Validation of Innovative Storage Technologies for Resilience

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ENERGY STORAGE DIVISION

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Project Overview

- **Project Goal**: Develop an integrated framework to assess the techno-economic viability of innovative storage technologies for resilience and apply the framework in field validation
- **Current Practice**:
  - Lack of standardized metrics, data requirements, and methods for resilience quantification
  - Simplified modeling without properly capturing unique techno-economic characteristics
  - Insufficient treatment of operational uncertainty and risk-aware operation
- **Why PNNL**: Unique capabilities in storage modeling and validation; established optimization & control approaches to capture full system benefits; strong industry partnerships and ongoing field validation efforts
- **Innovation**: Integrated framework combining resilience quantification, advanced storage modeling, economic-resilience tradeoff analysis, uncertainty-aware operation, and performance validation

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Project Overview

- **Duration:** FY25–present
- **Impact:** Advances storage validation for resilience through standardized metrics, enhanced analytical approach to capture full system benefits, and field testing and operational evaluation to support broader adoption
- **Vertical/Investment Area**: Grid Integration and Field Validation
- **Alignment:**
  - *Stabilize*: Enhance resilience of critical facilities and infrastructure using innovative storage solutions
  - *Optimize*: Optimize storage operation to maximize net benefits
  - *Grow*: Accelerate innovative storage deployment and capacity growth to meet rising electricity demand

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

Device Performance

- ❑ Number of failed device
- ❑ Duration of device failures:
  - MTR/MTTR
- ❑ Device failure probability/frequency
  - MOF
- ❑ Weighted device performance
  - AST
- ❑ Unique functionality:
  - Black start
  - Ride through voltage, current, and time

Impact

Determine

Economic Performance

- ❑ Monetary value
  - Return: WTP, TOAC
  - Loss: LOR, TOC, VOLL

Grid Performance

- ❑ Adequacy
  - Transmission level: LOLE, ENS, EENS, EUE, UM, MPS, LSR, CLES
  - Distribution level: SAIFI, SAIDI, CAIDI, TCHO
  - Both level: CLES, CLC, UCL, LOLP, MPS, LSR
- ❑ Static security
  - Operational region: DyOE, volume, SAR
  - Voltage violation: UP/OP, VFR, VRC, PVUR
  - Thermal violation: UP/OP
  - Topological metrics: EB, vertex importance
- ❑ Dynamic security
  - Transient performance: RoCof, nadir, RoCoV
  - Small-signal stability: DR, EigV, gSCR
  - Large-signal stability: ROA, TSI, CCT

Resilience Objective

$$\underbrace{\min_{\Theta}}_{\text{Decision Set}} \sum_{t\in T} \underbrace{C_t}_{\text{Economic Objective}} + R_t$$

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.

Resilience Quantification Tool

https://eset.pnnl.gov

Summary of Benefits

- Tabular comparison of metric evaluation results

Resilience Assessment

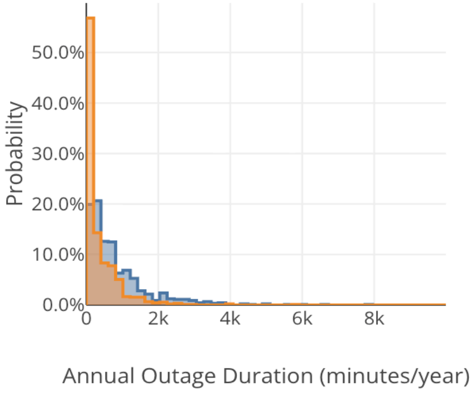
- Discretized probability distribution plots
- Complementary cumulative distribution plots

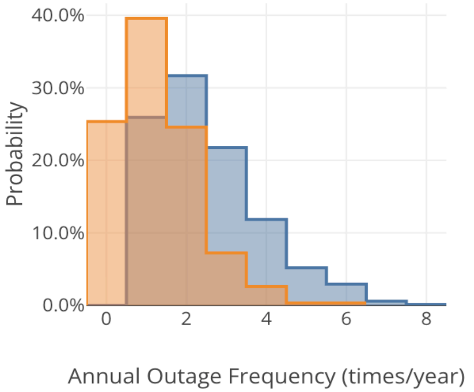
Event-Oriented Analysis

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

Annual Energy Service Disruption Metrics

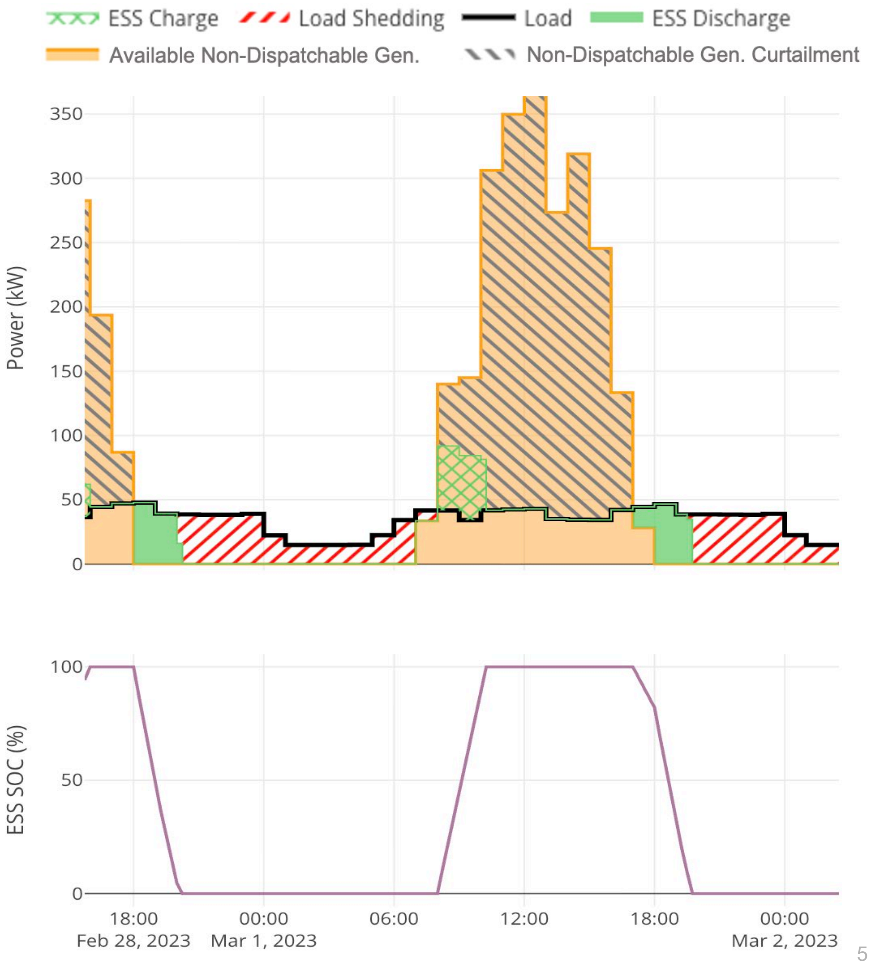
	Baseline	With Storage Solution	Improvement
Lost Load (MWh/year)	0.59	0.17	0.43 (72%)
Value of Lost Load ($/year)	47K	15K	32K (68%)
Outage Duration (minutes/year)	839	350	489 (58%)
Outage Frequency (times/year)	2.5	1.2	1.3 (50%)





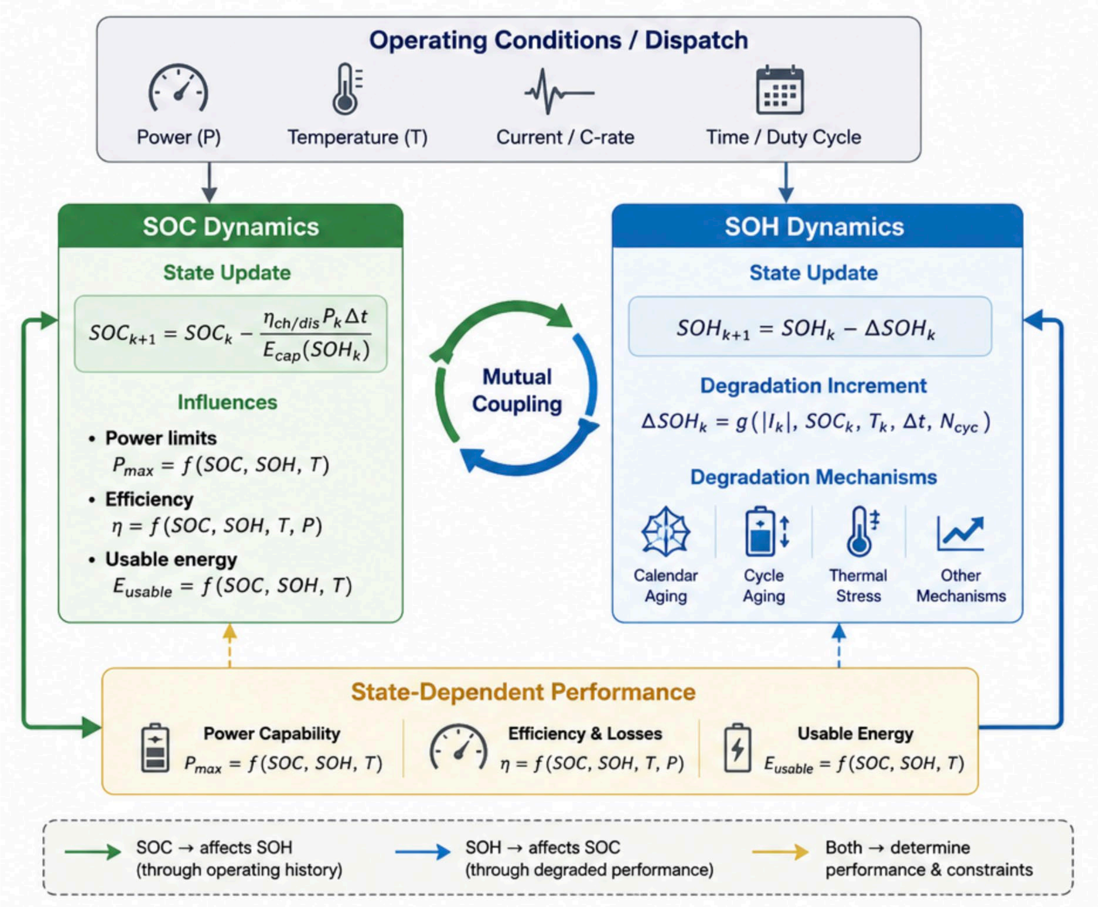
Historical Year/Sample Index 1

Event Index 1



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*

Operational Uncertainty and Risk-aware Dispatch

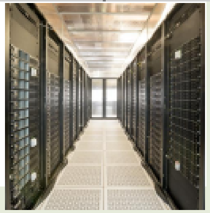
- Manage uncertainty and tradeoffs
  - Resilience vs. economic benefits
  - Short-term value vs. degradation/service life
- Integrated forecast and storage dispatch
  - Forecasts of outages, peak days, etc.
  - Adaptive reserve management and dispatch activation
- Adaptive energy reserve and dispatch
  - 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.

Resilient Energy Storage Platform with Enhanced Ceramic Technology (RESPECT)

Main Grid



Critical Facility

Binghamton University, State University of New York

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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

EATON Powering Business Worldwide

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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

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Main Grid

Alliance Redwoods Convention Center

Water Pumping Station

Battery Modules

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

INLYTE ENERGY

GTI FABRICATION

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

Next Steps

Conclusions

- Developed an integrated framework combining resilience quantification, advanced storage modeling, uncertainty-aware operation, and performance validation
- Integrated previously developed capabilities to enable technology-aware modeling, economic-resilience tradeoff analysis, and full-system-benefit evaluation
- Applying the framework in ongoing validation projects through partner collaboration

Future Work

- Continue applying and customizing the framework in ongoing projects, including data collection, model calibration, TEA, control development, and performance evaluation
- Refine and enhance the framework through ongoing field validation and lessons learned
- Expand application of the framework across diverse technologies, use cases, and field validation environments/sites

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U.S. DEPARTMENT of ENERGY | Office of Electricity

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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