

Elevating Grid Deployments of Storage with Advanced Analytics and Tools

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Project Team and Collaborators

PNNL Team

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Unlock Storage Potential with Advanced Analytics

ESS design and characteristics

• Energy storage technology, physical capability, and characteristics

Deployment Scenarios

Pacific

Northwest

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

Use Cases and Applications

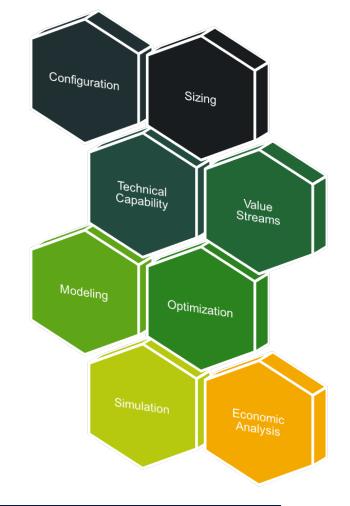
• Bulk energy, ancillary service, transmission-level, distribution-level, and end-user services

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

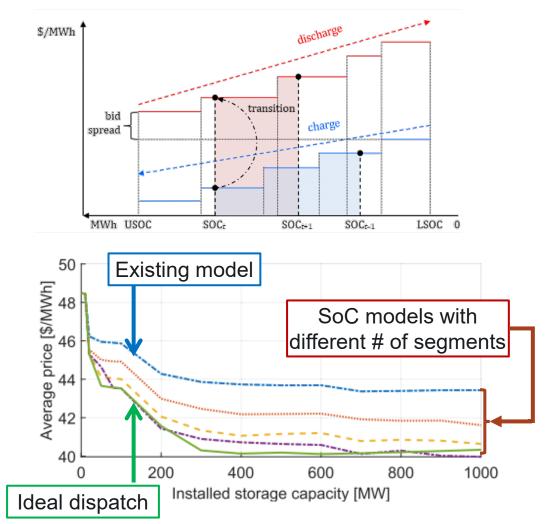


- Developed advanced modeling, optimization, and control methods
 - Energy storage state-of-charge market model
 - Innovative hybridization for addressing hydro plant challenges
 - Pareto efficient microgrid designs for economic and resilience equilibrium
 - Customized policy design for learning-based dispatch under uncertainties
 - Modeling and control of energy storage for enhanced system inertia
- Developed and enhanced storage valuation and control tools
 - ESET: continued maintenance and support, enhanced modeling, and database expansion
 - MSP: final adjustments, enhanced user experience, and official launch
 - ES-Control: from conceptual design to a comprehensive tool launch, including frontend/backend development, testing, and final implementation
- Provided analytical support to 10 energy storage assessment and demonstration projects



Energy Storage State-of-Charge Market Model

- Market models for energy storage resources
 - Existing: power-based bidding model, similar to generator resources
 - New: SoC-based bidding model, accounting for varying power rating, efficiency, and charge/discharge costs
- Research highlights
 - Established the theoretical foundation of the SOC-based model
 - Developed a dynamic programming algorithm for generating bids
 - Benchmarked against the existing model to quantify impacts on system costs, market prices, and storage revenue

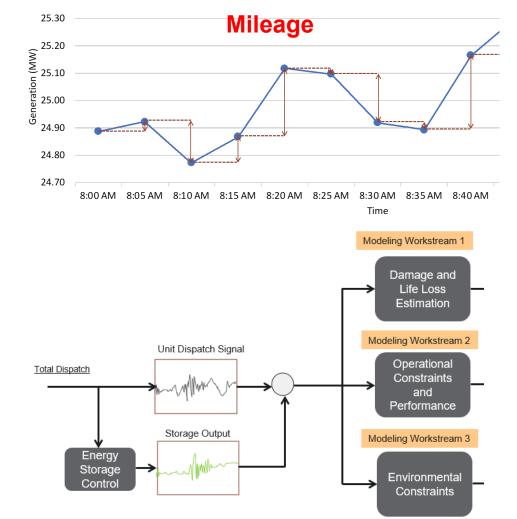


N. Zheng, X. Qin, D. Wu, G. Murtaugh, and B. Xu, "Energy Storage State-of-Charge Market Model," in *IEEE Transactions on Energy Markets, Policy and Regulation*, vol. 1, no. 1, pp. 11-22, March 2023



Innovative Hybridization for Tackling Hydro Plant Challenges

- Hydro plant challenges
 - Rising environmental constraints
 - Frequent starts and stops
 - Growing turbine mileage
 - Inefficient operation
 - Limited flexibility
- Innovative battery-hydro hybridization
 - Dynamic: Disaggregation of grid signals
 ✓ Fast for battery
 - ✓ Slow for hydro
 - Steady-State: Multi-objective optimization
 - ✓ Maximize economic benefits
 - ✓ Minimize mileage & starts/stops
 - ✓ Constraints: water levels & outflow

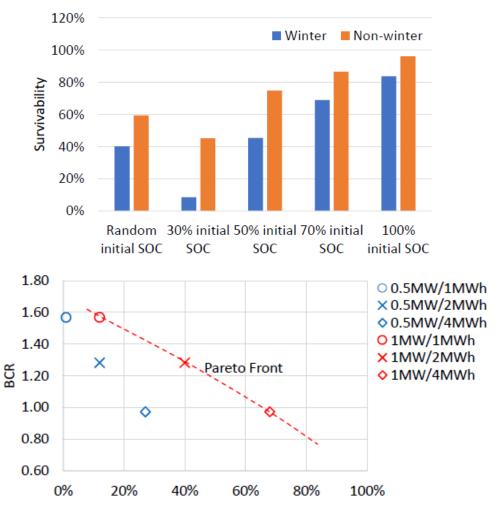


B. Bhatti, S. Hanif, J. Alam, B. Mitra, R. Kini, and D. Wu, "Using energy storage systems to extend the life of hydropower plants," *Applied Energy*, 337, 120894, Mar. 2023.



Pareto-Efficient Microgrid Designs for Economic and Resilience Equilibrium

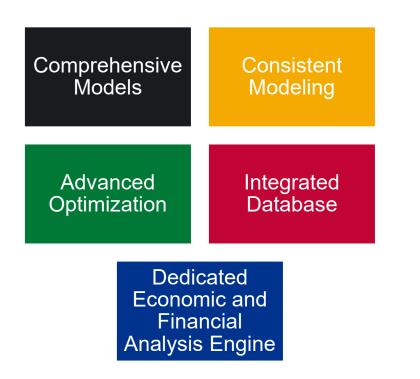
- Limitation of existing microgrid design
 - Resilience simplified as cost of unserved energy
 - Challenges in quantifying the economic value of resilience
 - Inability to effectively explore economicresilience trade-off
- Innovative multi-objective framework:
 - Separate modeling of resilience and economic benefits
 - Resilience quantification via Monte Carlo simulation
 - Multi-objective optimization to identify Pareto front



Y. Zhu, X. Ma, D. Wu, and J. Do, "A multi-objective microgrid assessment and sizing framework for economic and resilience benefits," in *Proceedings of the IEEE Power and Energy Society General Meeting*, Jul. 2023.



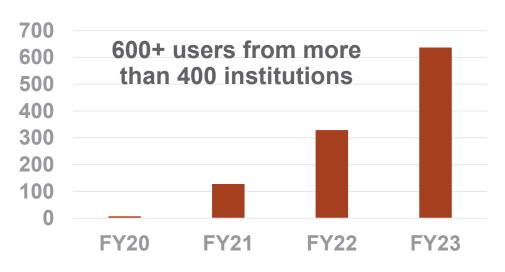
A suite of applications that enable various stakeholders to model, optimize, and evaluate various energy storage systems for stacked value streams





FY23 Progress

- Continued maintenance and support
- Integrated state of health modeling and simulation
- Enabled sensitivity analysis
- Expanded database and enhanced modeling



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Model Selection Platform

MSP

- Motivation
 - Numerous options: A variety of modeling and valuation tools exist
 - Selection complexity: General users may lack the time or expertise to navigate many options
- MSP: Facilitating Tool Selection
 - Reviews and compares 60+ DOE storage tools
 - Scores and suggests the best-suited tools to meet users' needs
 - ✓ A hierarchical *specification discovery* procedure governs information exchange
 - ✓ A *two-stage scoring engine* integrates offline setup and online calculation

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FIND BEST MATCH VIEW MODEL COMPARISON TABLE							
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Assess battery lifespan for behind-the-meter, rehicle, and stationary applications	Design and cost estimation of lithium-ion cells and packs			environmental impacts for the ages of a lithium ion battery		s of different repurposing sumptions on economics for	

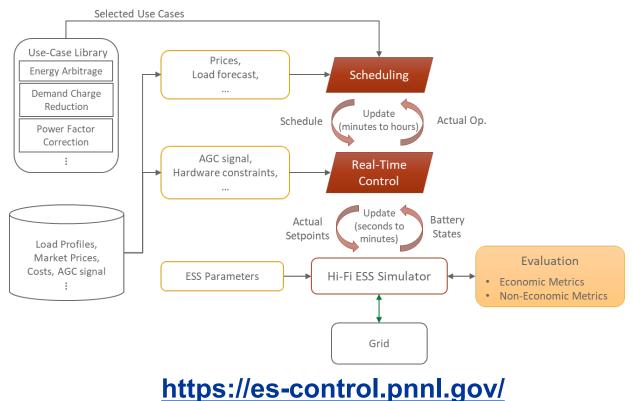
https://msp.pnnl.gov/





A platform for evaluation and testing of energy storage control strategies and algorithms with diversified time scales in a realistic setting, considering deployment options, use cases, and applications.

- Sandbox environment for modeling, control, simulation, and evaluation
- Representative built-in control strategies
 with adjustable parameters
- Open API for customized control
- Diversified energy storage models with different levels of complexity and fidelity
- Built-in database of energy storage costs, market prices, utility tariffs, etc.





ES-Control Hosting and Interface

- A web-based application
- Microservices architecture for rapid iteration and scalability
- Off-the-shelf AWS services for fast development and industry-standard security
 - Schedulers
 - Optimization
 - Reinforcement learning
 - Rule-based
 - Controllers
 - Rule-based
 - PID
 - Adaptive moving average filter
 - MESA-DER (selected modes)

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- Continue to develop advanced valuation and control capabilities
 - Optimal distribution of battery cycle life for grid services over the lifespan
 - Integration of distribution power flow and thermal/voltage constraints into siting/sizing
 - Risk-aware control to better balance economic and resilience benefits
 - Learning-based control for inter-area oscillation damping
 - Ensemble machine learning for long-duration energy storage scheduling
- Continue to enhance storage valuation and control tools
 - Provide technical support and collect feedback
 - Enhance user interface
 - Integrate additional database
 - Expand modeling, optimization, and control capabilities
- Continue to provide technical support to storage demonstration projects



- 1. B. A. Bhatti, S. Hanif, J. Alam, B. Mitra, R. Kini, and D. Wu, "Using energy storage systems to extend the life of hydropower plants," *Applied Energy*, vol. 337, May 2023, 120894.
- 2. A. Farakhor, D. Wu, Y. Wang, and H. Fang, "A novel modular, reconfigurable battery energy storage system: design, control, and experimentation," *IEEE Transactions on Transportation Electrification.*, vol. 9, no. 2, pp. 2878–2890, Jun. 2023.
- 3. N. Zheng, X. Qin, D. Wu, G. Murtaugh, and B. Xu, "Energy storage state-of-charge market model," *IEEE Transactions on Energy Markets, Policy and Regulation*, vol. 1, no. 1, pp. 11–22, Mar. 2023.
- 4. Fu T., H. Zhou, X. Ma, Z. Hou, and D. Wu, "Predicting Peak Day and Peak Hour of Electricity Demand with Ensemble Machine Learning," *Frontiers in Energy Research*, vol. 10, Dec. 2022.
- 5. A. Das D. Wu, and Z. Ni, "Approximate dynamic programming with customized policy design for microgrid online dispatch under uncertainties," *International Journal of Electrical Power & Energy Systems.*, vol. 142, Nov. 2022, 108359
- 6. Y. Zhu, X. Ma, D. Wu, and J. Do, "A multi-objective microgrid assessment and sizing framework for economic and resilience benefits," in *Proceedings of the IEEE Power and Energy Society General Meeting*, Jul. 2023.
- 7. R. Hu, K. Ye, H. Kim, H. Lee, N. Lu, D. Wu, and P. Rehm, "Design considerations of a coordinative demand charge mitigation strategy," in *Proceedings of the IEEE Power and Energy Society General Meeting*, Jul. 2023.
- 8. X. Ma, D. Wu, and A. Crawford, "Incorporating operational uncertainties into the dispatch of an integrated solar and storage system," in *Proceedings of the Innovative Smart Grid Technologies Conference*, Jan. 2023.
- 9. A. Das and D. Wu, "Optimal coordination of distributed energy resources using deep deterministic policy gradient," in *Proceedings of Electrical Energy Storage Applications and Technologies*, Nov. 2022.
- 10. A. Tbaileh, M.A. Elizondo, J. Alam, C.K. Vartanian, A. Mohammednur, H. Zargaryan, and M. Avendano, "Enhanced inertial support: modeling fast frequency response controls for energy storage system inverters," in *Proceedings of Electrical Energy Storage Applications and Technologies*, Nov. 2022.



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Mission – to ensure a resilient, reliable, and flexible electricity system through research, partnerships, facilitation, modeling and analytics, and emergency preparedness.

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



Thank You

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