From Promise to Performance: Evaluating Storage Controls with ES-Control

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Project Overview

- **Project Goal**: Provide a secure sandbox platform for evaluating and testing energy storage control strategies under realistic operating conditions, while integrating advanced controls for users to explore and benchmark — bridging the gap between modeled and realized storage benefits.
- **Current Practice**:
  - Deployed storage systems often underperform modeled expectations due to simplified control
  - Few accessible, high-fidelity sandbox environments exist for testing and comparing advanced storage controls prior to field deployment
  - Advanced controls at different levels are needed to improve performance while accounting for aging, losses, thermal behavior, and dynamics, etc.
- **Innovation**: A flexible, vendor-neutral platform with built-in standard and innovative controls with user-defined capabilities, side-by-side comparison, and high-fidelity simulations.
- **Impact**: Enable higher-performing deployed storage controls, closing the gap between modeled and realized benefits — reducing deployment risk, shortening development cycles, and expanding viable use cases for researchers, utilities, vendors, integrators, and project developers.

Project Overview

- **Why PNNL**: Deep expertise across power systems, storage modeling and control with strong engagement with utilities, developers, and industry partners enabling realistic validation.
- **Duration**: FY24 - present
- **Vertical/Investment Area**: Grid Integration and Field Validation
- **Alignment**:
  - Stabilize grid services: support testing of storage controls for grid-response and stability-related use cases
  - Optimize grid services: validate higher-performing control strategies that maximize efficiency and minimize degradation
  - Grow grid capacity: accelerate deployment of storage into new use cases by reducing risk and shortening development cycles through realistic, high-fidelity evaluation

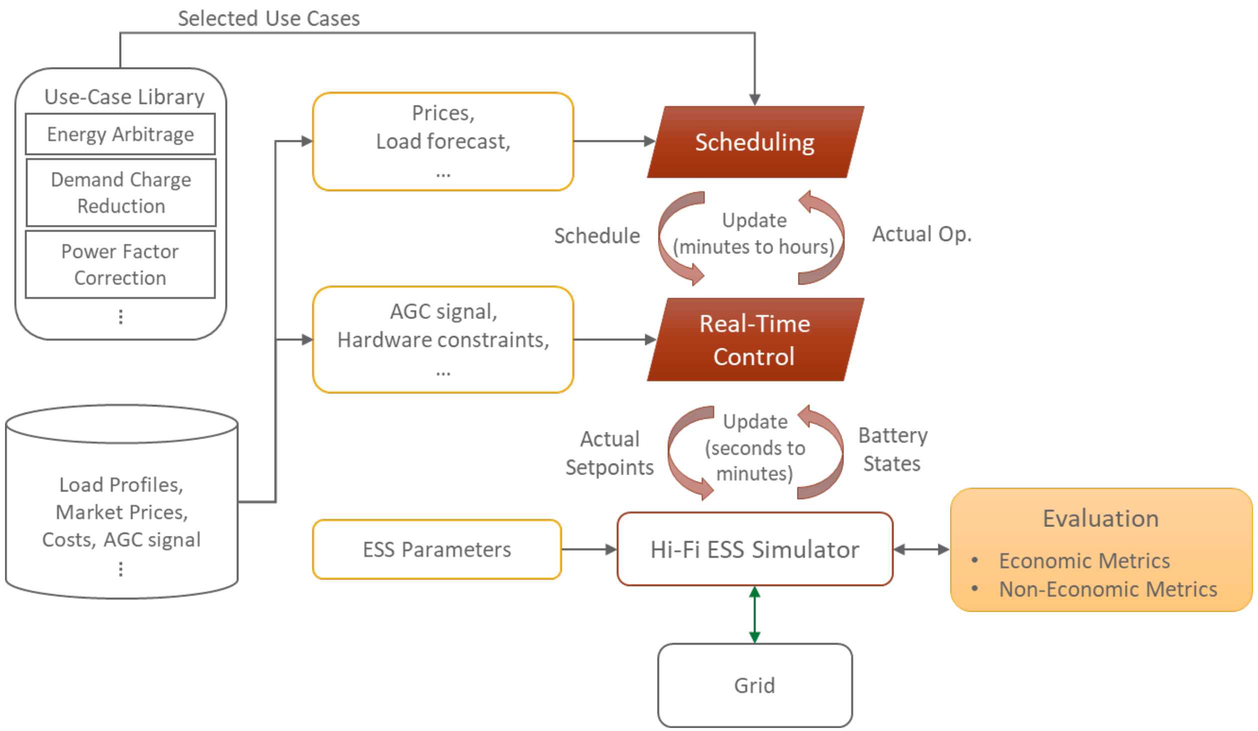
Problem

- Gap Between Modeled and Realized Storage Benefits
  - Deployed storage systems frequently underperform relative to modeled expectations
  - Simplified control strategies fail to capture multi-timescale dynamics, operational constraints, and heterogeneity
- Platform/Validation Challenges
  - Lack of accessible, high-fidelity sandbox environments for testing storage controls
  - Existing tools often limited to system-level models — missing cell- and module-level dynamics
  - Difficulty in comparing control strategies at different levels under consistent, realistic operating scenarios
- Why It Matters
  - Stakeholders need a trusted environment to validate controls before field deployment
  - Without it, commissioning risk rises, development cycles lengthen, and realized benefits fall short

ES-Control Overview

ES-Control is 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.

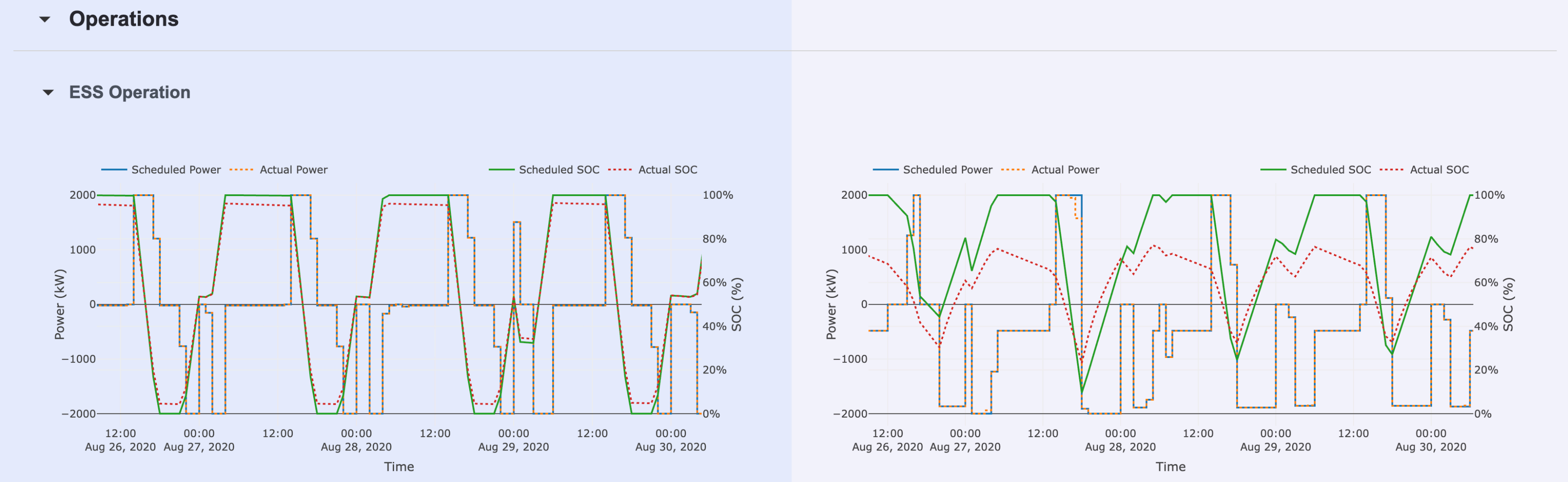
- Sandbox environment for modeling, control, simulation, and evaluation
- Representative built-in control strategies with adjustable parameters
- Open API for customized control
- Diversified energy storage models with different levels of complexity and fidelity
- Built-in database of energy storage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



Recent Enhancements

- User-defined control support: plug-in interface enabling users to implement and test custom control strategies alongside built-in methods
- Side-by-side evaluation reports: ability to compare two control strategies across consistent metrics and scenarios, facilitating direct performance benchmarking

Energy Storage Control | Home > Report Comparison | EA-LFP ⇄ VRFB test | Report Table | User Defined Controls | DEXIN WANG



Performance Statistics

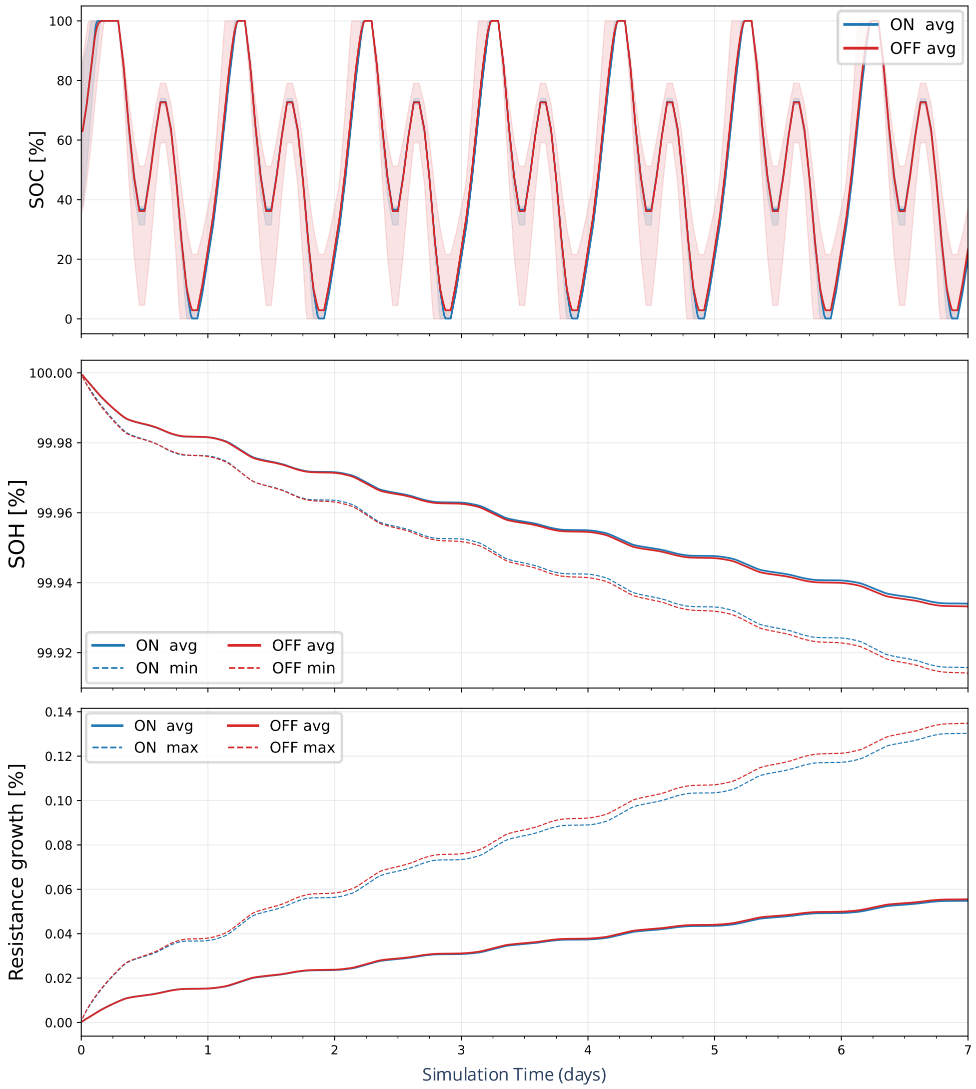
Annual Benefit	$172K	$80K
Present Value Benefit	$1.8M	$857K
Annual Discharged Energy	2760.0 MWh	1820.0 MWh
Annual Cycles	345	126
SOH Change	100% → 99.0%	100% → 100%
Energy Loss	124.0 MWh	838.0 MWh

Energy Arbitrage

Net Income	$29K	$13K

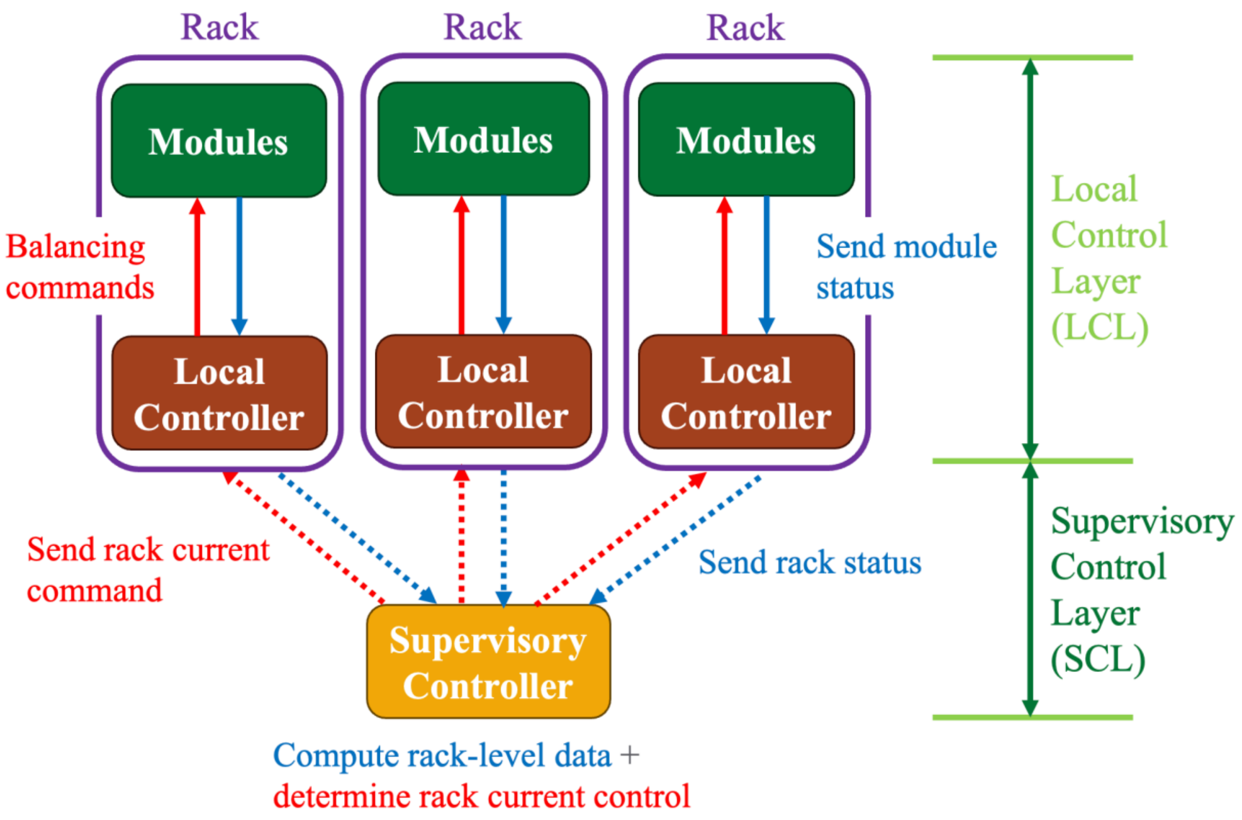
BMS Controls and Cell-Level Simulation

- Without explicit BMS controls
  - Aggregated battery models mask cell- and module-level dynamics and heterogeneity
  - Cannot evaluate methods for cell-balancing, protection, and thermal management, etc.
  - Risk overestimating realized benefits by missing internal constraints and inefficiencies
- Preliminary results on cell-level simulation and baseline BMS controls
  - SOC varies due to heterogeneity of cells
  - Cell-balancing helps reduce SOC spread across cells
  - Cell-balancing mitigates excessive battery degradation



Hierarchical BMS for Heterogeneous Grid BESS

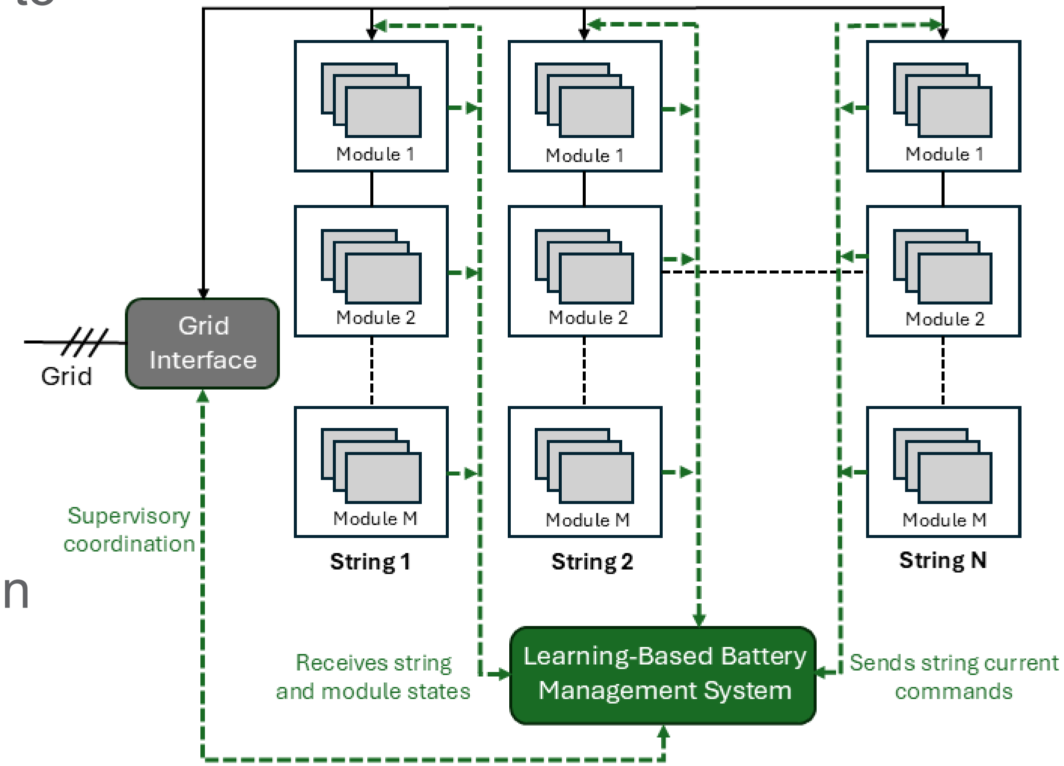
- MPC-based Supervisory Control:
  - Allocates charging/discharging currents based on each rack's or string's SOH and limits, reducing stress on weaker racks.
- Local Rack Control:
  - Executes fast module-level active balancing to correct SOC divergence with each rack/string, preventing individual modules from over-stress and improving rack-level uniformity.
- Cell-Level Monitoring & Protection:
  - Tracks voltage and temperature at the cell level.



K. Kwon, M. Gautam, and D. Wu, "A Hierarchical Battery Management System with Heterogeneity-Aware Control for Grid Storage," (Under Review).

Learning-Based BMS for Vanadium Flow Battery

- String-Level Modeling:
  - Moves beyond single-stack VRFB formulations to a string-level supervisory framework with coordinated current allocation across multiple strings.
- Physics-Guided Imitation Learning:
  - Uses a reduced-order supervisory optimizer as an expert policy to train an imitation learning controller for online current allocation.
- Health-Aware String Coordination:
  - Allocates charging/discharging current based on module-level states (SOC, SOH, voltage, temperature), together with aggregated string-level and system-level information, to reduce loss, limit thermal stress, and mitigate uneven aging.



Conclusion & Impact

- Key Accomplishments
  - ES-Control matured into a flexible platform with user-defined controls and side-by-side evaluation, now being extended with cell-level fidelity and baseline BMS controls
  - Advanced BMS control methods under development — integrating state estimation, loss minimization, health-aware operation, and thermal management
- Impact
  - Reduced gap between modeled and realized benefits: stakeholders can validate controls pre-deployment
  - Improved achievable benefits & reduced degradation: extending storage asset life and revenue potential
  - Reduced commissioning risk and shorter development cycles for BMS developers and integrators
  - Broader accessibility: consistent platform enables fair comparison across control strategies
- Beneficiaries
  - Researchers, ESS vendors and developers, utilities, BMS developers, system integrators

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Next Steps

Near-Term Milestones

- Cell-level ESS simulator developed and tested
- Baseline BMS controls implemented and validated in ES-Control
- Enhanced ES-Control released

Platform Roadmap

- Integration of hierarchical BMS control
- Integration of advanced BMS for flow batteries
- Expanded use case libraries and evaluation metrics
- Continued UI and user-experience improvements

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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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