Advanced Storage Planning for a Cost-effective and Resilient Grid

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Project Overview

- **Project Goal**: Develop advanced storage planning to address short- and long-term capacity, flexibility, and transmission needs under uncertainty.
- **Current Practice**: Storage planning often uses oversimplified models, treats storage, transmission, and generation separately, and addresses uncertainties through limited deterministic scenarios.
- **Why PNNL**: PNNL combines modeling expertise, real-world data, and industry partnerships to develop adaptable storage planning capabilities.
- **Innovation**: Advanced modeling framework for co-optimizing storage with transmission and generation across regions and timescales, incorporating uncertainty through stochastic planning.
- **Impact**: Enables stakeholders to better address growing electricity demand and system complexity through advanced storage planning capabilities.
- **Alignment**: Supports OE goals by developing advanced storage planning capabilities to enhance grid reliability, affordability, and resilience.

Project Team

- Dr. Kostas Oikonomou, Electrical Engineer
- Dr. Di Wu, Electrical Engineer
- Dr. Patrick Maloney, Electrical Engineer
- Dr. Jesse T. Holzer, Mathematician
- Dr. Osten P. Anderson, Electrical Engineer
- Dr. Saptarshi Bhattacharya, Mechanical Engineer
- Dr. Jeremy B. Twitchell, Senior Energy Analyst
- Dr. Meng Zhao, Electrical Engineer
- Dr. Casey D. Burleyson, Earth Scientist
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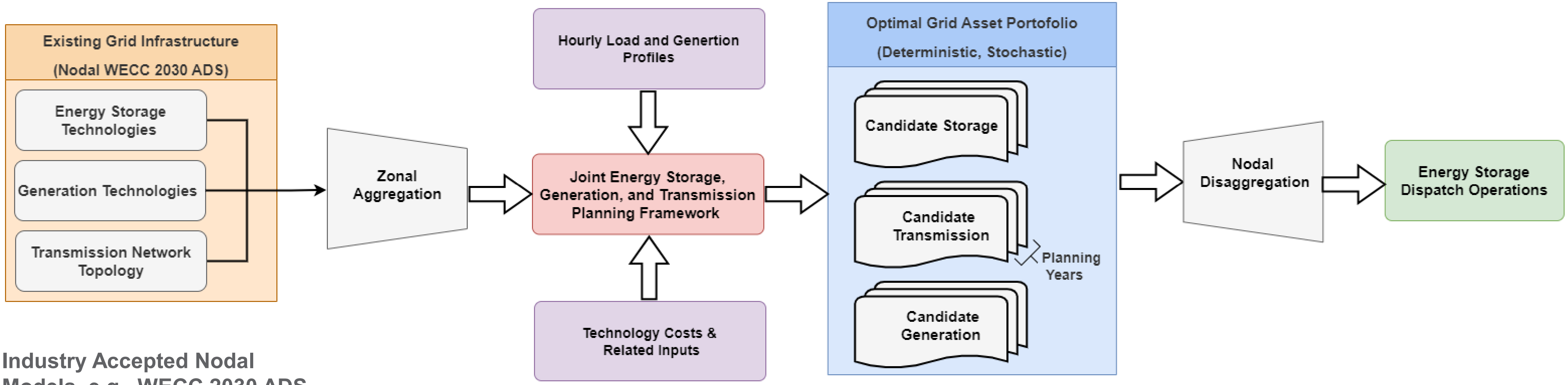
Objectives and Scope

Develop advanced framework, tools, and benchmarks to:

- Model storage technologies with appropriate fidelity, balancing accuracy and complexity to capture key techno-economic and physical capabilities
- Co-optimize storage, transmission, and generation planning by capturing key couplings, constraints, and trade-offs
- Assess storage's role in meeting capacity, flexibility, and transmission needs with reduced cost and improved resilience
- Evaluate planning sensitivities to factors such as technology advancement, load growth, and evolving system needs
- Account for uncertainties using scenario-based and stochastic methods to support robust planning

Enhanced Storage Expansion Planning Framework



Existing Grid Infrastructure

(Nodal WECC 2030 ADS)

Energy Storage Technologies

Generation Technologies

Transmission Network Topology

Zonal Aggregation

Hourly Load and Genertion Profiles

Joint Energy Storage, Generation, and Transmission Planning Framework

Technology Costs & Related Inputs

Optimal Grid Asset Portofolio

(Deterministic, Stochastic)

Candidate Storage

Candidate Transmission

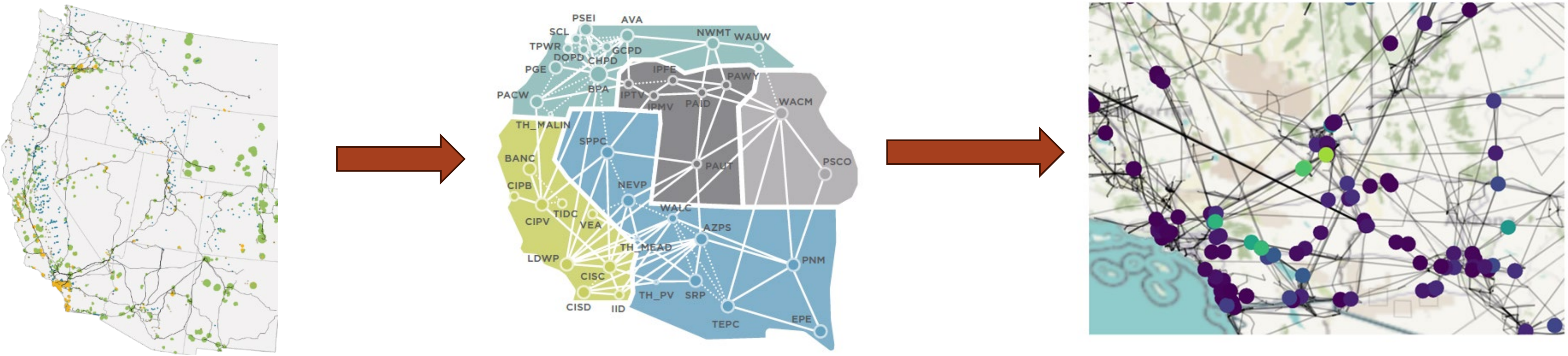
Candidate Generation

Planning Years

Nodal Disaggregation

Energy Storage Dispatch Operations

Industry Accepted Nodal Models, e.g., WECC 2030 ADS

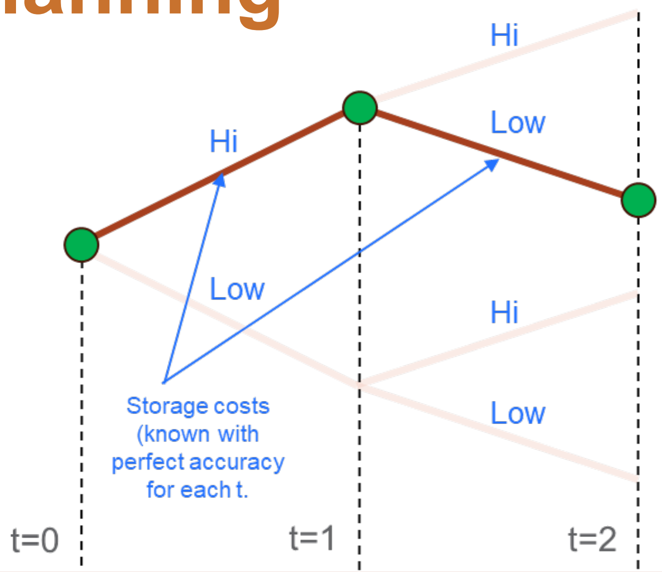


FY25 Research Progress and Activities

- Stochastic Energy Storage Planning Framework
- Advanced Modeling Techniques
  - Zonal-nodal mapping (at a substation level)
  - Detailed transmission cost modeling
- Comprehensive Planning Studies
  - Storage and transmission co-optimization
  - Nodal validation
- Planning Tool: Energy Storage – Planning, Resource Integration, Modeling and Expansion (ES-PRIME)

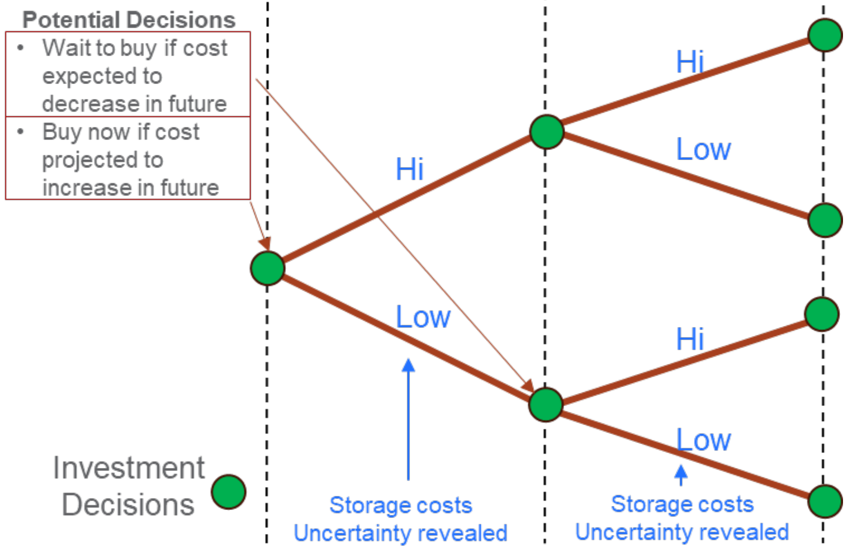
Stochastic Capacity Expansion Planning

- **Deterministic:** plan for a single future scenario (e.g., storage costs, hydro output, fuel costs)
  - Not robust to uncertainties
  - High risk of poor outcomes if the assumed future doesn't materialize



Storage costs (known with perfect accuracy for each t.

- **Stochastic**: plan across multiple possible future scenarios simultaneously
  - Each scenario represents a different realization of the future
  - Rather than optimizing for one assumed future, the model finds solutions that hedge against poor outcomes across many.



Potential Decisions
- Wait to buy if cost expected to decrease in future
- Buy now if cost projected to increase in future

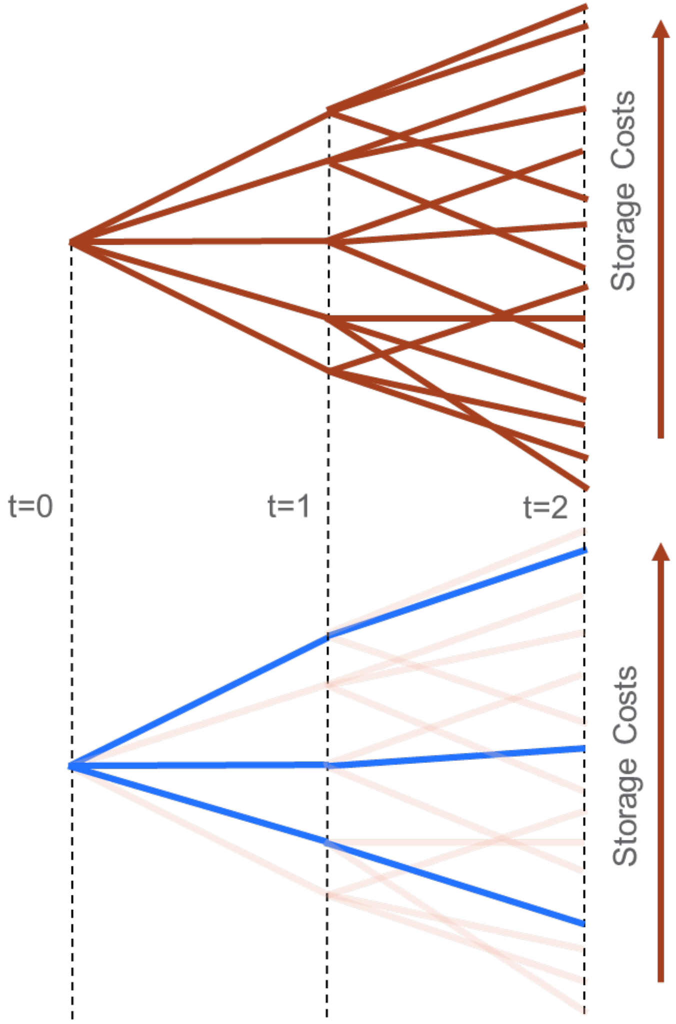
Storage costs Uncertainty revealed

Storage costs Uncertainty revealed

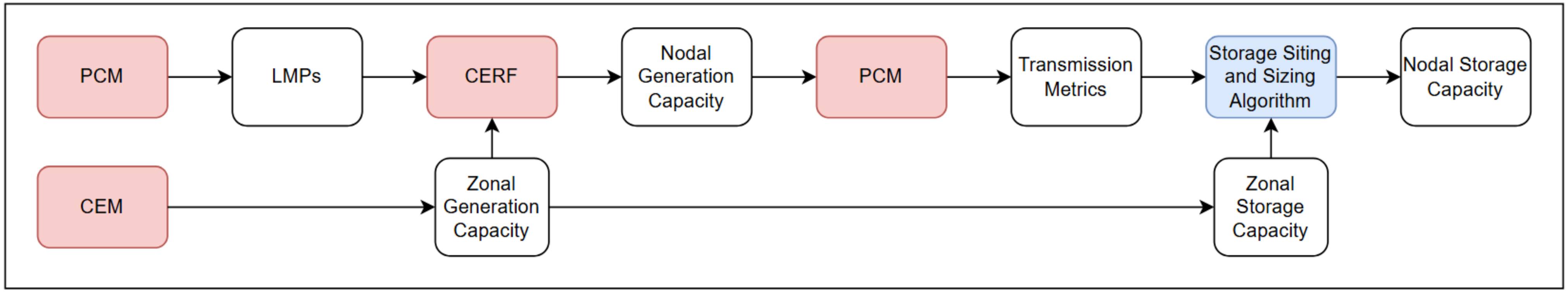
Scenario Reduction for High-Dimensional Stochastic Expansion Problems

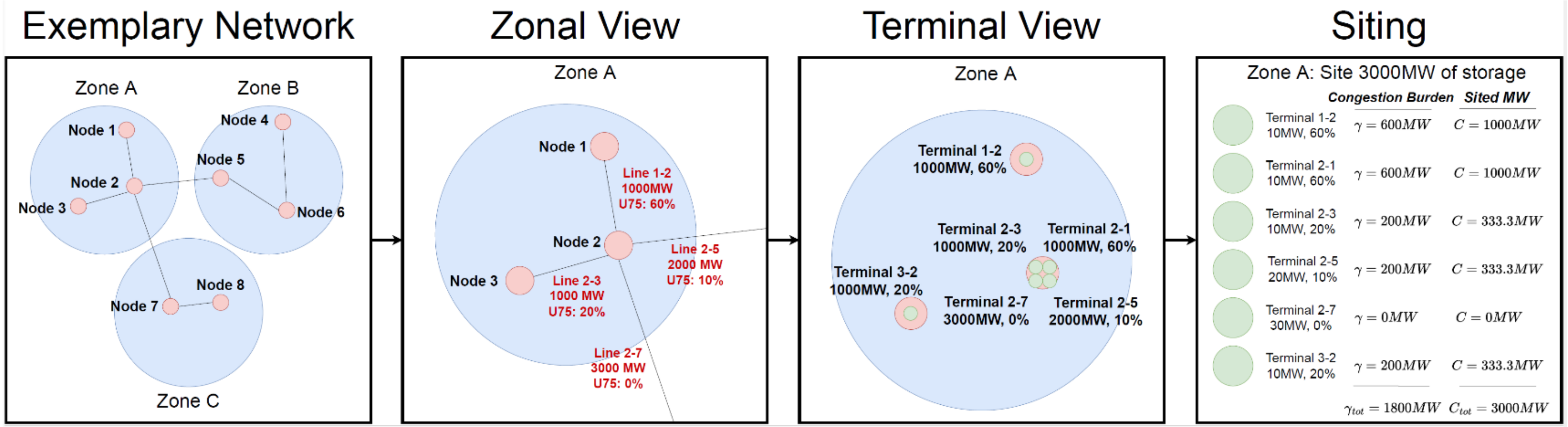
- Stochastic programming is computationally intensive
- Effective scenario reduction methods are needed to manage a high-dimensional attribute space
- **Proposed method**: Clustering algorithms require high scenario-to-attribute ratios to be effective
  - Singular value decomposition is used to reduce attribute space
  - Reduction uses K-medoids to reduce the number of scenarios

#	Scenario Name	Storage Capital Cost Maturation rate	Hydro Output in years >2030
1	Base	Typical maturation of CAPEX	Typical (2009)
2	Low Storage	Matures to lower CAPEX compared to Base	Typical (2009)
3	High Storage	Matures to higher CAPEX compared to Base	Typical (2009)
4	Low Hydro	Typical maturation of CAPEX	Low (2001)
5	High Hydro	Typical maturation of CAPEX	High (2012)
6	Low Storage Low Hydro	Matures to lower CAPEX compared to Base	Low (2001)
7	Low Storage High Hydro	Matures to lower CAPEX compared to Base	High (2012)
8	High Storage Low Hydro	Matures to higher CAPEX compared to Base	Low (2001)
9	High Storage High Hydro	Matures to higher CAPEX compared to Base	High (2012)



Congestion-based Zonal-to-Nodal Mapping



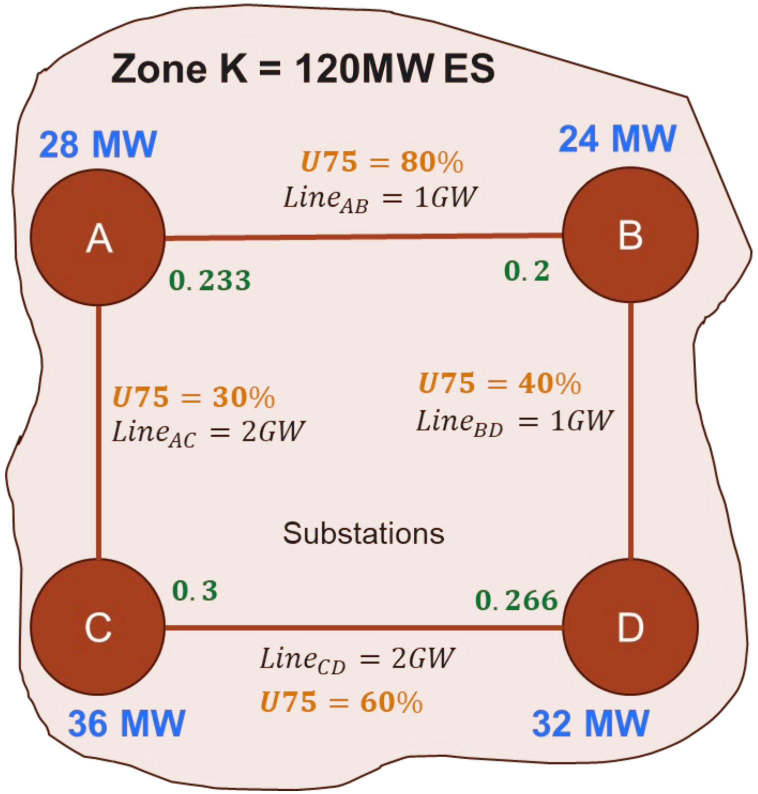


Disaggregation based on line congestion severity and transfer capability

Substation Mapping Example

To measure line utilization, we apply two WECC metrics:

- U75%: % of hours (out of 8,760) a line operates at ≥75% of its rated capacity
- U90%: % of hours a line operates at ≥90% of its rated capacity



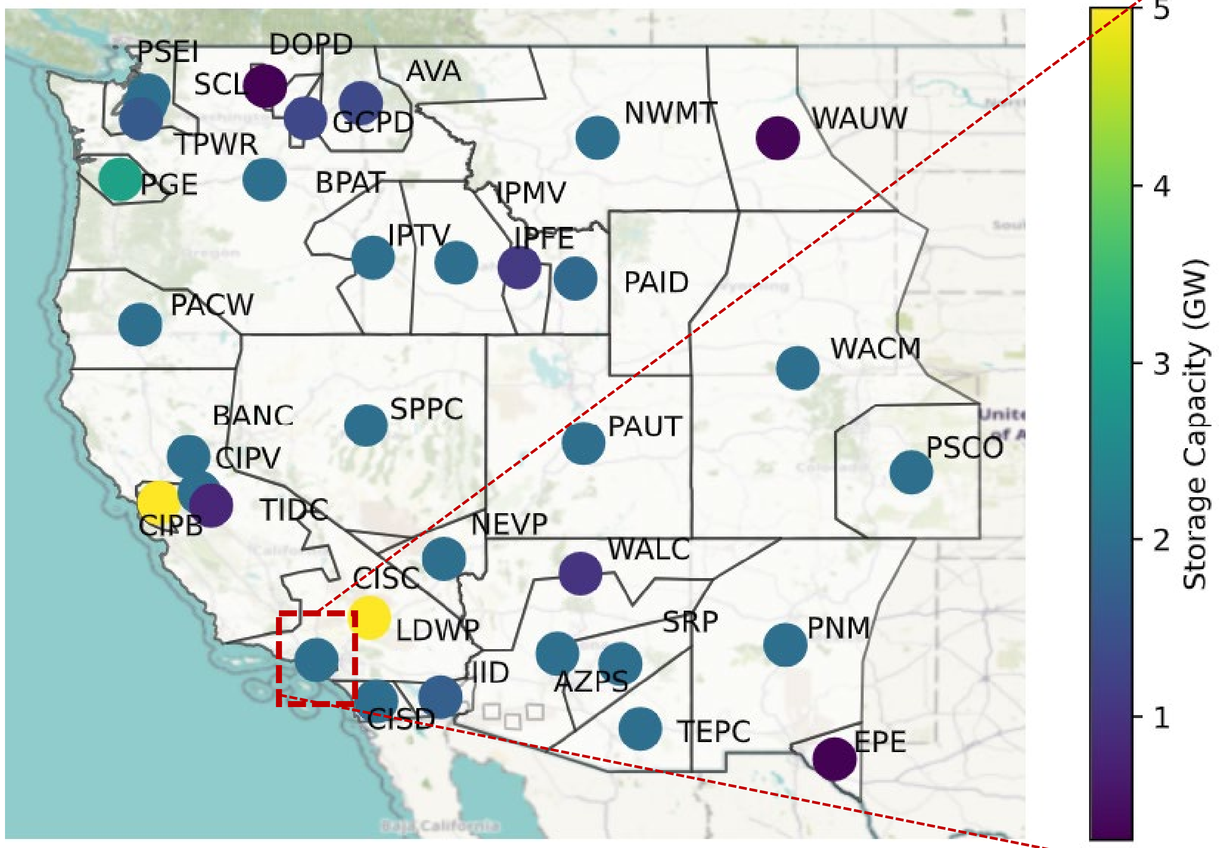
- **Step 1**: Calculate the U75 metric for each line using hourly flow data over the year
- **Step 2**: Compute a normalized weighting factor for each substation:

$$Substation_A = \frac{0.8 \times 1 \; + \; 0.3 \times 2}{2(0.8 \times 1) \; + \; 2(0.3 \times 2) \; + \; 2(0.6 \times 2) \; + \; 2(0.4 \times 1)} = \mathbf{0.2}$$

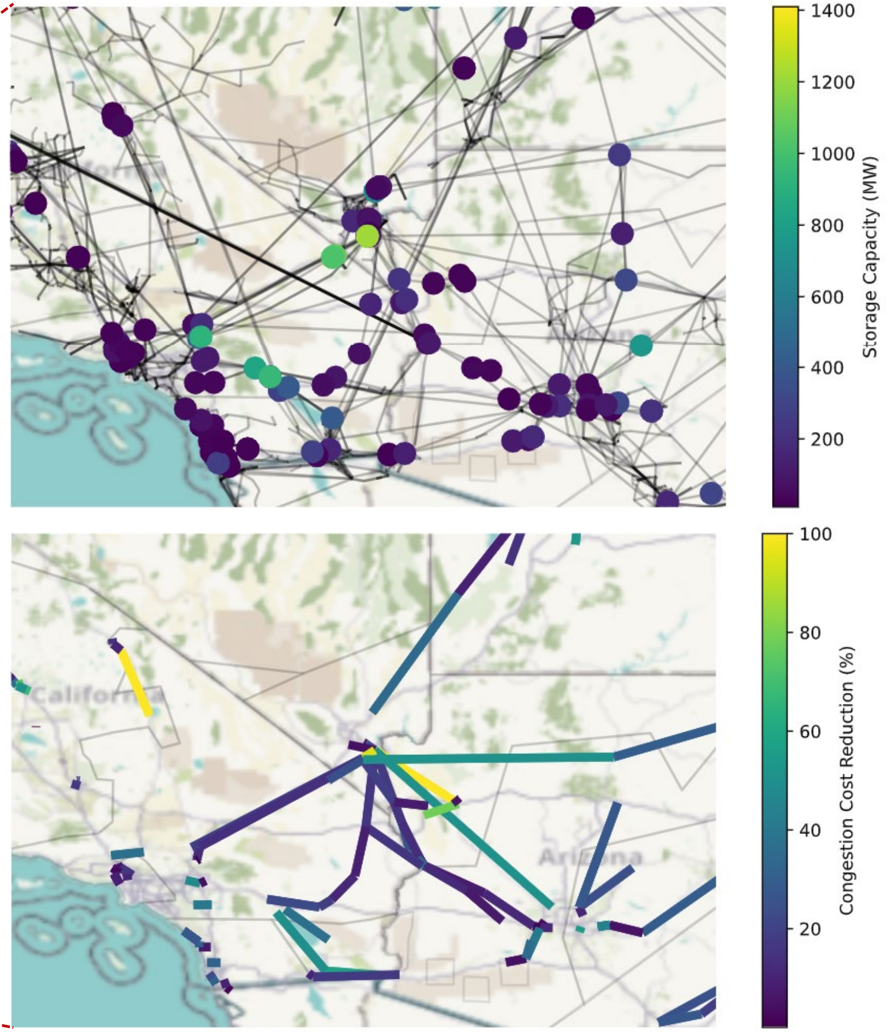
- **Step 3**: Allocate zonal storage capacity to substations using the computed weights

Nodal Validation

Zonal Capacity Expansion Results



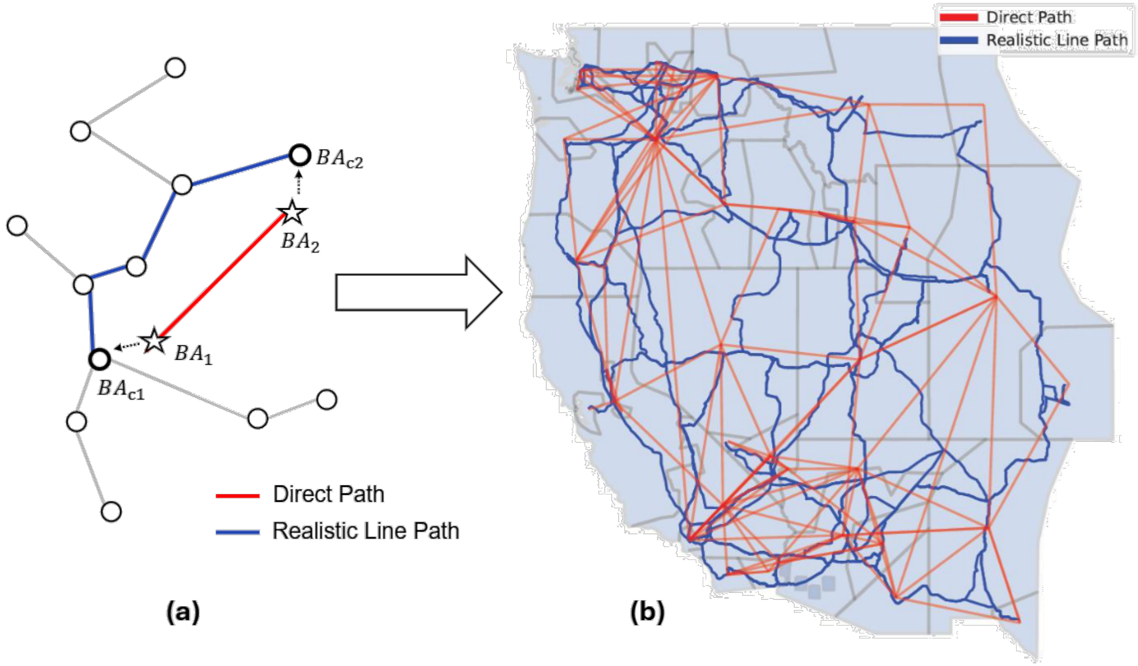
Nodal Energy Storage Disaggregation Results



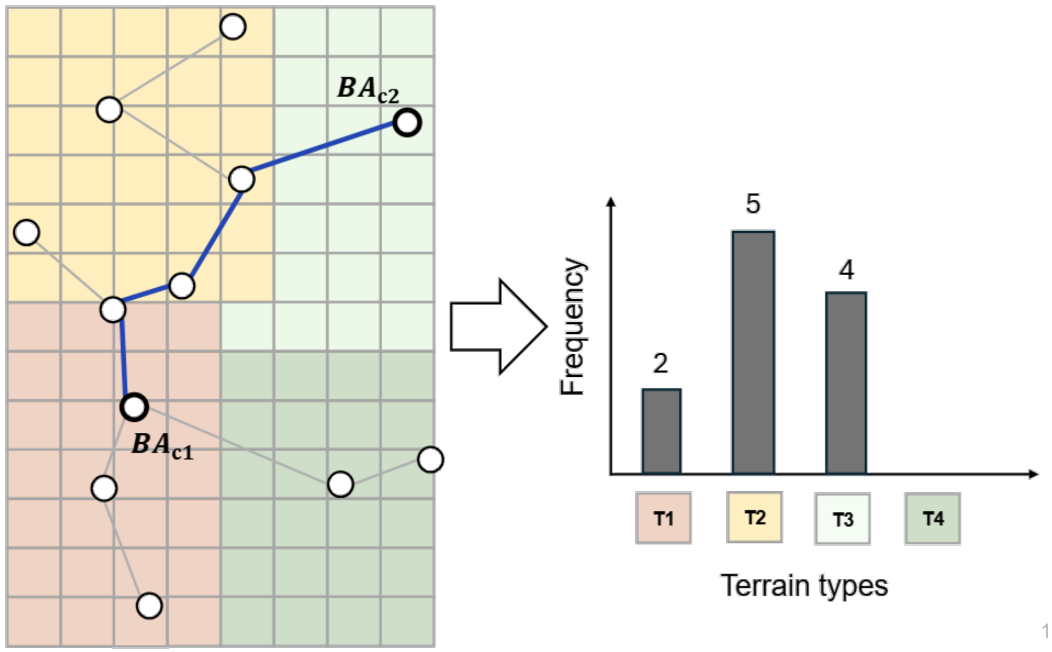
Storage and Transmission Co-Optimization

Accurate transmission modeling is critical for storage planning, particularly when evaluating where and how storage can defer or complement transmission investments under varying terrain, rights-of-way, and substation costs.

- Conventional Approaches: use straight-line distances with fixed per-mile costs, leading to inaccurate routing and cost estimates.
- Proposed Method**:** employ a graph-based network analysis that traces candidate transmission corridors along existing rights-of-way.

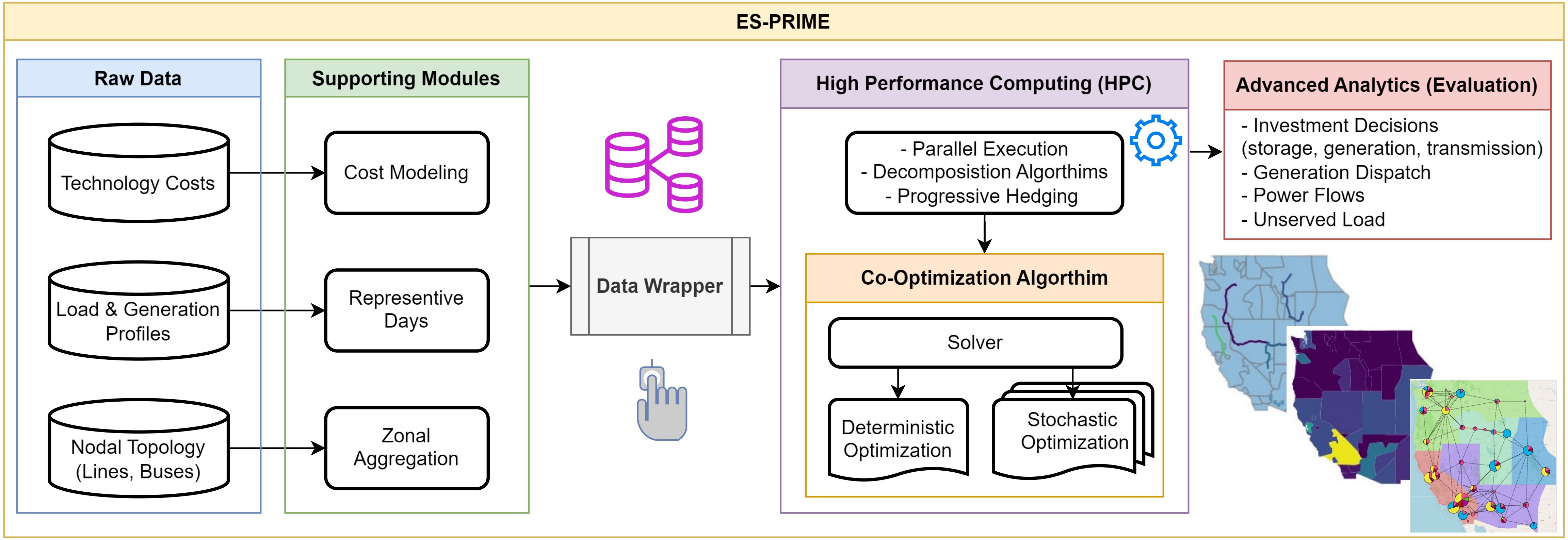


(a) (b)



Energy Storage Planning, Resource Integration, Modeling, and Expansion (ES-PRIME)

- ES-PRIME: A modeling platform focused on energy storage planning and its co-optimization with generation and transmission investments. It supports automated data integration, high-performance computing, and advanced analytics.



ES-PRIME

Raw Data

Technology Costs

Load & Generation Profiles

Nodal Topology (Lines, Buses)

Supporting Modules

Cost Modeling

Representive Days

Zonal Aggregation

Data Wrapper

High Performance Computing (HPC)

- Parallel Execution
- Decomposition Algorthims
- Progressive Hedging

Co-Optimization Algorthim

Solver

Deterministic Optimization

Stochastic Optimization

Advanced Analytics (Evaluation)

- Investment Decisions (storage, generation, transmission)
- Generation Dispatch
- Power Flows
- Unserved Load

Look Forward

- Enhance storage modeling by including additional technologies and optimizing firm capacity contributions as a perfect-capacity resource
- Explore additional zonal-nodal mapping strategies
- Improve stochastic planning by better accounting for uncertainties in interconnection queues
- Refine load modeling to better reflect emerging loads, including AI data centers
- Expand planning analysis to other regions to evaluate how storage roles and value vary geographically

Publications

- S. Bhattacharya, O. Anderson, K. Oikonomou, P. Maloney, J. Holzer, J. Twitchell, D. Wu, “Comparative Assessments for Transmission and Energy Storage Investments in Power Systems Expansion Planning,” to be submitted.
- O. Anderson, K. Oikonomou, K. Mongird, and D. Wu, "Congestion-based Zonal-to-Nodal Disaggregation for Energy Storage Planning," to be submitted.
- P. Maloney, O. Anderson, J.T. Holzer, S. Bhattacharya, K. Oikonomou, D. Wu, “Stochastic Capacity Planning Under Hydropower and Energy Storage Investment Uncertainties,” *IEEE Power Energy Soc. Gen. Meet.*, Austin, TX, July 2025.
- K. Oikonomou, P. R. Maloney, S. Bhattacharya, J. T. Holzer, O. Anderson, X. Ke, J. Westman, C. D. Burleyson, S. Datta, J. B. Twitchell, and D. Wu, “*Energy storage planning for enhanced resilience of power systems under extreme events*,” *Journal of Energy Storage*, May 2025.
- O. Anderson, N. Yu, K. Oikonomou, and D. Wu, “On the selection of intermediate length representative periods for capacity expansion,” *IEEE Power Energy Soc. Gen. Meet.*, Seattle, WA, July 2024.
- P. Maloney, S. Bhattacharya, X. Ke, A. Venkatraman, A. Somani, and D. Bhatnagar, “Capacity expansion planning for LA basin: The role of energy storage,” *IEEE Electr. Energy Storage Appl. Technol. Conf. (EESAT)*, pp. 1–5, 2022.

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The Office of Electricity leads the U.S. Department of Energy’s research and development to strengthen and modernize our nation’s power grid to maintain a reliable, affordable, secure, and resilient electricity delivery infrastructure.

https://www.energy.gov/oe/energy-storage

Thank You

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