DOE SETO Workshop Solar Applications of Artificial Intelligence and Machine Learning

Energy system digitization in the era of AI: A layered approach towards carbon neutrality

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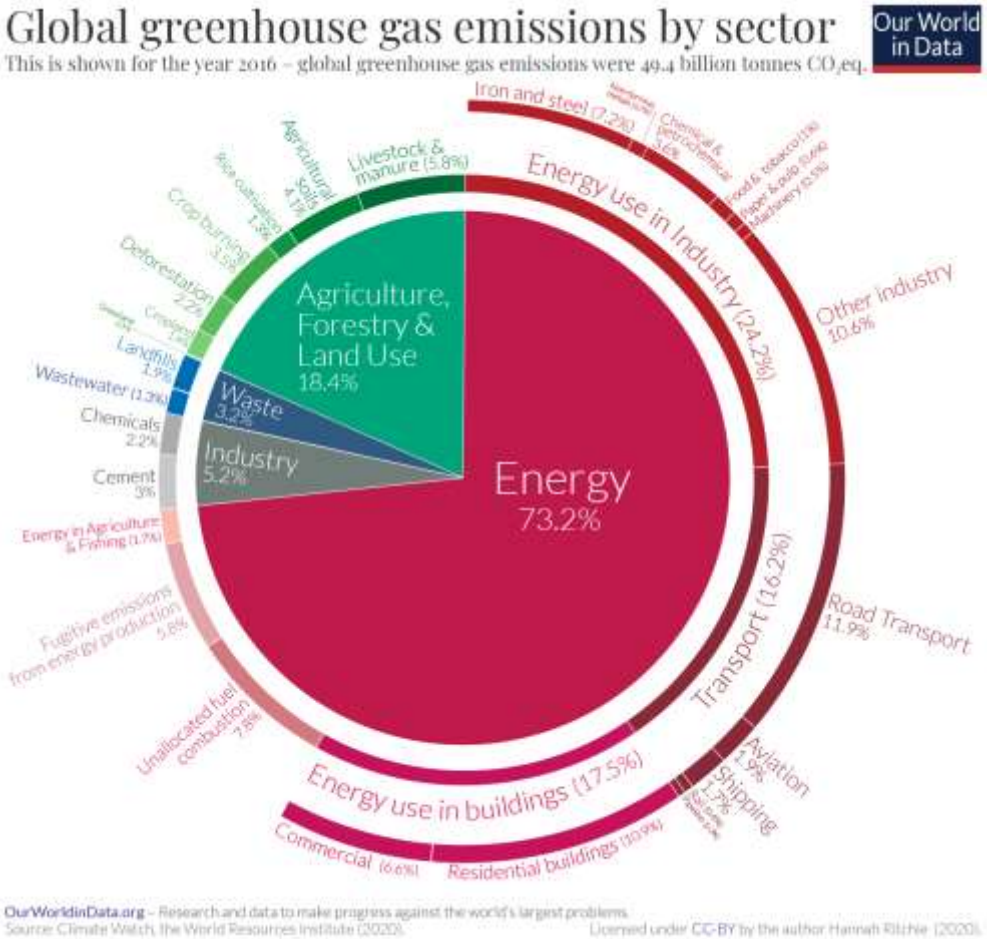
October 31, 2023

Tackling Climate Change: Scale and Speed Matters!



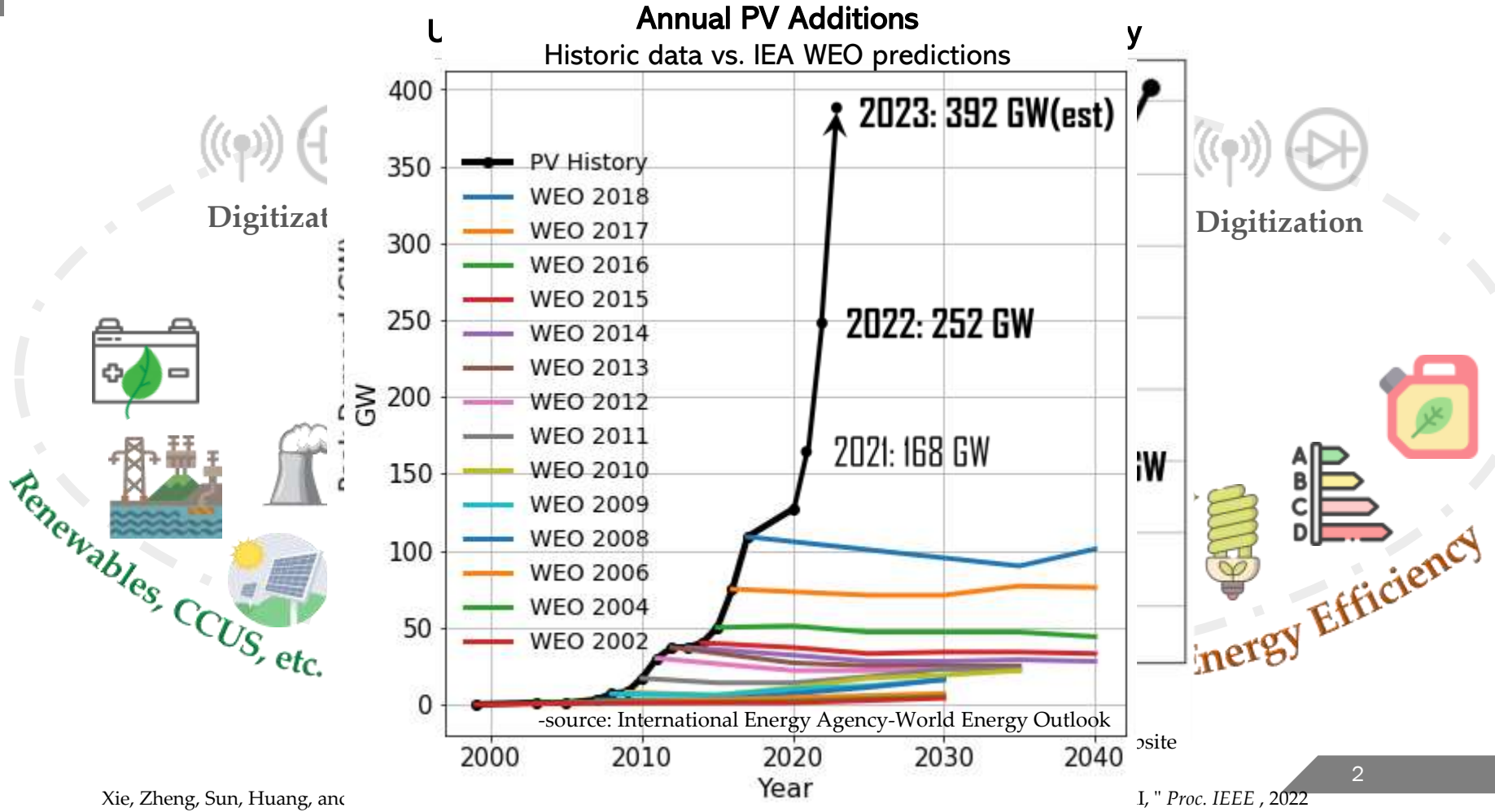
800 $GtCO_2$

40 $GtCO_2$/year

20 Years

Source: IPCC 2021

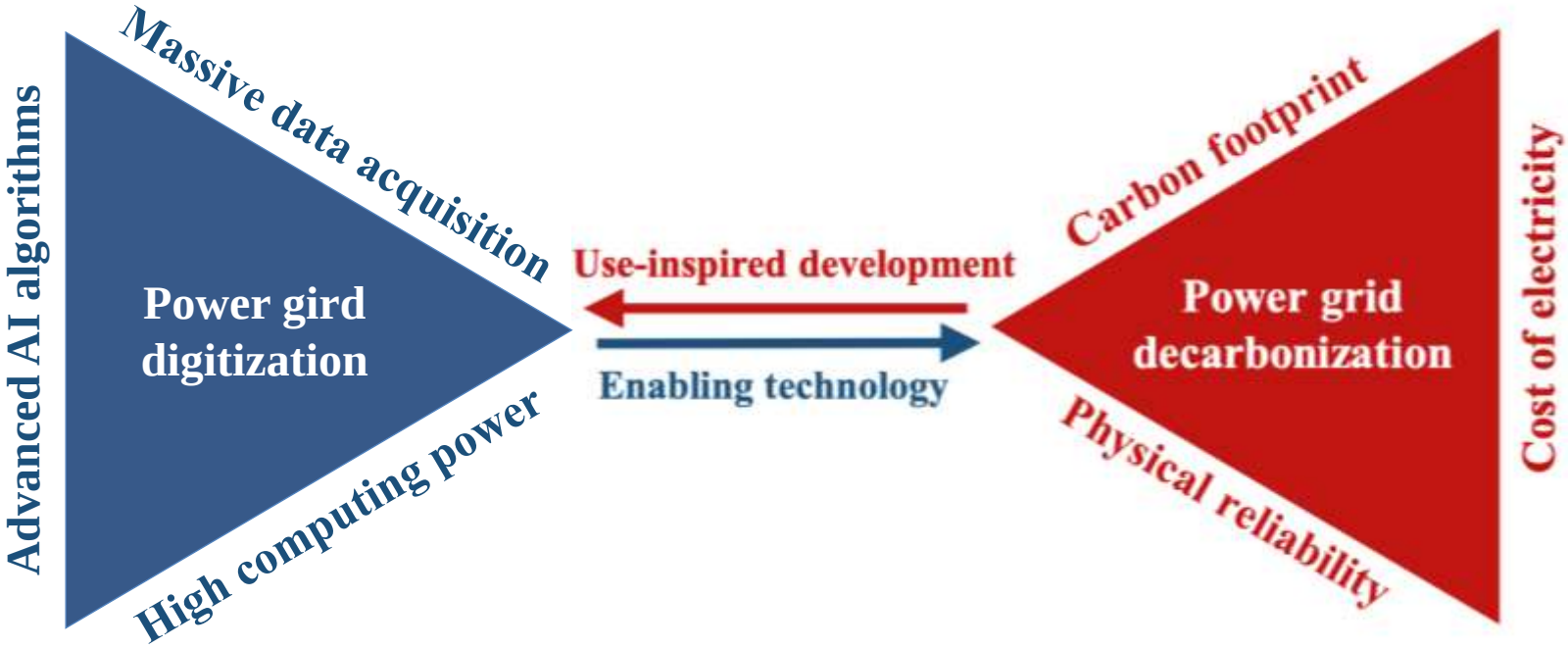
Energy Sector Decarbonization



Xie, Zheng, Sun, Huang, anc

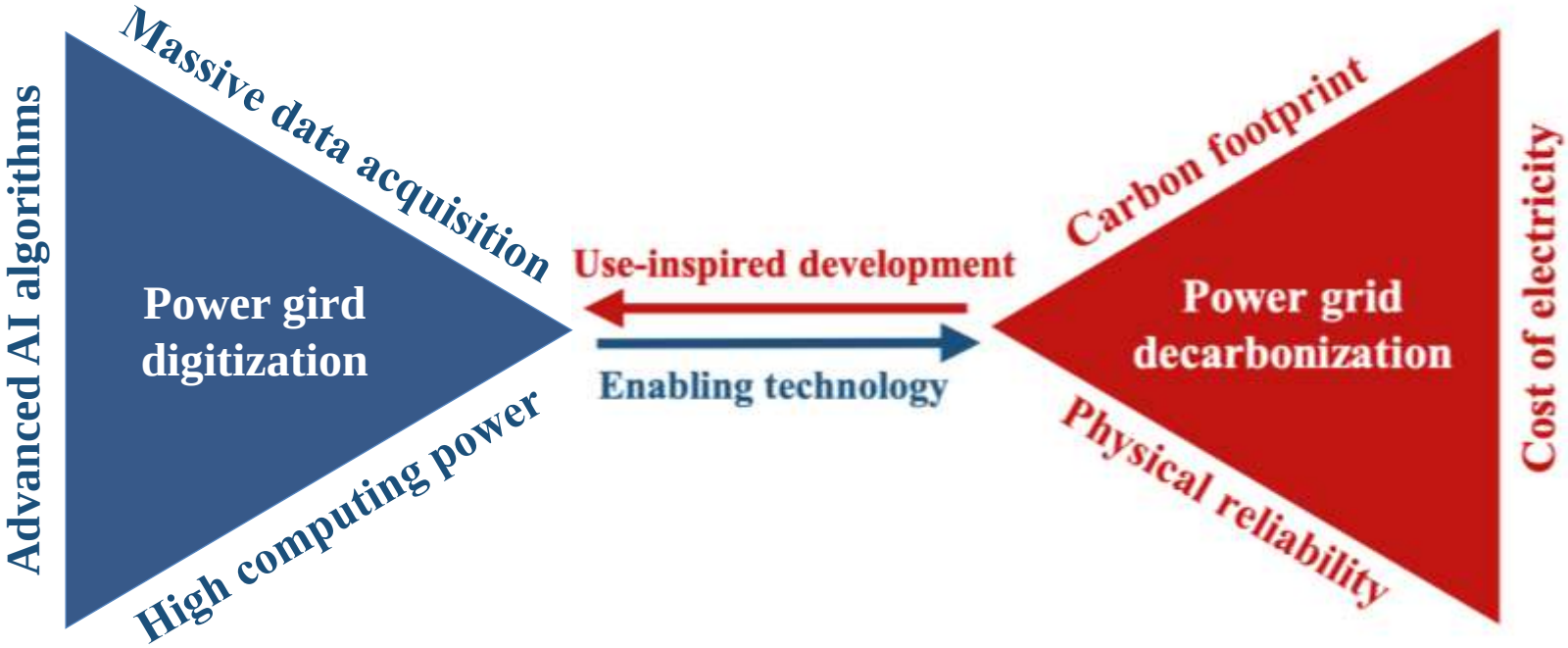
I, " *Proc. IEEE* , 2022

Tri-factors of Massively Digitized Power Grids



Xie, Zheng, Sun, Huang, and Bruton. "Massively Digitized Power Grid: Opportunities and Challenges of Use-inspired AI, " *Proc. IEEE* , 2022.

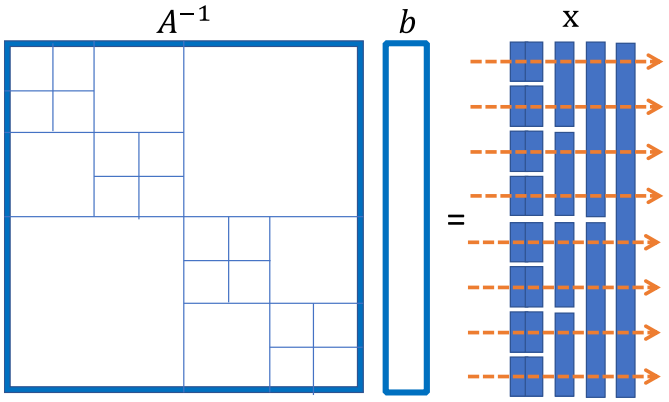
High Computing Power



Xie, Zheng, Sun, Huang, and Bruton. "Massively Digitized Power Grid: Opportunities and Challenges of Use-inspired AI, " *Proc. IEEE* , 2022.

Faster EMT Simulation (10X) in Solar-rich Grids

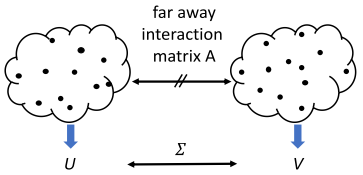
Parallelizable network solver $x = A^{-1}b$



Speed up computation

Reduce computation complexity

SVD based hierarchical low-rank approximation

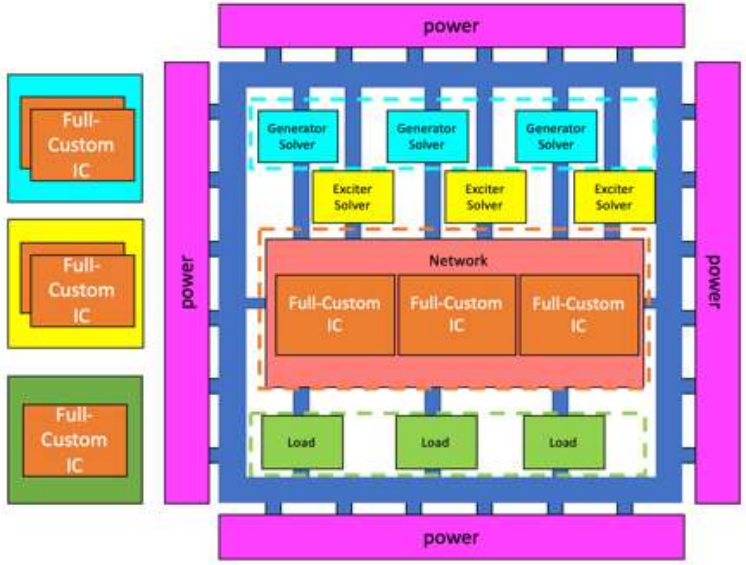


Truncated SVD

$$A = U\Sigma V^* = \sum_{i=1}^{p} \sigma_i u_i v_i^*$$

$$\tilde{A} = \tilde{U}\tilde{\Sigma}\tilde{V}^* = \sum_{i=1}^{r} \sigma_i u_i v_i^*, (r < p)$$

VLSI techniques: Application-specific-integrated-circuit (ASIC)

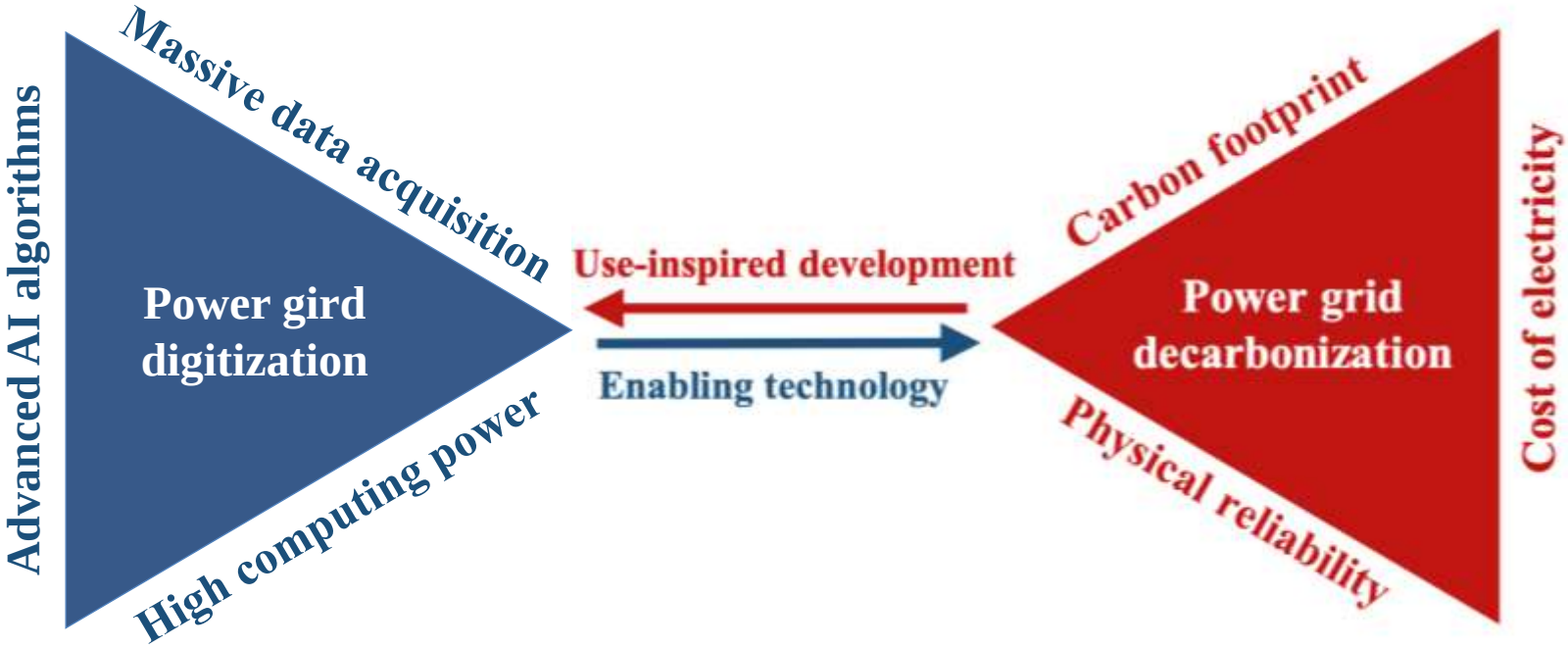


Target >10X faster!

Zhang, **Xie**, et al. "A hierarchical low-rank approximation based network solver for EMT simulation." IEEE Transactions on Power Delivery (2020)

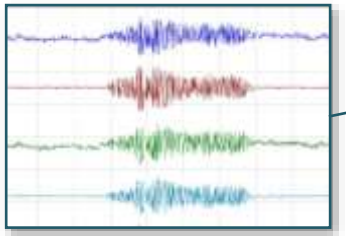
Ongoing **SETO** Project Entitled "Scalable Multi-Timescale Analysis Platform Based on System Transient and Dynamic Model"

Massive Data Acquisition

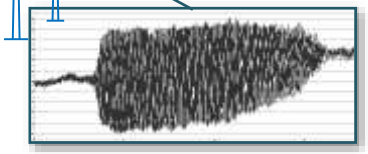


Xie, Zheng, Sun, Huang, and Bruton. "Massively Digitized Power Grid: Opportunities and Challenges of Use-inspired AI, " *Proc. IEEE* , 2022.

Instability in the Form of Oscillations

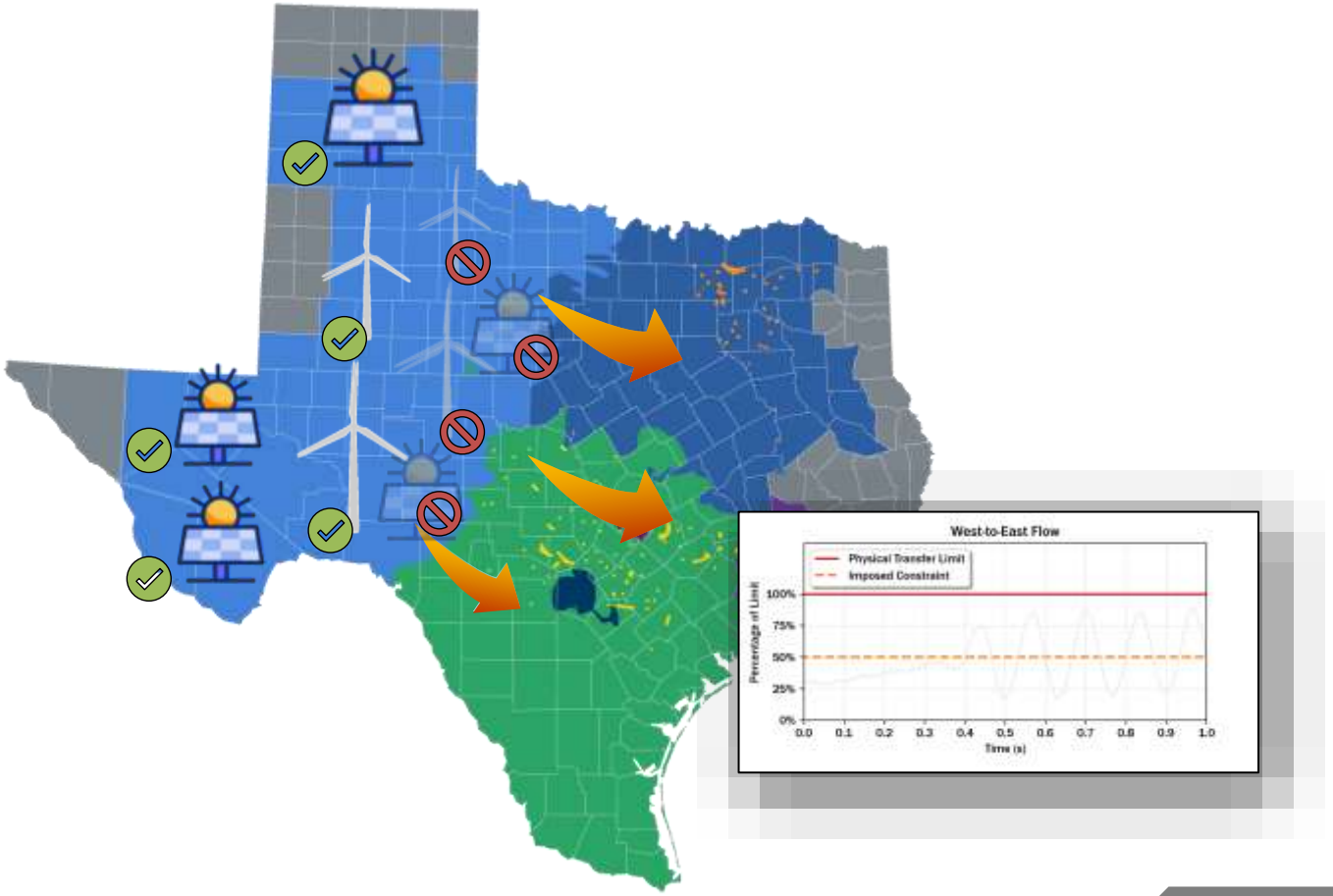


- 7 Hz oscillation
- 550 MW solar plant
- California



- 1.3 Hz oscillation
- New England area

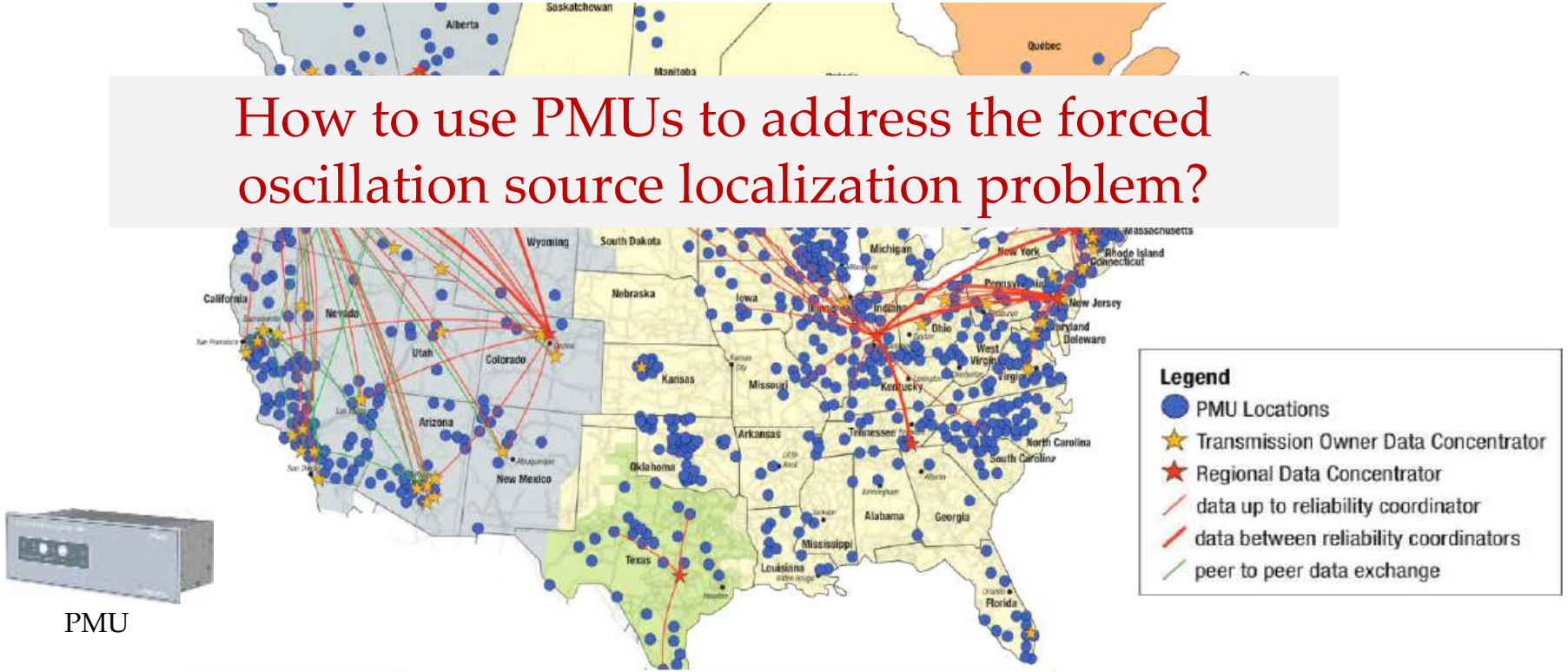
Impact of Instability: Transfer Limit Reduced



ERCOT GTC: https://www.ercot.com/files/docs/2020/10/07/05.__WESTEX_GTC_ROS_10_08_2020.pdf

Deployment of New Sensors

Distribution of Phasor Measurement Units (PMUs) in North America

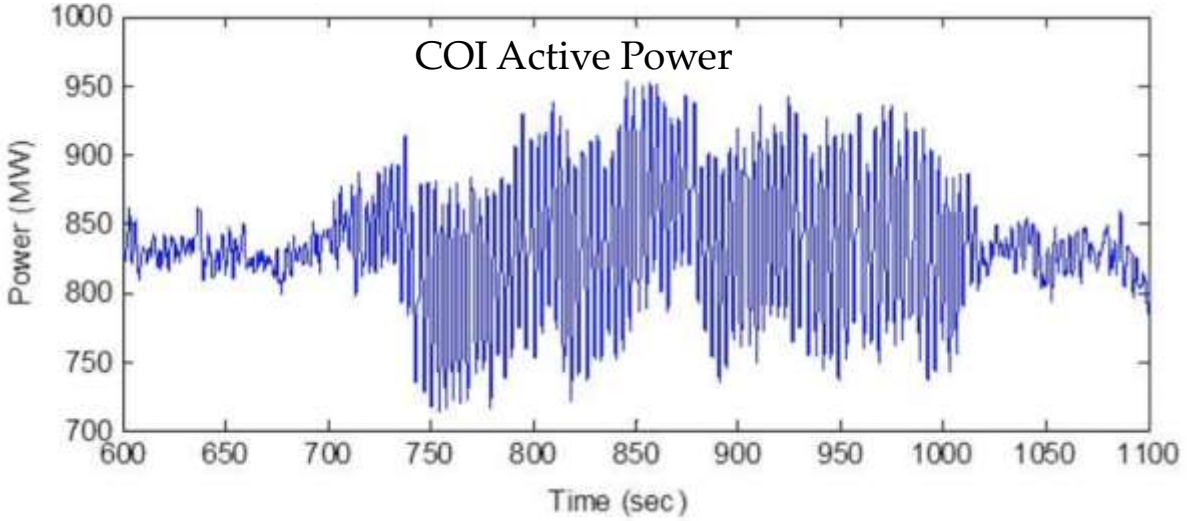


How to use PMUs to address the forced oscillation source localization problem?

PMU

Image source: https://www.naspi.org/sites/default/files/reference_documents/33.pdf?fileID=1326,
https://www.scopetnm.com/protection-solutions/phasor-measurement-unit/11-protection

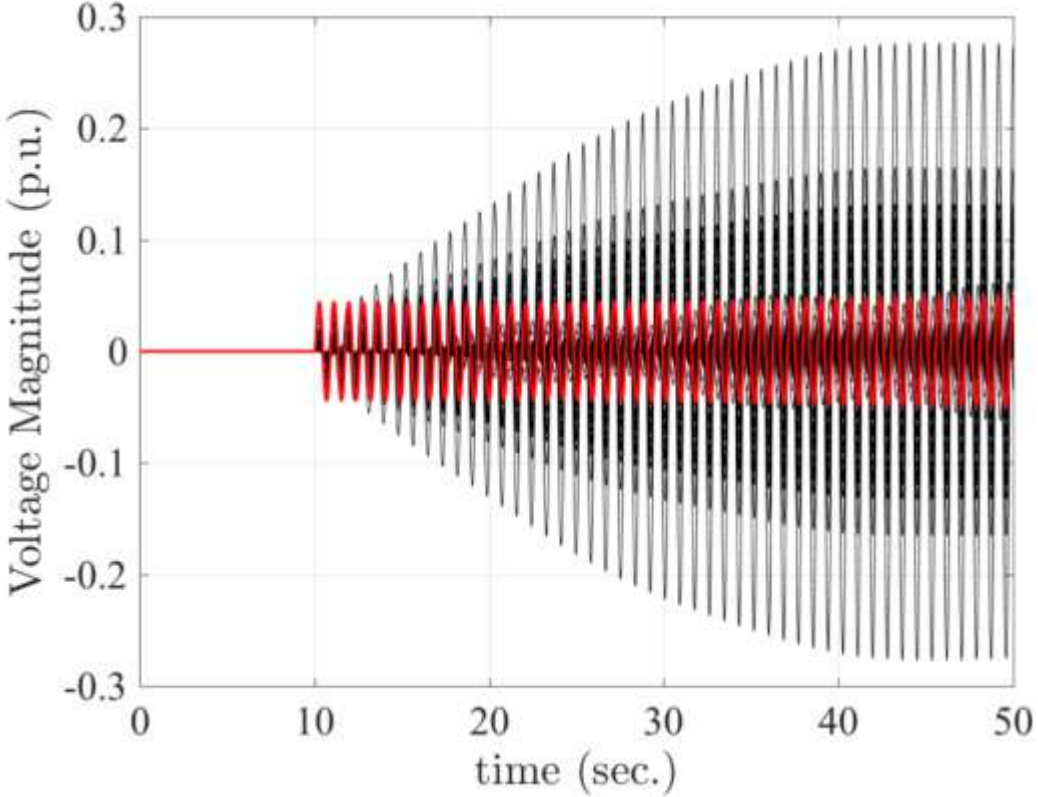
Instability in the Form of Forced Oscillation: An Example



- The California-Oregon Intertie (COI) has 200 MW oscillations, causing system islanding and blackout!
- Nova Joffre power plant (source) has 20 MW (peak-to-peak) oscillations
- The distance between these two places is 1100 miles

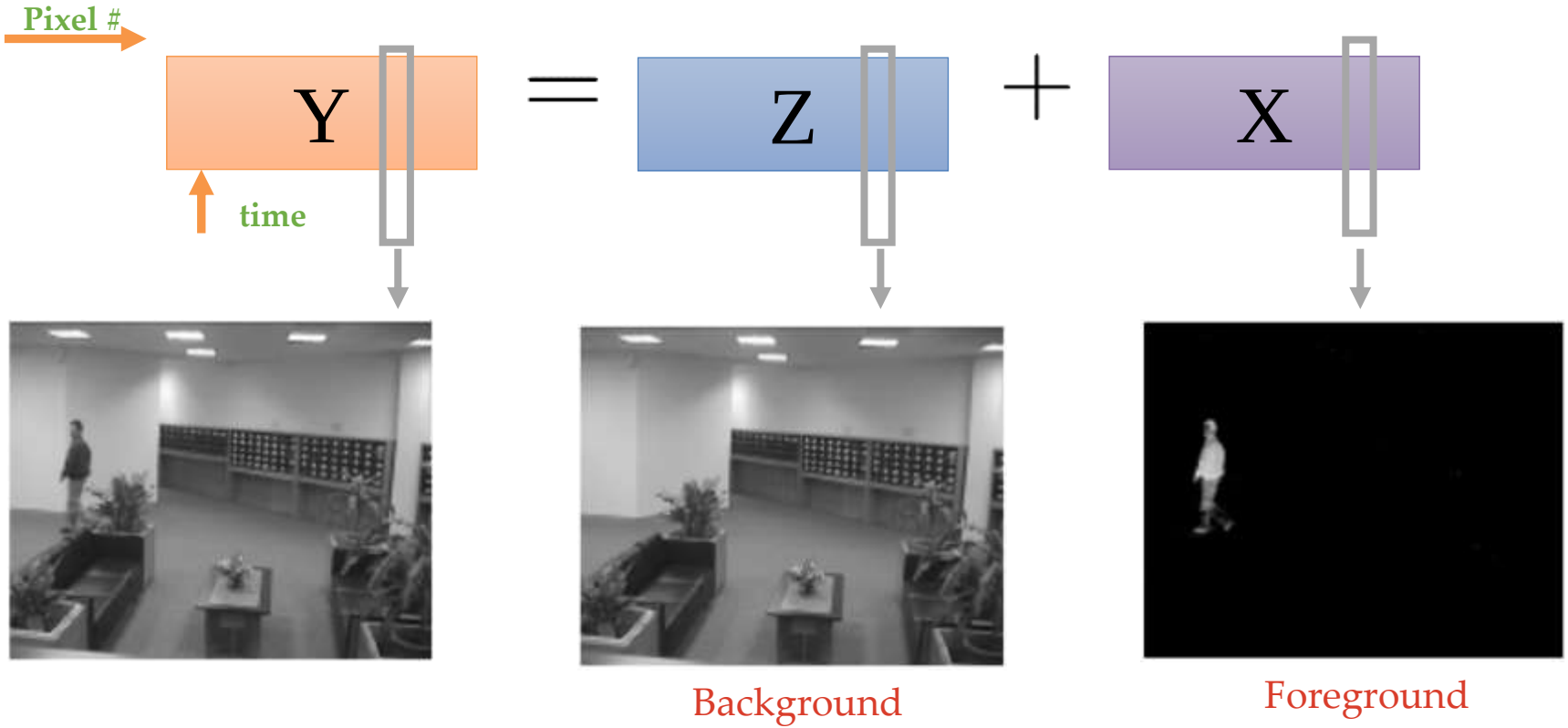
http://www.nerc.com/pa/RAPA/rg/ReliabilityGuidelines/Reliability_Guideline_-_Forced_Oscillations_-_2017.pdf

Challenge in Forced Oscillation Localization: Resonance

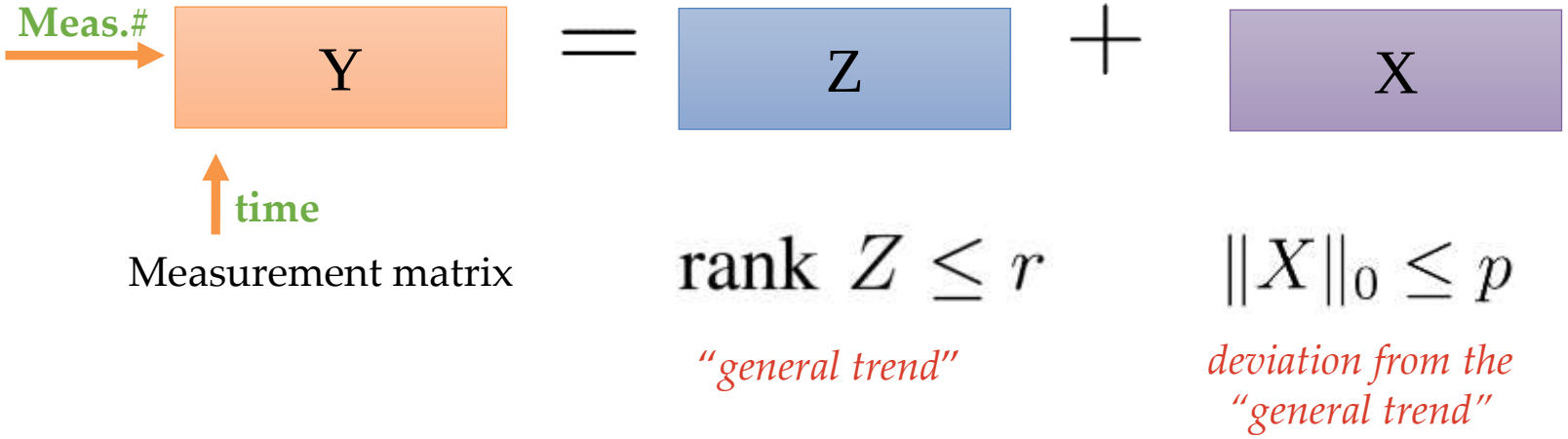


A simulated resonance case: *source* measurement (**red**);
the rest measurements (black)

Inspiration from Moving Object Detection



Problem Formulation: Robust PCA

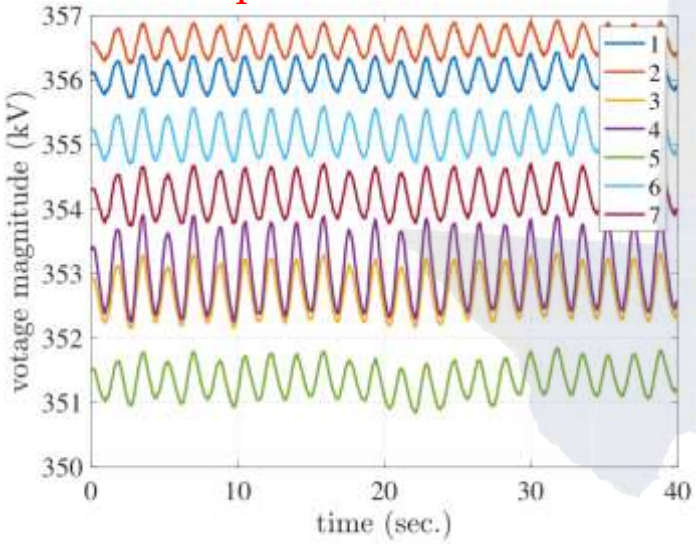


- Measurements should be correlated with each other and exhibit a *"general trend"*.
- The measurement near the source should *deviate most* from the "*general trend*".
- Synergy with spatial convolutional neural networks [Graham, 2014]

Graham, Benjamin. "Spatially-sparse convolutional neural networks." *arXiv preprint arXiv:1409.6070* (2014).

Real-world Evaluation in Texas Power Grid

PMU profiles from ERCOT



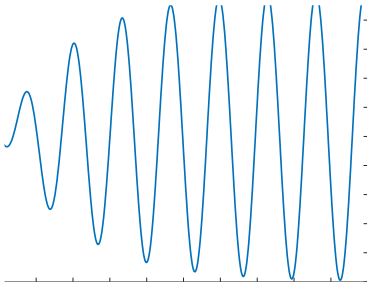
RPCA

PMU 4 is the one near the source.

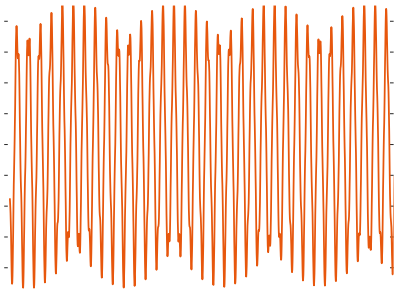
- Verified by ERCOT post-event model analysis.
- Scalable in real-time operation

Physics-Informed Interpretation of RPCA Result

$$y_k(t) =$$



$$+$$



Resonance

At most rank 2

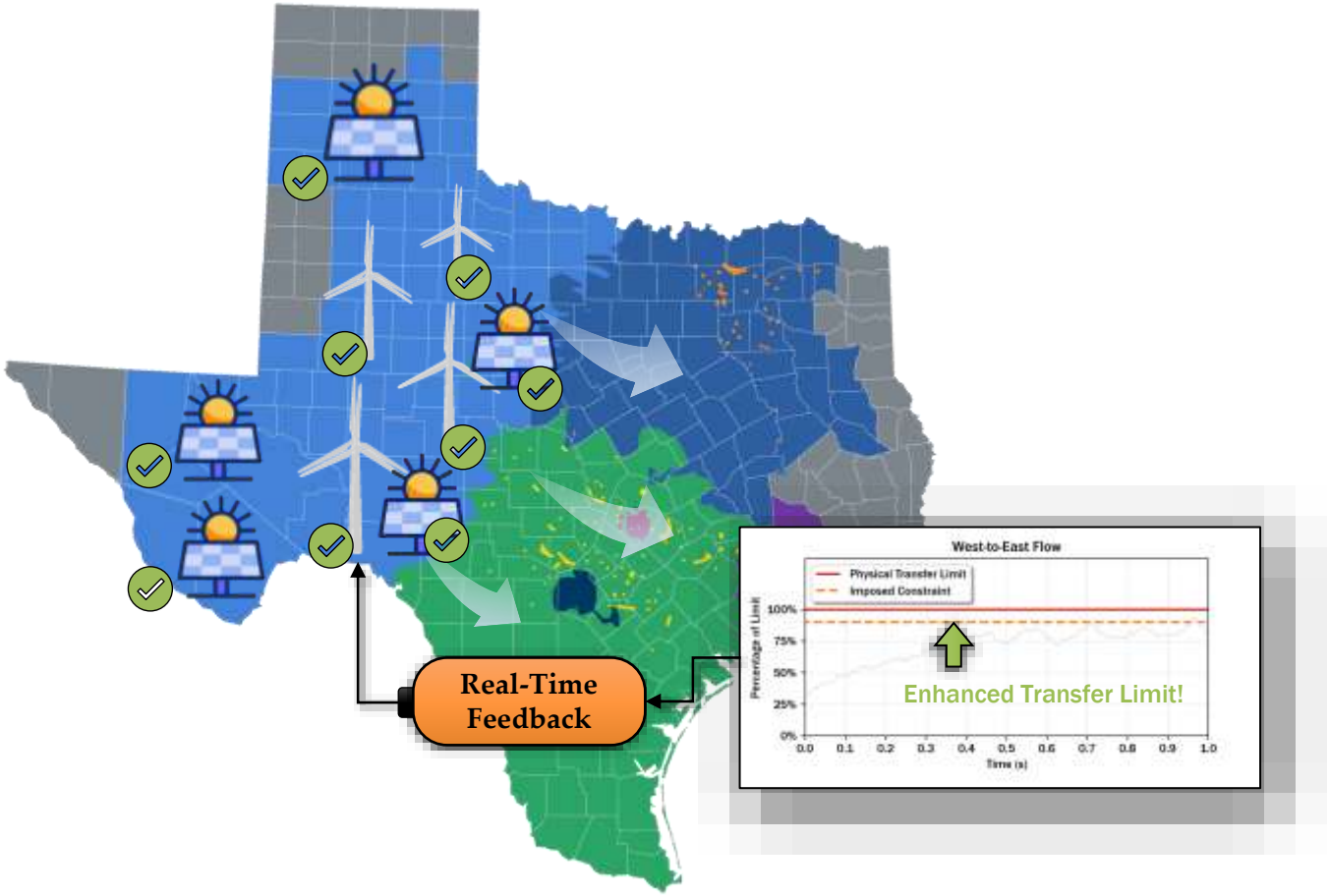
Resonance-free

Source location info.

Theorem: *For a linear time-invariant dynamical system, the resonance matrix has at most rank 2.*

Huang, Freris, Kumar and **Xie**, "A Synchrophasor Data-driven Method for Forced Oscillation Localization under Resonance Conditions," *IEEE TPWRS, 2020.*

Impact: Increasing GWs of Transfer Limit

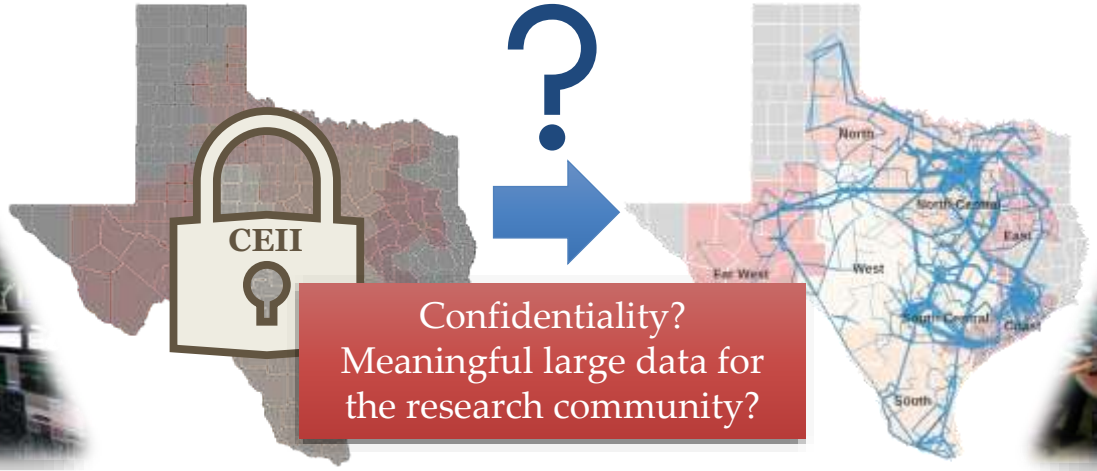


ERCOT GTC: https://www.ercot.com/files/docs/2020/10/07/05._WESTEX_GTC_ROS_10_08_2020.pdf

Feng, **Xie**, et. al.. "Mitigation of power system forced oscillations: An E-STATCOM approach." *IEEE Access 2017*

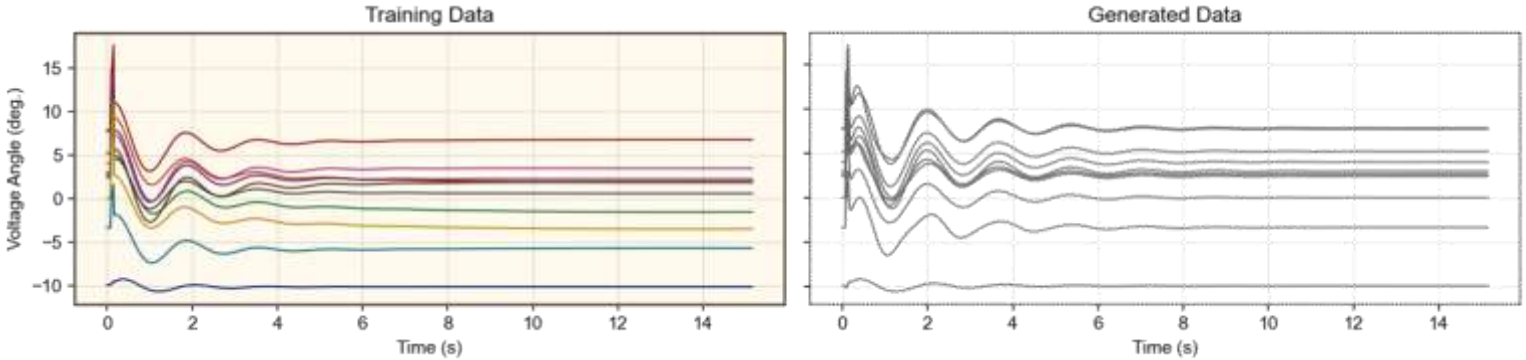
Data Creation with Critical Energy/Electric Infrastructure Information

ERCOT
Control Room



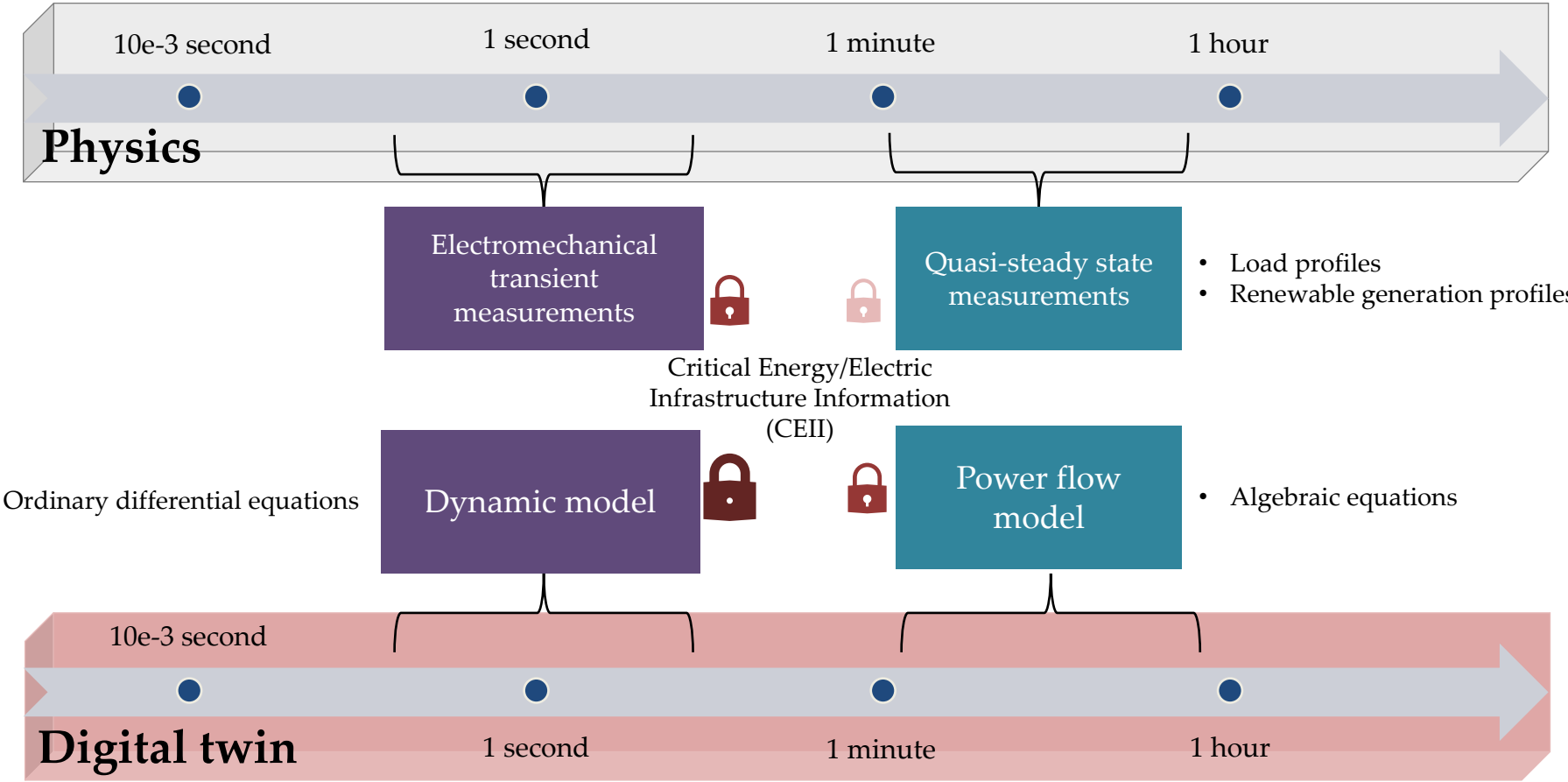
Confidentiality?
Meaningful large data for the research community?

Texas A&M
Control Room



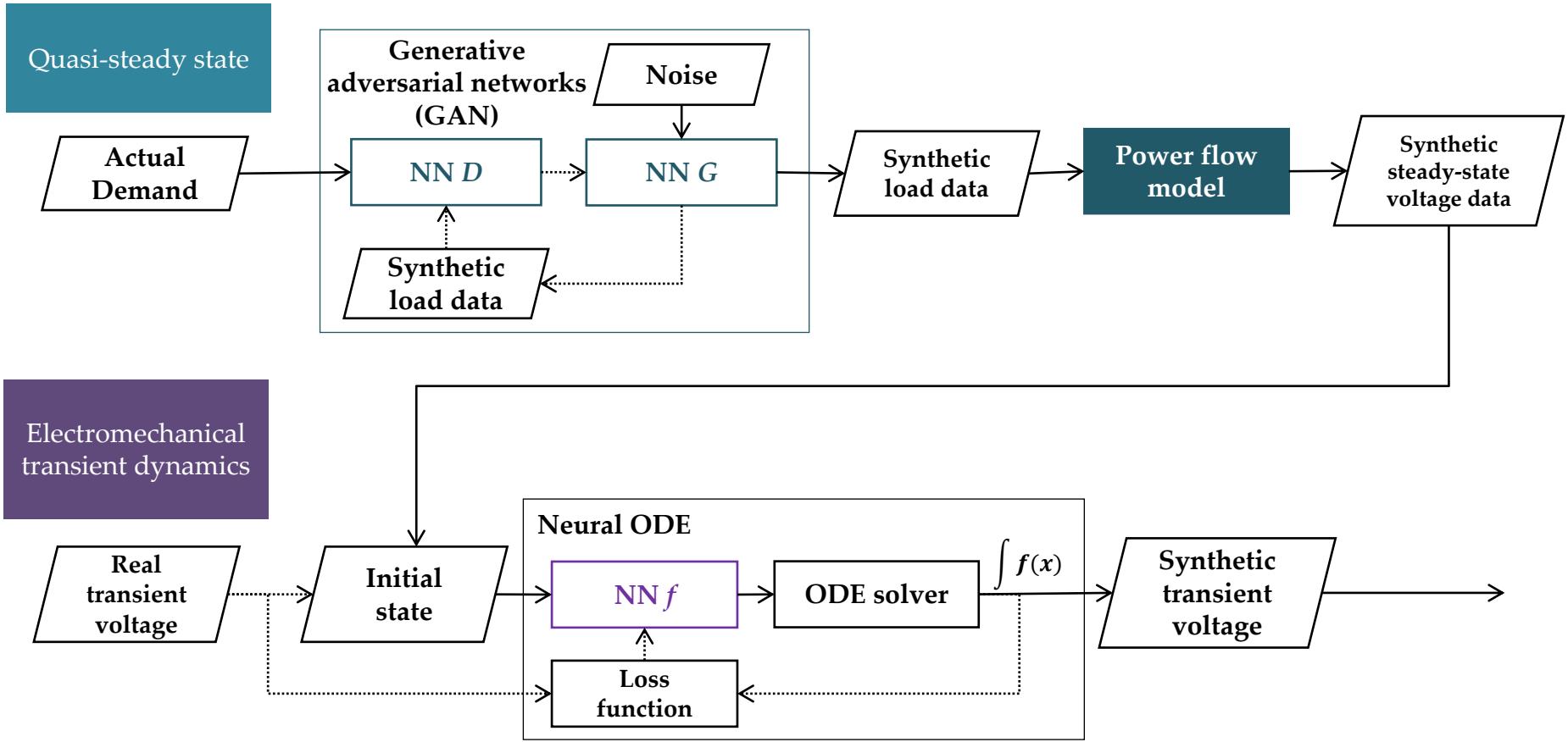
Xie, Huang, Zheng, Liu, Wang, Vittal, Kumar, Shakkottai, and Cui, "Energy System Digitization in the era of AI: A three-layered approach toward carbon neutrality", *Pattern (Cell Press)*, (2022)

Dynamic Data: A Generative Approach with Partial Physical Model



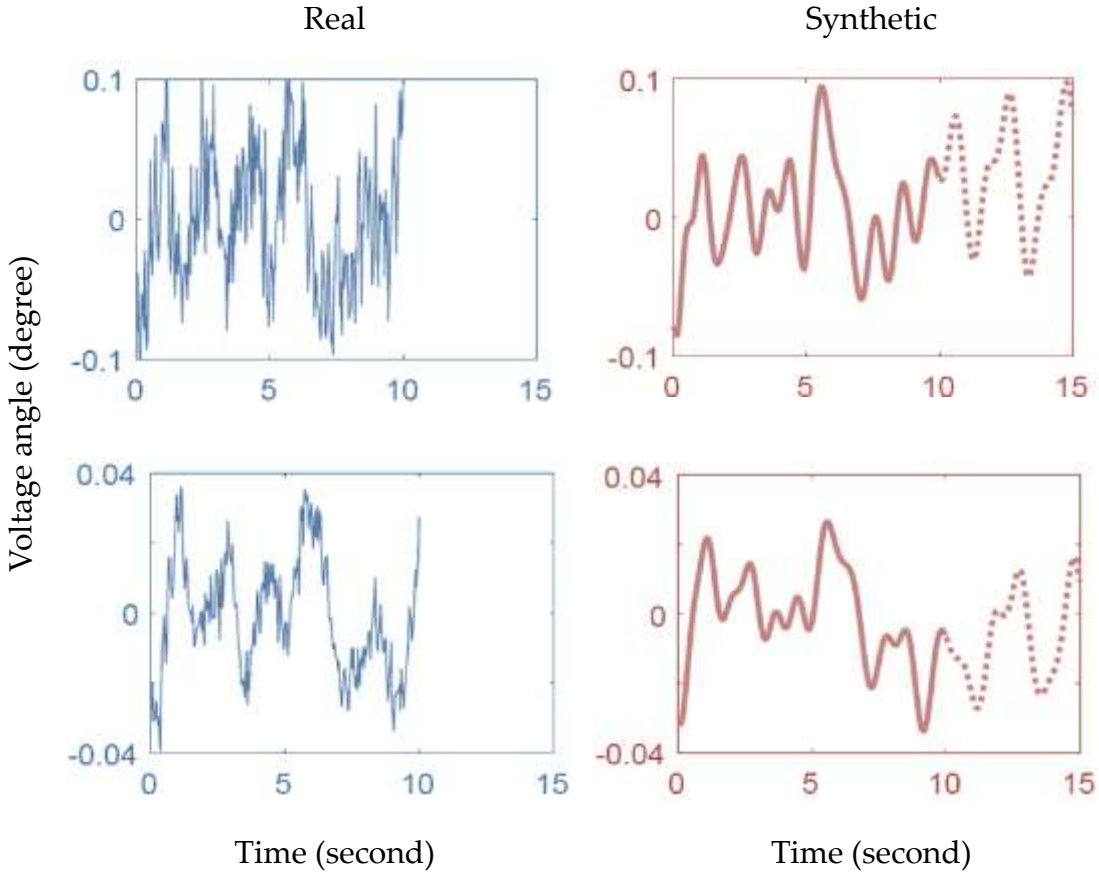
Zheng, Xu, Trinh, Wu, Huang, Sivaranjani, Liu, and **Xie,** "A multi-scale time-series dataset with benchmark for machine learning in decarbonized energy grids," *Nature Scientific Data*, (2022).

Combining GAN and Neural ODE



Zheng, Pinceti, Sankar, and **Xie**, "Synthetic PMU Data Creation Based on Generative Adversarial Network Under Time-varying Load Conditions", *MPCE*, (2021).

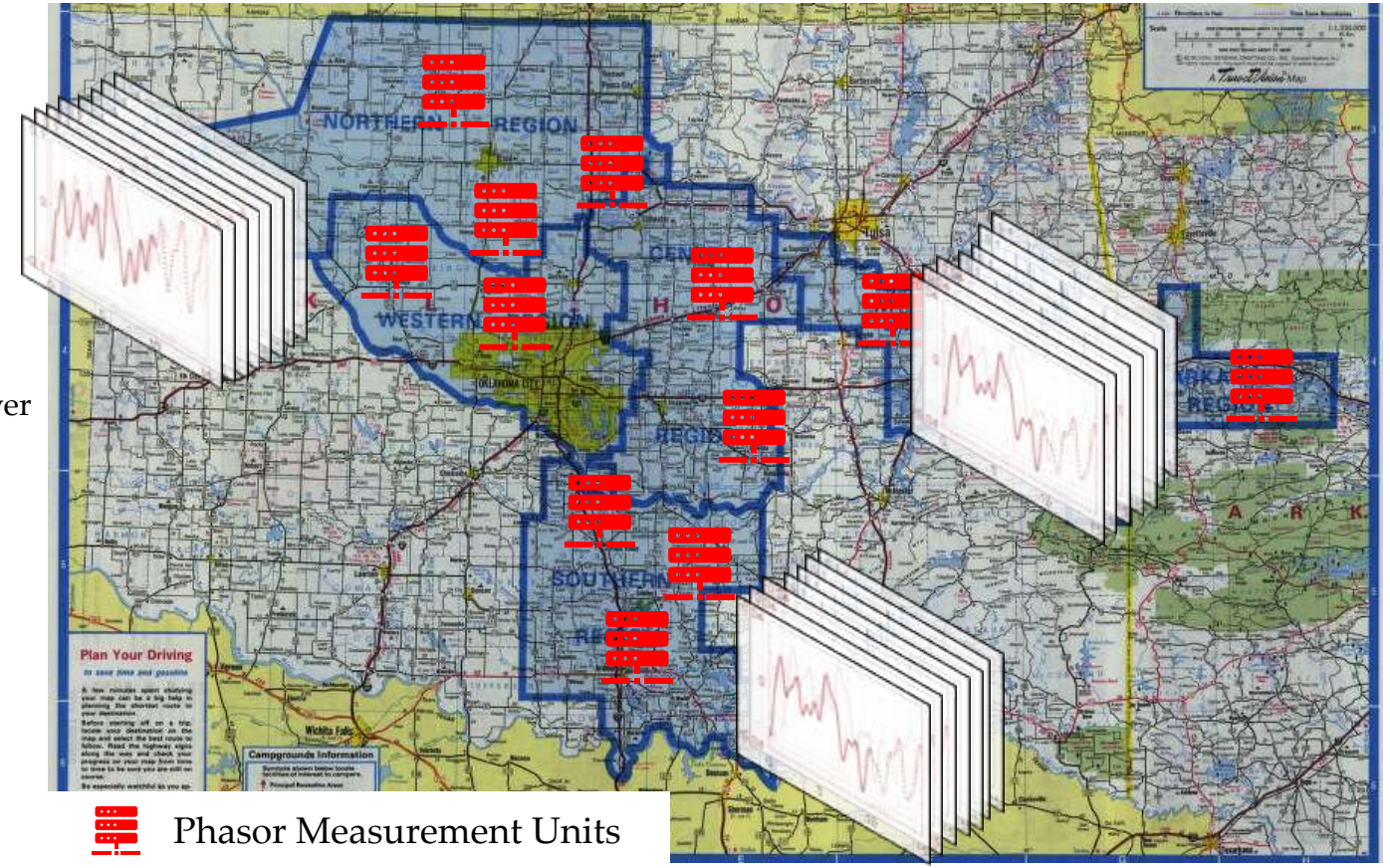
Synthetic Dynamic Voltage Data



Zheng, Pinceti, Sankar, and **Xie**, "Synthetic PMU Data Creation Based on Generative Adversarial Network Under Time-varying Load Conditions", *MPCE*, (2021).
Zheng, Wang, Kalathil, and **Xie**, "Generative adversarial networks-based synthetic pmu data creation for improved event classification", *IEEE Open Journal on Power and Energy Systems*, (2021).

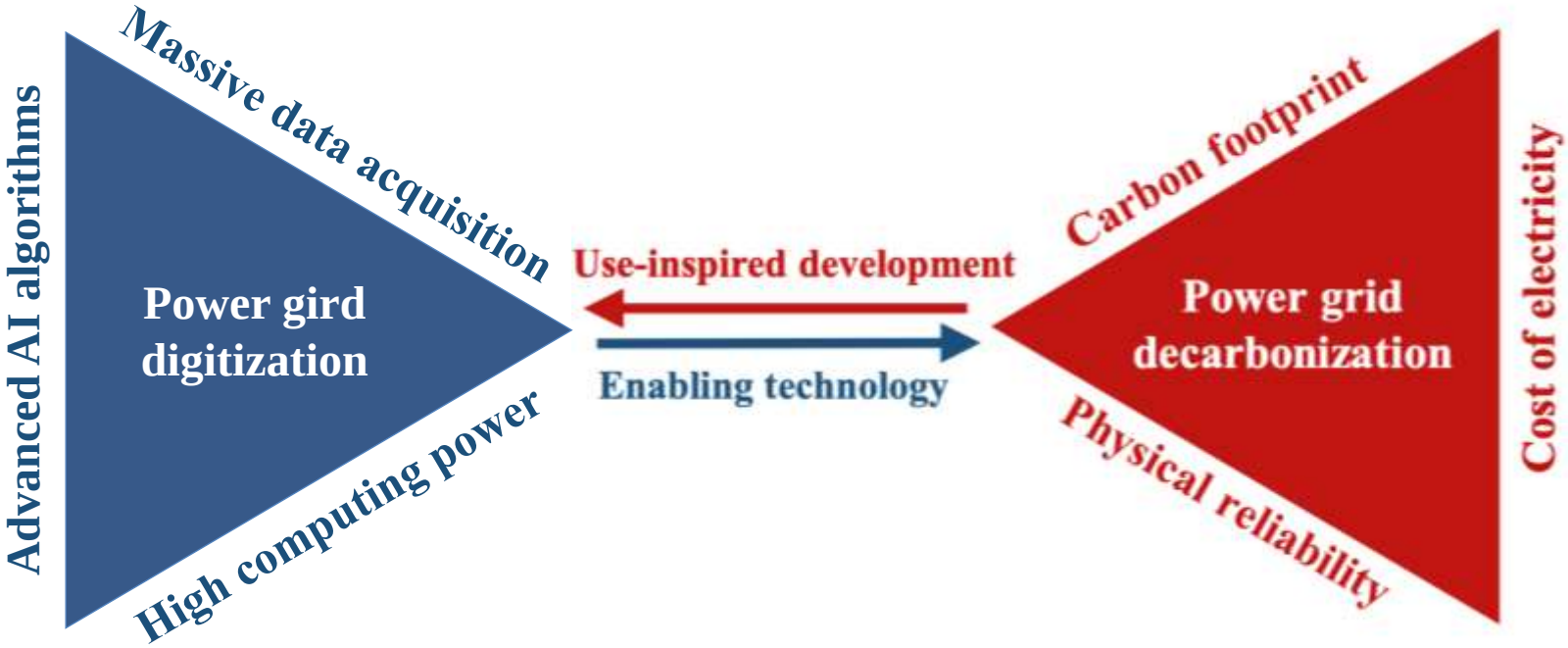
Large-scale Synthetic Dynamic Data

~30,000-node Southwest Power Pool (SPP) grid, with ~1,500 nodes in the OG&E territory.



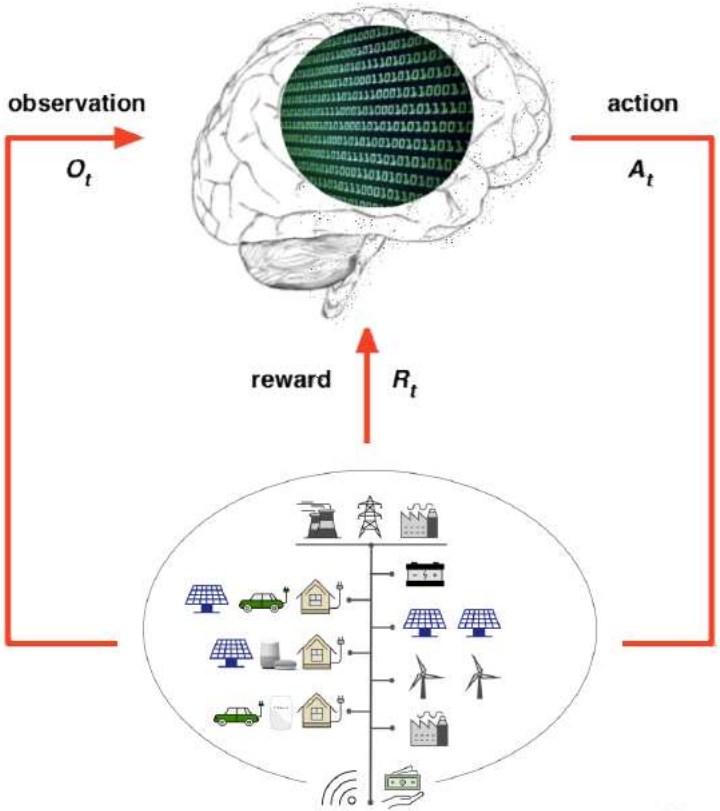
Zheng, Pinceti, Sankar, and **Xie**, "Synthetic PMU Data Creation Based on Generative Adversarial Network Under Time-varying Load Conditions", *MPCE*, (2021).

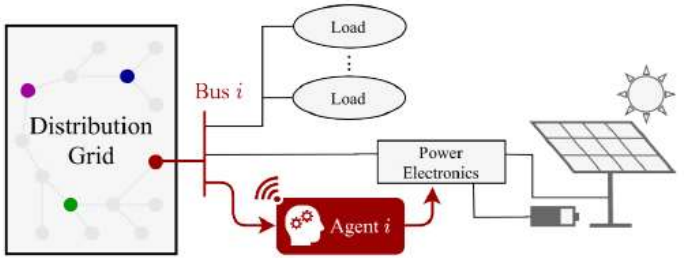
Advanced AI Algorithms

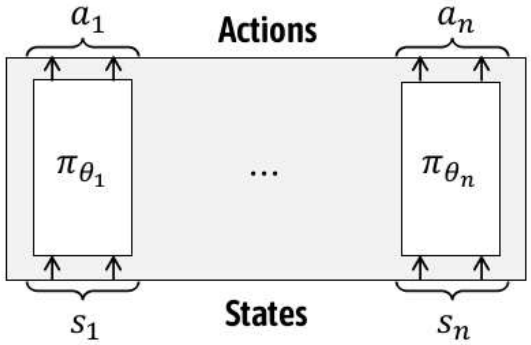


Xie, Zheng, Sun, Huang, and Bruton. "Massively Digitized Power Grid: Opportunities and Challenges of Use-inspired AI, " *Proc. IEEE* , 2022.

Reinforcement Learning-based Control of PV in Distribution Grids

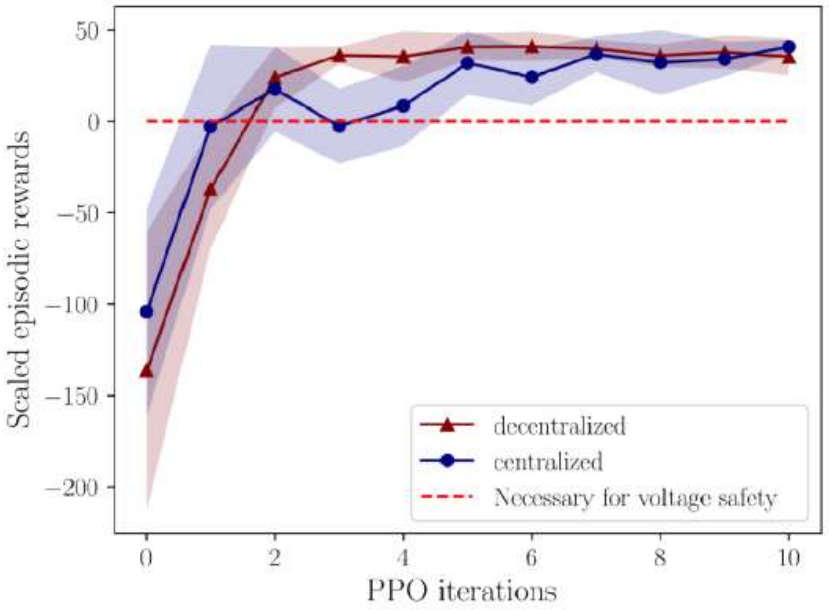


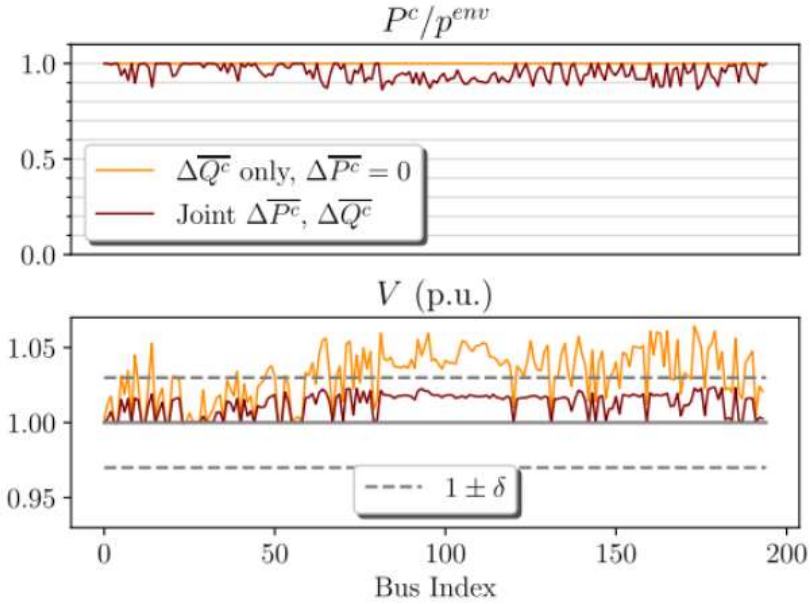




El Helou, Kalathil, and **Xie**. "Fully decentralized reinforcement learning-based control of photovoltaics in distribution grids for joint provision of real and reactive power." IEEE Open Access Journal of Power and Energy (2021).

Reinforcement Learning-based Control of PV in Distribution Grids

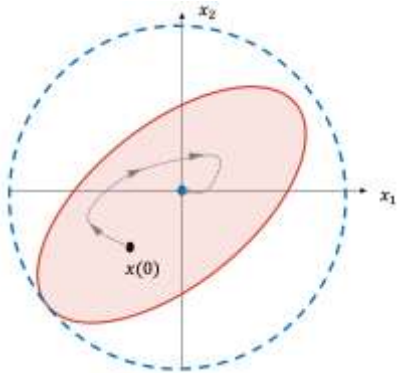


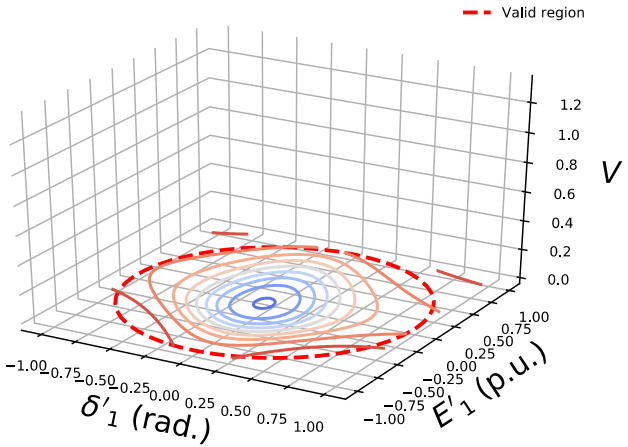


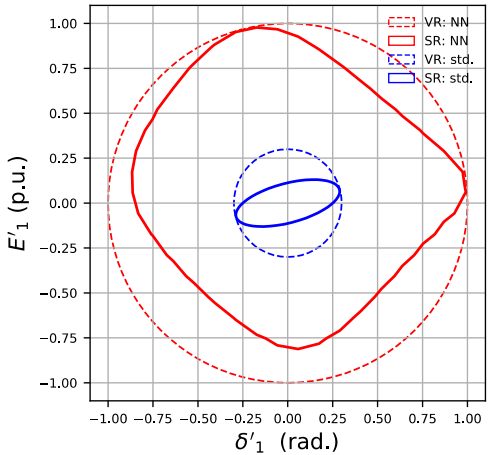
El Helou, Kalathil, and **Xie**. "Fully decentralized reinforcement learning-based control of photovoltaics in distribution grids for joint provision of real and reactive power." IEEE Open Access Journal of Power and Energy (2021).

Speeding Up Security Assessment via Neural Lyapunov Approach for Networked Microgrids

- Estimating a *security region* via learning a *Lyapunov function*
- *Less conservative* estimation can be achieved than the conventional approach

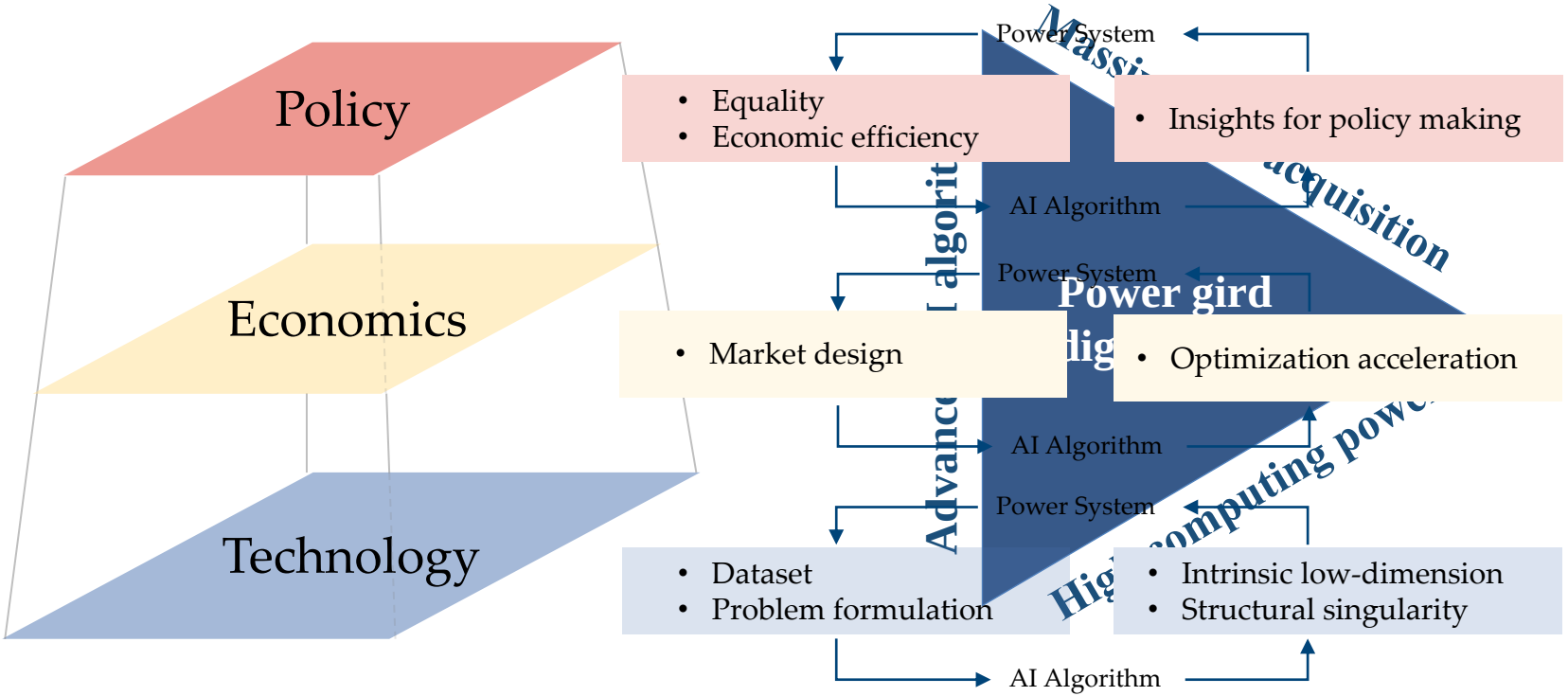






Huang, Gao, and **Xie**. "A neural Lyapunov approach to transient stability assessment of power electronics-interfaced networked microgrids." IEEE Transactions on Smart Grid (2021) (Technical Committee Prize Paper Award)

A Layered Approach to AI/Data Adoption in Energy Systems



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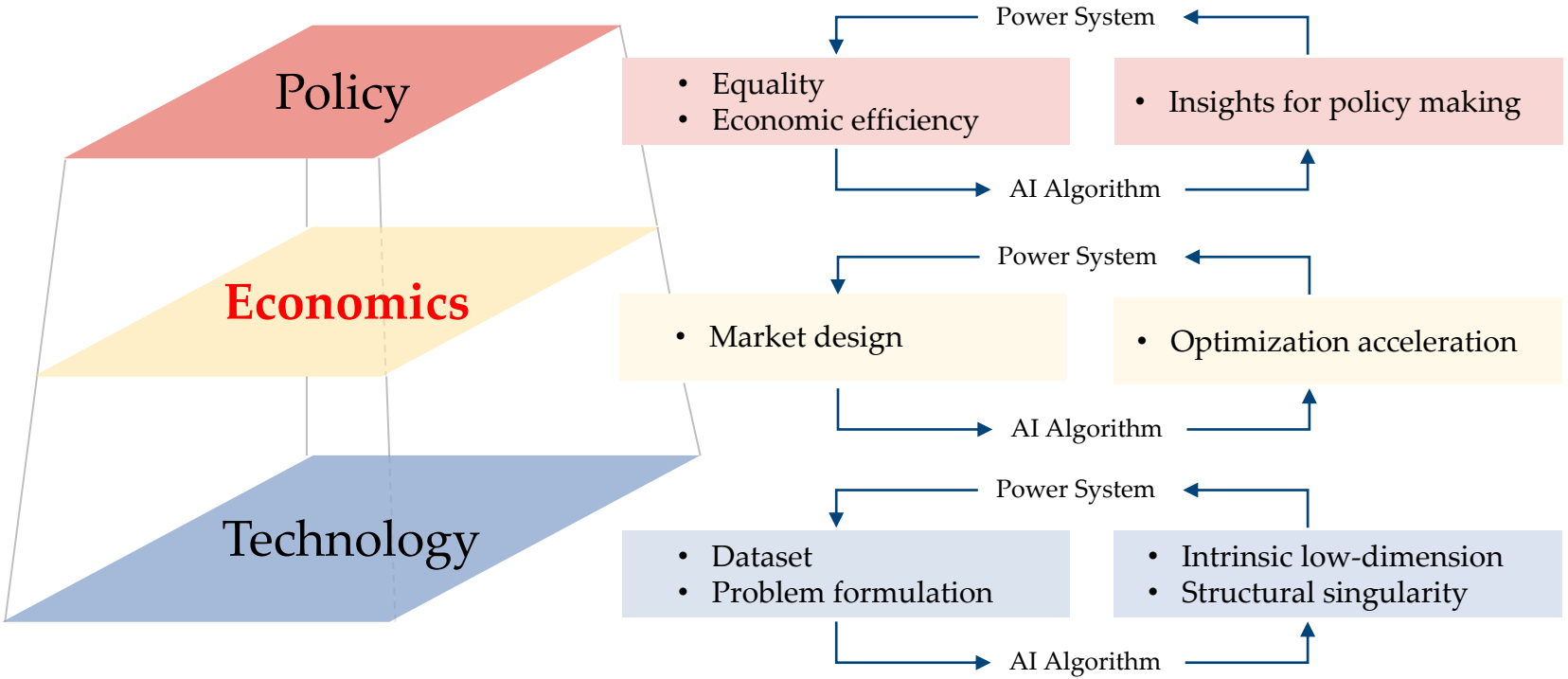
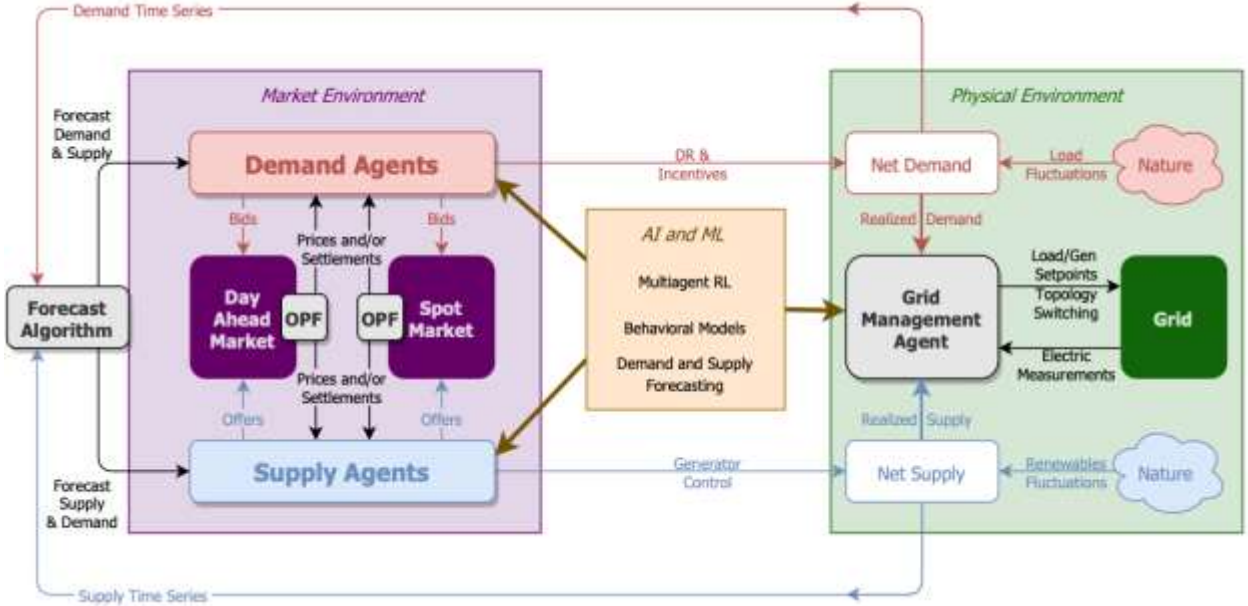
A Layered Approach to AI/Data Adoption in Energy Systems

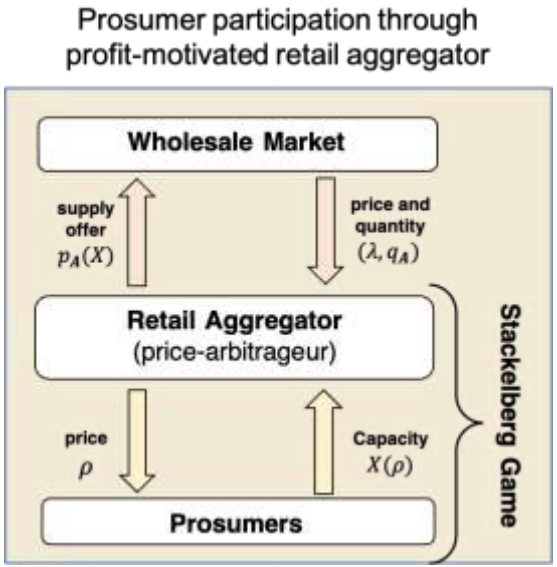


Xie, Huang, et al. "Energy system digitization in the era of AI: A three-layered approach toward carbon neutrality." Patterns (2022).

OpenGridGym

AI-Friendly, Scalable, Open Source, and Integrated Market Simulator



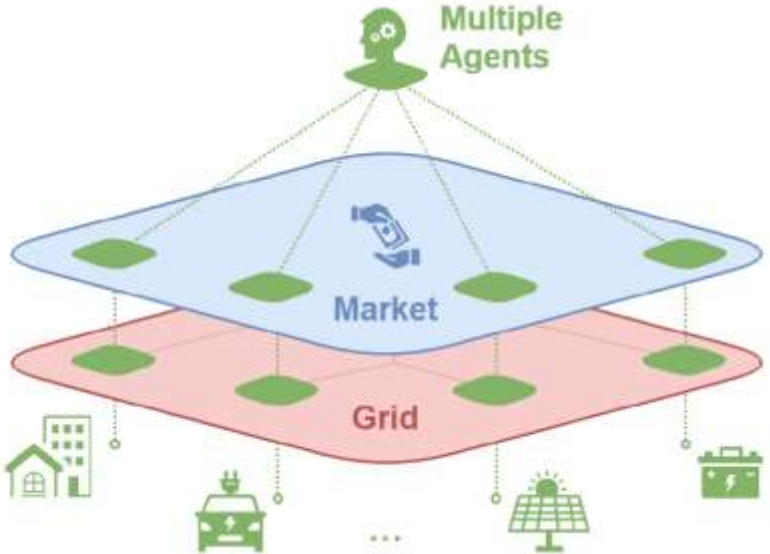


El Helou, Lee, **Xie**, et al. "OpenGridGym: An Open-Source AI-Friendly Toolkit for Distribution Market Simulation." IEEE Transactions on Smart Grid, (2022)

OpenGridGym

Agent-based framework

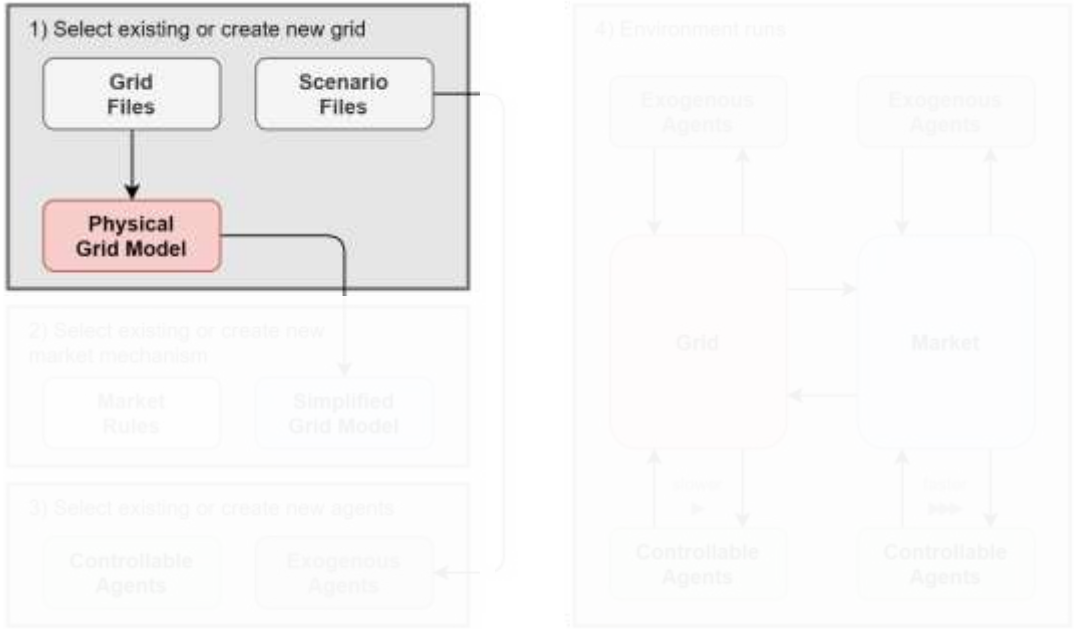
- **Agents** can observe and control two main subsystems:
  - Market
  - Grid
- **Market**
  - Negotiations
  - Financial settlements
  - Driven by a simplified grid model
- **Grid**
  - Physical setpoints changed at the end of market negotiations
  - Much more detailed model of the physical electric grid



El Helou, Lee, **Xie**, et al. "OpenGridGym: An Open-Source AI-Friendly Toolkit for Distribution Market Simulation." IEEE Transactions on Smart Grid, (2022)

OpenGridGym

Simulation Flowchart



- For each "grid" time step:
  - Loop through market negotiations until completed
  - Once market is cleared, send setpoints to grid

El Helou, Lee, **Xie**, et al. "OpenGridGym: An Open-Source AI-Friendly Toolkit for Distribution Market Simulation." IEEE Transactions on Smart Grid, (2022)

OpenGridGym

Use Case

- IEEE 34-bus
- Congestion near the source

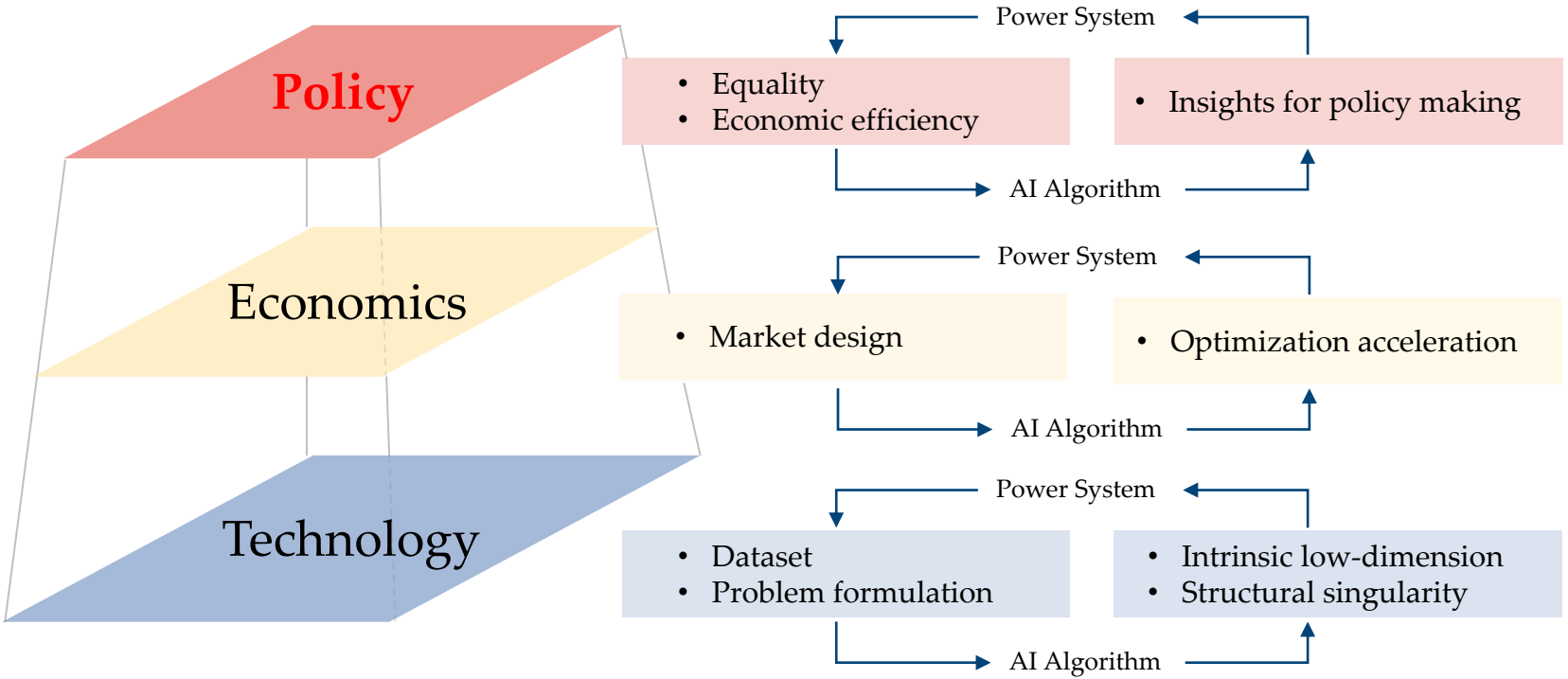
- As a result, expensive generation can raise prices

- With more demand elasticity, there's less market power for local generation resources despite congestion.

Average price reduced due to demand flexibility

El Helou, Lee, **Xie**, et al. "OpenGridGym: An Open-Source AI-Friendly Toolkit for Distribution Market Simulation." IEEE Transactions on Smart Grid, (2022)

A Layered Approach to AI/Data Adoption in Energy Systems



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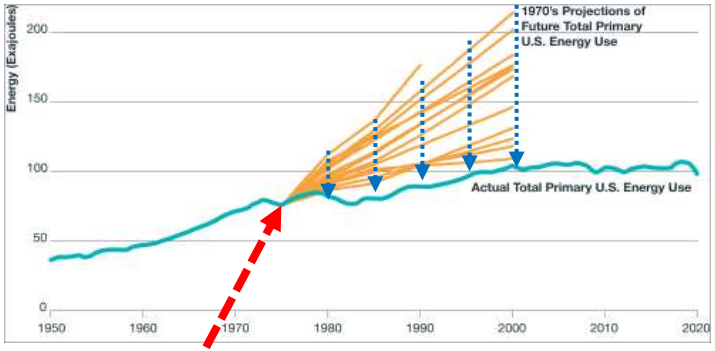
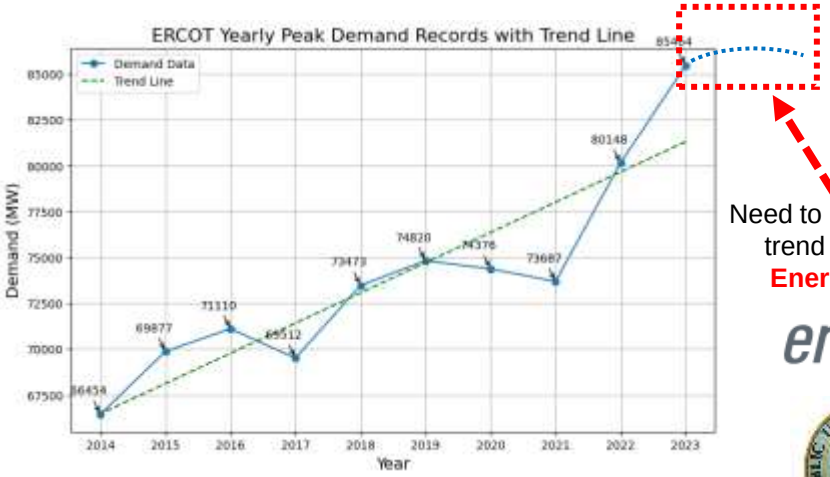
Strategic Allocation of Energy Efficiency Program



https://climatenow.com/article/decarbonizing-through-efficiency/

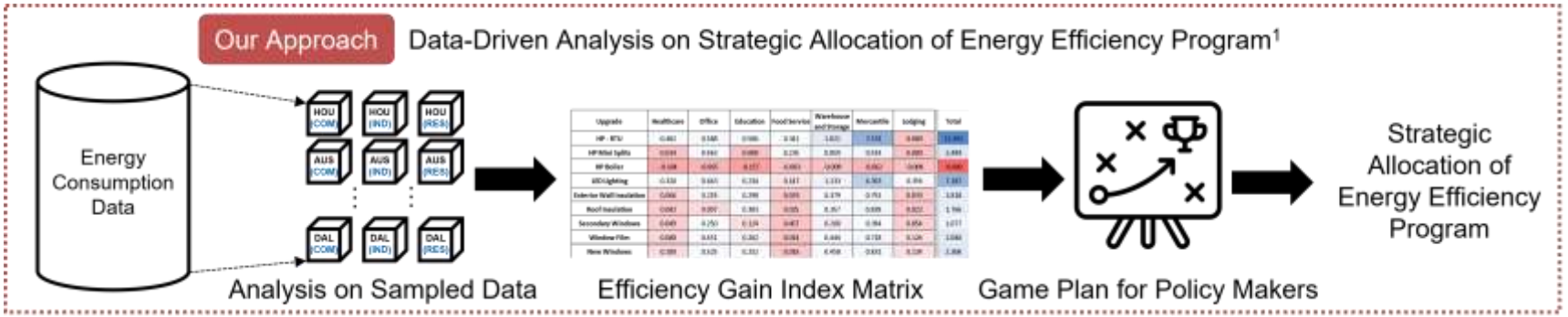
Due to the oil crises (1973, 1978), **the U.S. government started mandating efficiency improvements** to high-energy products like cars and appliances



The peak demand in Texas is growing rapidly

Need to break the upward trend **by improving Energy Efficiency**

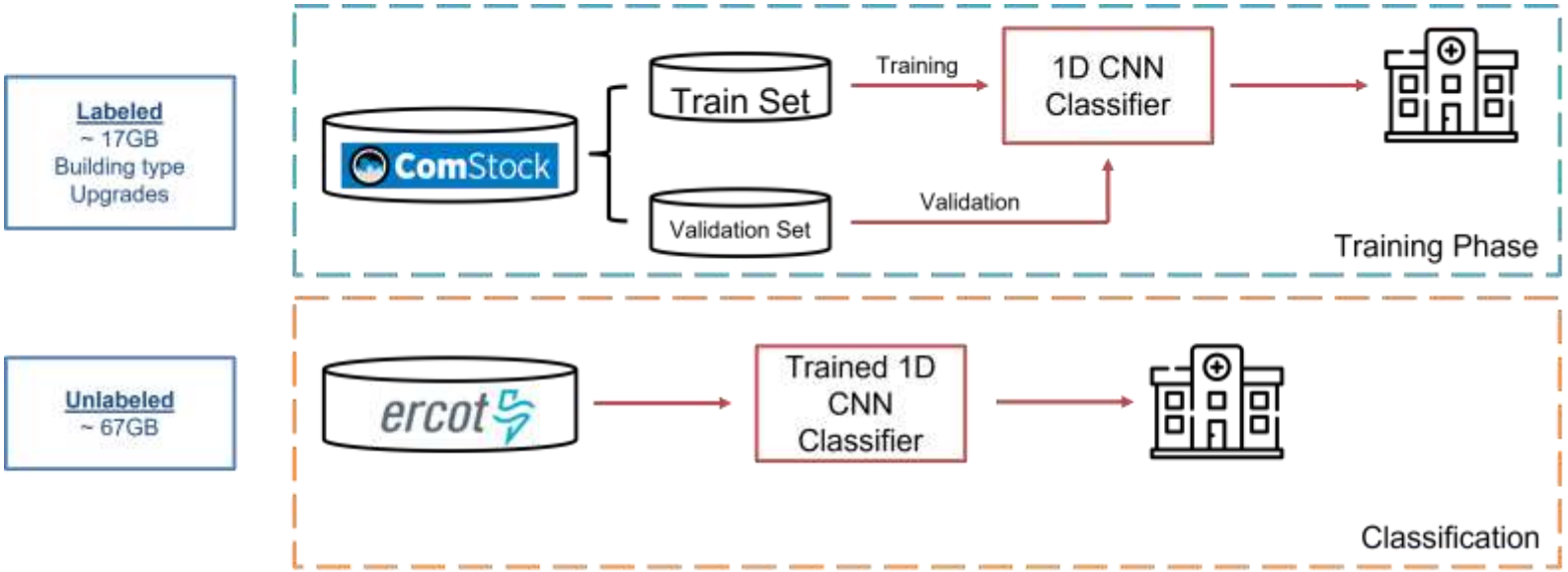
ercot



[1] D. Kim, A. Karngala, R. Shi, and L. Xie, "Data-Driven Analysis on Strategic Allocation of Energy Efficiency Program," *Working Paper,* TAMU 2023

Learning based Classification Model

- Validation set contained 3,504 buildings from Comstock
- > 98% Accuracy



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Dangers of Digitization

BRIEF

NERC to analyze first potential cyberattack on US grid

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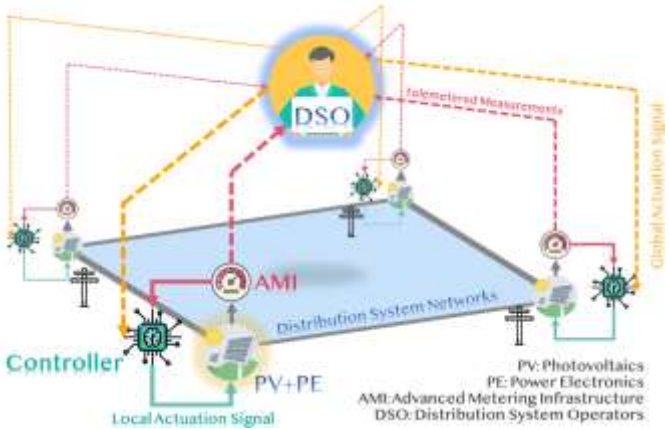
Dive Brief:

- The North American Electric Reliability Corporation (NERC) told Utility Dive it will conduct a root cause analysis to determine what caused a utility to temporarily lose visibility to certain parts of its supervisory control and data acquisition system.
- The March 5 cyber event, reported last month by E&E News, resulted in interruptions of electrical system operations across several states, including California, Utah and Wyoming.
- The electric disturbance report, filed by one of the affected utilities, suggests that this is the first time remote hackers interfered with U.S. grid networks. But the event had no impact on generation and there was no evidence to suggest malicious intent, NERC said.

https://www.utilitydive.com/news/nerc-to-analyze-first-potential-cyberattack-on-us-grid/554504/

Cyber Physical Security in Solar-rich Distribution Grids

- PV-dominant distribution grids are cyber-physical systems
- Attackers can compromise the system by manipulating inverters at the edges.



How to defend PV-dominant distribution grids against cyber attack?

There is a dangerous cyber vulnerability
to our national electrical grid network

Conclusion Remarks

- Renewable (in particular solar) energy adoption
  - **Scale**
  - **Speed**

- Massive digitization (computing, data, and AI algorithms) could offer tremendous opportunities through a *layered, domain tailored* approach
  - **Technology**
  - **Market/Economics**
  - **Policy**
  - **Cyber-physical security**

Thank You!

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