Adaptive Infrastructure

Planning and Operating in the Age of AI

Bala Natarajan
Clair N Palmer and Sara M Palmer Professor
Electrical and Computer Engineering
Kansas State University

Infrastructure 1.0: Classic Infrastructure Model

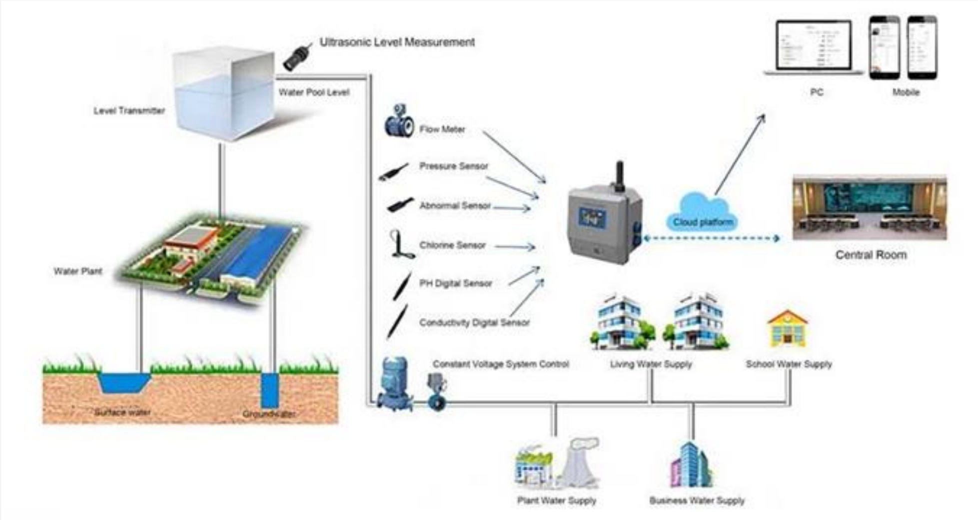
Build It and Run It

Driving Technologies	
Analog control systems	Periodic inspections
SCADA	Spreadsheet-based planning

Infrastructure engineered for functionality, stability

Infrastructure 2.0: Smart Infrastructure Era

Sense It and Manage It

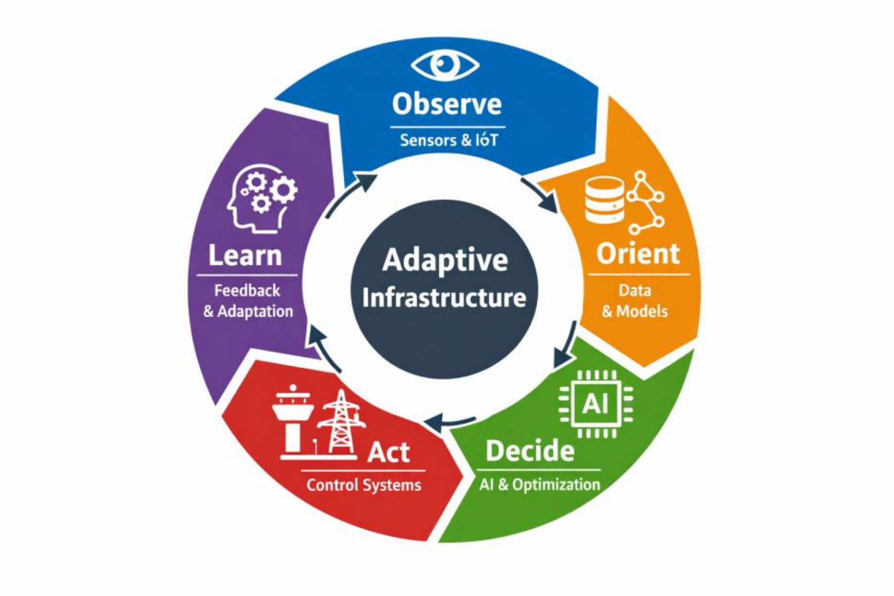


Driving Technologies	
IoT sensors	Cloud computing
Advanced analytics	Advanced Metering Infrastructure (AMI)

Infrastructure becomes observable and manageable in real time

Infrastructure 3.0: Adaptive Infrastructure

Predict, Adapt, and Learn



Driving Technologies	
Machine Learning	Edge & Generative AI
Reinforcement Learning	Advanced digital twins

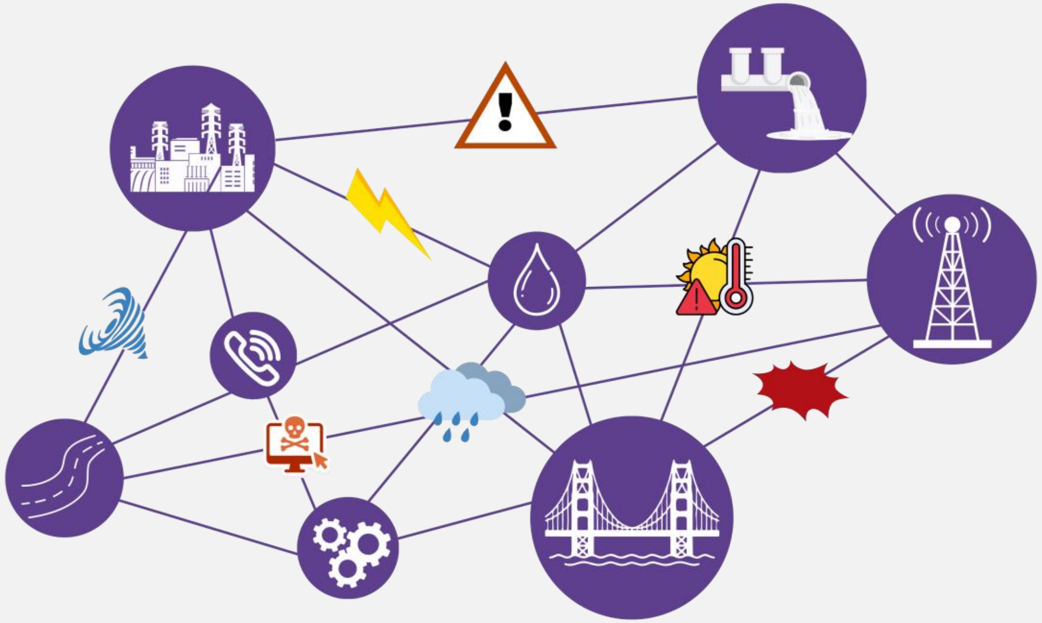
Infrastructure is no longer just managed – it learns

Why adaptive infrastructure now?

Static planning models are no longer sufficient

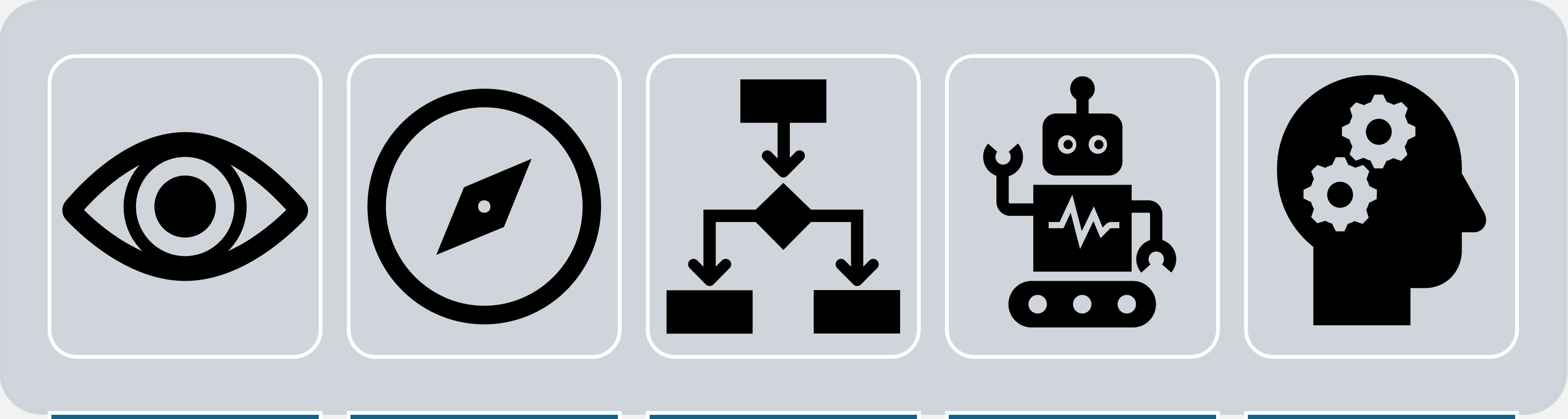
- Climate volatility & extreme events
- Aging infrastructure assets
- Increasing cyber-physical complexity
- Deep interdependencies across systems

(energy, water, transportation, communications, etc.)



Infrastructure must anticipate uncertainty not just withstand it

AI-powered Adaptation and Learning



Observe	Orient	Decide	Act	Learn
(What is happening?)	(What does it mean?)	(What should we do?)	(Execute Decisions)	(Improve over time)
* Extract information from raw data (e.g., autoencoders, vision apps, anomaly detection)	*Build System understanding (e.g., Digital twins, surrogate AI models, scientific ML)	*Optimize decisions under uncertainty (e.g., ML based optimization, RL, Transformer Forecasting models)	*Implement control actions (e.g., Agentic AI, Reinforcement learning)	*Adapt and improve performance (e.g., Online learning, transfer learning)

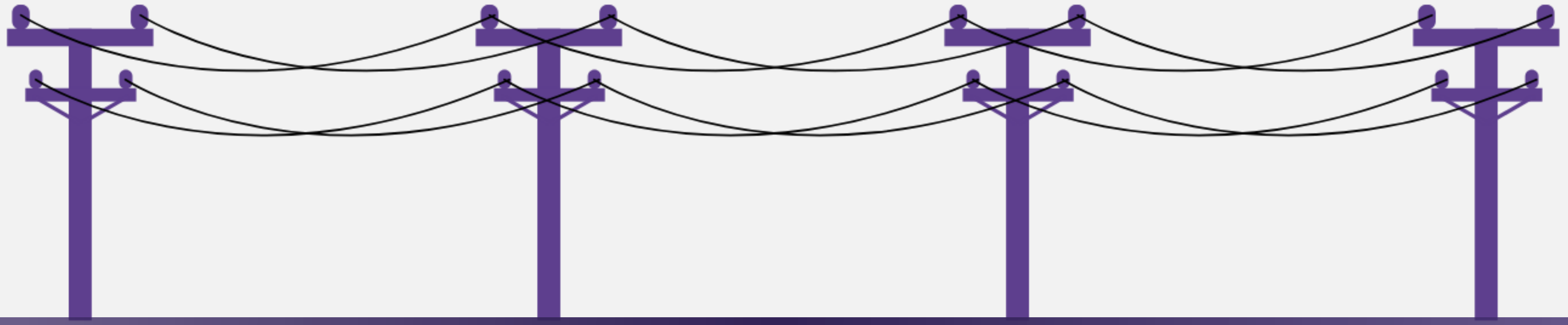
AI-Enabled Transmission Expansion

Planning Optimization

- Scenario-based capacity expansion modeling
- Congestion forecasting under extreme weather
- Renewable integration impact analysis
- Multi-objective optimization (cost, resilience, emissions)
- Probabilistic risk modeling

Permitting & Documentation

- Automated environmental impact assessment drafting
- Smart extraction from regulator documents
- Stakeholder comment summarization
- GIS-assisted route optimization
- Compliance tracking across jurisdictions



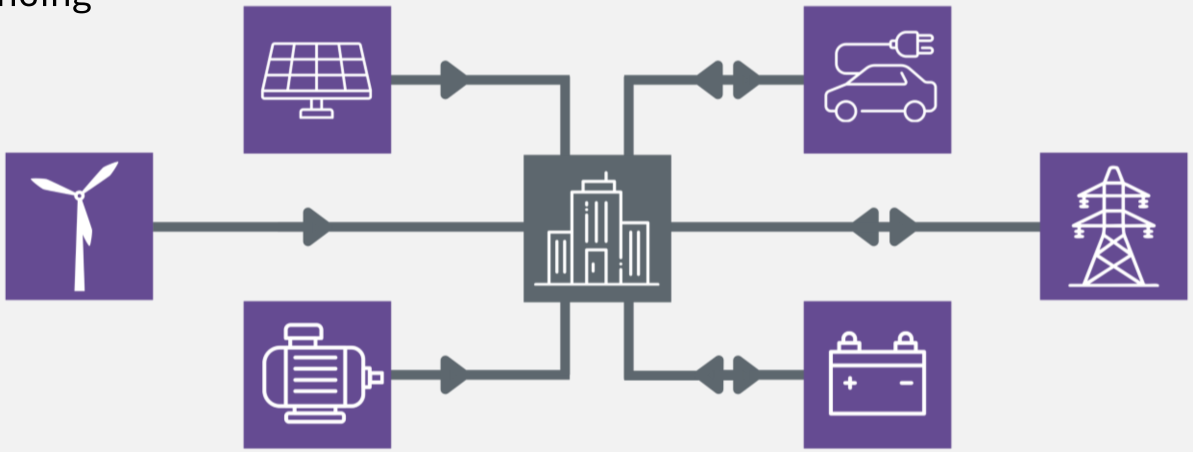
AI for DER Integration & Infrastructure Resilience

DER Optimization

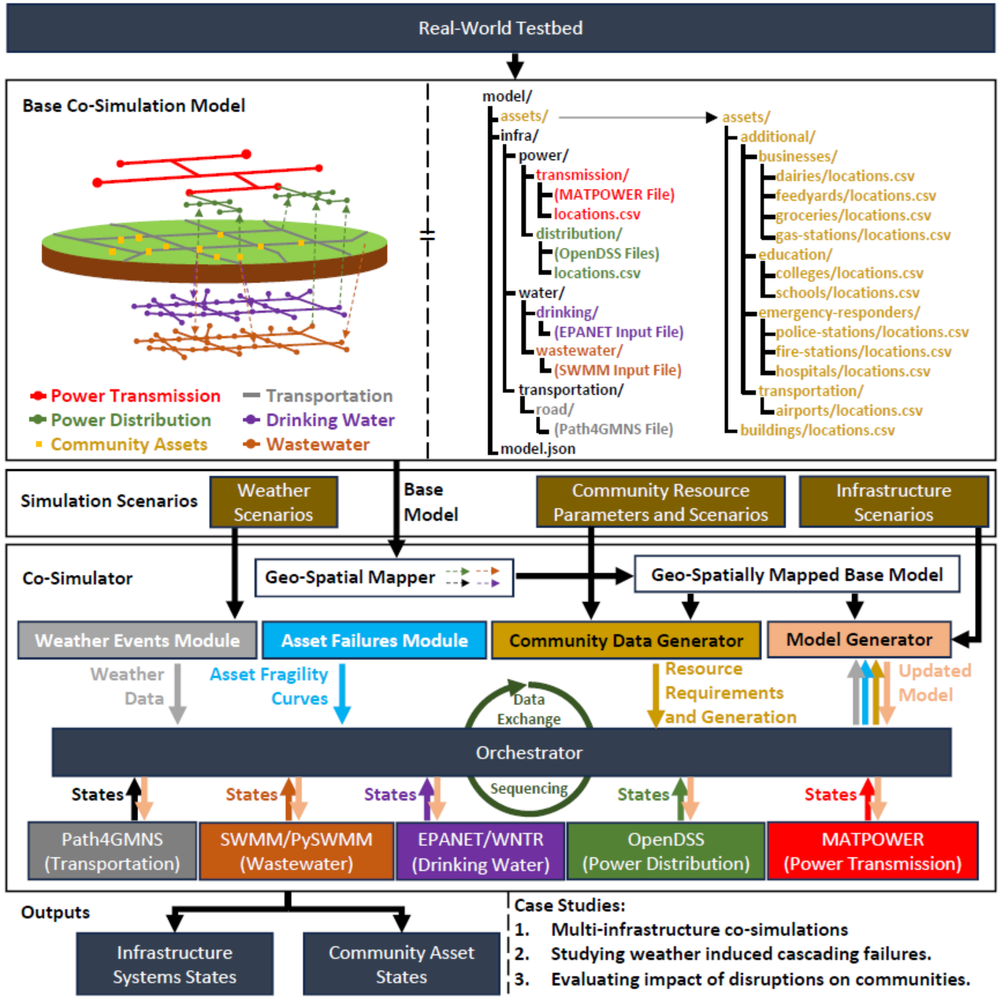
- Hosting capacity analysis
- DER siting optimization
- Grid-edge forecasting
- Microgrid configuration
- Dynamic load balancing

Cross-Infrastructure Modeling

- Power-water interdependency analysis
- Communications-grid coupling risk
- Climate-driven cascading failure prediction
- Multi-layer system hardening strategies



ARISE Project: Infrastructure Resilience



AI for Operations – Use Cases

Improving distribution system state estimation

- Accurate state estimation for power & water networks with limited data
- Sparse data + physics-informed AI
- Achieves situational awareness faster than traditional methods

AI/ML models learn and fill in the gaps from minimal data streams

AI for Operations – Use Cases

Optimizing integrated data center operations

- Dynamically balance power, cooling, and workloads for efficient energy use
- Adaptive optimization powered by AI/ML techniques
- Generative AI for support while minimizing cost and carbon footprint

"Using AI for AI" To plan and operate infrastructure for AI-driven demand

Why isn't AI already running infrastructure?

Technical Barriers

① Data Limitations

- Sparse sensing in legacy systems
- Incomplete or biased historical data
- Rare extreme events are underrepresented
- Data quality and synchronization challenges

② Reliability & Robustness

- Performance degradation under distribution shift
- Vulnerability to adversarial or corrupted data
- Limited guarantees in unseen scenarios
- Need for fail-safe and fallback modes

③ Interpretability & Trust

- Black-box models in safety-critical decisions
- Lack of explainability for operators and regulators
- Difficulty validating AI against physics-based models

④ Integration with Physical Systems

- Isolated AI will not work - Hybrid physics + AI modeling
- Real-time constraints
- AI decisions must be physically feasible and safe to implement

AI is powerful, but safety-critical infrastructure demands more

Why isn’t AI already running infrastructure?

Institutional, Economic, and Physical Barriers

1 Regulatory Constraints

- Strict safety and compliance requirements
- Certification processes not designed for adaptive systems

2 Economic Constraints

- High upfront modernization costs
- Retrofitting legacy systems
- Utilities operate on thin margins
- Risk-averse investment structures

3 Workforce & Organizational Readiness

- Skills gap in AI + infrastructure crossover
- Operator resistance to automation
- Need for retraining and interdisciplinary capacity

4 Governance & Public Trust

- Public skepticism
- Transparency and accountability expectations
- Equity considerations in infrastructure planning

Adaptive infrastructure requires computational AND institutional evolution

Infrastructure is Entering the AI Era

“Build Smart. Operate Smarter. Adapt Always.”

AI will not replace infrastructure engineers — but it will redefine how we design, plan, and operate systems.

- **Static Design** → **Continuous Learning**
- **Deterministic Planning** → **Uncertainty-Aware Adaptation**
- **Reactive Control** → **Predictive Resilience**

Not a replacement for engineering but an evolution of it