



# **The Stacked Value of Battery Energy Storage Systems**

*Final Project Report*

M-41

**Power Systems Engineering Research Center**  
*Empowering Minds to Engineer  
the Future Electric Energy System*



# **The Stacked Value of Battery Energy Storage Systems**

## **Final Project Report**

### **Project Team**

Meng Wu, Project Leader  
Arizona State University

Josue Campos do Prado  
Washington State University

### **Graduate Students**

Reza Khalilisenobari  
Mohammad Mousavi  
Zhongxia Zhang  
Arizona State University

Ugonna Chikezie  
Washington State University

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**For information about this project, contact:**

Meng Wu  
Arizona State University  
School of Electrical, Computer and Energy Engineering  
P.O. Box 875706  
Tempe, AZ, 85287-5706  
Phone: (480) 965-8706  
Email: [mwu@asu.edu](mailto:mwu@asu.edu)

**Power Systems Engineering Research Center**

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**For additional information, contact:**

Power Systems Engineering Research Center  
Arizona State University  
527 Engineering Research Center  
Tempe, Arizona 85287-5706  
Phone: 480-965-1643  
Fax: 480-727-2052

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## Executive Summary

This project is motivated by the growing integration of utility-scale and distributed energy storage resources in both transmission and distribution systems. As US Federal Energy Regulatory Commission (FERC) Orders No. 841 and No. 2222 request all the US system operators to completely open their energy and ancillary services markets to both utility-scale and retail-scale (distributed) energy storage resources, these energy storage resources bring in various challenges to the wholesale market operation and participation. This research focuses on three core areas: 1) understanding market participation activities of utility-scale batteries in the wholesale energy, reserve, and regulation markets; 2) data-driven day-ahead and real-time price forecasting approaches for profit-seeking utility-scale batteries and aggregators of distributed batteries; and 3) the distribution system operator (DSO) framework for coordinating market participation activities of distributed batteries and other distributed resources. The research is presented in six chapters (Chapters 2-7).

Chapters 2-3 present a comprehensive modeling framework for studying various market participation activities and operating patterns of utility-scale batteries in the energy and ancillary services markets, with detailed consideration of batteries' regulation market participation models and degradation cost models. Analysis on the impact of battery degradation on market participation strategies of utility-scale batteries is presented in Chapter 3.

Chapter 4 describes a framework for integrating BESSs in the wholesale and retail electricity markets and presents a case study on the integration of BESSs and virtual bidding on the decision-making model of an electricity retailer through a two-stage stochastic optimization framework.

Chapter 5-6 propose data-driven price forecasting approaches with improved forecasting accuracy, for profit-seeking battery owners and aggregators to forecast system-wide day-ahead and real-time locational marginal prices using public market data. The proposed approaches are built upon generative adversarial networks and convolutional long short-term memory networks which capture the spatio-temporal correlations among system-wide energy market data.

Chapter 7 presents a DSO framework to optimally coordinate the aggregators of various distributed resources for their wholesale market participation while operating the retail market, considering three-phase unbalanced distribution system operating constraints, as well as coordinated market clearing mechanisms between the balanced wholesale and unbalanced retail markets.

### Project Publications:

- [1] Reza Khalilisenobari and Meng Wu, "Optimal Participation of Price-maker Battery Energy Storage Systems in Energy, Reserve and Pay as Performance Regulation Markets," *51st North American Power Symposium (NAPS)*, Wichita, KS, USA, 2019 (Selected in Best Conference Paper Sessions).
- [2] Mohammad Mousavi and Meng Wu, "A DSO Framework for Comprehensive Market Participation of DER Aggregators," *2020 IEEE PES General Meeting*, Virtual Conference, 2020.

- [3] Zhongxia Zhang and Meng Wu, “Real-time Locational Marginal Price Forecasting using Generative Adversarial Network”, *2020 IEEE International Conference on Communications, Control, and Computing Technologies for Smart Grids (SmartGridComm)*, Virtual Conference, 2020.
- [4] Reza Khalilisenobari and Meng Wu, “Impact of Battery Degradation on Market Participation of Utility-scale Batteries: Case Studies”, *52nd North American Power Symposium (NAPS)*, Virtual Conference, 2021.
- [5] Mohammad Mousavi and Meng Wu, “Two-stage Stochastic Programming DSO Framework for Comprehensive Market Participation of DER Aggregators under Uncertainty”, *52nd North American Power Symposium (NAPS)*, Virtual Conference, 2021.
- [6] Zhongxia Zhang and Meng Wu, “Locational Marginal Price Forecasting using Convolutional Long Short-term Memory based Generative Adversarial Network”, *2021 IEEE PES General Meeting*, Virtual Conference, 2021 (Selected in Best Conference Paper Sessions).
- [7] Zhongxia Zhang and Meng Wu, “Predicting Real-Time Locational Marginal Prices: A GAN-Based Approach”, *IEEE Transactions on Power Systems*, Accepted, to appear.
- [8] U. Chikezie and Z. Chen, “Literature review of energy storage for power system economics,” *2020 IEEE 3rd International Conference on Renewable Energy and Power Engineering (REPE)*, Virtual Conference, 2020.
- [9] U. Chikezie, T. Karacolak, and J. C. do Prado, “Examining the applicability of blockchain to the smart grid using proof-of-authority consensus,” *9<sup>th</sup> IEEE International Conference on Smart Energy Grid Engineering*, Oshawa, Canada, 2021.
- [10] J. C. do Prado and U. Chikezie, “A decision model for an electricity retailer with energy storage and virtual bidding under daily and hourly CVaR assessment,” *IEEE Access*, in press, DOI 10.1109/ACCESS.2021.3100815.