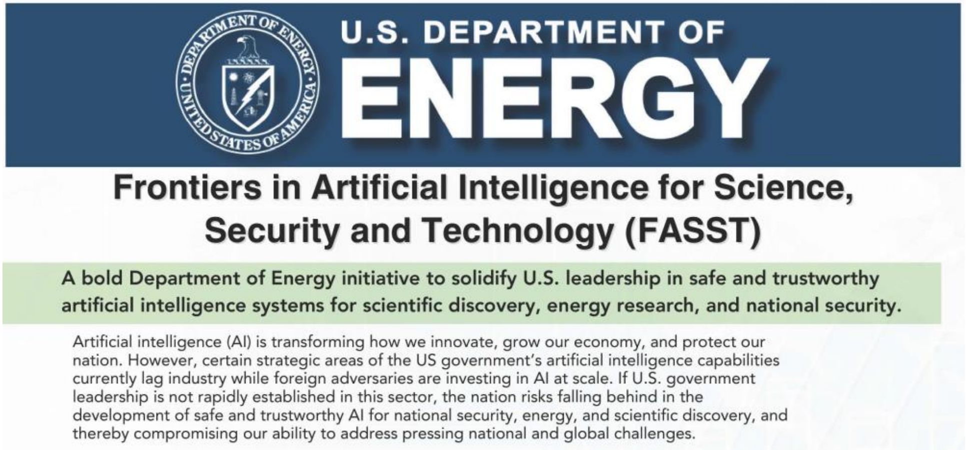
AI FOR CONTROLS APPLICATIONS

- Using AI for real-time controls requires processing large amounts of data very quickly
- Challenges with Applying AI for Controls
  - Many real-time power system controls applications operate sub-second to regulate the grid and maintain stability. Applying AI for controls applications requires processing large amounts of data size and significant computational effort
  - Uncertainty Quantification – How bad could the prediction/action be?
  - For controls applications, AI needs to be able to perform online learning, otherwise it will not be able to adapt to new situations
- Successful Applications of AI for Controls
  - Device control with reinforcement learning (generation, relays, substation)
  - Smart Home/Building control with reinforcement learning (HVAC, demand response, lighting)
  - Real-time forecasting with supervised learning (renewable generation, load)



CONCLUSIONS

- There are many promising applications of AI/ML in power systems.
  - It is an exciting time to be at this intersection – new algorithms, large datasets, computing power
- There are many challenging problems yet to be solved with some fascinating future research directions in ML for:
  - Integration of Physics-based Constraints into AI
  - Explainable AI and Uncertainty Quantification
  - Distributed AI-based Controls using Fog Computing
  - Semi-supervised, Few-shot learning, or Synthetically Generated Training Data


U.S. DEPARTMENT OF ENERGY

Frontiers in Artificial Intelligence for Science, Security and Technology (FASST)

A bold Department of Energy initiative to solidify U.S. leadership in safe and trustworthy artificial intelligence systems for scientific discovery, energy research, and national security.

Artificial intelligence (AI) is transforming how we innovate, grow our economy, and protect our nation. However, certain strategic areas of the US government's artificial intelligence capabilities currently lag industry while foreign adversaries are investing in AI at scale. If U.S. government leadership is not rapidly established in this sector, the nation risks falling behind in the development of safe and trustworthy AI for national security, energy, and scientific discovery, and thereby compromising our ability to address pressing national and global challenges.

SESSION OVERVIEW

This session of the ML/DL Workshop will cover a range of AI for Grid and Energy topics:

- AI for Grid Control – Miguel Jimenez Aparicio
- AI for Grid Resilience – Sam Ojetola
- AI for Clean Energy Integration – Joe Azzolini
- Machine Learning and Data Considerations for Distribution System Model Calibration Tasks – Logan Blakely
- Autoencoders for Cyber Physical Security – George Fragkos

MATTHEW RENO

MJRENO@SANDIA.GOV