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From Analytics to Field Validation: Insights and Lessons Learned from Storage-Enabled Microgrids

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MN DOC Webinar Series

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U.S. DEPARTMENT of ENERGY BATTELLE

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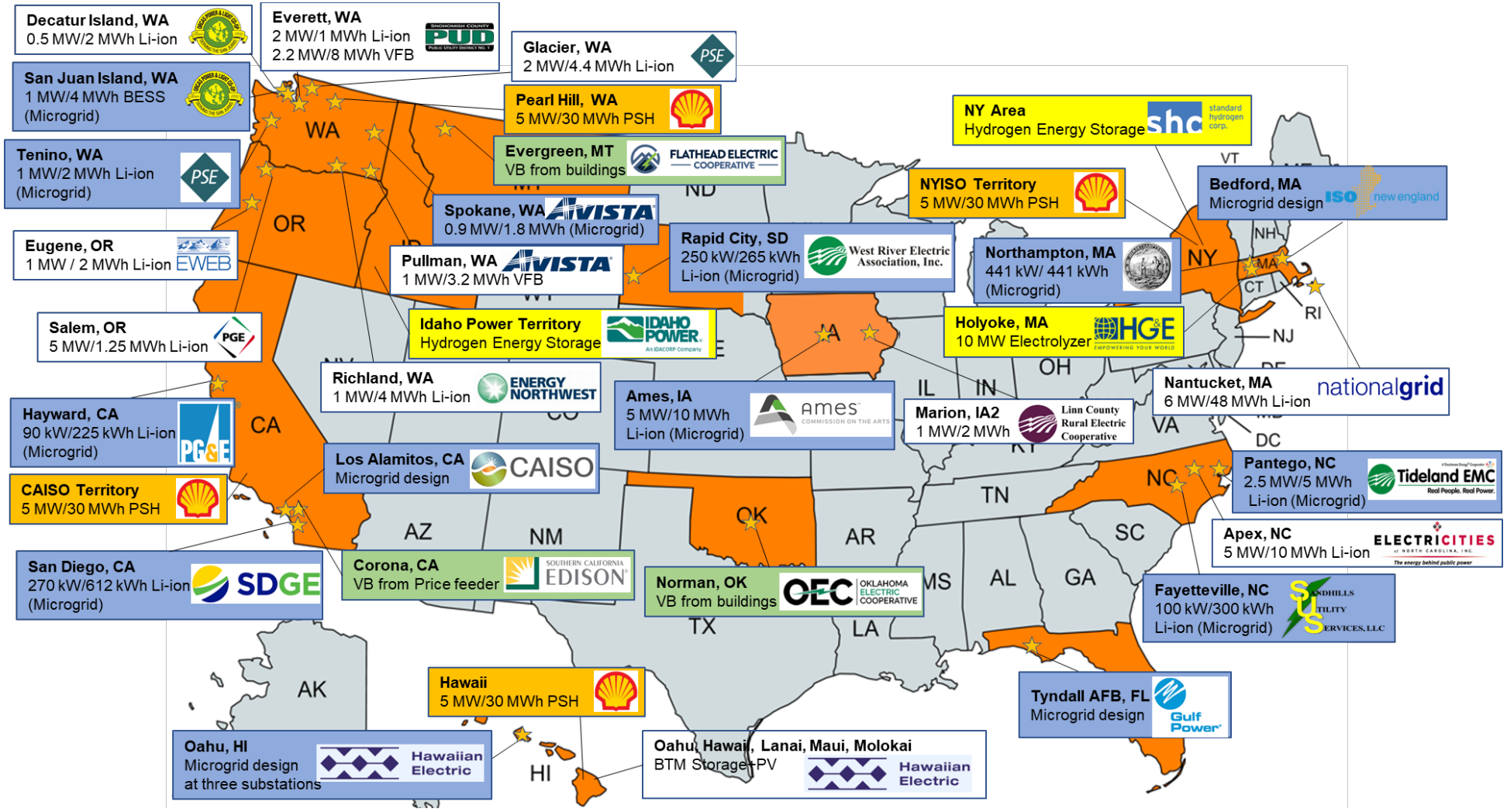
PNNL Has Assessed Energy Storage Systems at More Than 60 Sites



Battery Energy Storage | Microgrids | Hydrogen | Buildings as Storage | Pumped Storage Hydro

Unlock Storage Potential with Advanced Analytics

System Design and Characteristics

- Energy storage technology, physical capability, and characteristics

Deployment Scenarios

- Vertically integrated utilities, electricity markets, distribution utilities, and large C&I customers

Use Cases and Applications

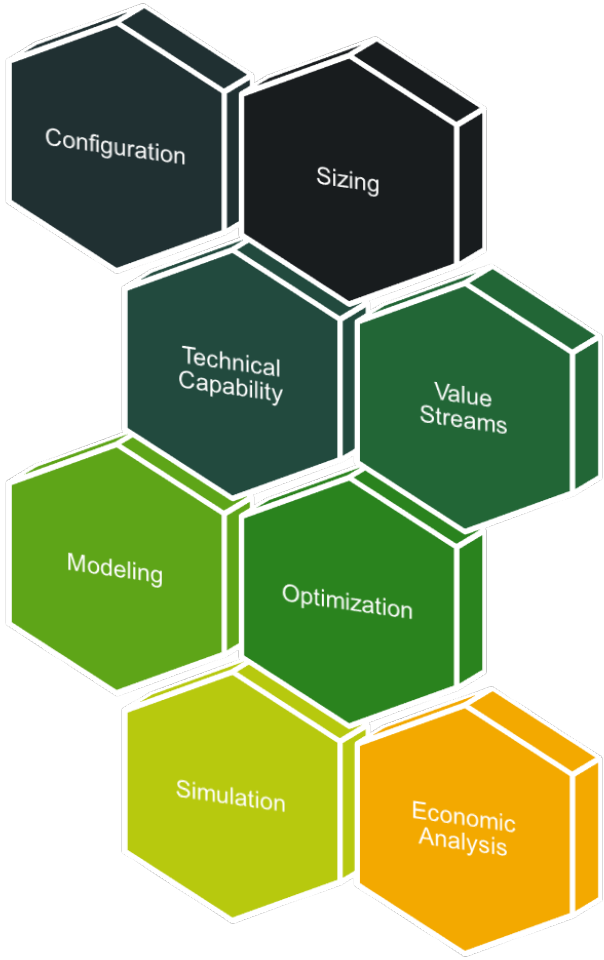
- Bulk energy, ancillary service, transmission-level, distribution-level, and end-user services

Dispatch and control strategies

- Co-optimization, rule-based control, mathematical programming, stochastic/risk-aware control, learning-based method, hybrid-control

Regions and systems

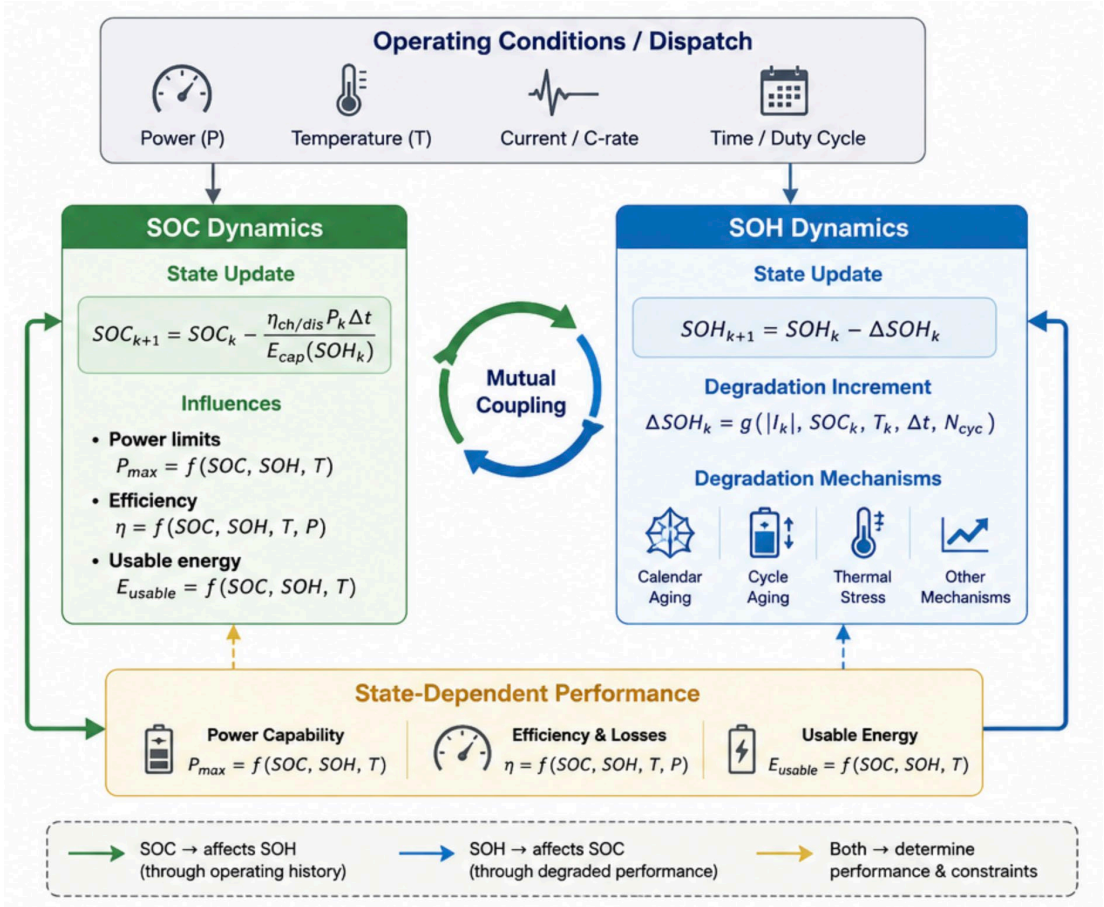
- Different generation mix, grid infrastructure, market structures/rules, distribution system capacity, and load growth rate



Inadequate capabilities for appropriately modeling and valuing energy storage have become a significant barrier to market penetration

Enhanced Storage Modeling

- Technology-Aware Representation
  - Coupled SOC and SOH dynamics
  - SOC/SOH-dependent power capability
  - Nonlinear efficiency and operating behavior
- High-Fidelity Model Development
  - Models derived from product specifications and field measurements
  - Calibration using testing/operational data
- Planning and Operational Integration
  - Integration into planning, techno-economic assessment, and dispatch
  - Methods addressing nonlinear, high-order, and intertemporal challenges

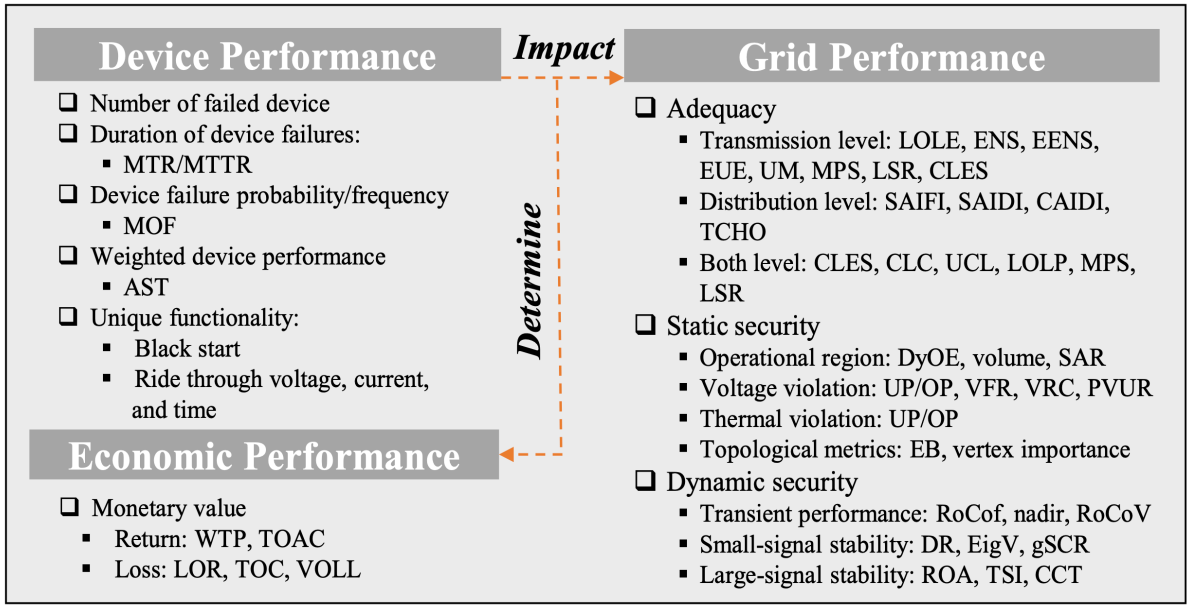


Crawford, V. Viswanathan, D. Wu, D. Choi, D.M. Reed, X. Ma, and V. Sprenkle, "BESS performance and degradation modeling with multi-system validation," under review.

A. Das, H. Kim, and D. Wu, "Learning-based dispatch for optimal energy storage operation considering degradation effects," *IEEE Electrical Energy Storage Applications and Technologies Conference, 2025*

Resilience Metric and Quantification

- Increasing operational challenges from aging infrastructure and growing system complexity
- Storage as a solution across the grid, especially for enhancing reliability and resilience
- Lack of clear metrics, data needs, and standardized quantification methods
- Need for an advanced framework to assess storage benefits and guide storage planning and operation decisions



Resilience Objective

$$\min_{\Theta} \sum_{t \in T} C_t + R_t$$

Decision Set

Economic Objective

For $\forall t = 1, 2, \cdots T$ and $\psi_t \in \Psi$, Event Set

$$s.t. \begin{cases} \dot{x} = f(x, y) \\ 0 = g(x, y) \\ \underline{r} \le r(x, y) \le \bar{r} \end{cases}$$

Resilience Constraints

B. She, D. Wu, and K. Kwon, "A Review of Energy Storage for Power System Resilience: Functions, Metrics, and Applications," *Applied Energy*, 2026.

Operational Uncertainty and Risk-aware Dispatch

- Manage uncertainty and tradeoffs
  - Resilience vs. economic benefits
  - Short-term value vs. degradation/service life
- Integrated forecast and storage dispatch
  - Forecasts of outages, peak days, etc.
  - Adaptive reserve management and dispatch activation
- Adaptive energy reserve and dispatch
  - Rule-based or learning-based reserve setting and dispatch activation
  - Adaptive dispatch optimization informed by Step-1 decisions

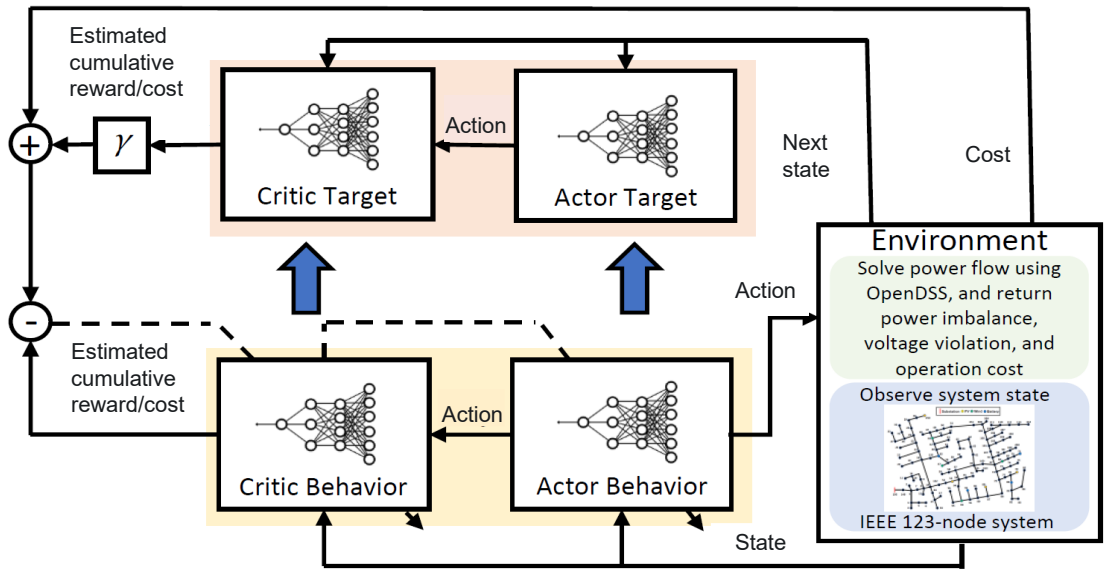
H. Kim, A. Das, D. Wu, R, Kini, Z. Hou, and N. Lu, "Generative modeling for mid-term probabilistic load forecasting based on latent diffusion," *Applied Energy*, vol. 406, 2026..

Z. Hou, T. Fu, H. Ren, D. Wang, X, Ma, and D. Wu, "An uncertainty-informed digital twin framework for optimal long-duration energy storage dispatch," *International Journal of Electrical Power & Energy Systems*, vol. 177, 2026.

Approximate Dynamic Programming with Enhanced Off-policy Learning and Battery Loss of Life

- Shortcomings of existing ADP methods
  - Battery life and degradation are not properly modeled
  - Lookup tables are infeasible for continuous states/actions
  - Gradient-based ADPs struggle with exploration, data usage, and computational complexity
- Innovative ADP for DER coordination
  - Explicit modeling of calendrical and cyclical aging effects
  - Customized policy with random exploration to enhance off-policy learning efficiency

Objective Function	Degradation Effects	Proposed ADP Approach	Power Flow and Safe Exploration
• BESS O&M cost • Energy cost	• Calendar life loss considering different SOC and ambient temperature • Cycle life loss based on BESS cycling	• Off-policy gradient-based learning • Customized policy to explore promising decisions	• Power flow solution from OpenDSS using actions from proposed ADP • Action clipping and reward shaping



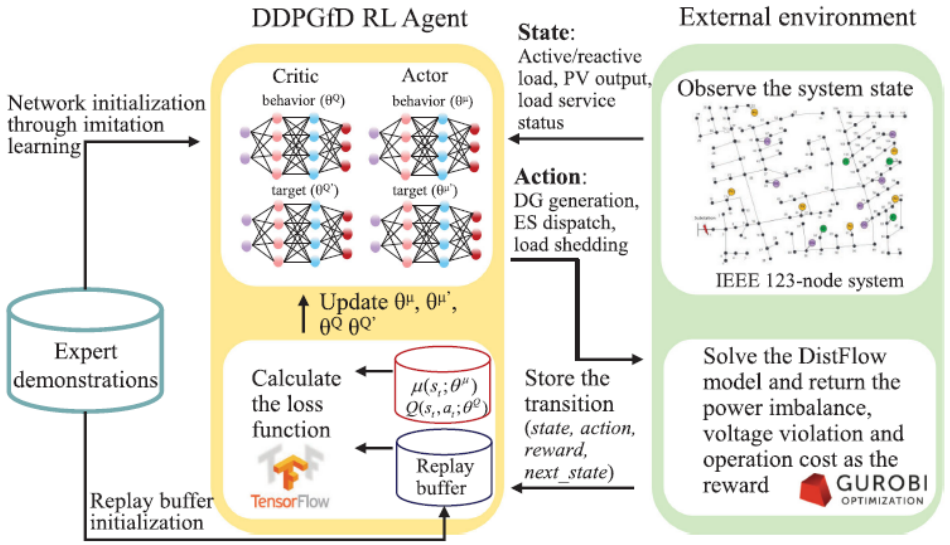
A. Das, D. Wu, B. Bhatti, and M. Kamaludeen, "Approximate dynamic programming with enhanced off-policy learning for coordinating distributed energy resources," *IEEE Transactions on Sustainable Energy*, vol. 15, no. 3, pp. 1614–1626, Jul. 2024.

Learning-based Control to Assist Service Restoration Through Microgrid

Deep reinforcement learning from demonstrations to assist service restoration in islanded microgrids:

- Pre-training stage: imitation learning is applied to equip the control agent with expert experiences to guarantee acceptable initial performance.
- Online training stage: action clipping, reward shaping, and expert demonstrations are leveraged to ensure safe exploration while accelerating the training process.

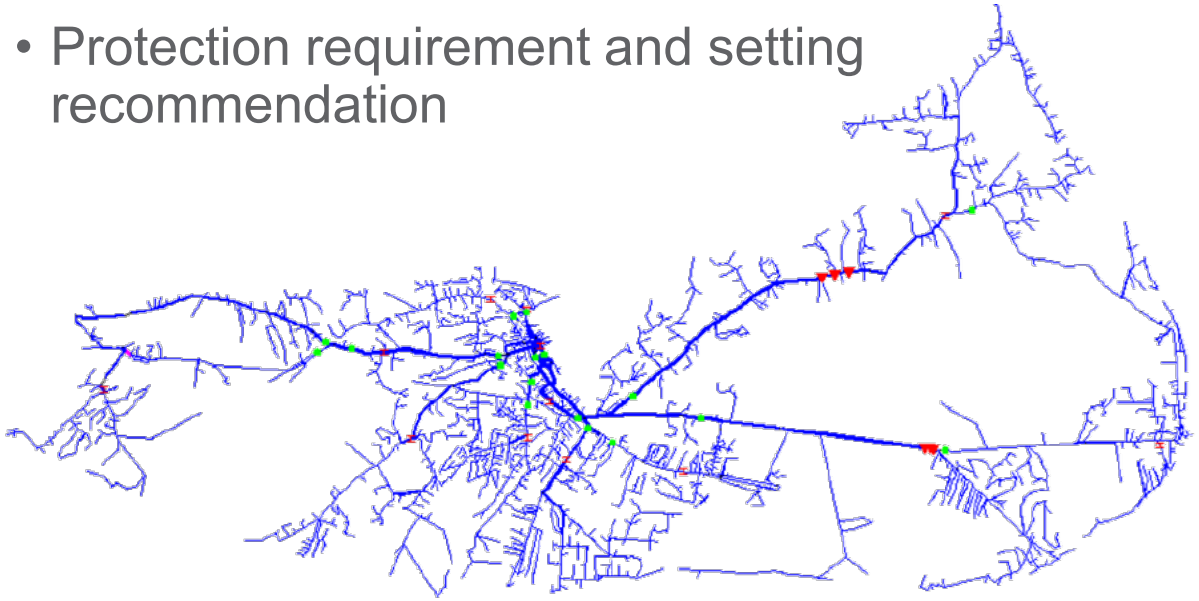
Data-driven methods face practical challenges such as potential hazards to microgrids during on-line training opportunities and insufficient on-line training due to low outage rates.

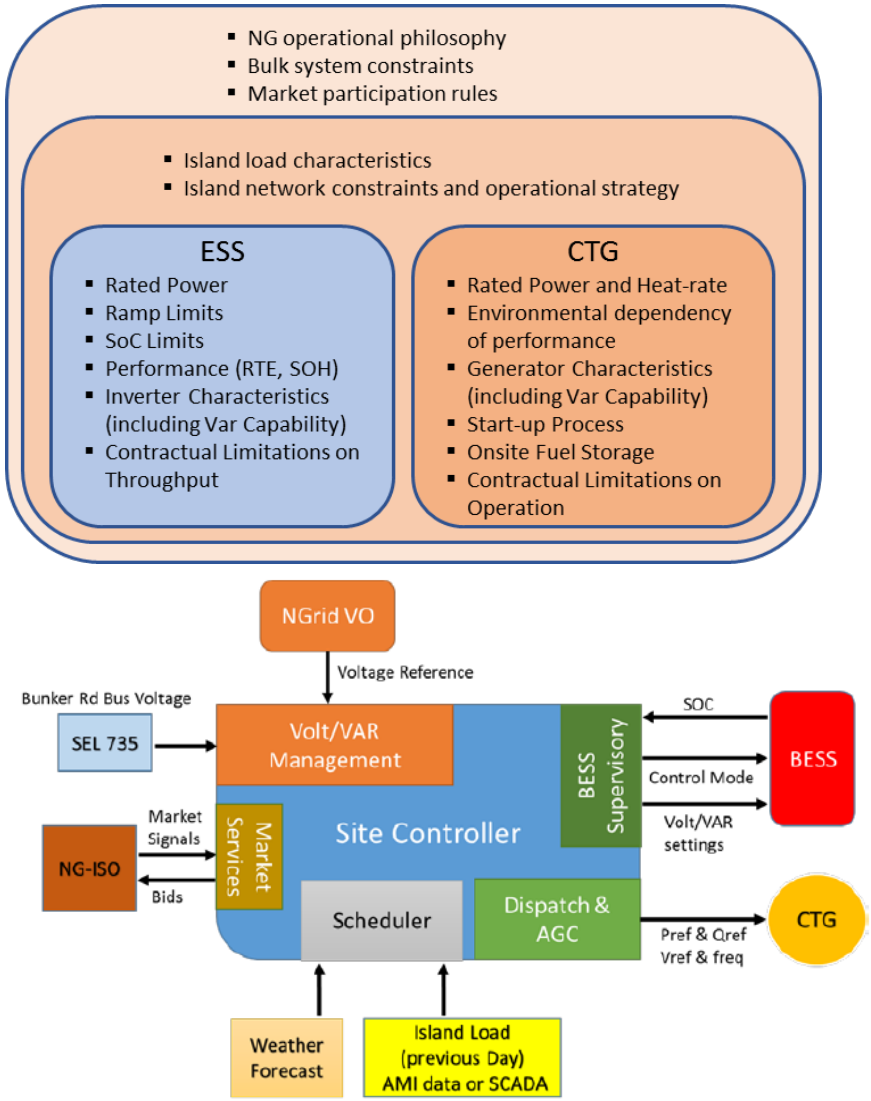


Y. Du and D. Wu, "Deep reinforcement learning from demonstrations to assist service restoration in islanded microgrids," *IEEE Transactions on Sustainable Energy*, vol. 13, no. 2, pp. 1062–1072, Apr. 2022.

Distribution Analysis and Control Design

- Model conversation and validation
  - CYMDIST and PSS/E → OpenDSS and GridLAB-D
- Distribution system analysis
  - Recommended upgrades
  - BESS dispatch
  - Harmonic analysis
- Protection requirement and setting recommendation



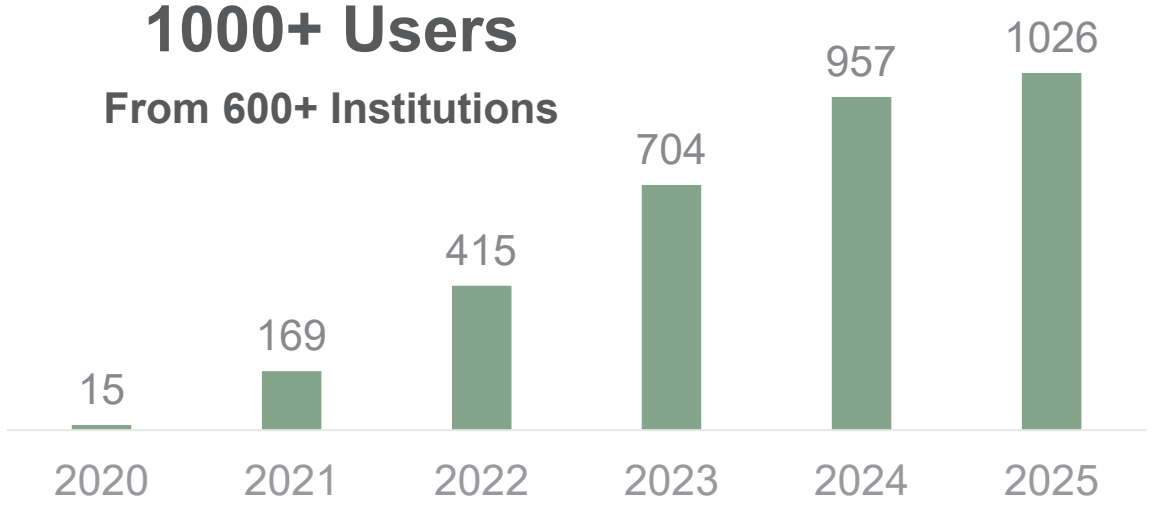


Energy Storage Evaluation Tool™

https://eset.pnnl.gov

ESET™ – a suite of applications that enable utilities, regulators, vendors, and researchers to model, optimize, and evaluate various energy storage systems for stacked value streams

- Battery Storage Evaluation Tool (BSET)
- **Energy Storage for Resilience and Reliability (ES4R2)**
- **Microgrid Asset Sizing considering Cost and Resilience (MASCORE)**
- Pumped-Storage Hydropower Evaluation Tool (PSHET)
- Virtual Battery Assessment Tool (VBAT)



A subset of features and capabilities of ESET are made publicly accessible as a web-based tool: https://eset.pnnl.gov/

Key Features of ESET™

https://eset.pnnl.gov

Comprehensive Models

Properly represent diversified technical and economic characteristics of different energy storage technologies and their hybridization

Advanced Optimization

Maximize benefits and determine optimal sizing/siting, considering multi-dimensional couplings and practical constraints

Consistent Modeling

Various use cases and assumptions across different technologies and deployments, allowing for fair comparisons

Built-in Databases

Utility rates, electricity market prices, generation and load profiles, and energy storage cost for easy and rapid input preparation

Integrated Uncertainties and Control

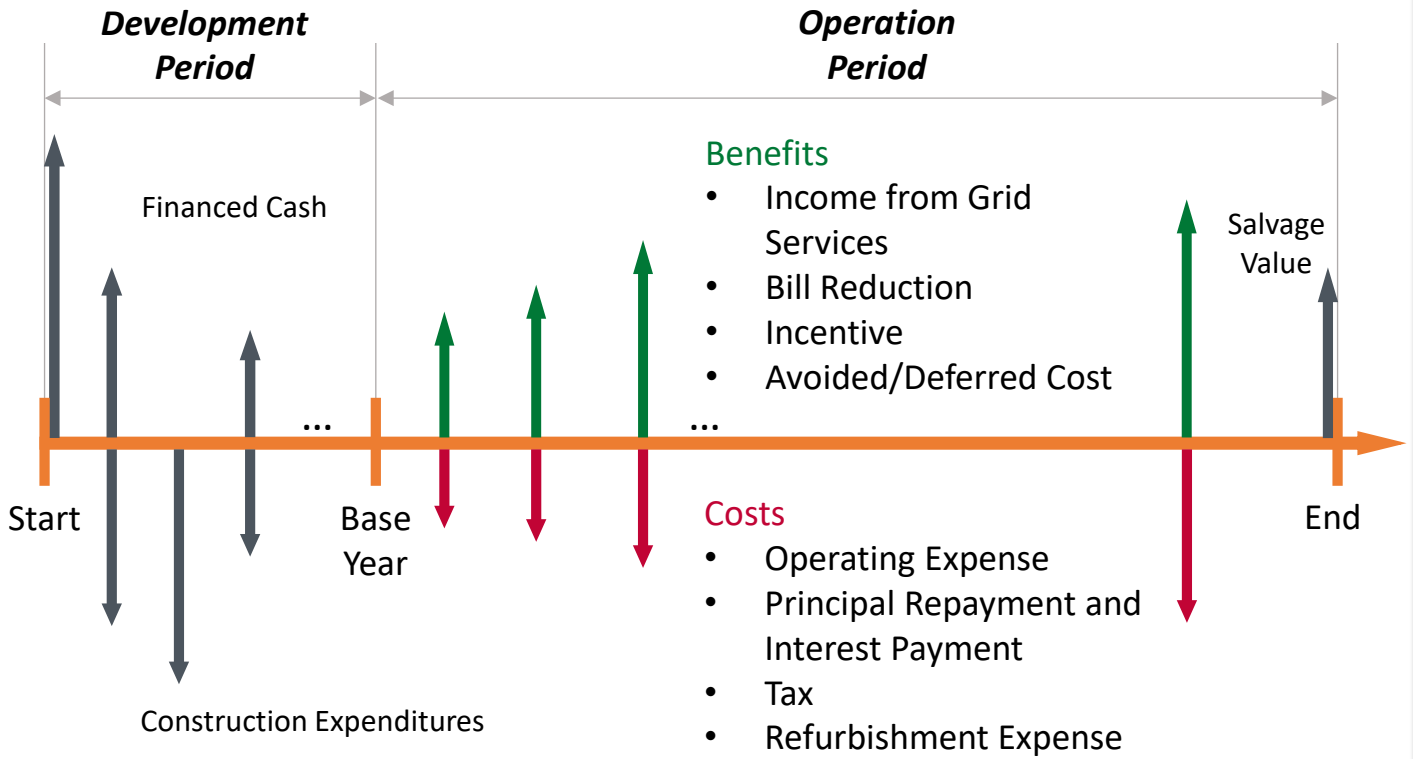
Ensure the estimated benefits align with the actual benefits of the deployed systems

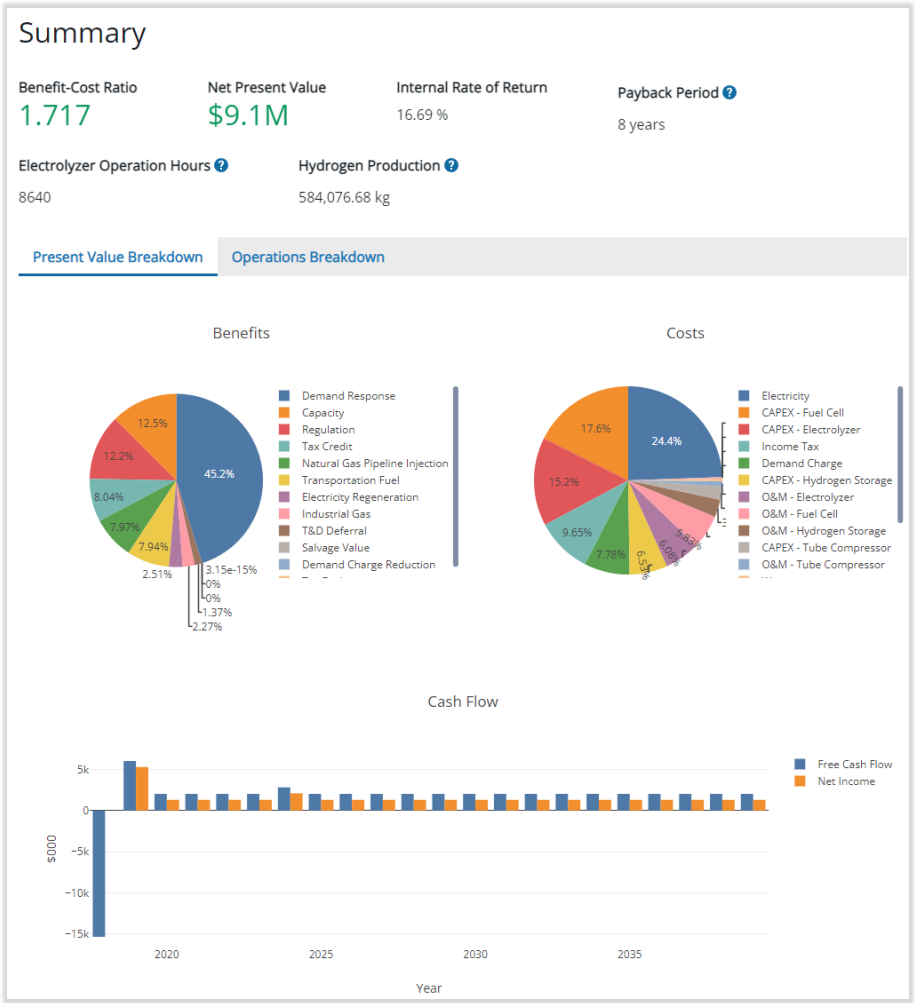
Economic/Financial Analysis Engine

Articulates benefits vs costs, calculates key metrics (BCR, NPV, IRR), and reports net income and cash flow

Comprehensive Cost-Benefit Analysis Engine

- Cash Flow for ESS Projects





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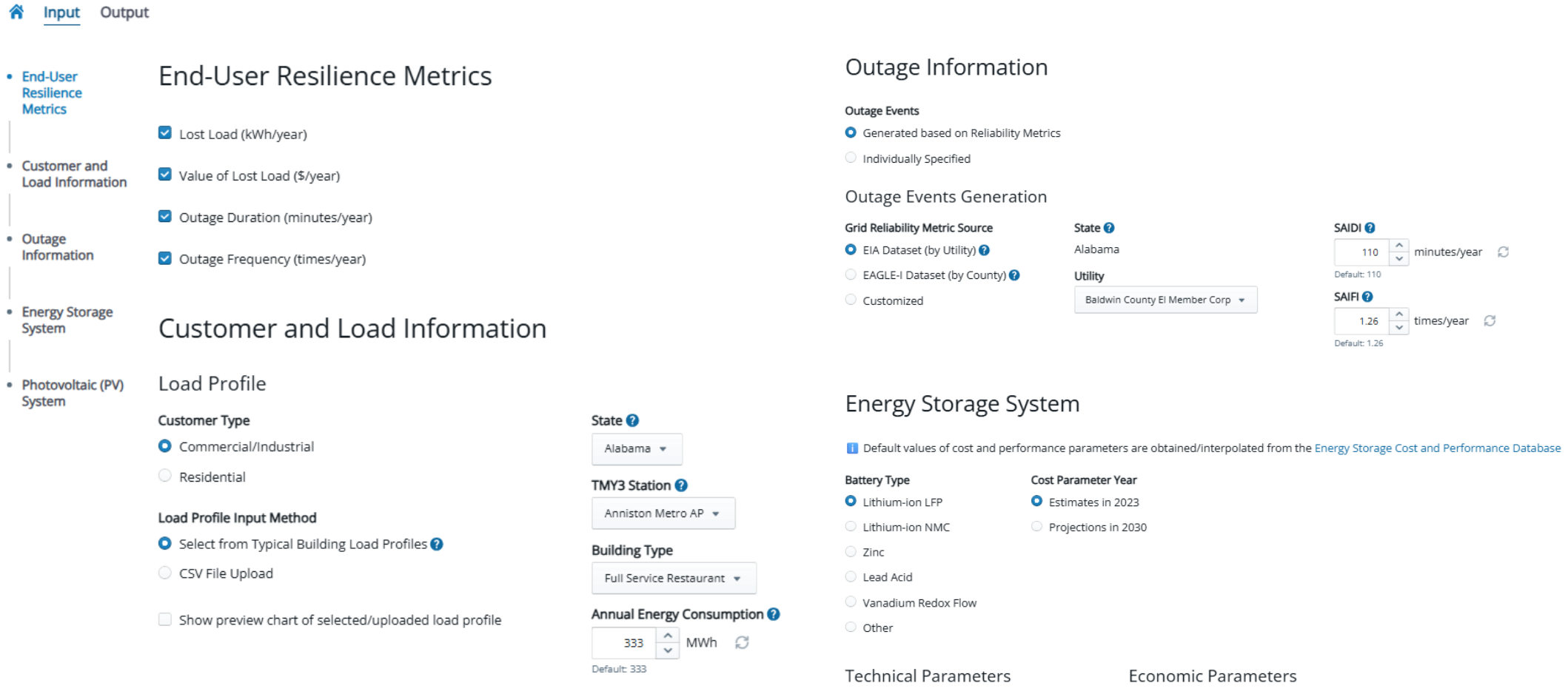
Energy Storage for Reliability and Resilience

A **web-based, easy-to-use app** that is **flexible and configurable** for customized storage benefit quantification



Resilience Quantification Tool

https://eset.pnnl.gov

Summary of Benefits

- Tabular comparison of metric evaluation results

Resilience Assessment

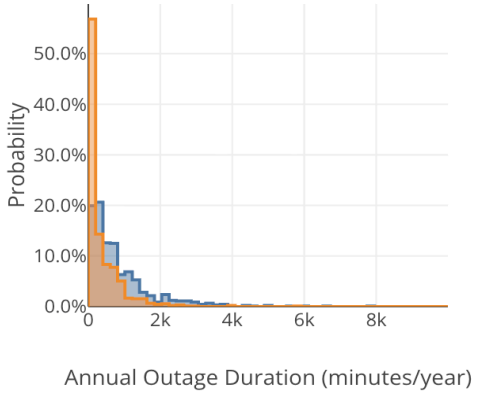
- Discretized probability distribution plots
- Complementary cumulative distribution plots

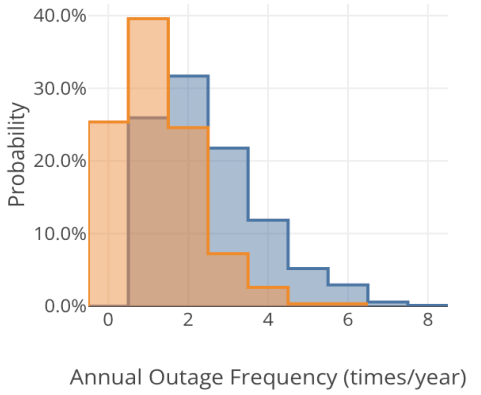
Event-Oriented Analysis

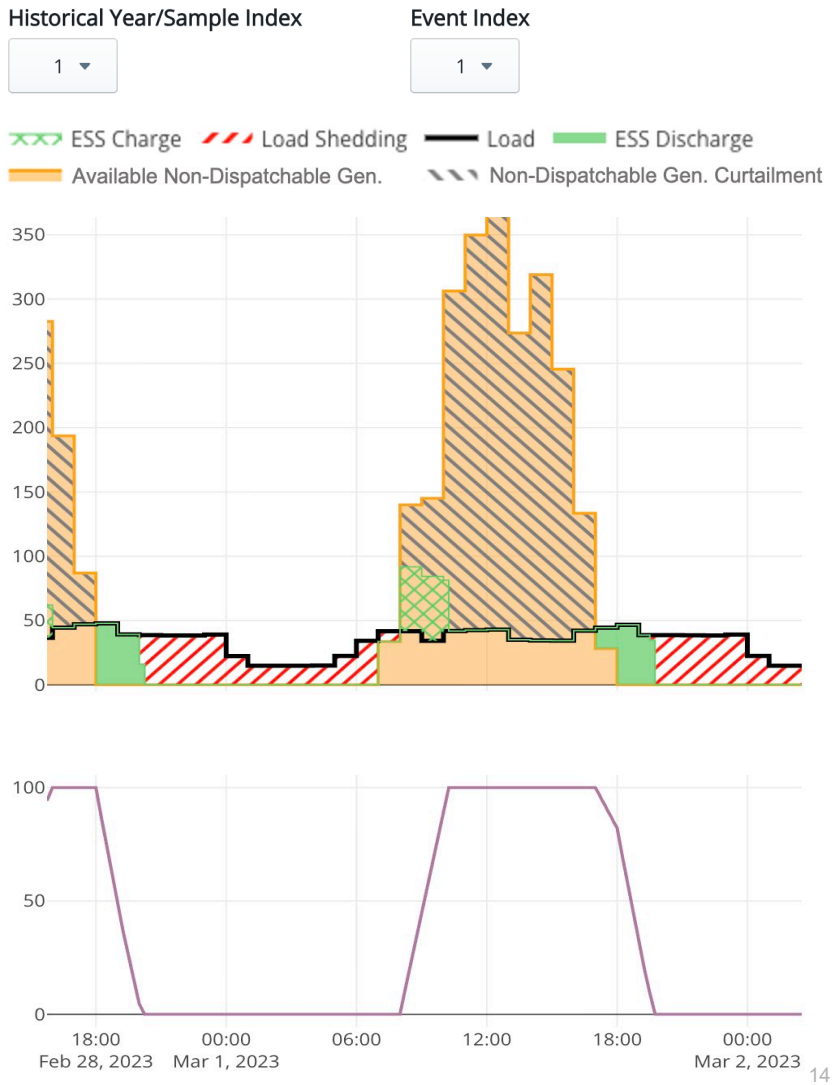
- Time-series visualization of ESS charge/discharge, load served/shedding, and other system components

Annual Energy Service Disruption Metrics

	Baseline	With Storage Solution	Improvement
Lost Load (MWh/year)	0.59	0.17	0.43 (72%)
Value of Lost Load ($/year)	47K	15K	32K (68%)
Outage Duration (minutes/year)	839	350	489 (58%)
Outage Frequency (times/year)	2.5	1.2	1.3 (50%)



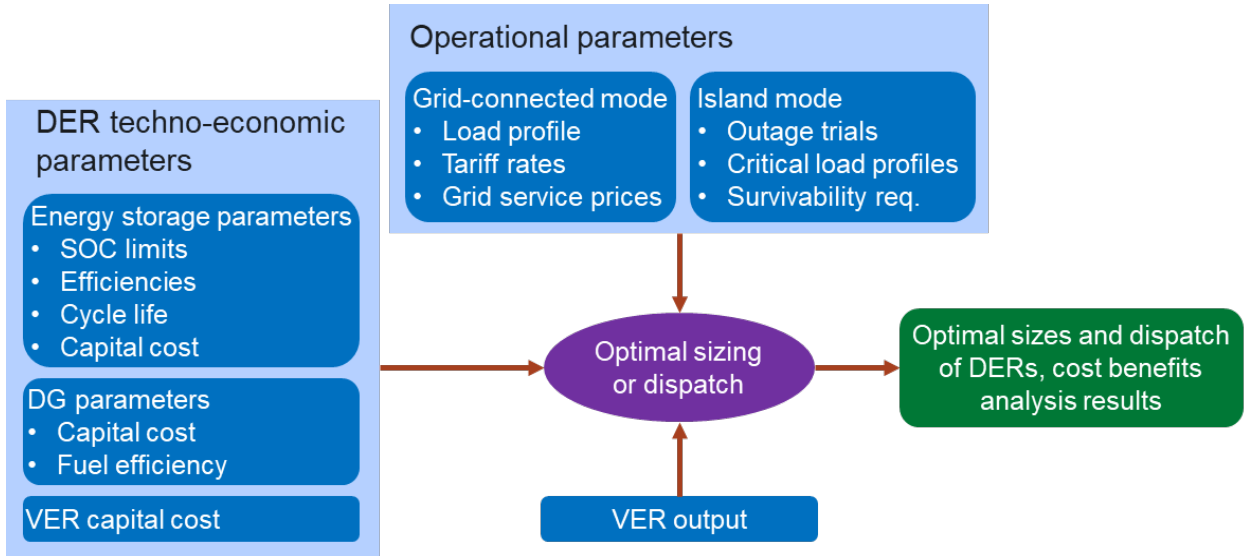




MASCORE

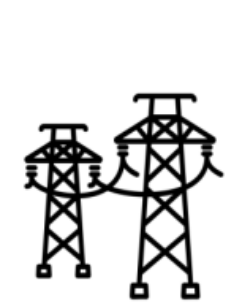
Microgrid Asset Sizing Considering Cost and Resilience (MASCORE): Select, size, and evaluate energy storage and other DERs for a cost-effective and resilient microgrid

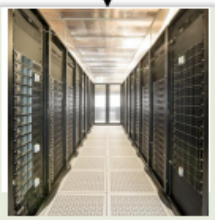
- Modeling various DER technologies with different economic and technical characteristics
- Modeling and capturing diversified system conditions in both grid-connected and island modes
- Capturing the interdependency between optimal size and dispatch
- Simultaneously determining the optimal sizes of different DERs



D. Wu, X. Ma, S. Huang, T. Fu, and P. Balducci, "Stochastic optimal sizing of distributed energy resources for a cost-effective and resilient microgrid," *Energy*, vol. 198, May 2020, 117284

Resilient Energy Storage Platform with Enhanced Ceramic Technology (RESPECT)





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TEA and Resilience Analysis

- Resiliency Definition
- Load Analysis
- ESS Planning Tool
- Resilience Operation Algorithm

Testing and Reporting

- Performance Validation
- Test Plans
- ROVI Report

PCS and Site Controller

- 100+ kW CPS Design
- Site Controller Integration

DC Block

- ESS DC block built
- PCS Integration

1.2MWh Cells

- Enhanced Ceramic Technology
- 8000-cycle life

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Technology, Host Site, and Resilience Use Cases

Technology

- Ceramic-separator lithium-ion architecture
- Enhanced safety through improved thermal stability and reduced short-circuit risk
- ~8000-cycle life supporting mission-critical applications

Host Site: BU ES2 Data Center

- Fully instrumented 4,500-sq-ft AI/HPC data center with 70+ racks and ~80 GPU servers
- Supports controlled and disruptive experiments impractical in production data centers
- Extensive monitoring, controls, and controllable loads for energy-smart operation and storage integration

Use Cases

- Critical load support during grid disruptions through islanded microgrid operation
- Peak reduction, energy shifting, and potential demand response
- Mitigating distribution constraints and enabling scalable data center load growth
- Assessment of how storage complements, extends, or partially offsets conventional UPS functions

Iron and Sodium Battery for Multi-day Resilience High Wildfire Risk Zone

Main Grid

Alliance Redwoods Convention Center

Battery Modules

- 2.5 MWh (10 hrs @100kW)
- Iron-Sodium Technology

INLYTE ENERGY

GTI FABRICATION

Water Pumping Station

BMS and EMS

NUVATION ENERGY

Site Planning and Microgrid Control

VITAL ENERGY Local Power Solutions

TEA & Resilience Analysis

- Adapt analysis methodology
- Quantify value of resilience

Testing and Reporting

- Test plan development
- Performance validation
- ROVI Reporting

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Prototype Test

- 40 kW/600 kWh string
- Independent assessment of performance and reliability
- Final system test plan

EPRI ELECTRIC POWER RESEARCH INSTITUTE

Technology, Host Site, and Resilience Use Cases

Technology

- Iron-sodium with competitive cost target and long service life
- Non-flammable materials with reduced safety risk
- Domestic, abundant material supply

Host Site: Alliance Redwoods

- Tier 3 High Fire Threat Zone with historically lower power reliability
- Community resilience site serving as an evacuation center
- Twenty-meter microgrid environment spanning diverse commercial and residential tariffs
- Supports a nearby water pumping station

Use Cases

- Enhanced resilience for critical facilities and community functions in a high wildfire-risk environment
- Integrated solution for backup power, diesel displacement, and daily cycling operation
- Customer bill savings through peak reduction and energy shifting across diverse tariff structures
- Support for critical water pumping operations during grid disruptions

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Acknowledgment

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To stabilize, optimize, and grow the electricity system to ensure the grid delivers affordable, reliable, and secure energy to the American people.

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

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Thank You

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