Pacific Northwest NATIONAL LABORATORY

Advanced Optimization and Control for Energy Storage

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ENERGY STORAGE PROGRAM

U.S. DEPARTMENT OF ENERGY BATTELLE

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Project Team and Collaborators

PNNL Team

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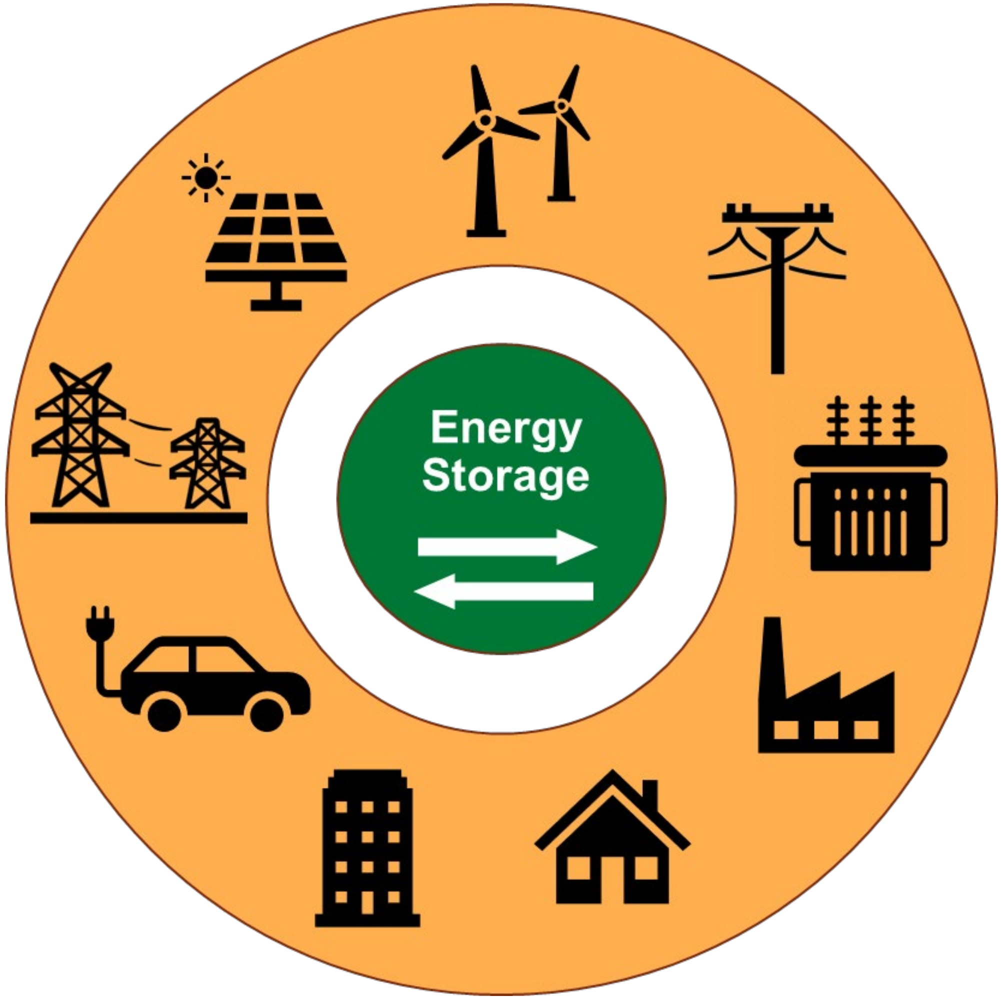
Storage Can Help Solve Problems in All Parts of The Grid

- Resource adequacy
  - System capacity
  - Flexible capacity
  - Local capacity
- Transmission adequacy
  - Support balancing load and generation
  - Support competitive markets
- Couplings between the two
  - Additional transmission capacity enhances the capacity value of variable generation
  - Energy storage and other resources are non-wire alternatives



Needs of Storage Analytics for Grid Deployment and Field Validations

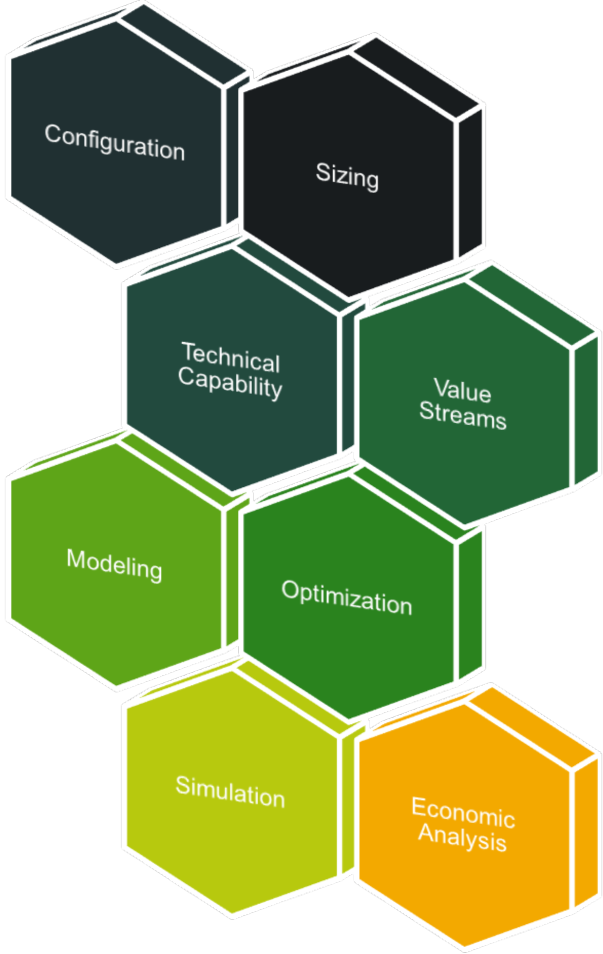
ESS design and characteristics
- Energy storage technology, physical capability, and characteristics

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

Applications and services
- 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



The lack of ability to model, optimize, value, and control energy storage systems became a significant barrier to their penetration in the marketplace

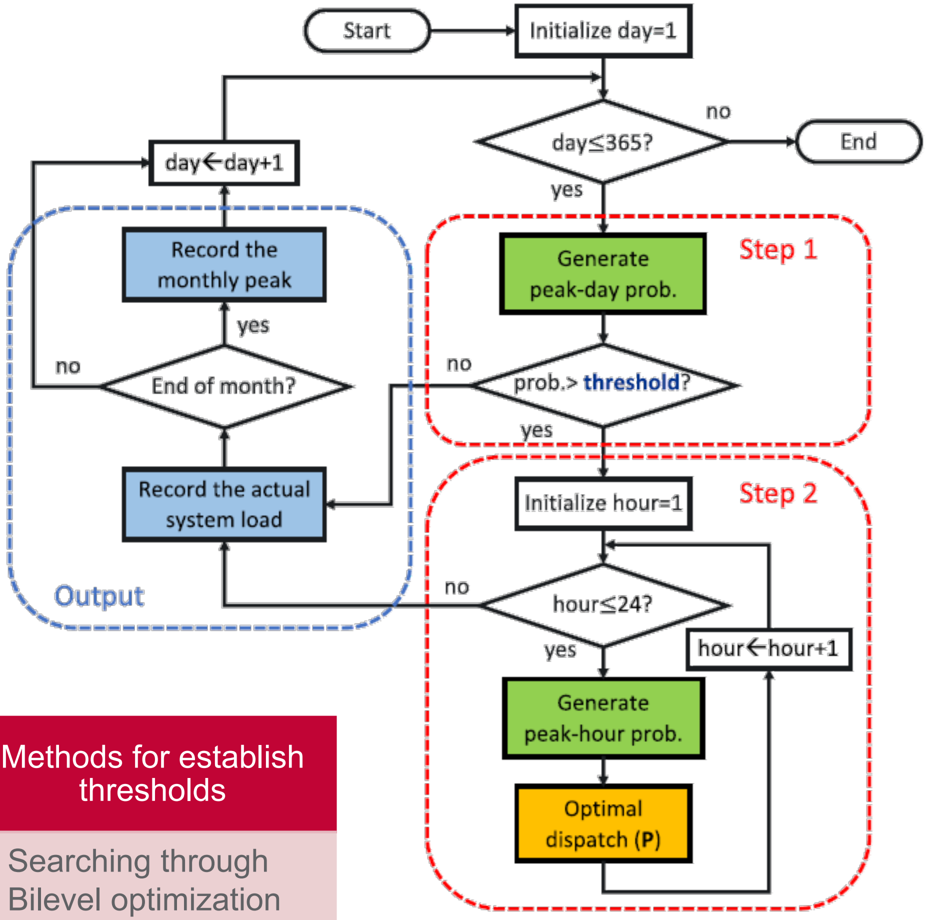
FY22 Research Activities

- Developed advanced modeling, optimization, and control methods
  - BESS dispatch and valuation framework for capacity charge reduction
  - A techno-economic assessment framework for hydrogen energy storage toward multiple energy delivery pathways and grid services
  - Deep reinforcement learning from demonstrations to assist service restoration in islanded microgrids
  - Multi-service battery energy storage system optimization and control
  - Approximate dynamic programming with customized policy design for microgrid online dispatch under uncertainties
- Provided analytical support to 11 energy storage assessment and demonstration projects
- Developed a new tool to assist control design and testing

BESS Dispatch and Valuation Framework for Capacity Charge Reduction

A holistic framework that

- Seamlessly integrates load forecast and BESS dispatch to model and address uncertainties
- Effectively explores the trade-off between demand reduction effectiveness and battery life
- Optimizes distribution of battery life to maximize the present value of benefits
- Optimizes battery duration considering both uncertainty and battery degradation



Two-step hybrid dispatch	Multi-time-scale forecasting models	BESS Model	Methods for establish thresholds
• Policy-based dispatch • Stochastic/robust dispatch	• Peak-day probability • Peak-hour probability	• Constant-efficiency or high-fidelity models • Degradation effects	• Searching through • Bilevel optimization • Learning-based methods

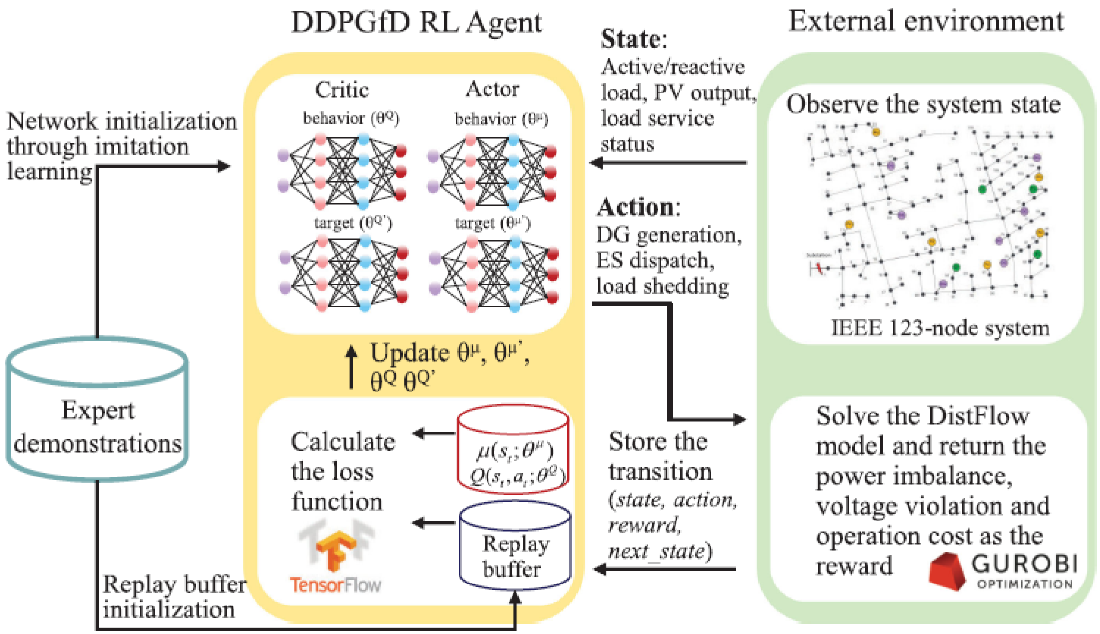
D. Wu, X. Ma, T. Fu, Z. Hou, P. Rehm, and N. Lu, "Design of a battery energy management system for capacity charge reduction," *IEEE Open Access Journal of Power and Energy*, vol. 9, pp. 351–360, Aug. 2022.

Learning-based Control to Assist Service Restoration Through Storage-enabled Microgrid

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

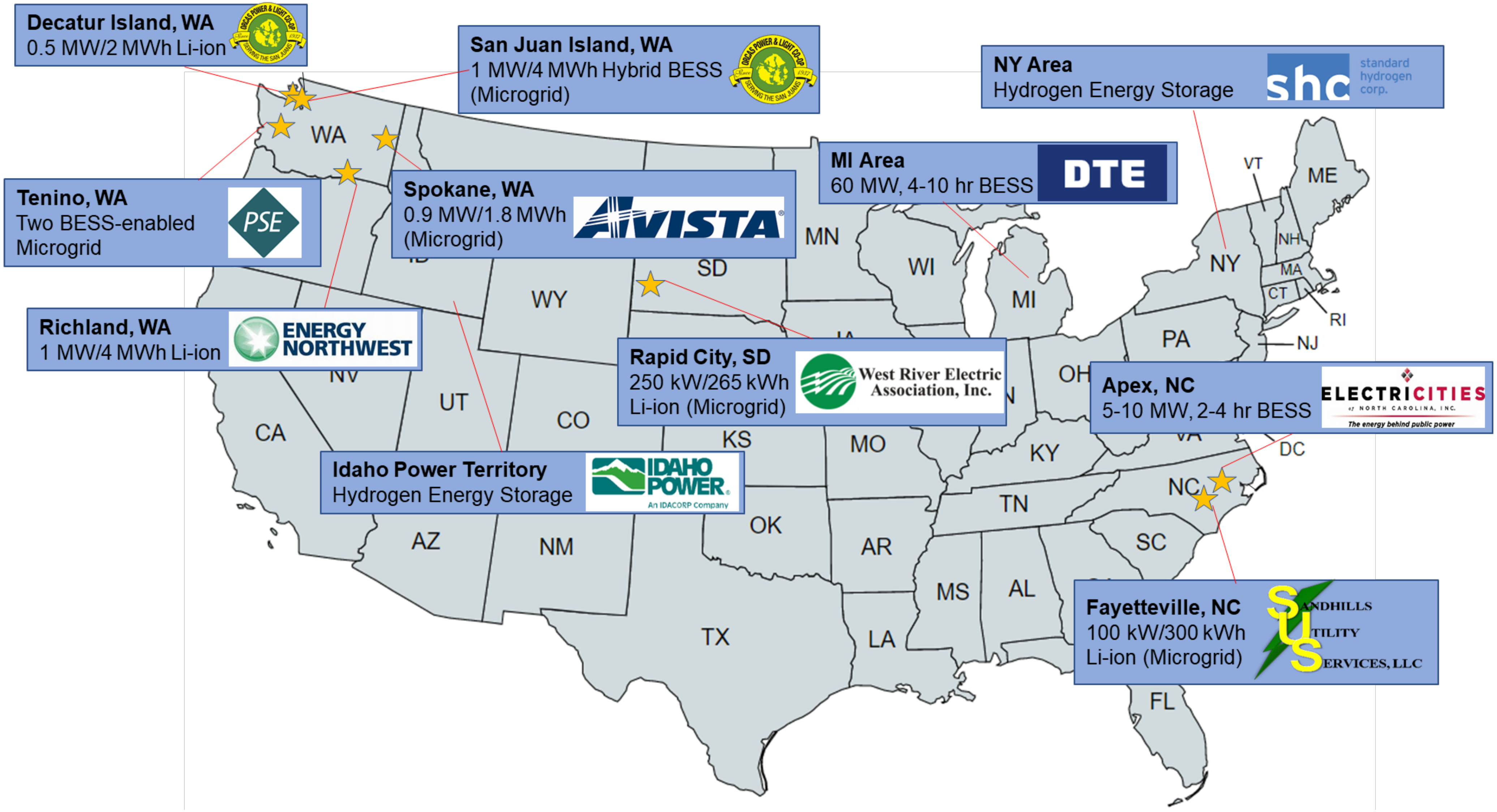
- Pre-training stage: imitation learning is applied to equip the control agent with expert experiences to guarantee acceptable initial performance.
- Online training stage: action clipping, reward shaping, and expert demonstrations are leveraged to ensure safe exploration while accelerating the training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

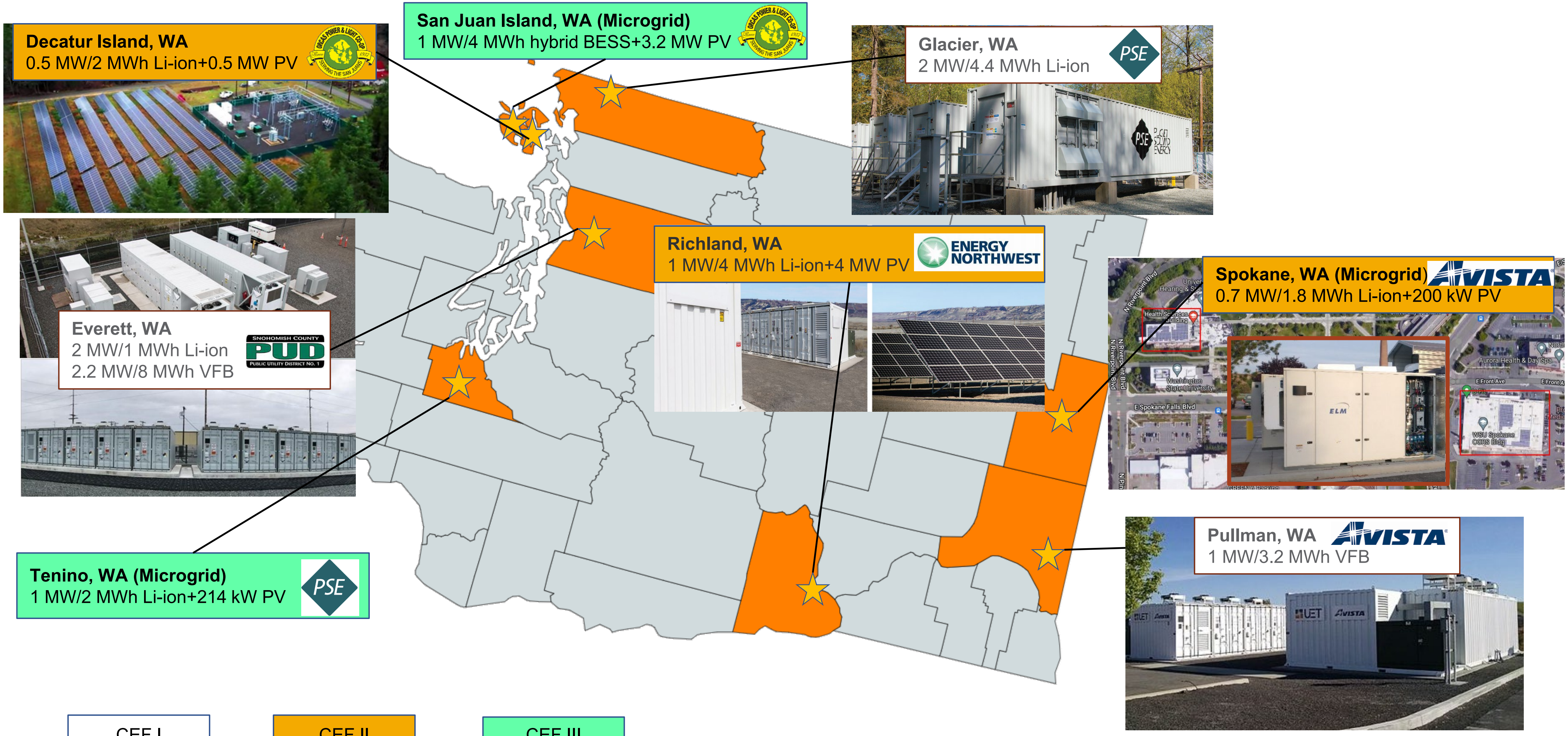


Y. Du and D. Wu, "Deep reinforcement learning from demonstrations to assist service restoration in islanded microgrids," *IEEE Transactions on Sustainable Energy*, vol. 13, no. 2, pp. 1062–1072, Apr. 2022.

Analytical Support to Storage Assessment and Demonstration Projects in FY22



Clean Energy Fund Grid Demonstration Projects

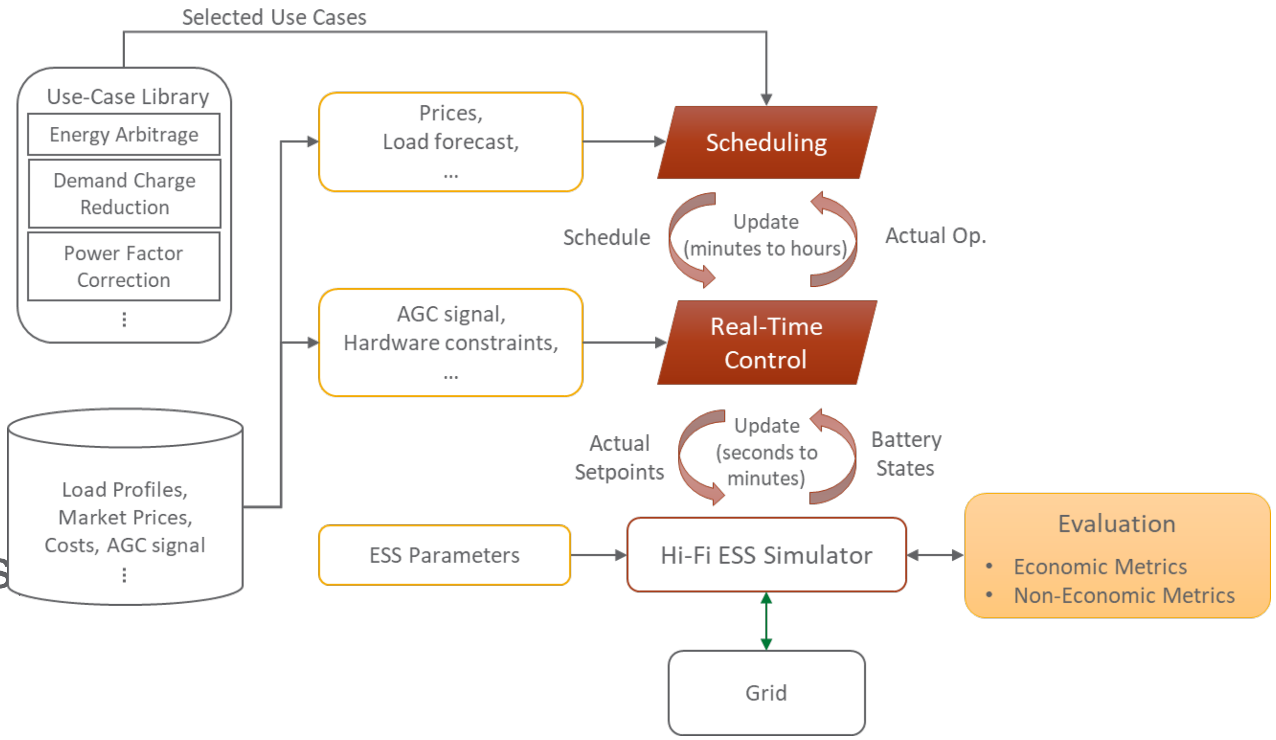


CEF I CEF II CEF III

ES-Control

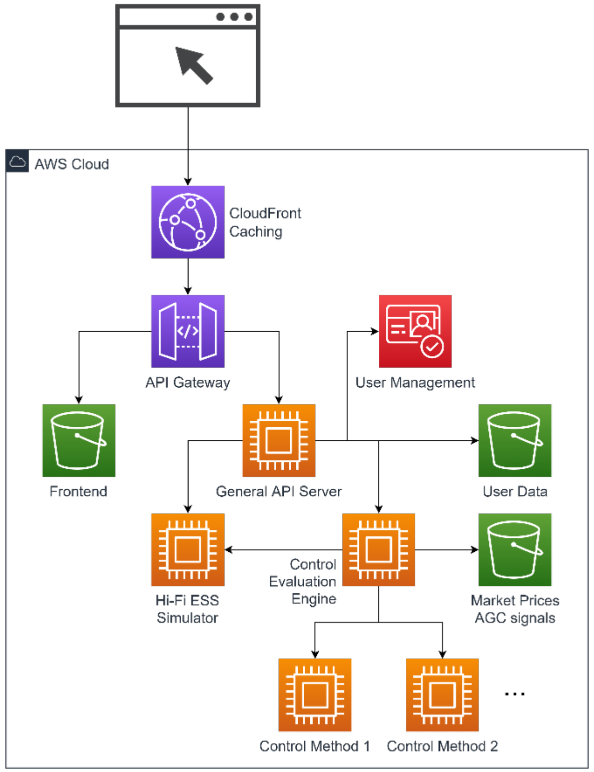
ES-Control is a platform for evaluation and testing of energy storage control strategies and algorithms with diversified time scales in a realistic setting, considering deployment options, use cases, and applications.

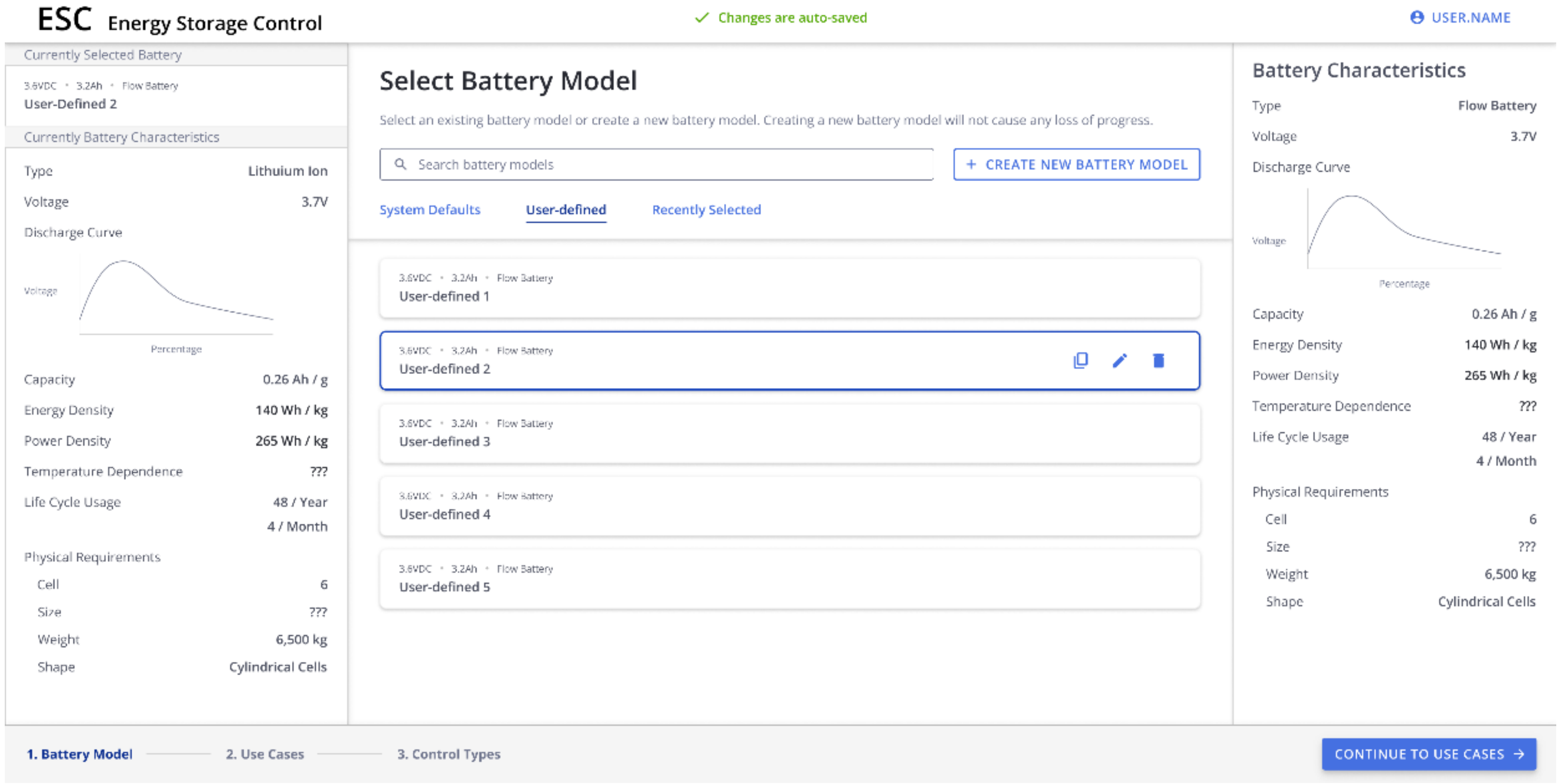
- Sandbox environment for modeling, control, simulation, and evaluation
- Representative built-in control strategies with adjustable parameters
- Open API for customized control
- Diversified energy storage models with different levels of complexity and fidelity
- Built-in database of energy storage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



Software Architecture

- A web-based application
- Microservices architecture for rapid iteration and scalability
- Off-the-shelf AWS services for fast development and industry standard security





Look Forward

- Continue to develop advanced analytical capabilities
  - Design and evaluation of energy storage state-of-charge market model
  - Risk-aware scheduling to better balance economic and resilience benefits
  - Approximate dynamic programming with enhanced off-policy strategies
  - Long-duration energy storage optimization with ensemble machine learning
  - Deep Koopman representation learning methods
- Continue to provide technical support to energy storage assessment and demonstration projects
- Continue to develop ES-Control
  - Front- and back-end implementation, including environment setup, dispatch/control module, simulator, evaluation, and post-processing
  - Testing and quality control
  - Launch and support

Selected FY22 Publications

1. D. Wu, D. Wang, T. Ramachandran, and J. Holladay, "A techno-economic assessment framework for hydrogen energy storage toward multiple energy delivery pathways and grid services," *Energy*, vol. 249, Jun. 2022, 122628.
2. 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.
3. D. Wu, X. Ma, T. Fu, Z. Hou, P. Rehm, and N. Lu, "Design of a battery energy management system for capacity charge reduction," *IEEE Open Access Journal of Power and Energy*, vol. 9, pp. 351–360, Aug. 2022.
4. S. Hanif, M. E. Alam, R.L. Kini, B. Bhatti, and J.C. Bedoya Ceballos, "Multi-Service Battery Energy Storage System Optimization and Control", *Applied Energy*, vol. 311, 118614, 2022.
5. M. Perez, R. Fan, and D. Wu, "Optimal operation and sizing of pumped thermal energy storage for net benefits maximization," *IET Generation, Transmission & Distribution*, pp. 1–13, Jul. 2022, gTD212541.
6. 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.
7. A. Das, Z. Ni, and D. Wu, "An efficient distributed reinforcement learning for enhanced multi-microgrid management," in *IEEE World Congress on Computational intelligence*, Jul. 2022.
8. D. Wu, R. Hu, X. Ma, S. Huang, B. Huang, K. Oikonomou, C. K. Vartanian, and M. Diedesch, "Avista's shared energy economy model pilot–a techno-economic assessment," Pacific Northwest National Laboratory, Tech. Rep. PNNL-33107, 2022.
9. D. Wu, A. D. Das, S. Hanif, A. J. Crawford, V. V. Viswanathan, V. L. Sprenkle, D. A. Baldwin et al., "San Juan hybrid battery energy storage – preliminary techno-economic assessment," Pacific Northwest National Laboratory, Tech. Rep. PNNL-ACT-10119, Feb. 2022.
10. A. J. Crawford, V. V. Viswanathan, D. Wu, and A. F. Barbaro dos Santos, "Energy Northwest Horn Rapids solar and storage: An assessment of battery technical performance," Pacific Northwest National Laboratory, Tech. Rep. PNNL-ACT-10122, 2022.

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Acknowledgment

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U.S. DEPARTMENT OF ENERGY

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/activities/technology-development/energy-storage

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Thank You

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