FEBRUARY 13, 2024

3RD WORKSHOP: FOUNDATION MODELS FOR THE ELECTRIC GRID

RESEARCH HIGHLIGHTS FROM ENERGY SYSTEMS AND INFRASTRUCTURE ANALYSIS (ESIA) DIVISION

MODERNIZE THE GRID: BOTH BIG AND SMALL… AND WE NEED AI!

HENRY HUANG
Division Director, Interim Grid Program Lead
Energy Systems and Infrastructure Analysis (ESIA)
Argonne National Laboratory

U.S. DEPARTMENT OF ENERGY
Argonne National Laboratory is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC.

Argonne NATIONAL LABORATORY

One Argonne Approach: We deliver impact across the continuum from discovery science to technology deployment

PHYSICAL SCIENCES AND ENGINEERING

- Chemical sciences and engineering
- Materials science
- Nanoscience and technology
- Nuclear and particle physics

COMPUTING, ENVIRONMENTAL AND LIFE SCIENCES

- Biological and environmental science
- Computational science
- Data science and learning
- Mathematics and computer science

MCS

PHOTON SCIENCES

- Accelerator systems
- X-ray science

ADVANCED ENERGY TECHNOLOGIES

- Applied materials
- Energy systems and infrastructure analysis

ESIA

- Transportation and power systems

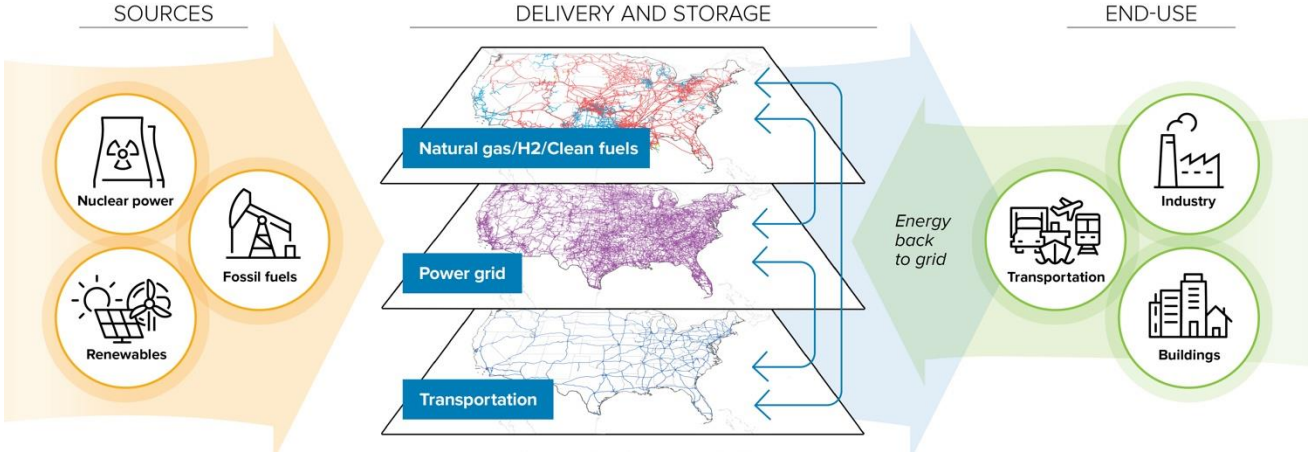
NUCLEAR TECHNOLOGIES AND NATIONAL SECURITY

- Chemical and fuel cycle technologies
- Decision and infrastructure sciences
- Nuclear science and engineering
- Strategic security sciences

SCIENCE AND TECHNOLOGY PARTNERSHIPS AND OUTREACH

- Academic and industrial partnerships
- Community STEM engagement
- Entrepreneurship programs
- Technology commercialization

ESIA: TOOLS AND ANALYSIS FOR MODERNIZING OUR GRID AND ENERGY SYSTEMS



Solar/wind resource forecasting and integration

Short- and long-term resource optimization

Thermal/hydro optimization

Energy storage

Stochastic short-term operations; long-term investment/expansion

Power market analysis; capacity expansion

Smart grid and microgrids

EV-grid interaction

Advanced Distribution Management/DERMs

Building efficiency and building/grid interaction

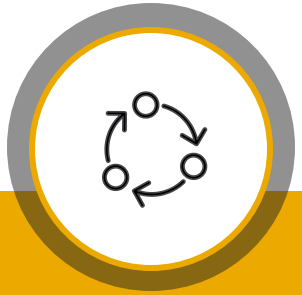
Grid resilience to external events

T&D co-simulation

Cyber security

Energy affordability metrics and analysis

ESIA RESEARCH AREAS (I)



LIFE CYCLE ANALYSIS/TECHNO-ECONOMIC ANALYSIS

Holistic and data-driven results to inform R&D decisions, policies, and economy-wide impact, including cost, energy, water consumption

HYDROGEN TECHNOLOGY ASSESSMENT

Leading evaluation of economic and environmental performance of H_2 supply chains and H_2 delivery options

TECHNOLOGY DEPLOYMENT AND ENERGY IMPACT

Guiding workforce development, supporting energy future, tracking outcomes, and informing policies

TECHNOLOGY MARKETS AND IMPACT ASSESSMENT

Tracking the trends and assessing the impact of EV adoption, energy technologies, supply chains, and their connections with energy and economics

ESIA RESEARCH AREAS (II)

POWER SYSTEMS & ELECTRICITY MARKETS

Optimizing system operations and capacity expansion, analyzing markets, and investigating potential energy pathways

ADVANCED ELECTRIC GRID MODELING

Empowering the sector with AI/ML optimization, control, simulation, cybersecurity, microgrids, asset health management

GRID STORAGE INTEGRATION & VALUATION

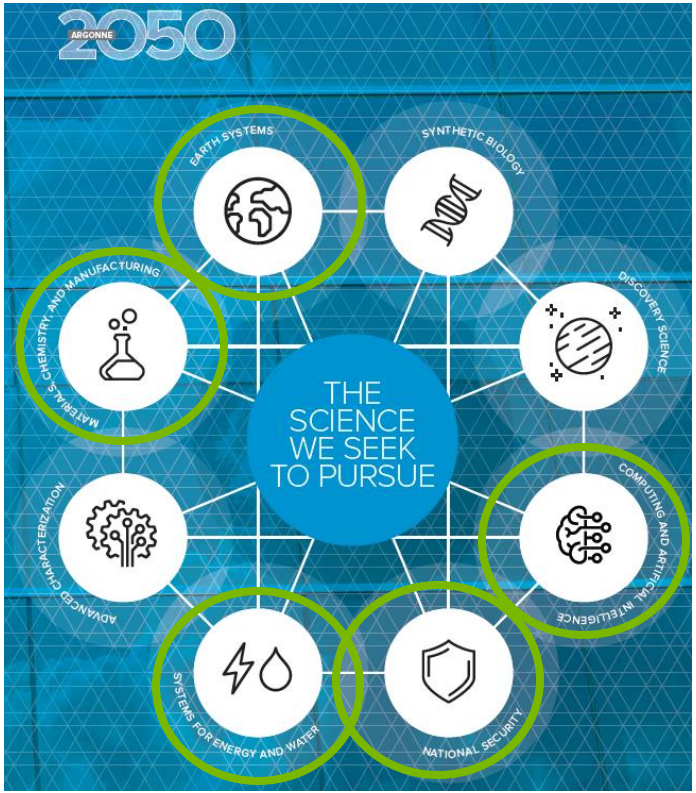
Enabling energy storage for grid integration and an affordable, reliable, and resilient grid

BUILDING & INDUSTRIAL TECHNOLOGIES

Analyzing building technologies and industrial systems to reduce energy use and accelerate technology adoption

THE GRID IS AN ARGONNE PRIORITY

The grid research directly supports five Argonne strategic objectives



ANL Strengths for Grid Research

- Math/computing/AI/ML methods and solvers for grid optimization and dynamics
- Transportation modeling and EV charging management supporting the grid
- Energy storage technologies and evaluation for grid applications
- Critical infrastructure vulnerability analysis, security, and interdependencies
- Weather/climate modeling and impact analysis
- Life cycle analysis for energy systems
- Materials and manufacturing scale-up
- Urban science applied to energy and the grid

STRATEGIC CONTEXT

The electric grid is facing significant changes across many vectors

Generation sources are changing and becoming more decentralized

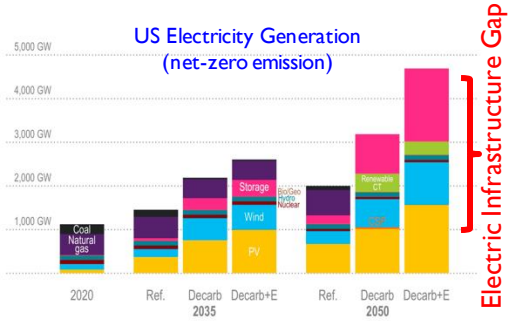
- > 1000 GW more renewables and > 900 GW energy storage, in the mix with nuclear, hydro, natural gas, etc.
- > 5x hydrogen and hydrogen-like fuels as an energy carrier
- > 2x grid to accommodate increasing demand and renewables

Demand profile is changing and forecasted to grow

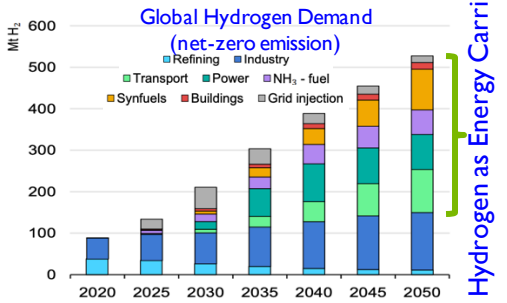
- > 2x demand growth due to electrification (electric vehicles, buildings, industrial) and data centers
- Millions of grid edge players

Resilience and adaptation needs are increasing

- Increasing natural and manmade threats, including weather-related uncertainties and extreme events.
- Long lead time in supply chains



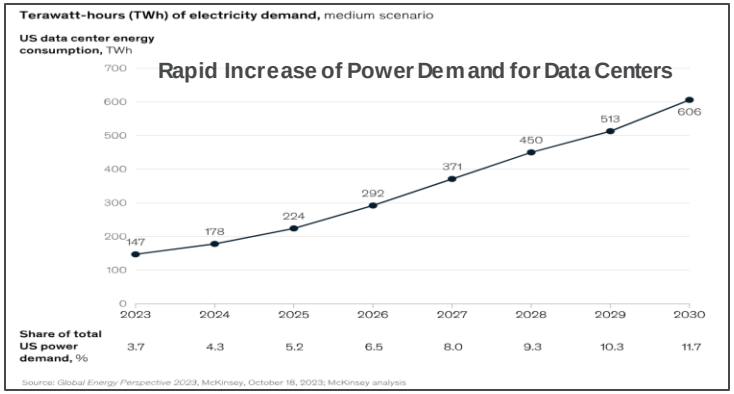
Credit: DOE EERE SETO Solar Futures Study 2021.

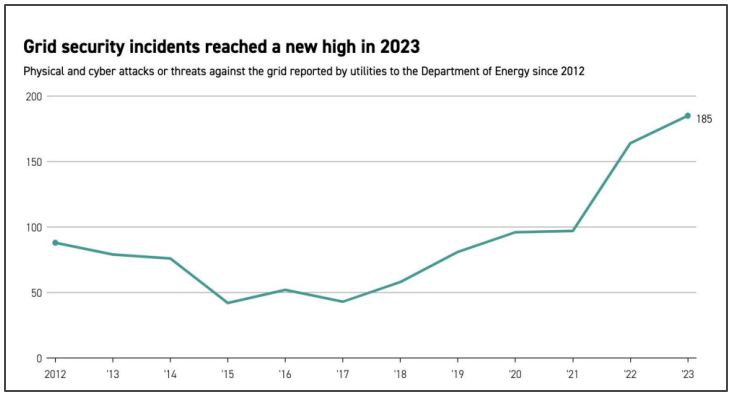


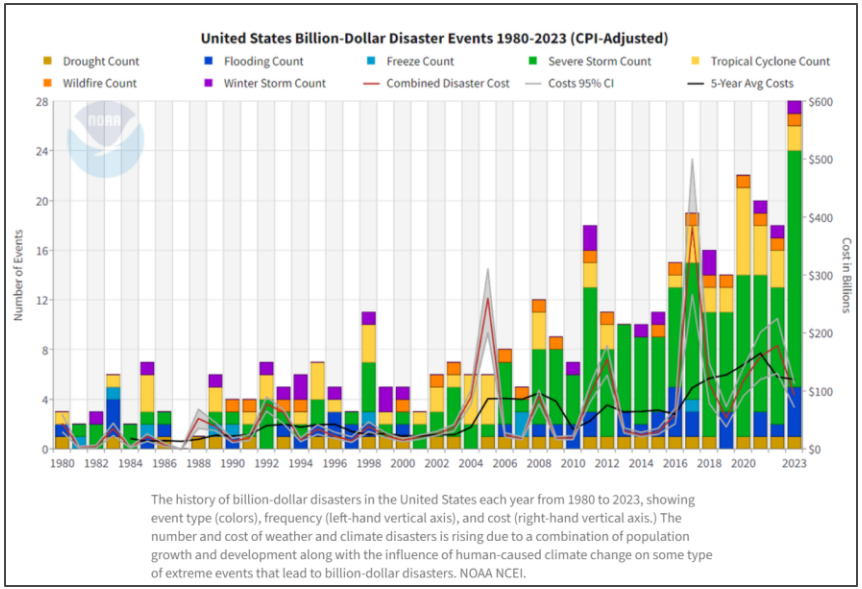
Credit: IEA Global Hydrogen Review 2021.

STRATEGIC CONTEXT

Disruptive trends continue to emerge that are difficult to forecast







Sources: McKinsey, Global Energy Perspective 2023 | DOE | NOAA

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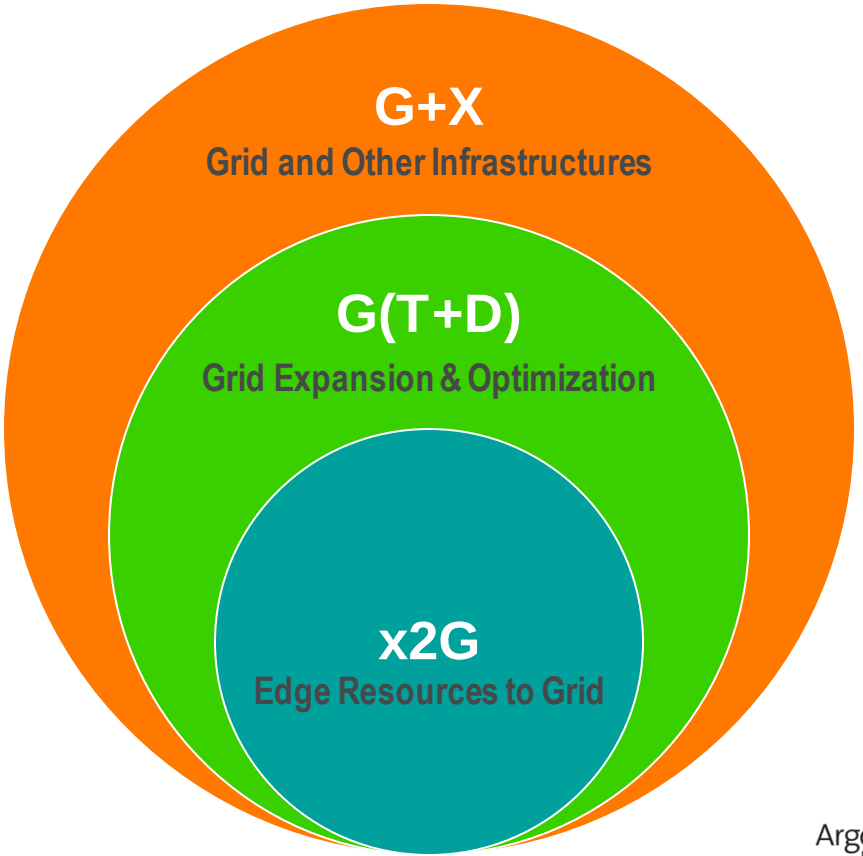
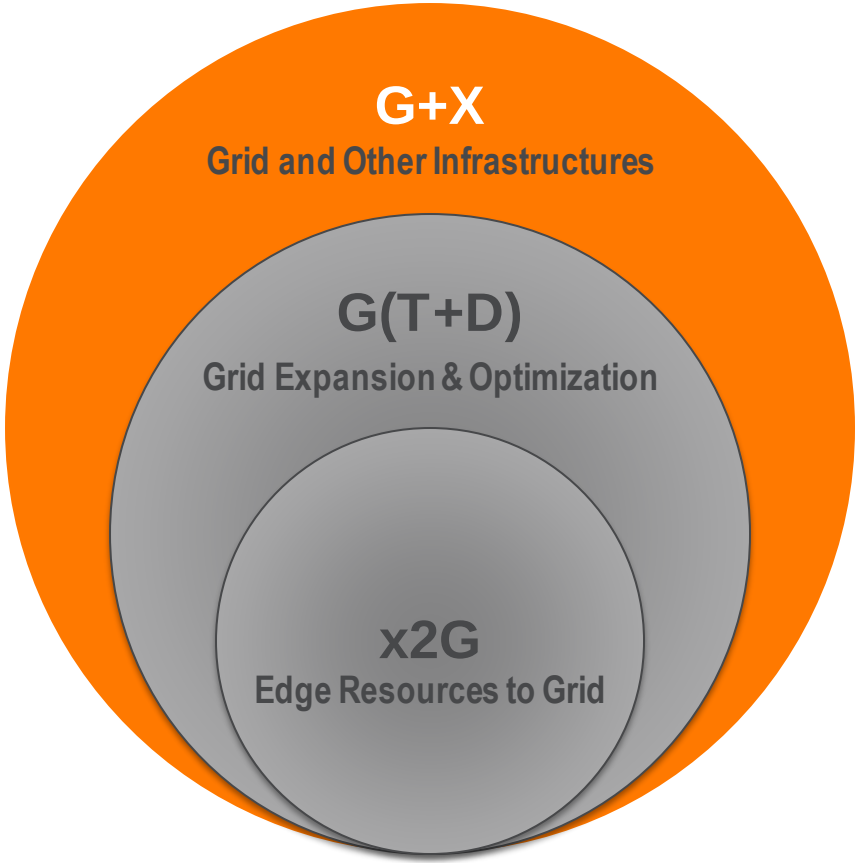
CHALLENGES AND RESEARCH NEEDS FOR A CLEAN AND SECURE ENERGY FUTURE

Challenges:

- Understand and manage increasing interdependency of energy systems – power systems, natural gas/hydrogen systems, communications, transportation systems , weather/climate, …
- Enable unprecedented grid expansion, control, and optimization for both transmission and distribution.
- Integrate and incentivize millions of diverse grid edge assets with mixed ownership.

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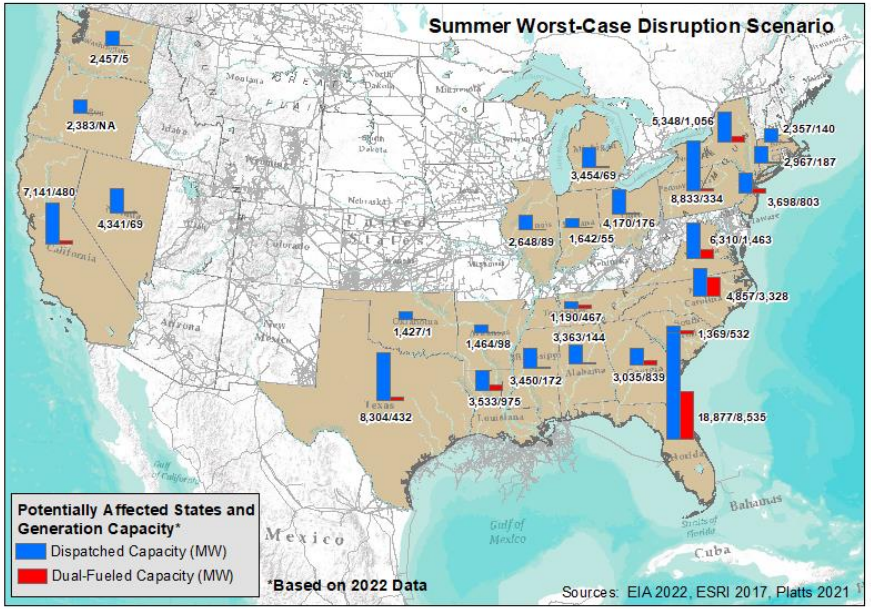
NAERM: NATURAL GAS DISRUPTION RELIABILITY IMPACTS

Reliability Need

Assess bulk electric reliability impacts for all interstate natural gas pipeline contingencies so that NERC can readily calculate the risk to summer reserve margins.

Results

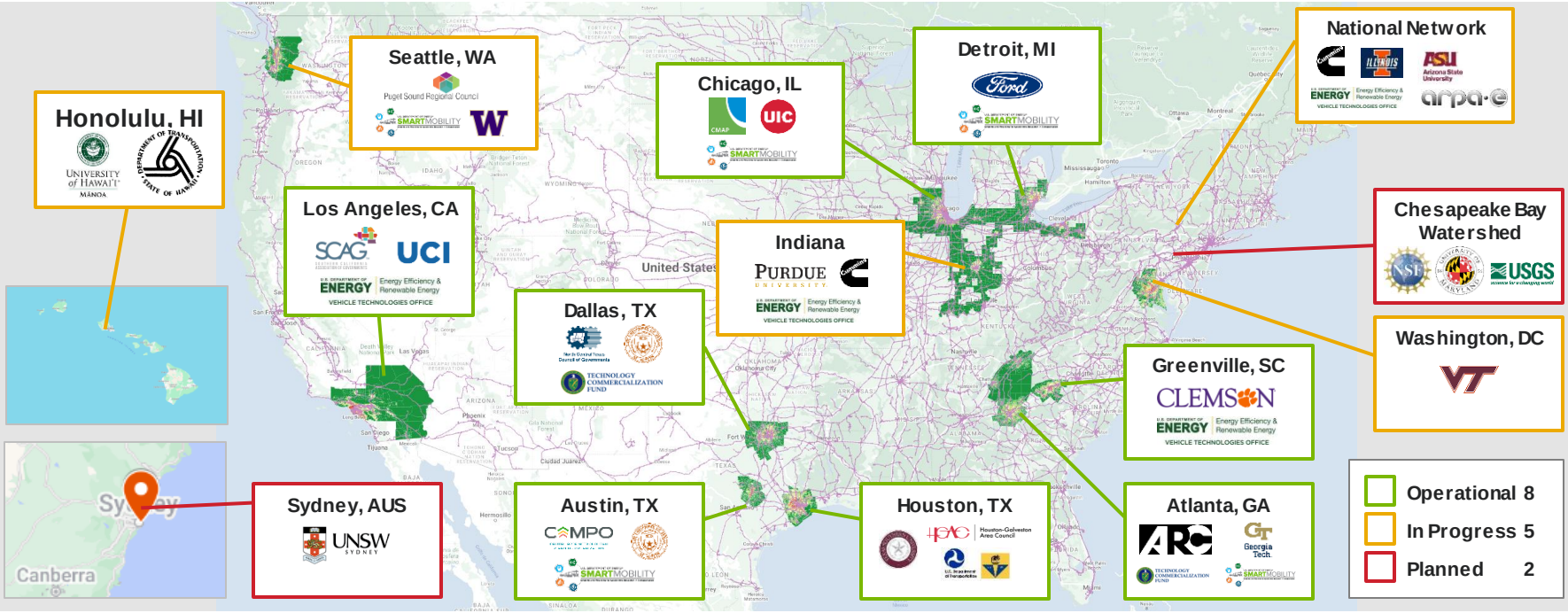
Estimated natural gas power plant capacity impacts under worst case scenario (i.e., no mitigation) and with compensation through underground storage, LNG, pipeline interconnects, and LDC contracts.



NGFast: a simulation model for rapid impact assessment of natural gas pipeline breaks and flow reductions

POLARIS: EXTENSIVE, NATIONWIDE TRANSPORTATION SYSTEM MODEL

Fourteen operational and planned models connected by national networks



EXTREME WEATHER EVENT ANALYSIS THROUGH HYPER-LOCAL MODELING

Weather-related threats can be assessed by **historical** events or **future** projections using Argonne's Advanced Climate Model (ClimRR, https://climrr.anl.gov/)

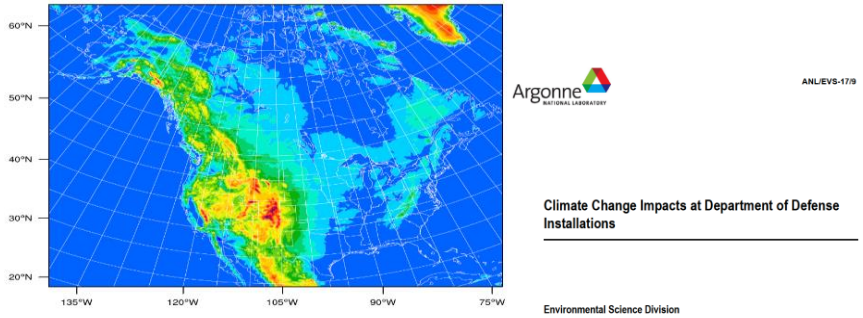
HIGHEST RESOLUTION climate model over all North America

Spatial resolution: **12 km** (soon 4km)

Temporal resolution: 3 hours

Amount of data: **330+ years** of model simulation output

Data size: 8.8 GB/day; **700+ TB**

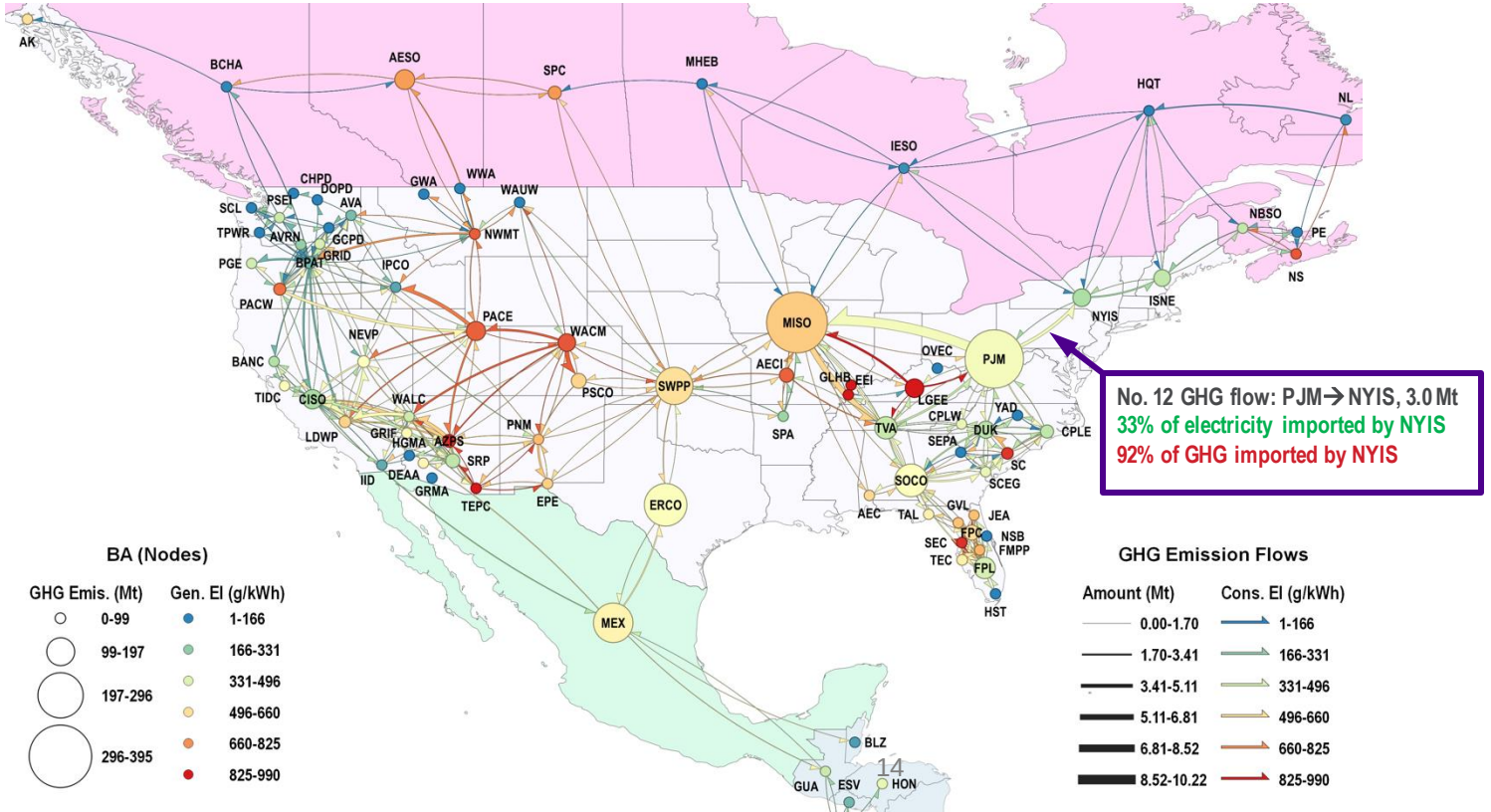


Risk Projections at Neighborhood Scale

Predicted inland 100-year water depth

GREET: LIFE CYCLE ANALYSIS OF ENERGY CONSUMPTION, WATER USAGE, AND POLLUTION

https://www.energy.gov/eere/greet



2020 Example

Total emissions
1671.6 Mt

Total transfer
165.8 Mt (9.9%)

Top emitters
MISO, PJM, ERCO

Top exporters
PJM, BPAT, AZPS

Top importers
MISO, CISO, AZPS

Top emission flows
PJM to MISO
LDWP to CISO
SRP to AZPS

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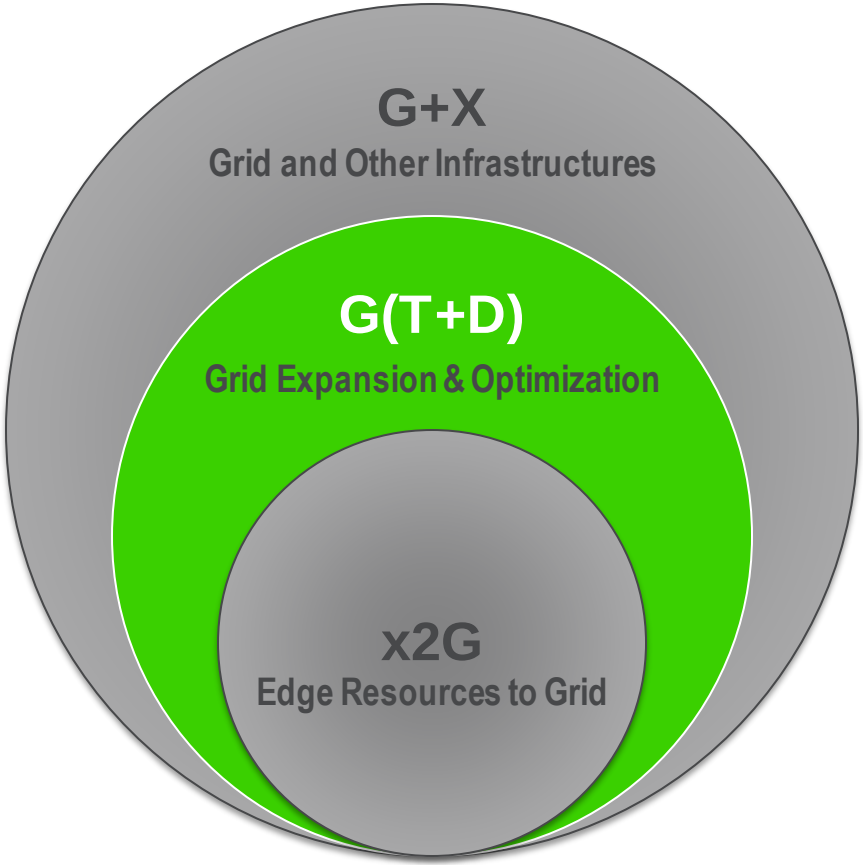
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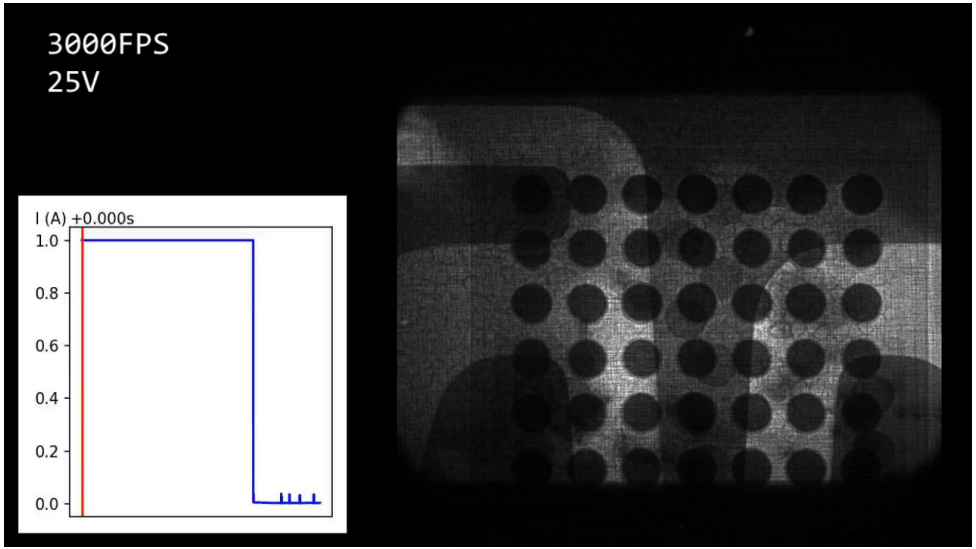
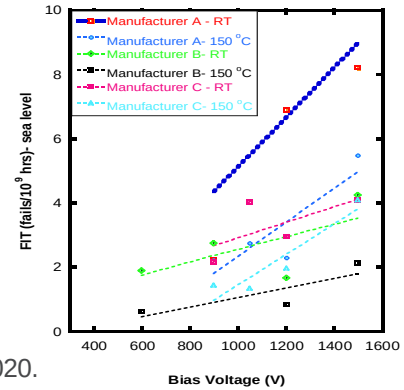
IN-SITU TESTING OF NEXT-GENERATION WIDE BANDGAP GaN POWER ELECTRONICS

Material testing using Argonne's Advanced Photon Source



5KV platform for harsh environment test

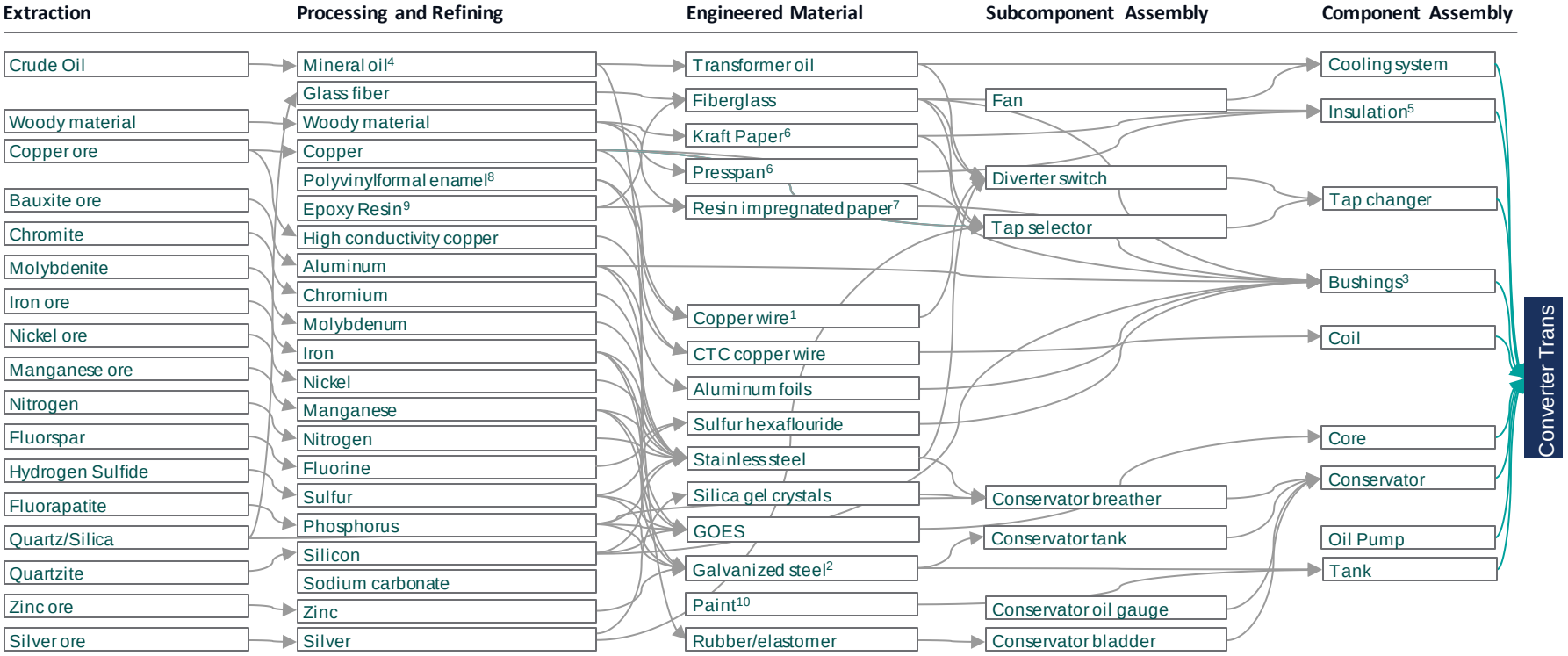


M. Ahmed *et. al.*, U.S. Patent No. 11493548

M. Ahmed *et al.*, Proc. 2020 NSREC Data Workshop, paper no. 187, 2020.

SUPPLY CHAIN MAPPING

EXAMPLE: CONVERTER TRANSFORMER (250 MVA)



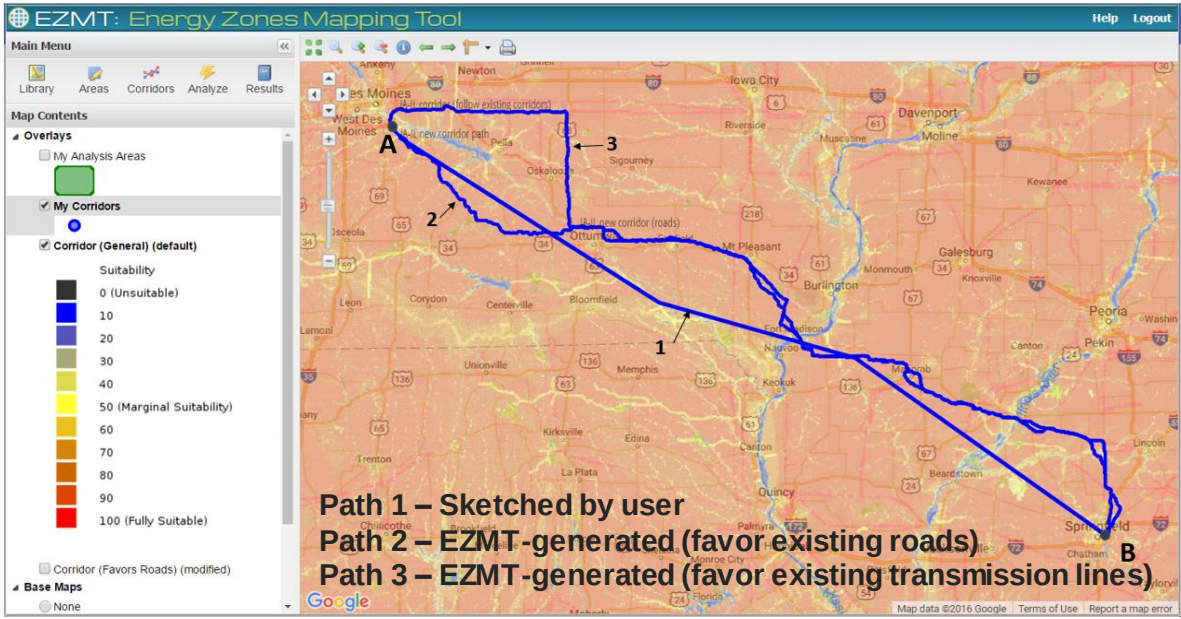
Notes: 1. Alternatives: Aluminum wire 2. Alternative: Aluminum 3. Alternatives: Bushings can also be filled with dry insulation materials (e.g., polyurethane elastomer) 4. Alternatives: Natural ester, silicone oil, synthetic ester, mixed insulating oil (e.g., soybean oil with mineral oil) 5. Alternatives: Core insulation can also be gas 6. Alternatives: Nomex, Denison, corrugated papers 7. Bushings can also beinsulated by oil impregnated paper 8. Alternatives: Polyester, polyimide, PAI, polyesterimide enamels 9. Epoxy Resin can made of Epichlorohydrin (ECH), Bisphenol-A (BPA), Aliphatic glycols, Phenol, o-Cresol novolacs, Caustic soda (20–40% solution), Methylisobutylketone (MIBK) 10. Liquid paint compound example: n-Butyl Acetate, Methyl n-Amyl Ketone, Aspartic Ester, 2-Ethyl-1,3-hexanediol, 2-methoxy-1-methylethyl acetate, UV Light Absorber, Benzotriazole Hydroxyphenyl Polymer, Bis(pentamethyl-4-piperidyl)sebacate, Butyl Methacrylate, 2-Hydroxyethyl Methacrylate, Methyl Methacrylate, Methyl pentamethylpiperidyl sebacate, Medium Aliphatic Hydrocarbon Solvent, Xylene (mixed isomers)
Source: BCG SWITCH-gt modeling and analysis

GEM: FOR CORRIDOR AND RESOURCE SITING/ROUTING

- >240 layers of environmental, geological, and societal information.
- DOE Grid Deployment Office using GEM for siting NIETCs
  - CITAP version of GEM is publicly available at: https://gem.anl.gov/tool/citap

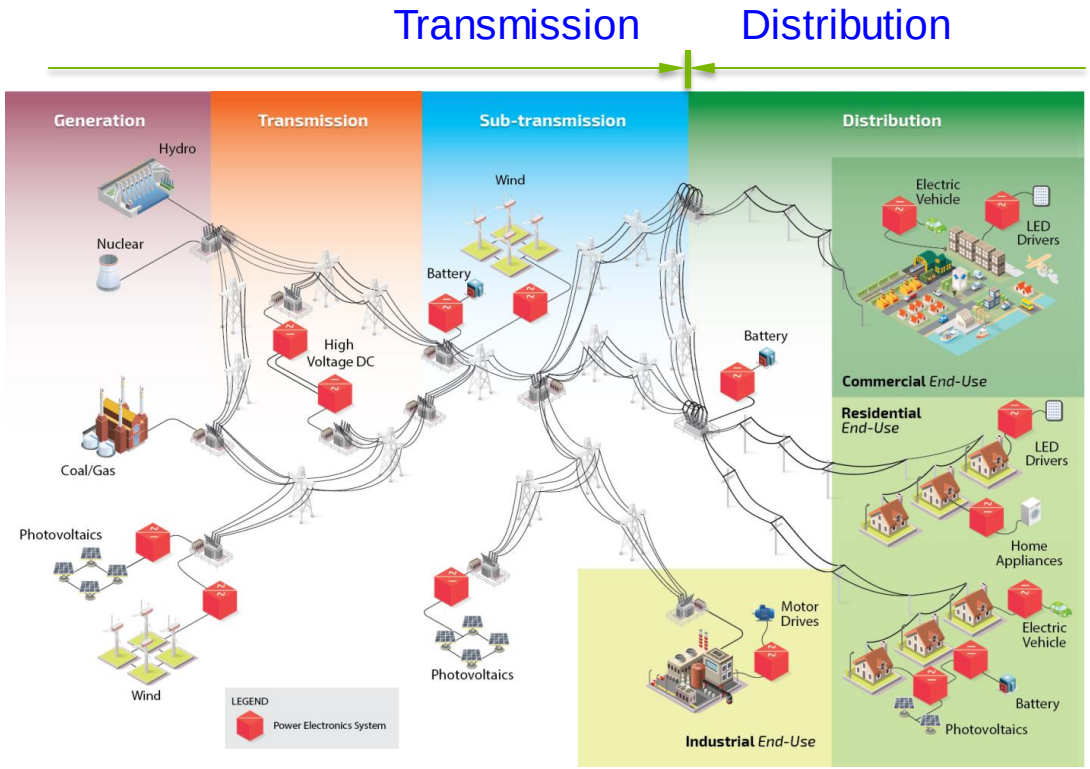
Coordinated Interagency Transmission Authorizations and Permits Program

Grid Deployment Office



Geospatial Energy Mapper (GEM)

TDcoSIM: TIGHTLY COUPLED TRANSMISSION AND DISTRIBUTION CO-SIMULATION



- **Support static and dynamic simulation**
- **Built-in data visualization and data analytics tools**
- **Capable of simulating large interconnections (Over 250,000 T&D nodes)**

- **Software Implementation**
  - Python based interfaces for T&D and D&DER
  - Python-based Dynamic DER model
  - OpenDSS for Distribution
  - PSS®E for Transmission (Siemens)

MIPLEARN: AI-ENHANCED MIXED-INTEGER OPTIMIZATION

Motivation:

- Grid optimization have become increasingly complex and hard to solve. Classical approaches provide only incremental improvements; AI-based efforts discard important feasibility and optimality guarantees.

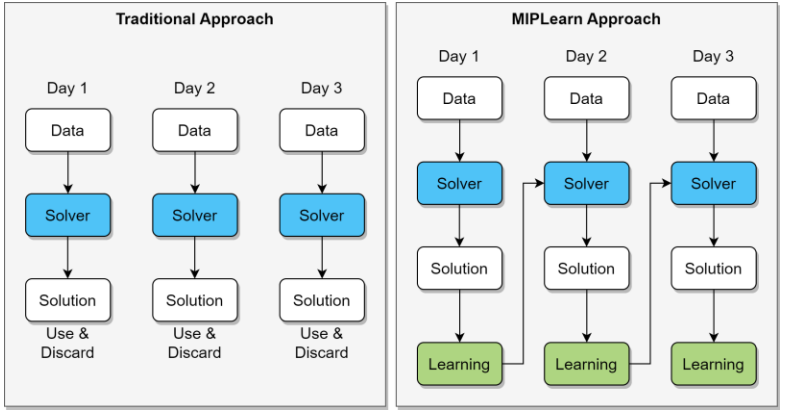
Technical Approach:

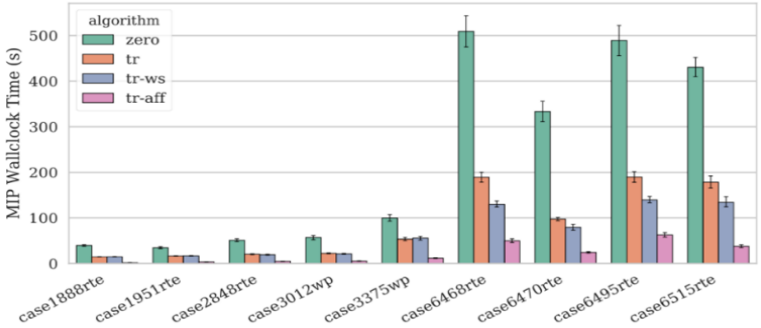
- Use AI to *accelerate* (instead of *replace*) existing state-of-the-art mathematical solvers, which are already trusted by the industry.
- AI guides solver towards the solution faster using data-driven adaptive search strategies while maintaining guarantees.

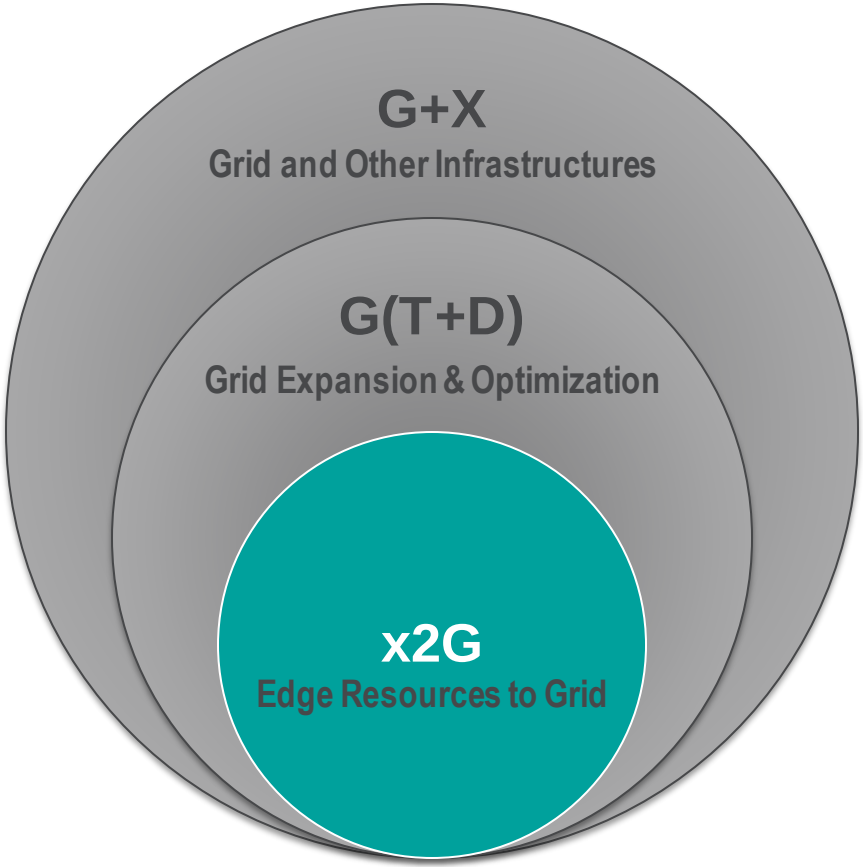
Impact:

- 5-10x speedups in *large-scale power systems* applications;
- Open-source framework compatible with multiple solvers (Gurobi, CPLEX, XPRESS) and modeling languages (Gurobipy, Pyomo, JuMP)

Repository: github.com/ANL-CEEESA/MIPLearn



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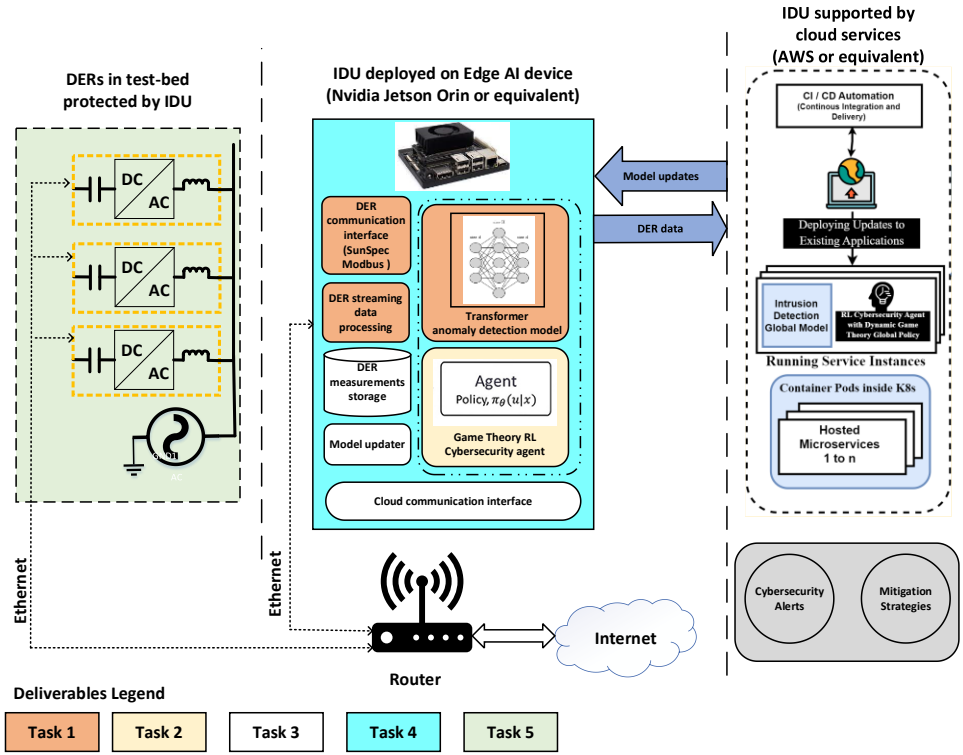
HIL FOR ADAPTIVE DER CYBERSECURITY

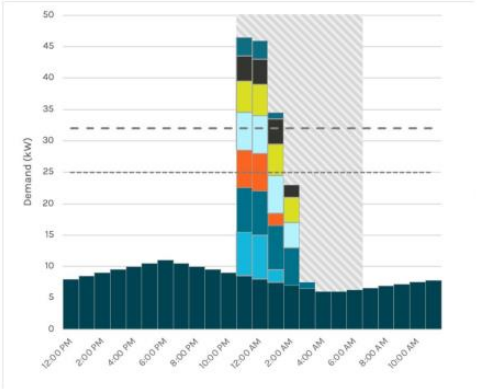
- **New Approach**: A Game-Theoretic and Machine Learning Approach for Real-Time Threat Detection and Mitigation
- **Low cost implementation**: Intrusion diagnostic unit (IDU) deployed on an edge computing device ("plug-and-play") for real-time monitoring, detection, and mitigation of cybersecurity threats
  - Incorporating dynamic game theory, RL, and transformer architecture to develop passive and adaptive defense mechanisms.
  - Updating detection models using federated learning.



IMPACT OF LARGE-SCALE UTILITY-MANAGED SMART CHARGING

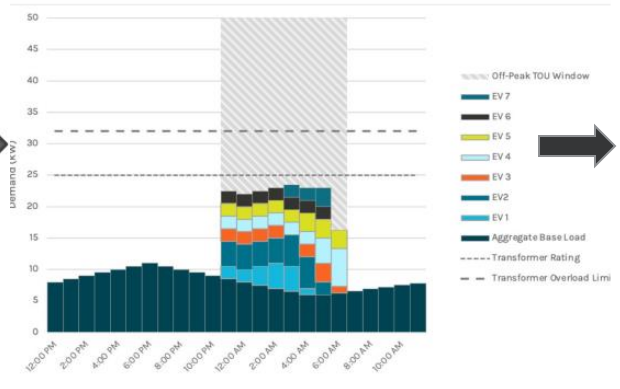
- ATEAM (Agent-based Transportation Energy Assessment Model): Integrated simulation platform to evaluate the impact to the grid and consumers

TOU-OPTIMIZED CHARGING



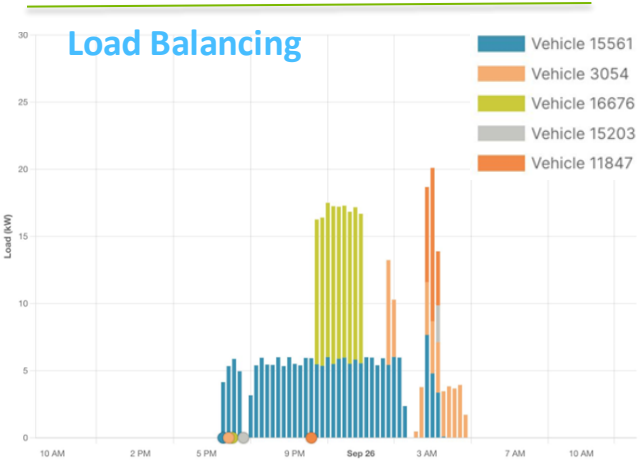
- Charging starts when TOU starts, resulting in stress on distribution infrastructure

DISTRIBUTION-OPTIMIZED CHARGING



- Charging starts when plugged in but with an adjusted charging speed

Load Balancing



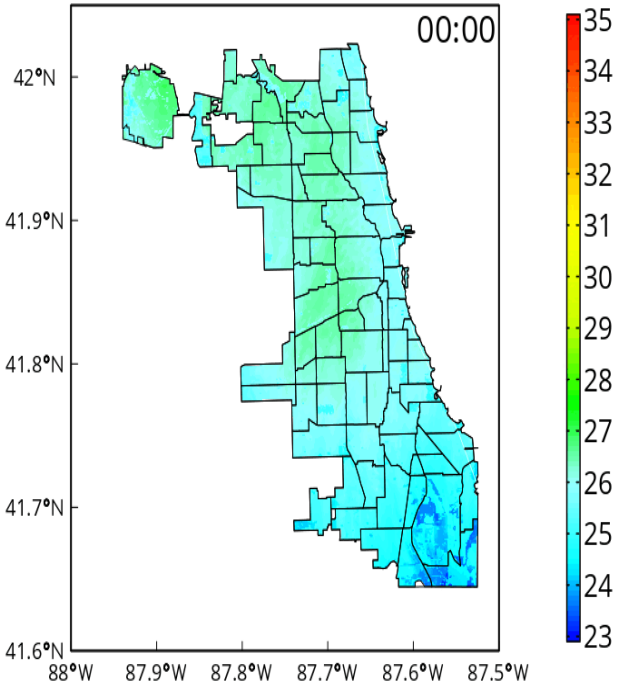
- Manage charging start time and balance the load to reduce peak demand and stress on distribution infrastructure.

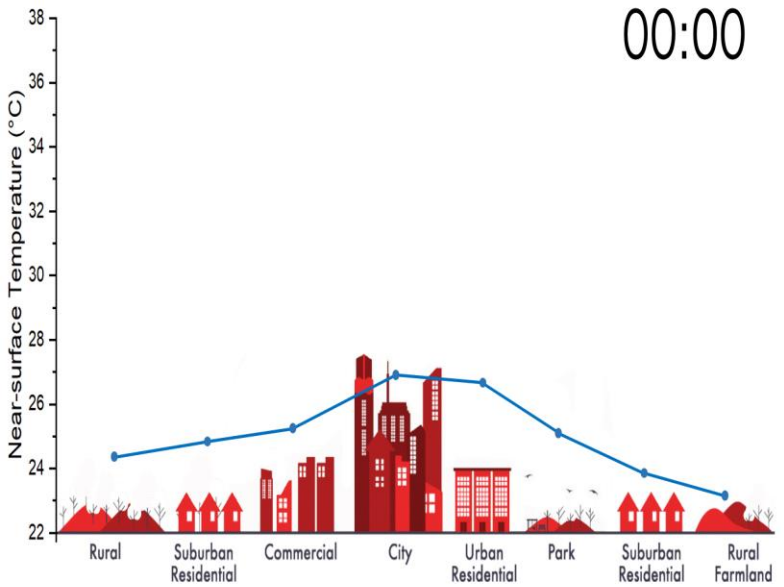
Figure Credits: WeaveGrid

POC: Joann Zhou, ANL

STREET SCALE SIMULATION OF TEMPERATURES

CROCUS
Community Research on Climate & Urban Science



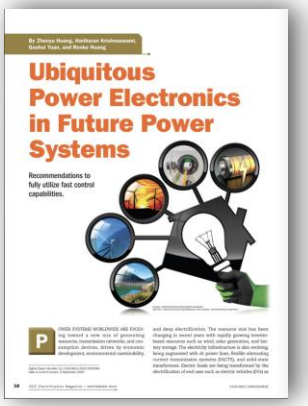


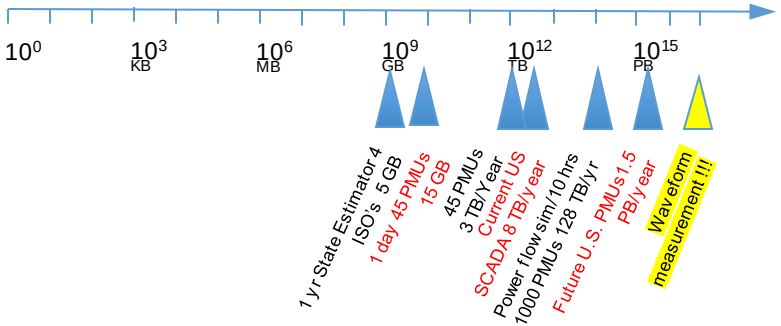
Source: Haochen Tan, Argonne National Laboratory

WHERE IS AI IN THE GRID?

- AI for large-scale grid optimization
- AI for extreme weather modeling and impact on the grid
- AI for charging management in transportation electrification
- AI for prognostics-based health management of grid assets
- AI for load forecasting, esp. smart loads and net loads
- AI for renewable forecasting at all levels
- AI for cybersecurity detection and defense
- …

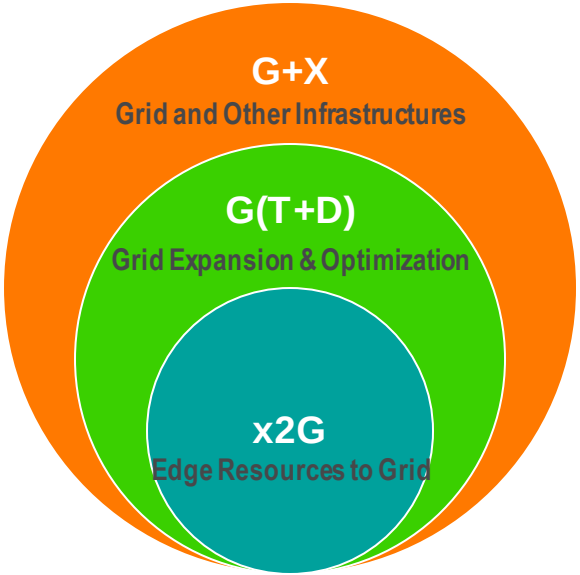
Grid data explosion!





WHERE NEEDS MORE AI IN THE GRID?

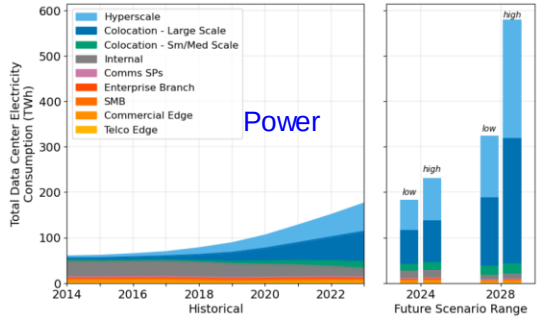
- Bring them all together → GridFM!
  - Multi-Sector Physics
  - Multi-Variate Modeling
  - Multi-Modal Data
- Example Use Case: Assessing impact of impending extreme events on the grid
  - Satellite weather images, weather forecasting with uncertainty intervals
  - Grid sensor data, grid models, grid structural data
  - GIS, topo maps
  - social media posts
- Another Example Use Case: Vegetation Management
  - …

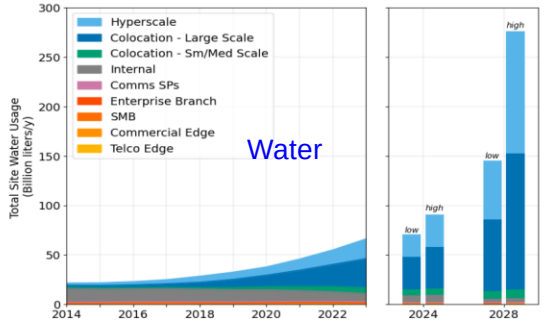


THE OTHER STORY:

AI NEEDS THE GRID AS MUCH AS THE GRID NEEDS AI

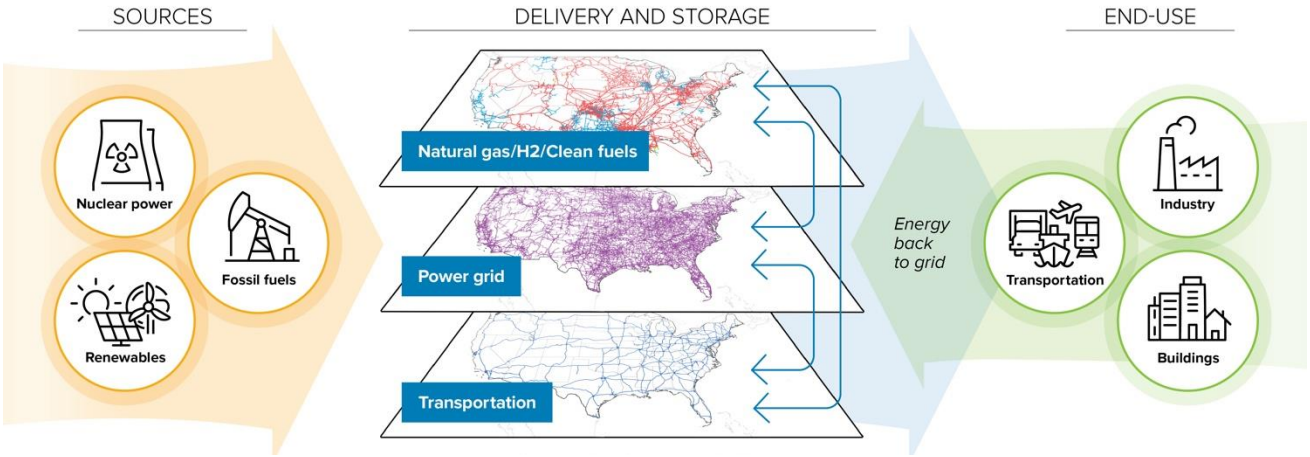
- **AI needs power!**
  - An "AI+Power+Water" nexus and a co-design opportunity!
    - Siting, permitting, grid reliability, water availability, contingency planning, economic and societal impact, …
    - This can be another GridFM use case.





Source: LBNL. 2024

TOGETHER WE CAN TACKLE THE FUNDAMENTAL ENERGY INFRASTRUCTURES AND SYSTEMS CHALLENGE!

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