Controlling Energy Storage Systems: Lessons Learned from the Washington Clean Energy Fund Demonstration Projects

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***Abstract*- Washington State Clean Energy Fund energy storage demonstration projects created opportunities for learning various aspects of Energy Storage Systems (ESSs), including its control for optimum economic return under various conditions. As the lead for ESS use-case analytics program in the ESS demonstration projects, the authors experienced practical aspects of ESS control in terms of control strategy development, control systems deployment, and performance during actual operation. This paper presents some of the learning opportunities availed from the demonstration projects along with a few key lessons for the benefit of the broader energy storage community.**

***Keywords*- Washington CEF, ESS control strategy, control system, ESS performance, power and SoC deviation**

I. Introduction

With all its advantages of being a source of fast and on-demand power supply, Energy Storage Systems (ESS) are being considered by utilities and industry players as a means of enhancing the efficiency and resilience of electric power systems. As a device with certain physical constraints, and then subject to the complexities of grid interfacing, and finally with the expectations to fulfill deployment objectives, ESS installations require significant considerations for their control. To successfully control an ESS for a given service, the control strategy needs to be appropriate, the control system it will run through needs to be well-understood and reliable, and the ESS needs to perform as anticipated during the design of the control strategy. As one could imagine, all of these elements may be affected by practical issues and hence, achievement of ESS deployment goals may be challenging.

Lessons from field demonstrations on the control aspects mentioned above could provide useful insights and guidance on designing and deploying effective and reliable control systems. This paper presents the learning opportunities obtained and key lessons learned by the authors on ESS control from the Washington State Department of Commerce Clean Energy Fund (CEF) demonstration projects across the state of Washington. Various use cases relating to ESS application for bulk energy, ancillary services, and distribution grid efficiency and reliability improvement were run at different utility sites. Experience from these field demonstrations would help better understand practical requirements of ESS control for different ESS services. Lessons that particularly relate to deviations between desired and actual ESS power, and estimated and actual State of Charge (SoC) that were observed during use case tests are presented and discussed for the benefit of the energy storage community.

The paper will first provide an overview of the CEF program and the ESS demonstration project sites. This will be followed by a description of the type and scope of learning opportunities from experience at CEF demonstration sites with practical lessons from use case testing performed to date. Finally, the paper will conclude with a general outline of how these experiences, observations, and lessons could enhance the ESS community's understanding of ESS control.

II. Washington CEF Program and ESS Demonstration Projects

In 2013, the Washington State Legislature appropriated funding for the advancement of renewable energy technologies throughout the state [1]. A Smart Grid grant of $15M was created from that funding to support efforts by three Washington utilities (Avista Utilities, Snohomish Public Utility District, and Puget Sound Energy) to install ESS to help with outage mitigation and renewable integration issues. Below are brief descriptions of these participating utilities and their ESS projects. The locations of the ESS demonstration sites at these three utilities' service area are identified in Fig. 1.

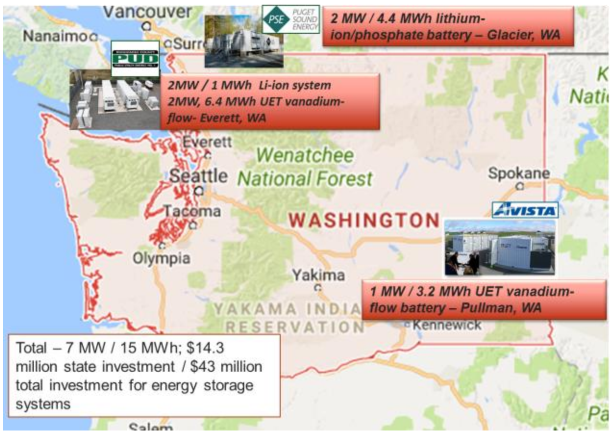

Fig. 1. Washington CEF ESS Demonstration Project site locations.

A. Avista Utilities

Avista Utilities, an investor-owned utility in the Pacific Northwest region, serves more than 600,000 electric and natural gas customers over a service territory of 30,000 square miles in eastern Washington, northern Idaho and parts of southern and eastern Oregon—an area with a total population of 1.6 million. With a $3.2M grant from Washington CEF and $3.8M of matching funds, Avista installed a 1 MW/3.2 MWh flow type ESS near Avista Turner substation, which is connected to Schweitzer Engineering Laboratories' (SEL's) premises in Pullman, Washington [2]. The SEL facilities and its ESS are shown in the top panel of Fig. 2. This ESS will serve as a critical resource to supply uninterrupted power to SEL loads during transition between one feeder and another, and also as backup power during outages at the upstream network. The ESS is built on advanced Vanadium Redox flow battery technology developed by Pacific Northwest National Laboratory (PNNL) and further improved and commercialized by Uni Energy Technology (UET). This technology consists of a thermally stable, aqueous system with no risk of thermal runaway. Commercially named "Uni.System" [3-4], each of these ESS units consists of five 20-foot factory-integrated standard containers, of which four contain the battery stacks and the fifth houses the Power Conversion System (PCS). The four containers of battery stacks are connected in series to form a string. Each unit of Uni.System provides 500 kW of power for up to 4 hours, with peak power capability of 600 kW and maximum energy capability of 2.2 MWh. There are two Uni.System units at the Avista ESS installation.

Fig. 2. Avista ESS at SEL manufacturing plant (top) and PSE ESS at Glacier Substation (bottom) provide critical backup power and outage mitigation support.

B. Snohomish Public Utility District

Snohomish Public Utility District (SnoPUD) is located approximately 20 miles north of Seattle and serves over 327,000 electric customers and 19,000 water customers over 2,200 square miles of service territory. SnoPUD received $7.3M from the Washington CEF towards installation of two ESSs [5] - both built using Modular Energy Storage Architecture (MESA) and are identified as MESA 1 & MESA 2. SnoPUD's motivation behind the ESS projects was to acquire assets with capabilities to help integrate renewable energy resources with their network, and could be fully integrated with their control systems. MESA 1 ESS is comprised of 2 × 1 MW, 0.5 MWh lithium-ion battery system installed at SnoPUD's Hardeson substation. One of the 1 MW banks is manufactured by Mitsubishi and GS Yuasa, the other by LGChem. MESA 2 is built on Vanadium Redox flow battery technology and consists of two UET-supplied Uni.System units, each with a 2 MW/6.4 MWh capacity.

C. Puget Sound Energy

Puget Sound Energy (PSE) provides electric and natural gas services to more than 1.7 million customers over a 6,000 square-mile service area, primarily in the Puget Sound region of western Washington. Headquartered in Bellevue, Washington, PSE's service area is home to some of America's most recognized and respected businesses, including the Boeing Commercial Airplane Group, Microsoft, and Amazon.com. With $3.8M funding from the CEF Smart Grid Grant and $5.8M of their own, PSE installed a 2 MW/4.4 MWh lithium-ion ESS near its Glacier Substation [6]. Glacier is a small, geographically isolated town in northern Washington state that suffers frequent outage of electricity supplied by a long, exposed 55 kV transmission line, vulnerable to severe storms and falling trees [7]. This situation makes the Glacier ESS, with its outage mitigation capabilities, highly important and valuable to PSE. The ESS at Glacier substation was integrated by Renewable Energy Systems Americas, Inc. (RES Americas), with lithium-iron phosphate ($LiFePO_4$) cells manufactured by BYD[1]. The system consists of four containers, each having six strings connected in parallel through a 500 kW bi-directional converter manufactured by BYD (model BEG500KTL-U). Bottom panel of Fig. 2 shows an image of the ESS with four containers and the electrical interconnection with Glacier substation.

III. ESS Control Learning Opportunities

PNNL is leading the Use Case Testing and Analytics effort under the Washington CEF program and is responsible for scoping the use cases for each of the participating utilities. Use case testing process of a service starts with designing a duty cycle that represents the charge/discharge operations an ESS will be subjected to while engaged in that specific service. Therefore, one of the first learning opportunities encountered was in the design of control strategies.

The next step is to implement the designed duty cycle through a control interface. This step presents opportunities to learn about different control systems, particularly how the participating utilities implemented these systems onsite, and how they impact the fulfillment of the utilities' deployment goals.

Finally, during the execution step of the duty cycle, there are opportunities to learn how practical operational issues of a given system influence the ESS performance. In-service performance provides critical information about the ESS that will help researchers to model ESS performance more accurately, leading to better control strategies to meet deployment objectives. Fig. 3 illustrates these three elements related to ESS control and the following sections enlarge on them.

[1] http://www.byd.com/usa/energy/

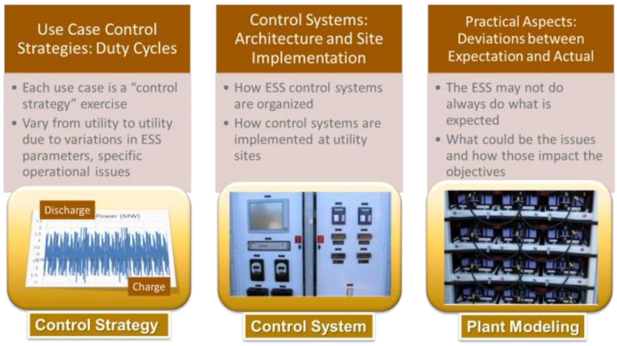

Fig. 3. Types of control learning opportunities gained from Washington CEF ESS demonstration projects.

IV. Control Strategy Development

Use cases under the Washington CEF program are built upon a variety of power system services, such as bulk energy applications (e.g., energy arbitrage, system capacity support), ancillary services (e.g., regulation), distribution system services (e.g., investment deferral by peak shaving, load shaping), and Volt/VAR applications. Controlling a given ESS for a particular use case at a specific utility requires a unique duty cycle, and provides an opportunity to go through a control strategy design exercise. A generic list of the use cases included in the CEF program can be found in Fig. 4. The control strategies were developed using either a rule-based approach or an optimization-based approach, as described below.

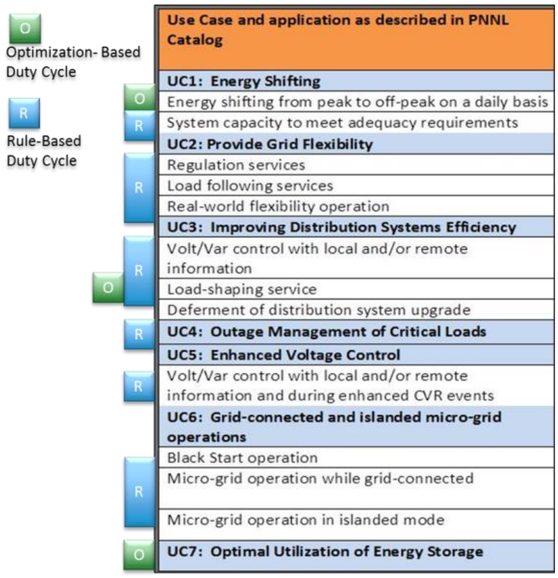

Fig. 4. Washington CEF use cases.

A. Rule-Based Approach

Generally, control strategies of the use cases that did not explicitly require an optimization to be performed were modeled using rule-based approaches. For instance, providing capacity support during a system-wide peak, or performing a load shaping service. System wide peak support duty cycle is developed by studying the system peak hours for a given utility and the ESS was controlled to discharge power at different length of periods (e.g. 1-4 hours) with adequate charging to maintain SoC level. Load shaping could take a variety of forms, and both types of control approaches (rule-based, and optimization-based) can be used to develop duty cycles for this service. For the rule-based approach, a strategy was set up to charge and discharge the ESS to reduce the gap between peak and valley of the load profile to make it flatter. The logic was to reduce efforts of control and regulating devices to manage these two opposite scenarios. A schematic of the rule-based load shaping duty cycle using historical load data and the result of performing that duty cycle is presented at the top panel of Fig. 5. As observed, the gaps between peaks and valleys of the load profile (brown: original, violet: with ESS) reduced by charging/discharging the ESS as per the duty cycle (green).

As one would understand, different approaches can be adopted to develop a rule-based duty cycle for a given service. PNNL focused on finding the appropriate match for the utility and the scenario under consideration. Ancillary service use cases (e.g., Regulation, Load Following) were developed using the rules of power system dynamics. Data (e.g., Area Control Error, Wind Generation) supplied by the participant utilities was used so that the duty cycles developed resemble the dynamics of that particular system, and the ESS is tested to the situations it would be subjected to in actual operation.

Outage mitigation and micro-grid operation use cases were also tested using rule-based duty cycles. ESS performance in these services depend on how effectively the ESS control performs in conjunction with distribution automation system. For CEF use case analytics program, these tests were performed based on U.S. Department of Energy test protocol using historical load and outage data. While CEF program scope did not require an actual outage to be conducted for these use case tests, PNNL closely engaged with the utilities in planning, execution, and analyzing results of similar tests conducted by the utilities for their own purposes. Precise timing of distribution system switching operations and ESS load pick-up was found to be very important for this type of services.

B. Optimization-Based Approach

An optimization-based approach is used for use cases that inherently require optimization to be performed for benefit maximization. Energy arbitrage is a classic example of such a use case because it involves maximizing the revenue from "buy low, sell high" transactions. Duty cycle for optimization-based load shaping service under CEF has been designed by minimizing payment to the balancing authority to reduce the gap between scheduled and actual load. A more complex and comprehensive use case is the optimal bundling of multiple services to maximize revenue from ESS operation. PNNL's in-house Battery Storage Evaluation Tool (BSET) has been used to develop optimization-based control strategies. A schematic of the optimization-based duty cycle development process using BSET is shown in the bottom panel of Fig. 5.

Fig. 5. Rule-based (top) and optimization-based (bottom) control strategies for ESS duty cycle development.

IV. Control Architecture and Site Implementation

Understanding the control architecture, systems, and equipment used for ESS control and how they interface and interact with a utility's existing control systems or SCADA is highly important. During the testing process, PNNL experienced multiple interruptions because control systems at different levels (e.g., Battery Management System [BMS], and inverter controller) failed to communicate and interact properly. Without adequate understanding of the control systems and their interoperability issues, it could be difficult to operate ESS reliably to achieve expected benefits. The following paragraphs outline the architecture and equipment used to control ESS at each of the CEF program utility sites.

A. Control Architecture

CEF demonstration projects (except Glacier ESS) deploy a two-layer control architecture for their ESS control systems (represented in Fig. 6). The top layer consists of an optimal scheduler that features capabilities to incorporate economic aspects (e.g., electricity price and/or other financial inputs) and ESS technical parameters to optimally run the ESS. An optimal scheduler can schedule multiple ESSs and other distributed resources. The bottom layer consists of controllers for each individual ESS, which perform detailed control and monitoring functions (e.g., charge/discharge, ramping, maintaining SoC) in coordination with the BMS. Of the three utilities, SnoPUD and PSE used the control and communication architecture proposed in MESA. A detailed discussion of MESA appears later in this paper.

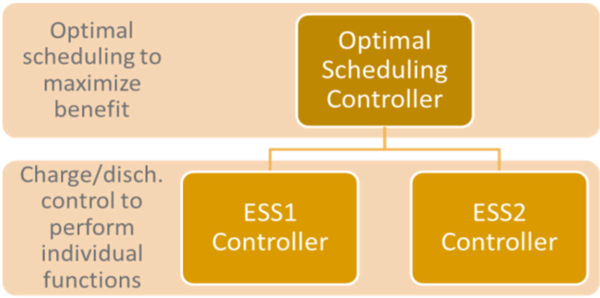

Fig. 6. General control architecture used at Washington CEF ESS projects.

B. Avista ESS Control System

Avista's UET flow batteries installed at SEL facilities are controlled using a Siemens PLC-based control system. A site controller using the Simatic WinCC Open Architecture (OA) SCADA system is installed for visualization and operation of processes. One site controller can control up to 100 strings of UET batteries. Each string, consisting of four batteries, one power conversion system, cooling system, and communications system, is controlled by a Simatic S7-1500 PLC which accomplishes day-to-day operational functions (e.g., charge and discharge control, SoC management, and reactive power control) of each ESS unit. A schematic of the control architecture is shown in the top panel of Fig.7.

Avista is in the process of deploying an optimization controller (the SPIRAE Wave™ [2]) as the top-layer controller (see Fig. 6) to optimize the ESS operation for maximizing the benefit of various services tied with their deployment goals. To compare with the architecture in Fig. 6, control layers in Fig. 7 are identified with dashed boxes.

C. SnoPUD and PSE ESS Control Systems

ESS Control systems at SnoPUD and PSE are built on MESA standards. At the planning stage, SnoPUD explored different standards for software and control system integration of ESS and experienced lack of adequate open standards [8]. Therefore, in collaboration with a number of partners, MESA – an open, non-proprietary standard was developed that helps accelerate interoperability, scalability, safety, quality, and affordability in energy storage components and systems.

The MESA standard has two major components. One is "MESA-ESS," which addresses ESS configuration management, ESS operational states, and the applicable ESS functions of IEEE 1815 (DNP3) profile for advanced DER functions. The other is "MESA-Device," which addresses how energy storage components within the ESS communicate with each other and other operational components and is built on the Modbus protocol.

SnoPUD deployed 1Energy-Intelligent Controller (1E-IC) built by 1Energy, which has been acquired by Doosan GridTech that renamed the controller "DG-IC". Supervisory control, including optimal control for different use cases, is performed by Doosan's Distributed Energy Resources Optimizer (DG-DERO™), a management system that optimally aggregates economic values from fleets of ESSs and other distributed resources. Built-in operating modes of DG-IC include Market-based Charge/Discharge, Frequency Correction, Spinning Reserve, Forecast Assurance, Power Following, Peak Power Limiting, Power Factor Correction, Volt/VAR, Volt/Watt, Power Smoothing, Islanding, and SoC Maintenance. A schematic of the DERO and DG-IC control deployment is shown at the bottom panel of Fig. 7. PSE deployed DG-IC without DERO at its Glacier ESS.

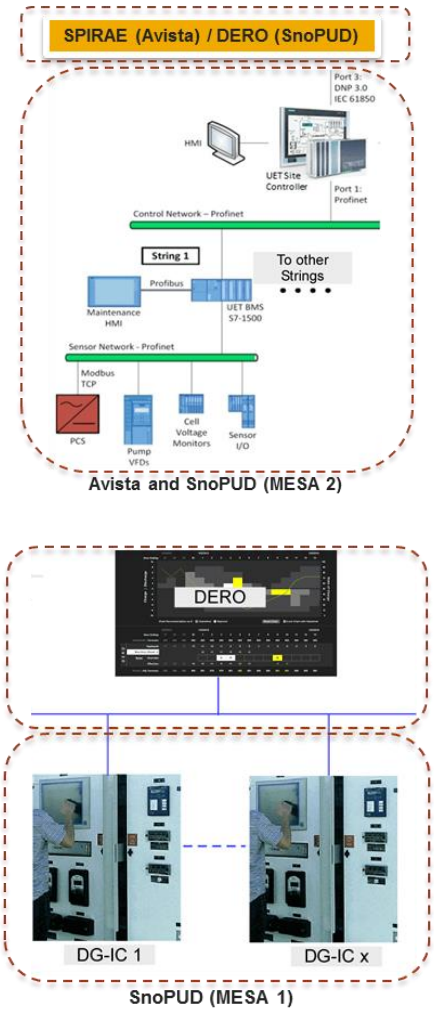

Fig. 7. Control system deployment at Washington CEF ESS project sites.

[2] http://www.spirae.com/microgrid/about-microgrid

V. DEVIATION BETWEEN EXPECTED AND ACTUAL PERFORMANCE OF ESS

In the process of running use case tests, it was observed that the ESS may perform differently in actual operation than predicted during the design of control duty cycles. This might create unacceptable engineering and economic outcomes. Analysis of these deviations using test results can provide useful insights on ESS performance, and more importantly, how performance could drift from that anticipated. Two such examples of deviation between expected and actual performance are presented below.

A. Scheduled and Actual Power Input

While engaged in providing a service, an ESS is expected to charge/discharge at scheduled rates over a given horizon of time. However, during the course of use case testing under the CEF program, deviations were observed between scheduled and actual power output at multiple instances. An example is shown in Fig. 8 in which the ESS was commanded to charge at a certain power level, but it charged at a lower level than commanded. Similar deviations were observed for discharging operations as well, as identified in Fig. 8. Discussion with utility personnel on these incidents helped in the development of some hypotheses on the cause (e.g., conflicts between different scheduling modes in the control system), but no definitive cause was identified.

Examination of SoC profiles from the past and future operations did not provide any evidence to support the idea that these particular deviations were caused by BMS interventions to prevent overcharging or overdischarging. Failing to follow a power command properly could be economically detrimental for power intensive applications (e.g., regulation), which happens to be a major component of ESS revenue for many deployment sites and therefore, needs to be treated with importance. With energy intensive applications, this could result in having inadequate amount of energy (or empty space) and could affect economic benefit achievement.

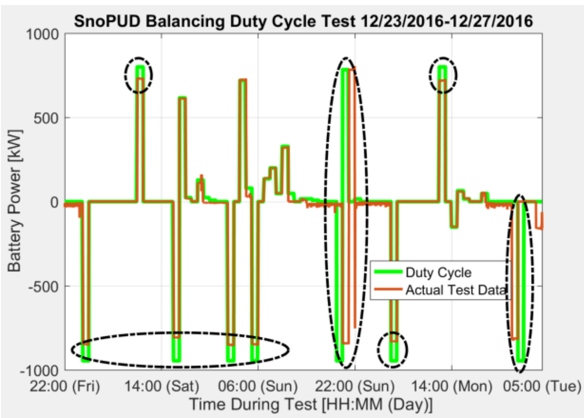

Fig. 8. Deviation between scheduled and actual power output of ESS.

B. Predicted and Actual SoC

Deviation between predicted and actual SoC could usually be observed with real world ESS because the SoC depends on many physical parameters (e.g., charging/discharging rate, temperature) during operation and could largely vary with time. If not tracked and corrected time to time, these variations could cause the SoC to exceed recommended operational bounds. If there are not enough protective features enabled in the BMS, an ESS could operate outside recommended SoC limits for longer than its designed tolerance, which could shorten its lifetime. Fig. 9 illustrates such an instance extracted from a 28-days-long use case test. The red circle between August 3 and 5 identifies a situation where the SoC went down to 1 percent, which is typically not recommended.

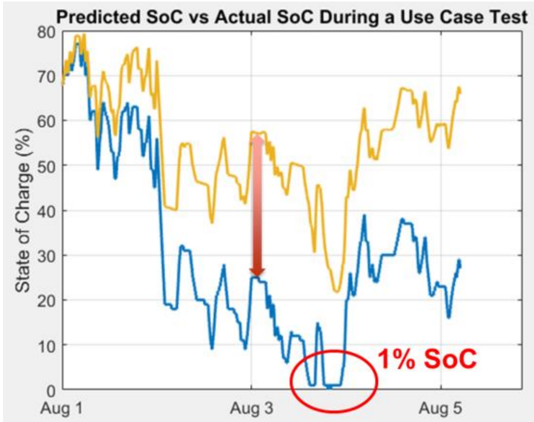

Fig. 9. Deviation between actual and expected SoC.

The researchers use PNNL's advanced nonlinear battery model to predict SoC profile over the test period and adjust the duty cycle as necessary to keep the SoC within limits. The same practice was exercised for the use case shown in Fig. 9. However, analyzing data from this low SoC event suggested that the ESS' performance drifted from the previously used performance parameters used for SoC prediction model and therefore failed to predict the SoC limit violation. This suggests that a check and balance of ESS performance parameters while developing and deploying a control strategy could be useful for ensuring operation within specifications. Another important lesson from this incident is that the monitoring and protection features in the BMS should be enabled to send alarm to the operators, and if required, execute a shutdown to save the ESS from possible damage.

VI. CONCLUSION

Three utilities across the state of Washington (Avista, SnoPUD and PSE) installed ESS, partially funded by the Washington State Department of Commerce under Washington CEF program. This paper presented the learning opportunities and key lessons in three areas of ESS control based on the Washington CEF ESS demonstration projects – control strategy development, control system deployment, and practical challenges with ESS control during operation.

Duty-cycle development for Washington CEF use-case testing essentially consists of exercises in developing control strategies for the various types of ESS services (e.g., bulk power, ancillary services, and distribution support). With the variations of economic and technical constraints including ESS parameters from one to another utility, the same use case could take different forms and therefore different control strategies will be needed for duty cycle development. Depending on the nature of a given use case, either optimization- or rule-based, control strategies could be used to develop the test duty cycle. The physical process of conducting use-case testing by running the duty cycles through ESS control systems provides opportunities to understand how control systems are designed, implemented, and integrated with a utility's existing control system or SCADA. Such exercises yield valuable insights on control and communication failure that can help achieve more reliable ESS operation.

Further, deviations between expected and actual performance (e.g., between commanded and actual power, predicted and actual SoC) of the ESS during testing provide opportunities to learn what practical challenges exist in ESS control. Information obtained by analyzing these deviations is vital in modeling and predicting ESS performance more accurately so that ESSs operate within acceptable parameters and impart values estimated.

While the learning opportunities and lessons presented in this paper relate to Washington CEF demonstration projects, they are likely applicable to many other ESS projects of similar size and complexity, both across the USA and in other parts of the world. The authors hope the lessons learned from these projects help to improve control system performance for existing ESS projects, and to develop new control systems for future projects.

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