PNNL-ACT-10121

OPALCO – Decatur Island Solar and Energy Storage Project

An Assessment of Battery Technical Performance

June 2022

A Crawford
D Wu
V Viswanathan

Prepared for the U.S. Department of Energy
under Contract DE-AC05-76RL01830

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under Contract DE-AC05-76RL01830

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Executive Summary

Orcas Power & Light Cooperative (OPALCO) is a member-owned, nonprofit cooperative utility that provides energy services to approximately 11,200 customers across 20 islands in San Juan County, Washington. OPALCO's mostly hydroelectric power is generated by Bonneville Power Administration and delivered to the islands by submarine cables. In 2016, as part of the second round of funding from the Washington Clean Energy Fund, OPALCO received a $1 million matching grant to support a project that deployed a 504-kW LG community photovoltaic (PV) system in combination with a 1 MW/2 MWh lithium-iron-phosphate battery energy storage system (BESS) on Decatur Island, Washington.[1] The Decatur Island Substation is essential to ensuring reliable energy for the residents of the San Juan Islands as it is the point of interconnection with the mainland transmission system. The BESS, in combination with the community solar array, will deliver an innovative method to both defer the costly upgrade of the transmission system and allow for other high-value applications intended to benefit the utility and its customers.

In 2018, Pacific Northwest National Laboratory (PNNL) completed a preliminary economic assessment for several identified use cases in collaboration with OPALCO.[2] Between August 2021 and May 2022, extensive testing was conducted, and the results were used to assess the technical performance of the BESS subjected to actual field operations. Both reference performance and use case tests were performed:

- Reference performance tests assess the general technical capabilities of the BESS, such as energy capacity, round-trip efficiency (RTE), ramp rate, and signal tracking capability. These are the first tests performed (baseline) and are repeated after use case tests (post cycle). A standardized U.S. Department of Energy (DOE) energy storage performance protocol[3] that included representative duty cycle profiles, test procedure guidance, and calculation guidance for determining key metrics, was used to characterize the BESS.
- Use case tests examine the performance of the BESS for specific use cases using duty cycles developed by PNNL in collaboration with OPALCO. Four use cases were selected for testing: 1) demand charge reduction, 2) load shaping, 3) outage mitigation, and 4) transmission deferral. The use case duty cycles were developed based on utility and site-specific characteristics in addition to the technical characteristics of the BESS. Use case tests were performed between the baseline and post cycle tests.

This report describes the BESS and its components, presents testing and performance analysis results, and shares key insights and lessons learned from this project. Outcomes of the tests and analyses will help OPALCO understand the performance of the Decatur Island BESS in its current state and design appropriate operational strategies for this and other BESSs over the long term.

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[1] Orcas Power & Light Cooperative. 2021. *Quick Fact: Decatur Island Battery Storage Project*. May 19, 2021. https://www.opalco.com/quick-fact-decatur-island-battery-storage-project/2021/05/

[2] Mongird K, P Balducci, J Alam, Y Yuan, D Wu, T Hardy, J Mietzner, T Neal, R Guerry, and J Kimball 2018. *Decatur Island Community Solar and Energy Storage Project – Preliminary Economic Assessment*. PNNL-27696, Pacific Northwest National Laboratory, Richland, WA.

[3] Conover D, A Crawford, J Fuller, S Gourisetti, V Viswanathan, S Ferreira, D Schoenwald, and D Rosewater 2016. *Protocol for Uniformly Measuring and Expressing the Performance of Energy Storage Systems*. PNNL-22010, Rev. 2; SAND2016-3078 R, Pacific Northwest National Laboratory, Richland, WA, and Sandia National Laboratories, Albuquerque, NM.

Key Questions Addressed

A thorough analysis of BESS performance was carried out using metrics developed in the DOE protocol and additional metrics identified in this project. In combination, these general and project-specific metrics allowed a set of structured evaluations that are key for ultimately determining the technical capabilities and cost-effectiveness of BESS for grid applications.

The following questions were addressed:

1. How does the BESS perform with energy-intensive duty cycles? For example, what is the RTE of the BESS? This analysis determined the RTE of the BESS under various conditions such as different charge-discharge power levels, with/without rest periods, and with/without auxiliary consumption.
2. How does the BESS perform for duty cycles with a high ramp rate?
3. What are the challenges in assessing the BESS performance? What can be improved in testing and data collection?

Key Outcomes

Outcome 1

Outcome 1 revealed findings related to charge/discharge energy capacity and RTE. Figure ES.1 summarizes the test results for energy-intensive applications, including the reference performance energy capacity tests as well as four use cases. The duty cycles for the four use cases are characterized by long duration and steady charging/discharging without rapid power fluctuation, and therefore are classified as energy-intensive applications and are appropriate for comparison to energy capacity reference performance test results. The metrics such as energy capacity and RTE are evaluated at the system level of the BESS, including power conversion system (PCS) loss and auxiliary system power consumption. The charge and discharge energy per 100% state of charge (SOC) is provided along with the efficiency. The x-axis is the average absolute power, which also shows how intensive the power is for each application.

- In general, both the energy charged and the energy discharged decrease with increased applied power. The effect of the discharge energy decreasing with increasing power wins out, and thus the efficiency at the PCS level decreases with increasing power. In general, RTE was consistently in the range of 89% to 97%, with one outlier in the UC4, for which a fault was encountered during testing.
- The energy discharged per 100% SOC ranged from 2550 to 2750 kWh. Note that the BESS was not allowed to go below 20% or above 95% SOC, only allowing a depth of discharge (DOD) of 75% at the maximum. If scaled accordingly, this discharge energy per DOD comes to about 1990 kWh, a bit lower than the 2000 kWh nameplate capacity. The corresponding charging capacity is around 2080 kWh.
- It was also found that the efficiency depends on SOC operating range, with the maximum efficiency being found in the 40% to 90% SOC range. The efficiency decreased rapidly beyond this range.
- Under optimal operating conditions, the BESS RTE is extremely high, sometimes approaching 97%. The high efficiency made performance assessment difficult because the change in SOC due to losses could be less than or close to the SOC resolution of 1%, which makes it difficult to accurately estimate losses.

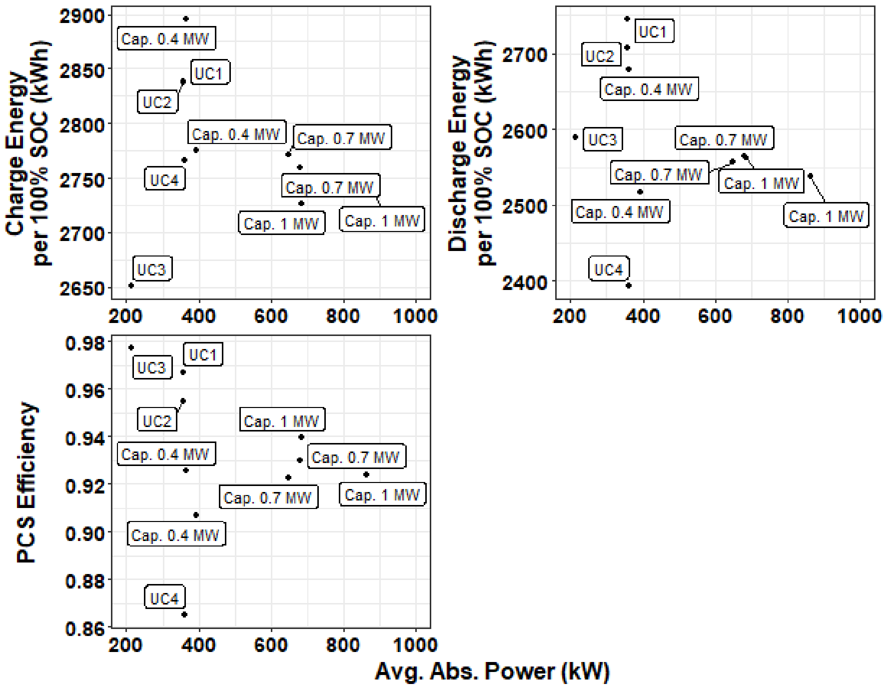

Figure ES.1. Charge energy, discharge energy, and RTE in capacity and use case tests.

The energy capacity and efficiency of the BESS were evaluated before (baseline) and after (post cycle) use case testing. The results are plotted in Figure ES.2. All discharge capacities per 100% SOC increased slightly, indicating improved discharge efficiency.

There was no noticeable decrease in discharge energy capacities or efficiencies. In fact, most of them increased slightly. All efficiencies increased, and the only measured decrease in performance was the capacity with 0.4 MW charging power, where the BESS took more charging energy during post cycle testing compared to baseline. This indicates that the performance of the BESS is stable, with any degradation that took place being lost in the noise.

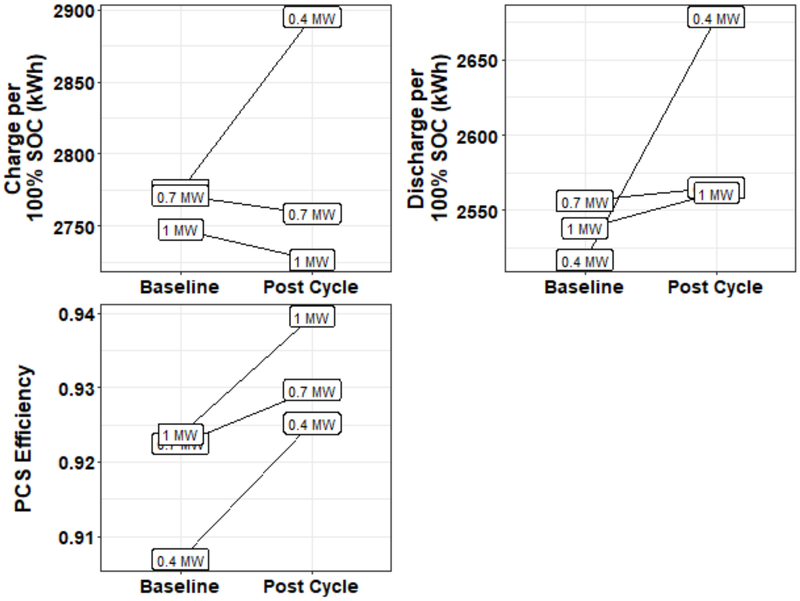

Figure ES.2. Charge and discharge energy and PCS efficiency comparison between the baseline and post cycle capacity tests.

Outcome 2

Outcome 2 revealed findings related to response time, internal resistance, and signal tracking. With the measurement data collected every minute, the calculations of response time and internal resistance are somewhat coarse. As the BESS can reach full power in less than a minute, it is impossible to calculate the ramp rate. The internal resistance of the BESS was calculated to be on the order of 1 mΩ. No meaningful trends were observed for pulse resistance vs. SOC, nor were there any statistically significant differences between the baseline and post cycle pulse resistance. The internal resistance vs. SOC is plotted in Figure ES.3.

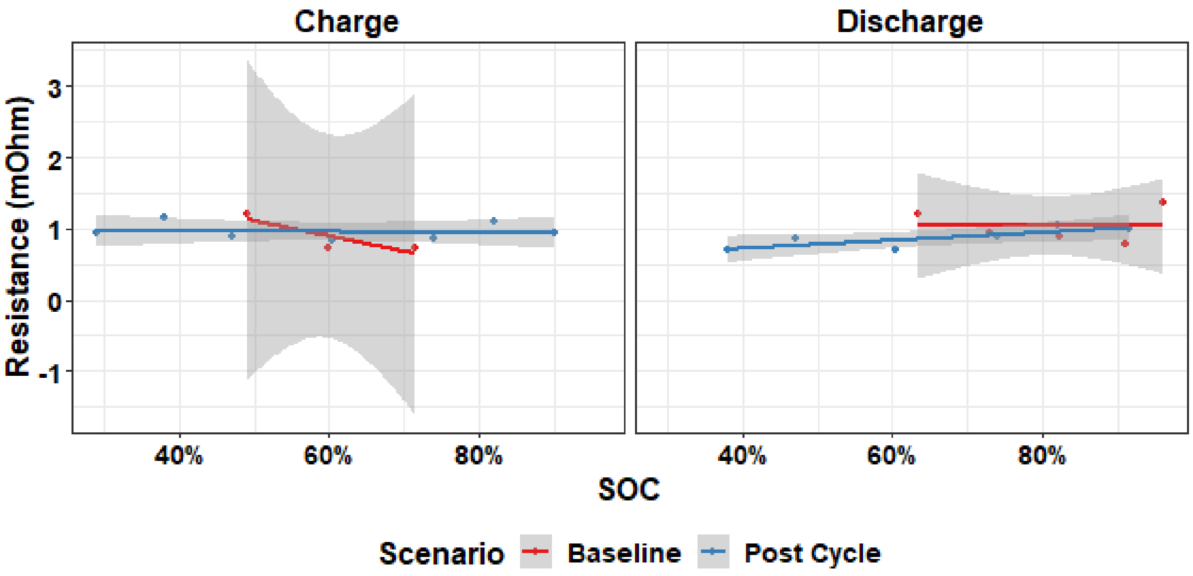

Figure ES.3. Pulse test results for charge and discharge for baseline and post cycle tests.

To measure the signal tracking performance, the standard DOE frequency regulation duty cycle was used. The regulation signal changes every 4 seconds over a 24-hour period. The error is defined as the difference between the power reference and the power provided by the BESS. Despite the 1-minute resolution, we were still able to estimate the signal tracking performance. There are 21,600 steps within 24 hours with a step size of 4 seconds. The 1-minute resolution means that each 15 steps were grouped into one data point, leading to 1440 data points within 24 hours. The 1-minute average power provided is compared with the reference signal to quantify the tracking performance. The distribution of the errors is plotted in Figure ES.4. As can be seen, the signal tracking performance was poor, with a root mean square error of 81 kW, which is about 8% of rated power. The error distribution tends to be negative, which means that the BESS tended to provide less power than was requested, i.e., higher than desired during charging and lower than desired during discharging.

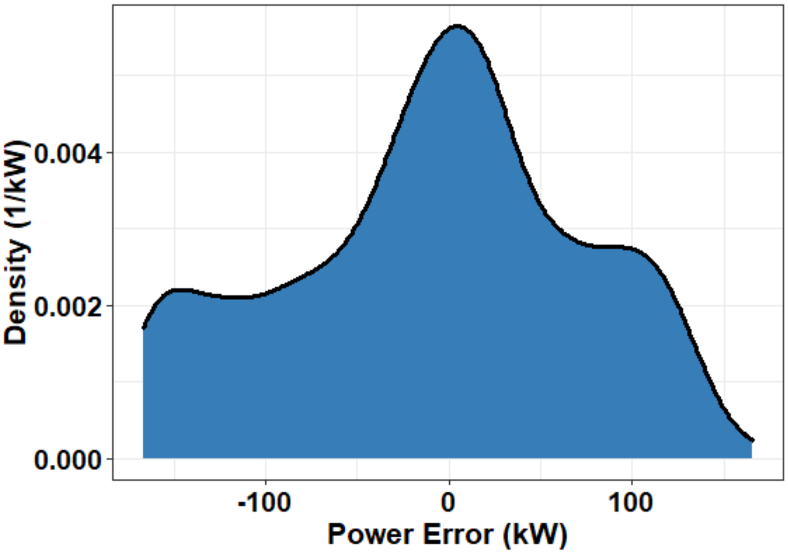

Figure ES.4. Frequency regulation error distribution.

Outcome 3

Outcome 3 revealed issues and challenges during testing and performance assessment, which are summarized below and described in detail in the body of this report.

- To obtain the data using the BESS web interface, a Selenium script had to be written to scrape the data day-by-day, as no native method for programmatic data extraction existed.
- The SOC resolution of 1% presented challenges to performance assessment, especially with such a high-efficiency BESS.
- A power outage disturbed one of the tests, requiring a manual reset of the system. This made one of the tests artificially report its SOC as 0.
- For the first round of baseline performance tests, an app was accidentally enabled, which automatically started charging when the SOC was below a 50% threshold. This caused the BESS to charge unexpectedly, which was not detected until troubleshooting later with Powin. This caused issues during the pulse tests, as the system started charging back up whenever it was idle below 50%.

- The 1-minute data resolution presented challenges in calculating the value of some metrics that require measurement data with high temporal resolution, such as signal tracking and pulse resistance.
- The 1-minute data resolution also affected system efficiency estimation when the efficiency is high.
- While using the website interface, the ability to upload a CSV file or operate the BESS according to a predetermined power signal was not available until a few months into testing. To perform the frequency response test, a Python script was run to control the BESS remotely.

Acknowledgments

We are grateful to Mr. Bob Kirchmeier, Senior Energy Policy Specialist at the Washington State Department of Commerce, for providing Clean Energy Fund program leadership to support Pacific Northwest National Laboratory (PNNL) and our utility partners. We are also grateful to Dr. Imre Gyuk, Director of the Energy Storage Program in the Office of Electricity at the U.S. Department of Energy, for providing financial support and leadership on this and other related work at PNNL. We wish to acknowledge team members from OPALCO, including Robert Smallwood and Russell Guerry. We also wish to acknowledge Matthew Beckers and Kian Dashti from Powin.

Acronyms and Abbreviations

A	amperes
AC	alternating current
BESS	battery energy storage system
BMS	battery management system
BSET	Battery Storage Evaluation Tool
CEF	Clean Energy Fund
DC	direct current
DOD	depth of discharge
DOE	U.S. Department of Energy
kW	kilowatts
kWh	kilowatt-hours
LFP	lithium-iron-phosphate
MW	megawatt(s)
MWh	megawatt hour(s)
OPALCO	Orcas Power & Light Cooperative
PCS	power conversion system
PNNL	Pacific Northwest National Laboratory
PV	photovoltaic
RMSE	root mean square error
RPT	reference performance test
RTE	round-trip efficiency
SOC	state of charge

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1.0 Introduction

1.1 Project Synopsis

The Washington Clean Energy Fund (CEF) is a publicly funded program that provides grants in support of the development of clean energy technologies in Washington state. Since 2013, the Washington State Legislature has authorized $122 million for the fund (Kirchmeier 2018), including Energy Revolving Loan Fund Grants, Smart Grid and Grid Modernization Grants to Utilities, Federal Clean Energy Matching Funds, and Credit Enhancement for Renewable Energy Manufacturing. To date, CEF funds have been distributed to electric utility companies, vendors, universities, and research organizations to fund projects that integrate intermittent renewables, improve grid reliability, expand grid modernization activities, reduce the costs associated with distributed energy resource deployments, and lower emissions.

Orcas Power & Light Cooperative (OPALCO) is a member-owned, nonprofit cooperative utility that provides energy services to approximately 11,200 customers across 20 islands in San Juan County, Washington. OPALCO’s mostly hydroelectric power is generated by Bonneville Power Administration and delivered to the islands by submarine cables. A map of the San Juan Islands is presented in Figure 1.1. In 2016, as part of the second round of funding from the CEF, OPALCO received a $1 million matching grant to support a project that deployed a 504-kW LG community photovoltaic (PV) system in combination with a 1 MW/2 MWh lithium-iron-phosphate (LFP) battery energy storage system (BESS) on Decatur Island, Washington (OPALCO 2021). The Decatur Island Substation is essential to ensuring reliable energy to the residents of the San Juan Islands as it is the point of interconnection with the mainland transmission system. The proposed BESS, in combination with the community solar array, will deliver an innovative method to both defer the costly upgrade of the transmission system and allow for other high-value applications intended to benefit the utility and its customers.

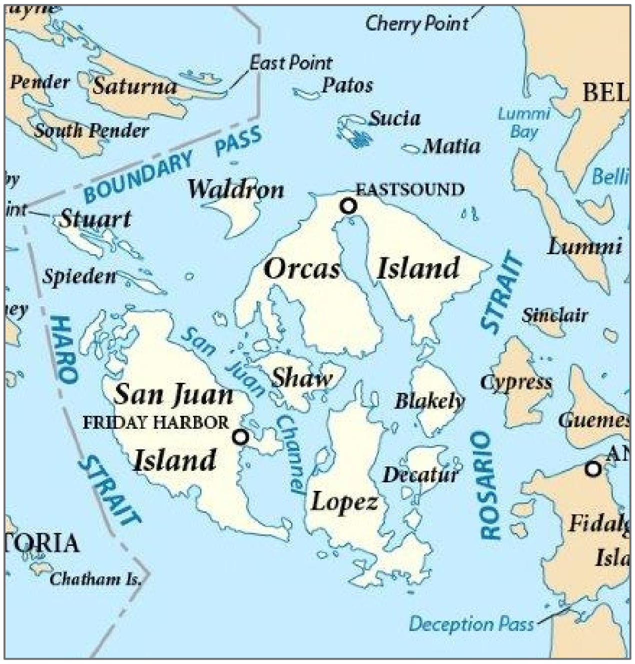

Figure 1.1. San Juan Islands, Washington.

In 2018, Pacific Northwest National Laboratory (PNNL) completed a preliminary economic assessment for several identified use cases in collaboration with OPALCO (Mongird 2018). Between August 2021 and May 2022, extensive testing was conducted, and the results were used to assess the technical performance of the BESS subjected to actual field operations. This report documents baseline and use case technical performance of the OPALCO BESS based on the framework and approaches defined by PNNL and the lessons learned from the testing and performance assessment. The reference performance test (RPT) vs. use case comparative analytic approach was used to evaluate the effectiveness of BESSs when operated for a set of grid applications. The technical support offered by PNNL included:

1. Development of protocols and duty cycles to test the ability of the BESS to safely and effectively be used for the use cases identified by OPALCO and PNNL.
2. Development and selection of performance metrics to be evaluated, such as ramp rate, round-trip efficiency (RTE), and internal resistance.
3. Assessment of technical performance against a set of selected metrics in different scenarios.

Baseline testing used cycles intended to quantify basic BESS characteristics, including charge and discharge energy capacities at various power levels, ramp rate/response time, and signal tracking. Reference performance for the BESS considered in this project used several duty cycles defined and described in the U.S. Department of Energy (DOE) Energy Storage Protocol (Conover 2016) and was evaluated at the beginning of the testing (baseline tests) and after cycle 1 of use case testing (post cycle 1).

Four use cases were selected for testing:

- Use Case 1 – Demand Charge Reduction
- Use Case 2 – Load Shaping
- Use Case 3 – Outage Mitigation
- Use Case 4 – Transmission Deferral

Detailed descriptions of these use cases can be found in Mongird (2018). The use case duty cycles were developed based on utility and site-specific characteristics in addition to the technical characteristics and physical capabilities of the BESS. Use case tests were performed between the baseline and post cycle tests.

1.2 Powin Battery

The project is located on Decatur Island, which is a part of the San Juan Islands in the northern portion of Puget Sound in Washington state. The project consists of a Powin 1 MW/2 MWh LFP BESS co-located with a 504-kW LG community solar array from Puget Sound Solar at the Decatur Island Substation.

The LFP is the safest among all Li-ion chemistries. The LFP's relative safety among the broader general family of Li-ion batteries is mainly due to the delayed onset of thermal runaway for the LiFePO4 electrode and the low energy content for the runaway reaction for this electrode, relative to other Li-ion chemistries (e.g., nickel-manganese-cobalt or nickel-cobalt-aluminum Li-ion). The lower specific energy also contributes to a greater thermal mass, resulting in a lower ΔT for a fixed heat generation, further reducing the chance of thermal runaway. However, in the event of external energy source such as fire, the flammable electrolyte will burn itself out, with total energy corresponding to this combustion equivalent for all li-ion chemistries.

1.2.1 Battery Architecture

The BESS consists of one container containing 12 rack-mounted strings, with each string consisting of 11 series-connected modules or trays, each containing 24 cells in series, for a total of 264 cells in series. Each string also has a string controller. Each of these strings is standardized, with customers choosing the number of modules or trays to purchase. The Decatur Island installation uses model S225 strings in one enclosure, with an individual string shown in Figure 1.2.

Figure 1.2. One S225 string.

1.2.2 Battery Management System

The battery management system (BMS) is provided by Powin, and a web interface is available for control and data collection. The state of charge (SOC) appears to be calculated based on the DC voltage after an internal resistance related ΔV correction, with the SOC as a function of DC voltage and current given in Figure 1.3.

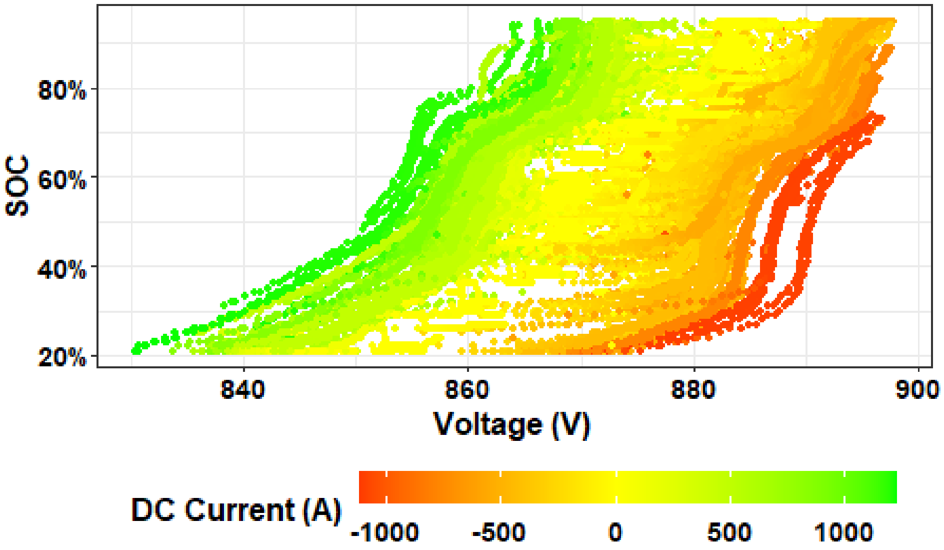

Figure 1.3. SOC vs. DC voltage and current.

The best fit for this data is:

$$SOC = (-1.836) + (2.17e - 2\, V^{-1})V_{DC} + (4.132e - 4\, A^{-1})I_{DC}$$

with an R^2 of 0.93, implying the SOC may be adjusted based on other factors. This relationship implies that 0% SOC corresponds to an open circuit voltage (OCV) of 845V and 100% SOC to an OCV 891V. Furthermore, it implies the internal resistance is 19 mΩ (based on the ratio of the current coefficient to the voltage coefficient), which we can check against the internal resistance calculated from the pulse tests.

There are three meters within the BESS from which we collect data. The string meter contains DC information about each of the 12 individual strings. The array meter contains DC information from the 12 strings aggregated together, including the average SOC. The PCS meter contains AC information. The layout of the three meters, along with hypothesized losses discussed in the subsequent sections is given in Figure 1.4.

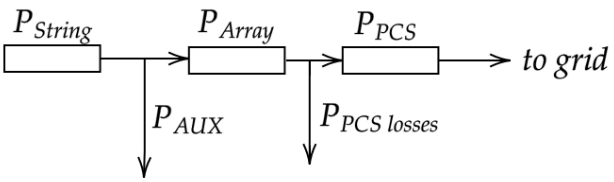

Figure 1.4. Metering layout

1.2.3 PCS Losses

The power conversion system (PCS) loss is calculated by subtracting the power at the PCS from the array DC battery power, as shown in Figure 1.4. Figure 1.5 plots this difference against the power at the PCS. This is a much lower loss than other systems we have analyzed in the past, which is likely a major contributor to this BESS's high efficiency of 97.7% at full charge and 98.2% at full discharge. The maximum PCS loss for this BESS appears to be around 25 kW, which is approximately a third of previously analyzed systems (after normalizing against the system rated power).

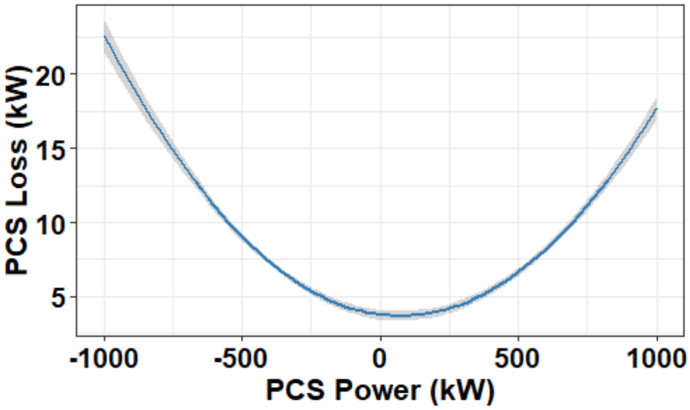

Figure 1.5. PCS loss vs PCS power.

The total energy charged and discharged over the BESS's history at each SOC was used to calculate the total PCS RTE at each SOC level, as plotted in Figure 1.6. As can be seen, very high (95%+) efficiency can be achieved for an SOC ranging from 40% to 90%. The BESS's efficiency significantly decreases beyond this range.

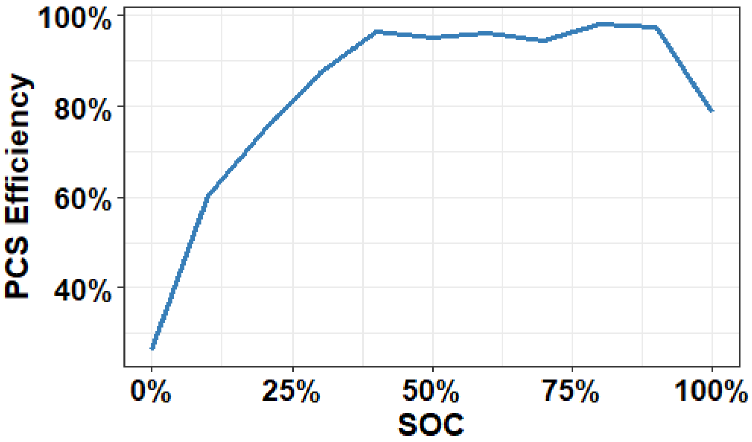

Figure 1.6. PCS RTE as a function of SOC.

It is assumed that the power measured at the array includes some DC auxiliary system power consumption, considering the difference between the two is a function of temperature, which is plotted in Figure 1.7. This quantity is given as P_{AUX} in Figure 1.4. The battery temperature ranges from 20°C to 35°C, corresponding to an auxiliary loss of 4 to 11 kW. This implies the auxiliary loads are mostly used for cooling within this temperature range.

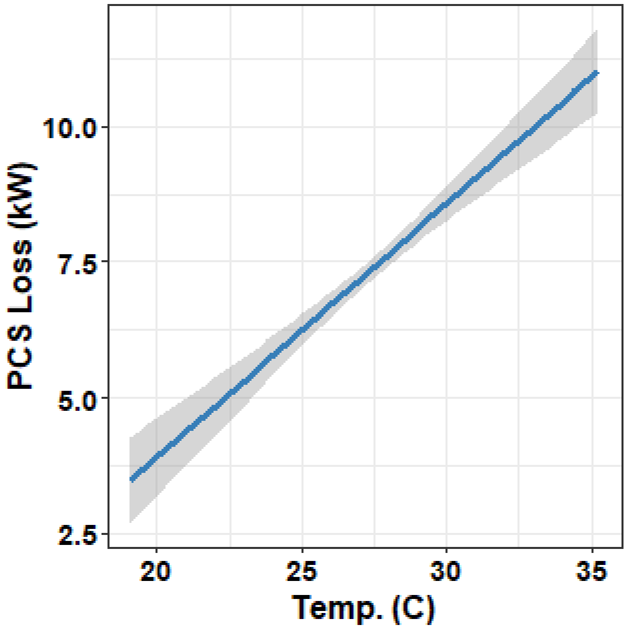

Figure 1.7. Auxiliary power consumption as a function of temperature.

2.0 Battery Performance Test Results

During the first phase of tests, the BESS was subjected to baseline testing as described in the DOE testing protocols (Conover 2016), with discharge at various powers for a constant power charge. Response time and ramp rate were measured at various SOCs, along with charge and discharge resistance. The results of these tests are presented in this section.

This report also introduces a few new metrics to accommodate the low granularity of the testing data. For all performance tests, the RTE was reported based on energy discharged and energy charged during the cycle. However, this is only valid if the SOC is the same at the start and end of the cycle. If not, the energy charged is adjusted based on the SOC difference (i.e., the charge energy is increased if the ending SOC is lower than the starting SOC, and reduced if the ending SOC is higher than the starting SOC) using a relationship based on the charge energy required per SOC over the course of the performance test. This has one more twist, however, in that the SOC is rounded to the nearest 1% in the data. Such a resolution is not high enough to estimate losses, especially when the BESS's efficiency is high. To address the challenge, a new metric is introduced, called regressed RTE. In this method, the BESS's change in SOC is regressed against the cumulative discharge and cumulative charge energy, returning two coefficients. The ratio of the cumulative discharge energy coefficient to the cumulative charge energy coefficient is the regressed RTE, which allows for calculating an RTE with different start and end SOCs, without the need to use data from other testing cycles. Another advantage of the regressed RTE is that errors in the start or end SOC do not throw the model off by much, as all the data is used to regress an RTE.

In this section, metrics are reported at the array meter and at the PCS meter (see Figure 1.4)

2.1 Capacity Test Results

The capacity tests cycled the BESS between 20% and 95% SOC at 1000, 700, and 400 kW to obtain a wide range of operating conditions. Figure 2.1 shows the power and SOC of the BESS during the cycle. Note that the capacity tests do not consistently hit the entire 20% to 95% operating range, which may be due to swings in SOC as the power changes. The SOC reported is a proxy for operating voltage, meaning that changes in power can result in swings in SOC, advancing the test to the next stage. This SOC fluctuation is especially obvious in the baseline 1000 kW test during charge. To account for differences in SOC range, the energy per SOC range is also reported in Table 2.1. The following observation can be made:

- In general, the RTE of the system increases with increased power. This is likely due to the thermal effect of the BESS operating at improved efficiency at higher temperatures, with the temperature increased during increased power. The BESS's efficiency likely does not decrease much with increased power, as this effect dominates.
- Notice that in Table 2.1, the regressed RTE is more consistent across power levels, demonstrating that this approach can help deal with some noise inherent in measuring the RTE. Also note that for none of the capacity tests was the entire nameplate discharge energy of 2.0 MWh/cycle able to be extracted, with the best performance being the 700 kW discharge giving 1.9 MWh/cycle.

- The regressed RTE was compared to the average temperature of each cycle, with the average temperature explaining 68% of PCS RTE variance. Higher average temperatures result in higher RTE, with an expected 0.5% efficiency increase for each 1°C increase.

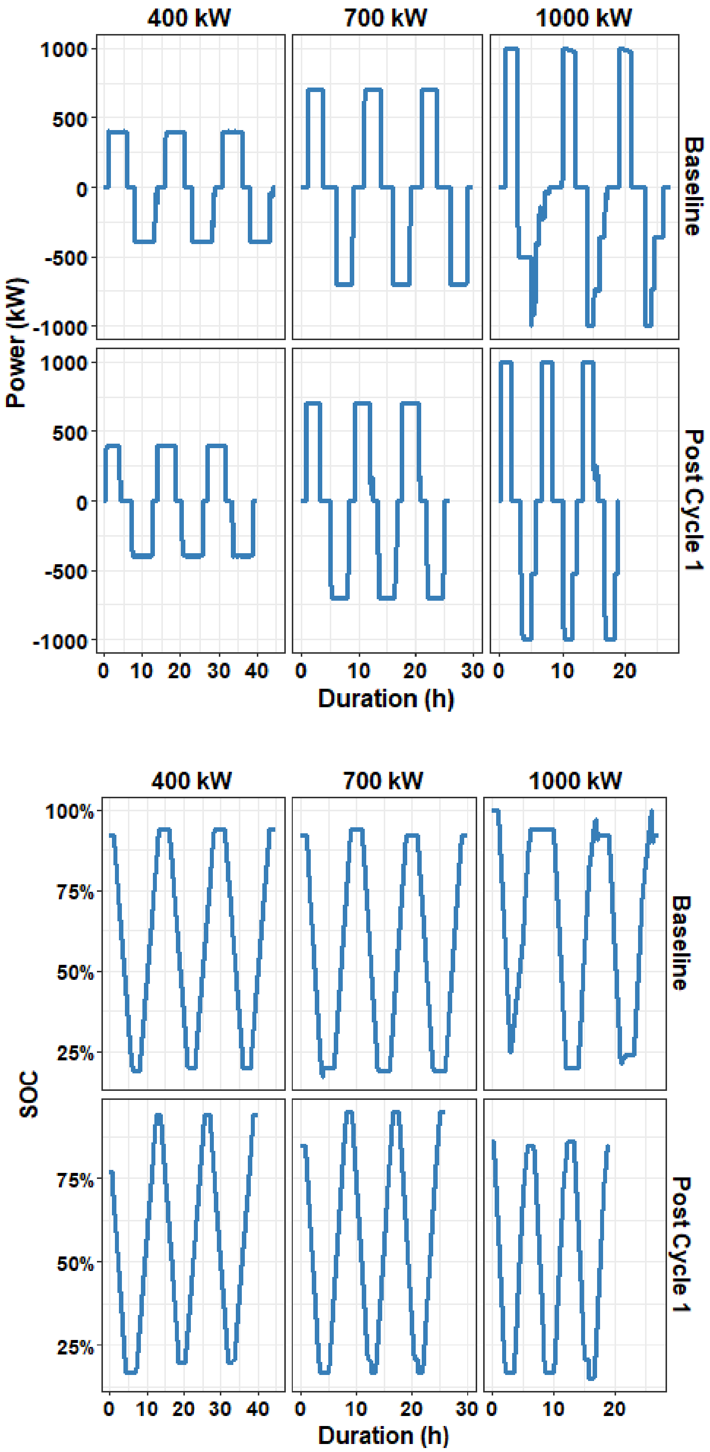

Figure 2.1. Power and SOC profiles for BESS at various rates for reference performance capacity baseline and post cycle 1 tests.

Table 2.1. Baseline Capacity Test Results

Scenario	Baseline	Baseline	Baseline	Post Cycle 1	Post Cycle 1	Post Cycle 1
Date	2021-08-14	2021-08-15	2021-08-17	2022-04-13	2022-04-14	2022-04-17
Discharge/Charge Power (kW)	1000	700	400	1000	700	400
Duration (h)	26	30	32	19	18	28
Average Charge Power (kW)	523	663	334	808	653	384
Average Discharge Power (kW)	995	699	402	937	643	402
SOC Range	20-92	17-92	20-94	15-85	17-95	20-94
Cycles	3	3	3	3	3	3
PCS Charge Energy per Cycle (kWh)	1975	2041	1460	1880	1439	1405
PCS Discharge Energy per Cycle (kWh)	1879	1895	1323	1738	1347	1310
PCS Discharge Energy per SOC (kWh)	2622	2620	2720	2582	2731	2672
PCS RTE (%)	95.1	92.9	90.6	92.4	93.6	93.1
Array Charge Energy per Cycle (kWh)	1929	2001	1422	1837	1412	1375
Array Discharge Energy per Cycle (kWh)	1903	1916	1388	1771	1364	1324
Array Discharge Energy per SOC (kWh)	2655	2649	2750	2630	2765	2702
Array RTE (%)	98.7	95.8	94.1	96.3	96.6	96.3
Array Regressed RTE (%)	97.5	95.8	95.9	96.2	95.2	93.8
PCS Regressed RTE (%)	93.4	93.0	92.5	92.4	92.2	90.1
Mean Charge Temperature (°C)	33	32	29	30	29	29
Mean Discharge Temperature (°C)	32	31	27	29	29	28
Mean Temperature (°C)	33	31	28	30	29	28

The discharge and charge energy per SOC and the efficiency were compared before and after the use case tests, as shown in Figure 2.2. The energy capacity is stable, even increasing slightly after the use case tests. This implies any state of health degradation is very small and is lost in the noise.

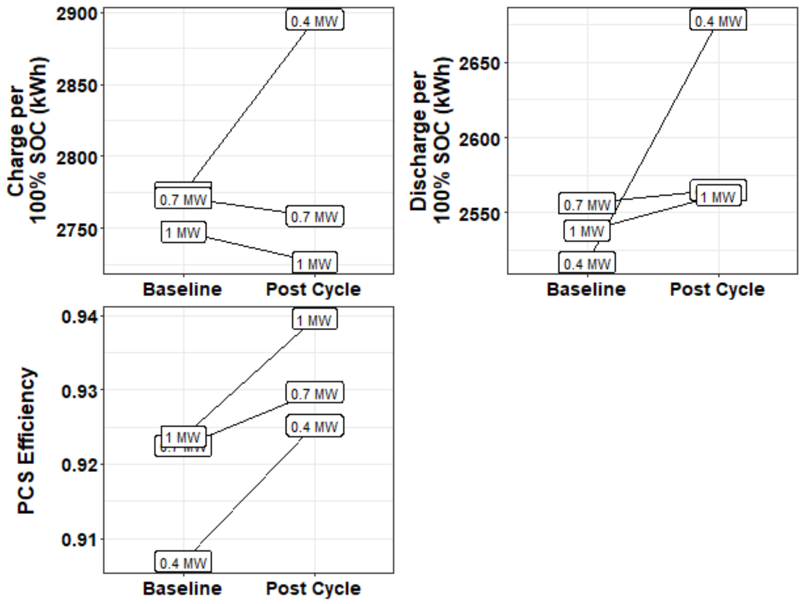

Figure 2.2. Capacity test results comparison post cycle vs. baseline.

2.2 Pulse Test Results

The pulse tests apply a 10-second pulse of maximum rated charge and discharge power at various SOCs to measure the BESS internal resistance and response time/ramp rate. After the pulse signal was sent, the time required for the BESS power increased to come within 1% of the signal was measured. This was set equal to response time, while the ramp rate in MW/second was calculated by dividing the rated power in MW by the response time in seconds. Over the course of the pulse, the change in DC voltage and DC current are measured, and their ratio is used to calculate the pulse resistance. The ΔSOC during this 10-second pulse is estimated to be 0.1% for both charge and discharge.

The data with a 1-minute resolution makes it difficult to accurately assess the results of the pulse tests. Only two points could be analyzed: one minute before the pulse started, and the instant the pulse begins. The ramp rate especially is of limited use – the BESS presumably can reach the rated power in less than 1 minute. Based on the power measured at the instant of the pulse beginning, the minimum possible ramp rate is reported in Table 2.3. The pulse resistance is on the order of 1 mΩ, or about 20 times lower than that calculated from the SOC model in Section 1.2.2. The results are plotted in Figure 2.3 and presented in Table 2.2. There were no meaningful trends calculated for pulse resistance vs. SOC, nor were there any statistically significant differences observed between the baseline pulse resistance and post cycle pulse resistance.

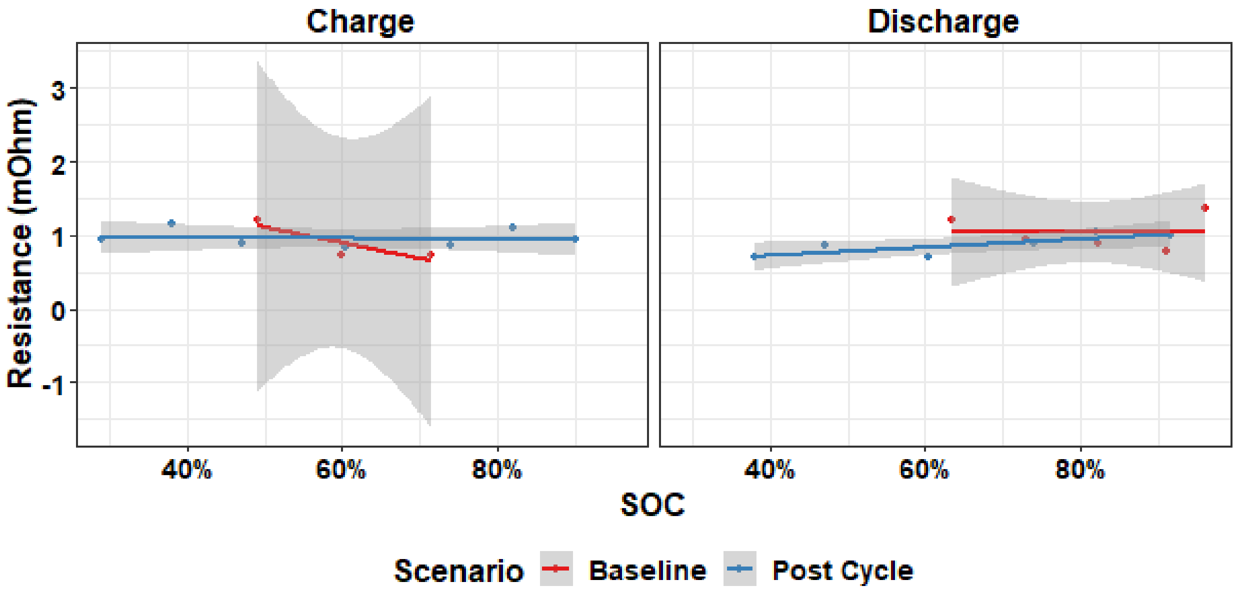

Figure 2.3. Pulse resistance vs. SOC for charge and discharge during baseline tests and post cycle tests.

Table 2.2. Resistance (mΩ) for Pulse Test

SOC	Baseline Charge	Baseline Discharge	Post Cycle 1 Charge	Post Cycle 1 Discharge
30	NA	NA	0.94	NA
40	NA	NA	1.14	0.70
50	1.2	NA	0.88	0.86
60	0.73	1.22	0.86	0.70
70	0.74	0.93	0.87	0.90
80	NA	0.88	1.1	1.04
90	NA	0.77	NA	1.00

Table 2.3. Minimum Ramp Rate (kW/min) for Pulse Test

SOC	Baseline Charge	Baseline Discharge	Post Cycle 1 Charge	Post Cycle 1 Discharge
30	NA	NA	768	NA
40	NA	NA	773	920
50	595	NA	933	985
60	88	935	627	684
70	421	593	242	540
80	NA	756	338	342
90	NA	301	NA	174

2.3 Frequency Regulation Test

The DOE frequency regulation signal was used to test the BESS as part of the RPT. The average discharge power was 432 kW, while the average charge power was 333 kW.

RTE from the RPT is about 71%, which is much lower than the RTE for capacity tests. Signal tracking was poor, with the root mean square error (RMSE) of the power being 81 kW at the PCS and 130 kW at the array. It was found that the error was independent of the SOC level and the power at the PCS. The increased RMSE at the array is because commands are applied at the PCS level rather than at the array. The results of these tests are provided in Figure 2.4 and Table 2.4.

Note that the RTE calculated from the charge and discharge energy was quite low, at 71%. The regressed RTE was much more in line with capacity test results, at 95% PCS RTE. This may be partially due to the rapidly fluctuating power swings affecting the measured SOC, making it hard to calculate the actual decrease in SOC level for calculating RTE in the normal way.

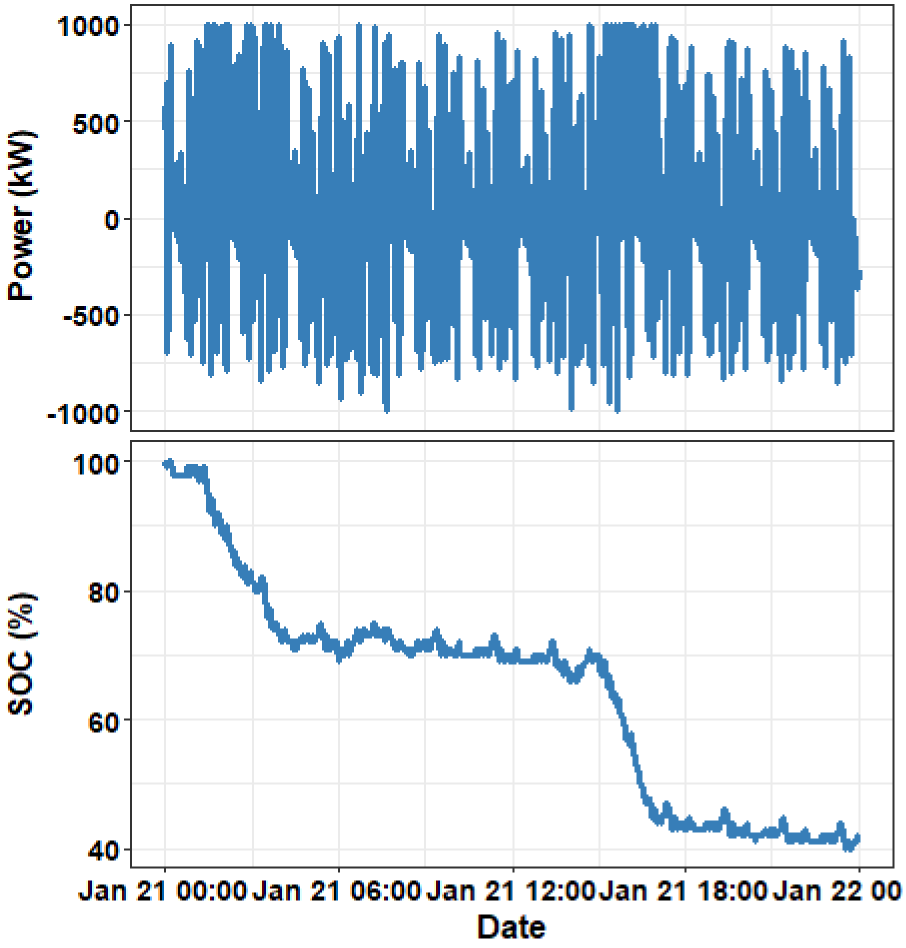

Figure 2.4. Frequency regulation DOE protocol tests.

Table 2.4. Frequency Regulation Test Results

Scenario	Baseline
Date	2022-01-20
Duration (h)	24
Start SOC (%)	100
End SOC (%)	40
Average Charge Power (kW)	333
Average Discharge Power (kW)	432
Array RTE (%)	71.3
PCS RTE (%)	70.6
Regressed Array RTE (%)	99.4
Regressed PCS RTE (%)	95.1
PCS RMSE (kW)	81
Battery RMSE (kW)	130

The error distribution is given in Figure 2.5. It appears the error tends toward the negative side, i.e., the battery tends to give less power than requested during the rapidly changing signal.

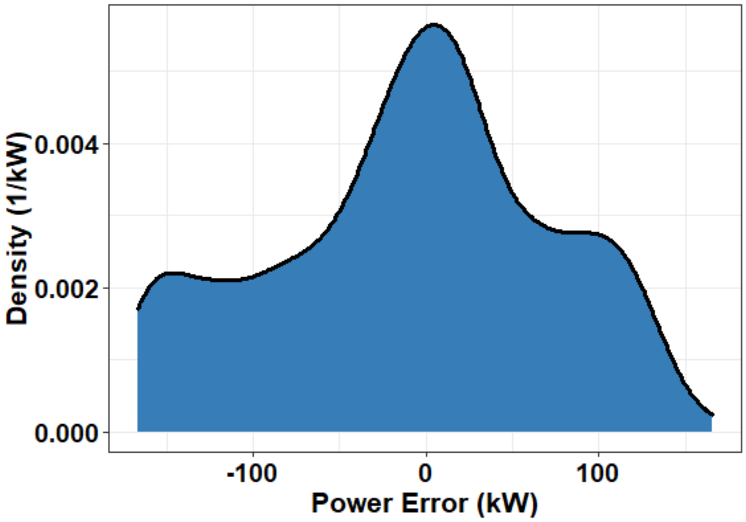

Figure 2.5. Frequency regulation DOE protocol error distribution.

2.4 Use Case 1: Demand Charge Reduction

2.4.1 Duty Cycle Summary

Demand charge benefits are tied to the use of the BESS to reduce the maximum monthly load for a customer, in this case, OPALCO. PNNL worked with OPALCO to identify demand and transmission charge rates it is currently subject to. These rates were combined with historical load data to develop a peak shaving duty cycle and determine annual savings to OPALCO realized through the peak shaving service offered by the BESS. The duty cycle operated for 1 week.

2.4.2 Test Results

The duty cycle ran for 1 week, and ended at a higher SOC (55%) than the ending SOC predicted from our preliminary analysis (20%). This is mostly due to the BESS's much higher than expected efficiency. The BESS had higher efficiency than the capacity tests, with a regressed PCS RTE of 96%. This is despite spending 78% of its time at rest, which typically results in lower RTE due to a cooler battery with lower electrochemical efficiency during operation, and losses to the auxiliary load during rest. The average charge power was 311 kW and the average discharge power was 432 kW. The power and SOC vs. time are plotted in Figure 2.6 and detailed results can be found in Table 2.5. The efficiency at the array of 99.7% is unrealistically high, and is likely due to error in the SOC measurement.

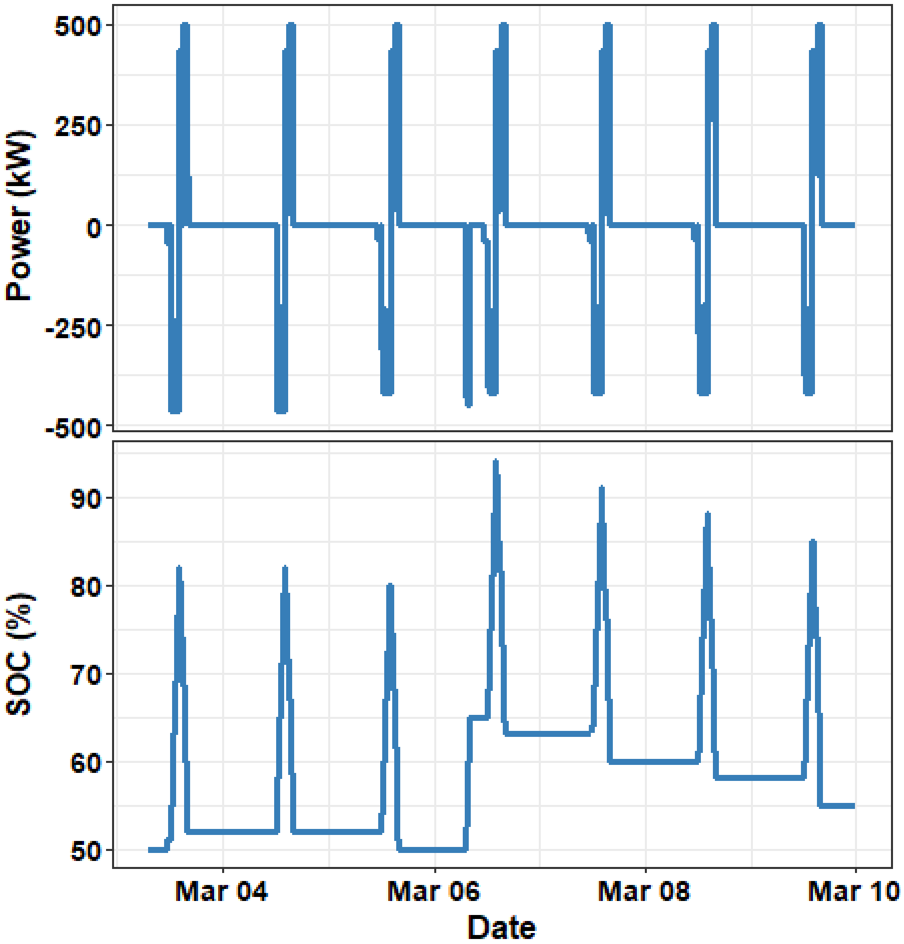

Figure 2.6. Demand charge reduction test.

Table 2.5. Demand Charge Reduction Test Results

Scenario	Cycle 1
Date	2022-03-03
Duration (h)	168
Average Charge Power (kW)	311
Average Discharge Power (kW)	421
Percent Resting (%)	79
SOC Range (%)	50-94
Charge Energy Array (kWh)	6014
Discharge Energy Array (kWh)	5864
Array RTE (%)	99.8
Charge Energy PCS (kWh)	6131
Discharge Energy PCS (kWh)	5804
PCS RTE (%)	96.9
Regressed Array RTE (%)	99.7
Regressed PCS RTE (%)	96.7
Mean Discharge Temperature (°C)	25
Mean Charge Temperature (°C)	24
Mean Temperature (°C)	24

2.5 Use Case 2: Load Shaping

2.5.1 Duty Cycle Summary

The load shaping duty cycle uses the BESS to reduce net load variation associated with the solar output. The BESS provides the benefit of solar integration by managing voltage instability and improving reliability. Increased solar integration expands the amount of green energy the system can safely manage without curbing power from the PV system.

PNNL’s Battery Storage Evaluation Tool (BSET) was used to run a 1-year simulation of energy storage operations at the Decatur Island site. In the control strategy, in each hour, a look-ahead optimization was first formulated and then solved to determine the BESS base operating point. A representative week was used to formulate a duty cycle.

2.5.2 Test Results

This duty cycle again resulted in RTE higher than the capacity tests, with a regressed PCS RTE of 95%. The average charge power was 350 kW and the average discharge power was 365 kW. Because the BESS spent time at a lower SOC in the first couple of days, this may have resulted in a slightly lower RTE as compared to the previous load shaping demand charge reduction duty cycle, offset by the battery’s temperature running slightly warmer. The power and SOC vs. time are plotted in Figure 2.7 and detailed results can be found in Table 2.6.

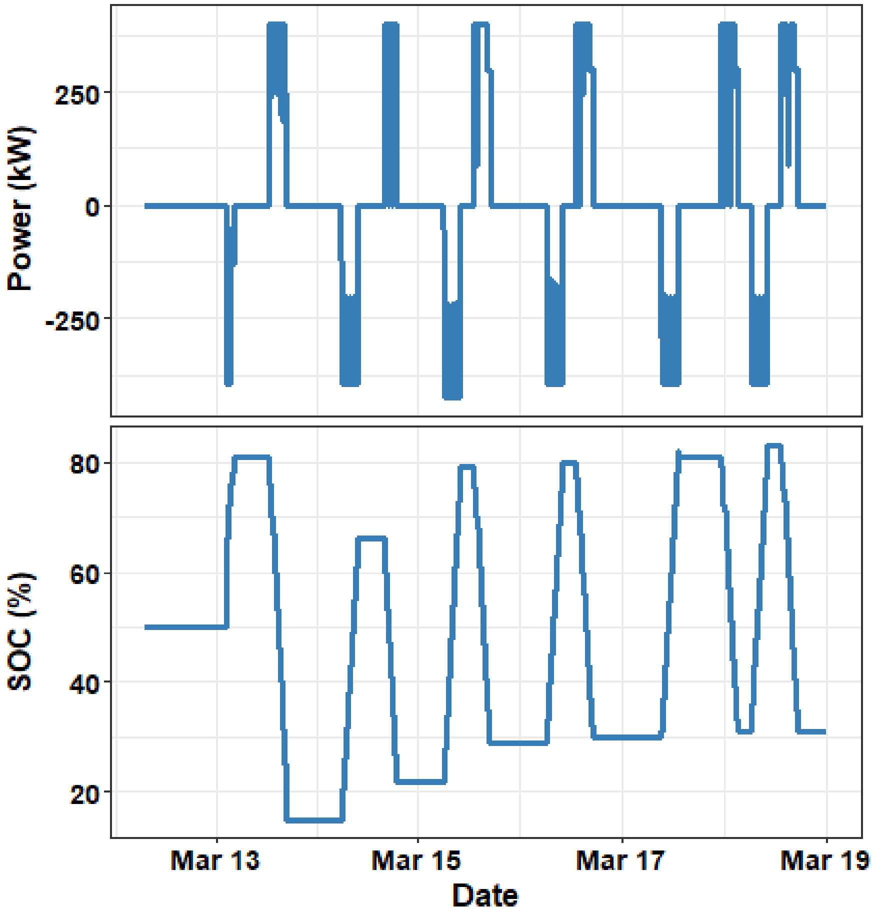

Figure 2.7. Load shaping test.

Table 2.6. Load Shaping Test Results

Scenario	Cycle 1
Date	2022-03-12
Duration (h)	168
Average Charge Power (kW)	350
Average Discharge Power (kW)	365
Percent Resting (%)	70
SOC Range (%)	15-83
Charge Energy Array (kWh)	7727
Discharge Energy Array (kWh)	8076
Array RTE (%)	97.8
Charge Energy PCS (kWh)	7886
Discharge Energy PCS (kWh)	7995
PCS RTE (%)	94.9
Regressed Array RTE (%)	98.3
Regressed PCS RTE (%)	95.4
Mean Discharge Temperature (°C)	26
Mean Charge Temperature (°C)	26
Mean Temperature (°C)	25

2.6 Use Case 3: Outage Mitigation

2.6.1 Duty Cycle Summary

The presence of the BESS will reduce the impacts of transmission outages on Decatur Island residents and will reduce the number of transmission outages more broadly. Further, the energy storage system will provide backup for communications and power to the substation. We modeled historical outages with and without the presence of the BESS to determine the benefits to customers and OPALCO. We used data on electricity interruption costs developed by Lawrence Berkeley National Laboratory to develop interruption cost functions in BSET.

In developing the duty cycles for this use case, we obtained outage data from 2009-2017 on Decatur Island. Based on the historical data, we estimate that customers on Decatur and Center islands face, on average, one unplanned outage per year lasting 152 minutes. Load data was obtained for the calendar days when the outage occurred. The load data for the entire feeder was reduced by 80% to account for the share of the feeder's load that could be islanded. We then assumed that the BESS would meet the load on the island for as long as feasible during an outage.

2.6.2 Test Results

This duty cycle had unusually high efficiency, with a regressed PCS RTE of 97.6% and a regressed RTE at the array of 99.9%. This is unrealistically high and may be due to error in SOC measurement. This duty cycle had lower average power than the capacity tests and the previous two duty cycles, which may explain the very high efficiency. Its temperature was in line with the previous tests. The power and SOC vs. time are plotted in Figure 2.8 and detailed results can be found in Table 2.7.

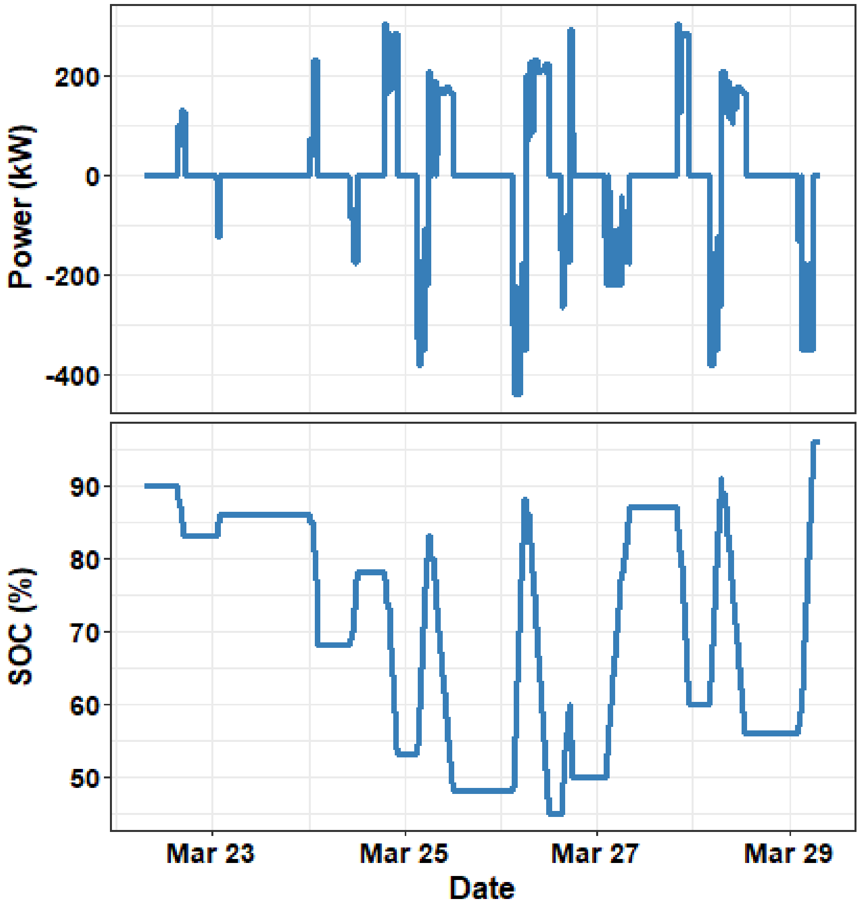

Figure 2.8. Outage mitigation test.

Table 2.7. Outage Mitigation Test Results

Scenario	Cycle 1
Date	2022-03-22
Duration (h)	168
Average Charge Power (kW)	240
Average Discharge Power (kW)	196
Percent Resting (%)	69
SOC Range (%)	45-96
Charge Energy Array (kWh)	5637
Discharge Energy Array (kWh)	5566
Array RTE (%)	99.9
Charge Energy PCS (kWh)	5774
Discharge Energy PCS (kWh)	5529
PCS RTE (%)	98.5
Regressed Array RTE (%)	99.9
Regressed PCS RTE (%)	97.7
Mean Discharge Temperature (°C)	25
Mean Charge Temperature (°C)	26
Mean Temperature (°C)	25

2.7 Use Case 4: Transmission Deferral

2.7.1 Duty Cycle Summary

The BESS was used to reduce peak demand. Reducing sudden spikes in load will reduce cable and substation heating. Submarine transmission cables have a life of 40 years and are expensive, with a capital expenditure of approximately $40 million. A duty cycle was produced using historical load data from Decatur Island to capture the peaks in demand, thus extending the life of the submarine cable.

2.7.2 Test Results

During testing, the duty cycle reported an artificial 0% SOC on the sixth day of testing. This was due to the strings being taken offline during a power outage. This power outage required OPALCO to send an engineer to manually reset the BMS. When this day with the artificial SOC decrease is omitted, the regressed PCS RTE increases to 86%, which still is not in line with the regressed RTE from the capacity tests. When the analysis was completed without this day, none of the metrics significantly changed, suggesting this did not affect the analytics.

This use case had lower efficiency than the capacity tests and the previous duty cycles while not having a meaningfully different temperature or average power. This is likely due to the time it spent cycling at an SOC less than 40%, which is where the efficiency of the system starts rapidly declining (see Section 1.2.3). The power and SOC vs. time are plotted in Figure 2.9 and detailed results can be found in Table 2.8.

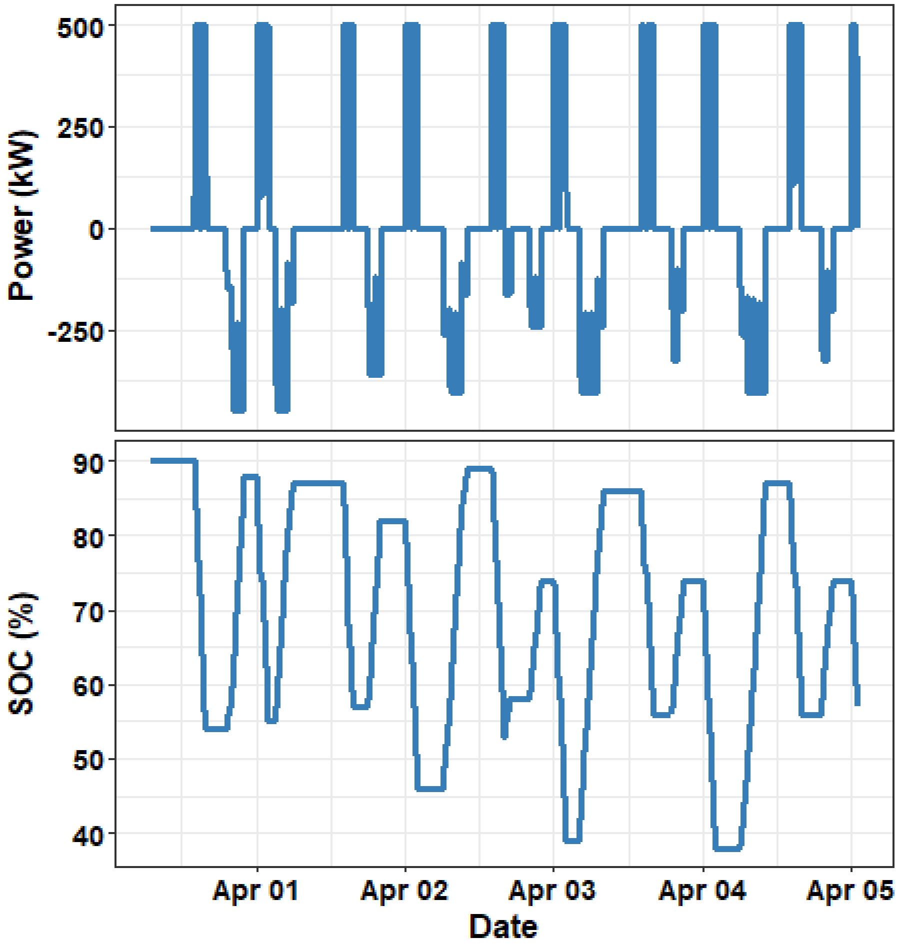

Figure 2.9. Transmission deferral test.

Table 2.8. Transmission Deferral Test Results

Scenario	Cycle 1
Date	2022-03-31
Duration (h)	114
Average Charge Power (kW)	291
Average Discharge Power (kW)	472
Percent Resting (%)	61
SOC Range (%)	38-90
Charge Energy Array (kWh)	7890
Discharge Energy Array (kWh)	8075
Array RTE (%)	91.9
Charge Energy PCS (kWh)	8051
Discharge Energy PCS (kWh)	7992
PCS RTE (%)	89.2
Regressed Array RTE (%)	89.1
Regressed PCS RTE (%)	86.5
Mean Discharge Temperature (°C)	27
Mean Charge Temperature (°C)	27

Scenario	Cycle 1
Mean Temperature (°C)	27

2.8 Duty Cycle Comparison

To compare the duty cycles and the capacity tests in one high-level view, the main results are plotted together in Figure 2.10. The charge energy and discharge energy (at the system level) per 100% SOC are plotted against the absolute average power.

While excluding use case 4 as an outlier (see discussion in Section 2.7.2), there seems to be a weak trend with efficiency at the PCS decreasing with increasing average power. Note, however, that from the charge and discharge energy per SOC, the charge energy decreases with increasing power, but the discharge energy does not have a consistent trend. This implies that the periods of charge are mostly responsible for the decreases in efficiency. As the economic benefits of a BESS mostly depend on the discharge, this could mean that the efficiency is somewhat misleading in terms of the best operating conditions economically. That is, a higher power may decrease the efficiency, but the BESS could still operate in a similar manner during discharge.

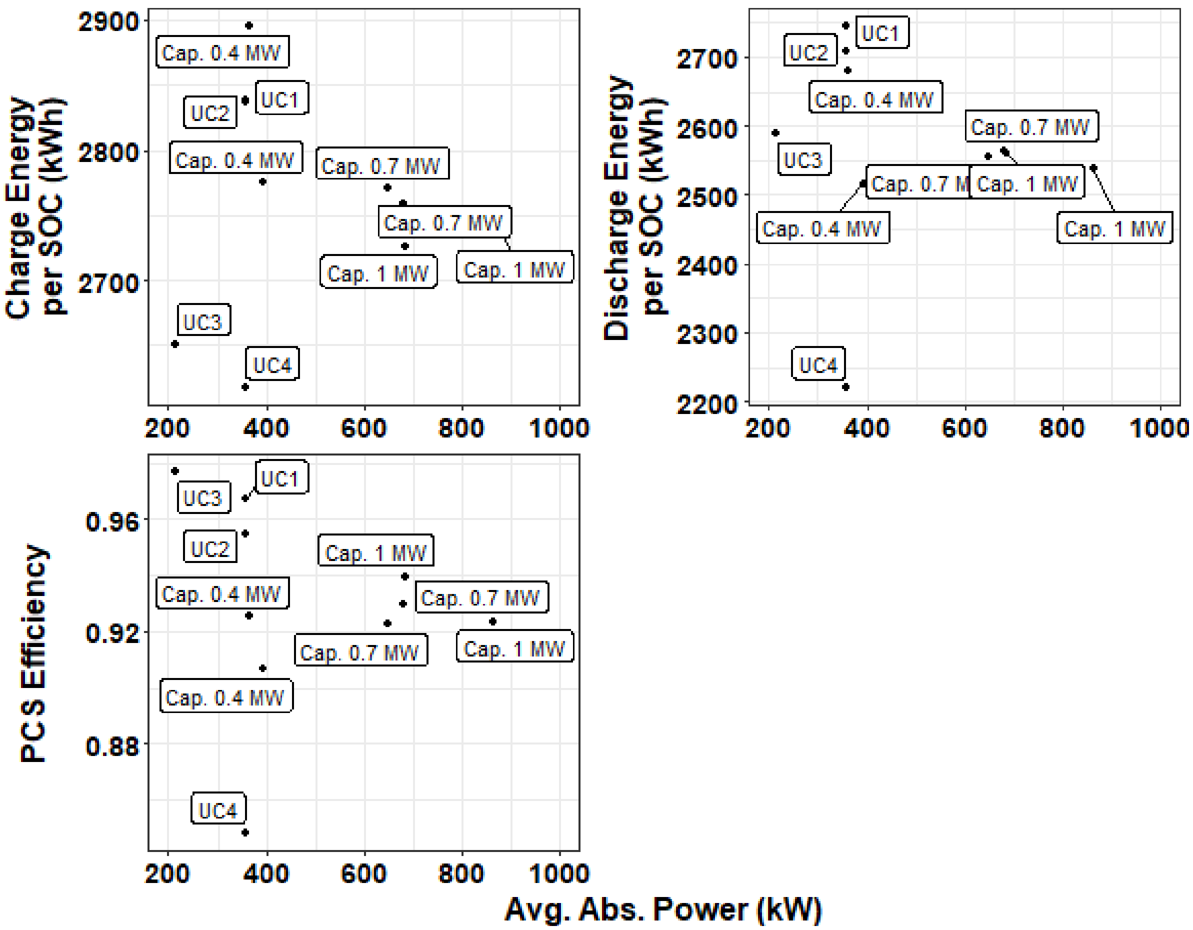

Figure 2.10. Duty cycle comparison vs. average power.

To further explain the differences in the efficiencies, the data is replotted against temperature in Figure 2.11. Here, some trends are more apparent, with the BESS's discharge and charge decreasing with increasing temperature. It is possible that the thermal management system is responsible for the trends in efficiency, with the higher temperatures leading to more power required to cool the system.

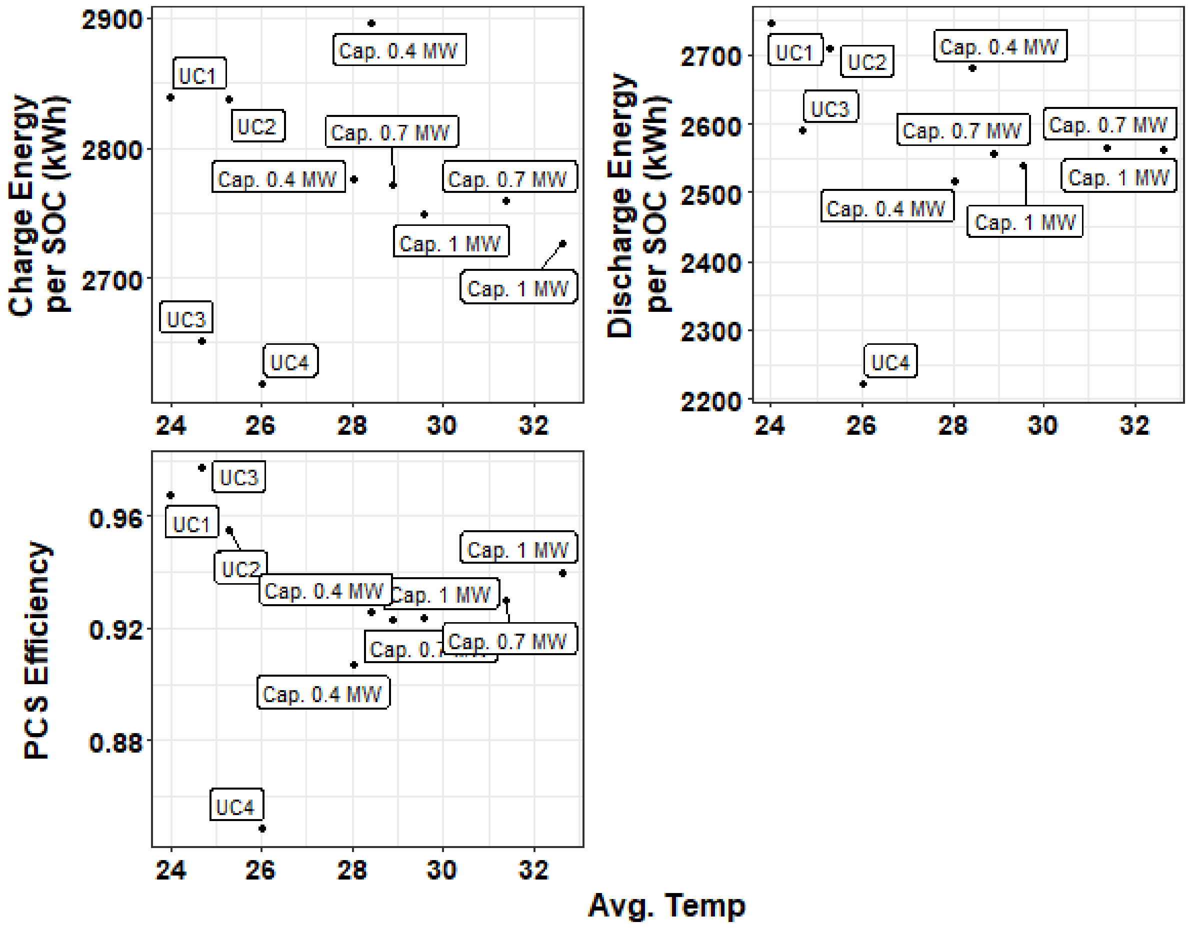

Figure 2.11. Duty cycle comparison vs. average temp.

3.0 Lessons Learned

This section provides an overview of important lessons learned from the testing and performance assessment of the Decatur Island BESS.

3.1 Lessons Learned from Test Results

1. The BESS was able to consistently provide the full nameplate energy of 2 MWh at high RTEs in the 87% to 97% range.

2. The BESS sometimes reports unusually high efficiencies at the DC array level, as high as 99.9%. This is unrealistically high and could be due to small errors in SOC calculation combined with a high efficiency system.

3. The BESS operates at the highest efficiency in the 40% to 90% SOC range.

4. The capacity test efficiency increased with increasing charge and power, which may be due to increasing operating temperature. The use case tests had higher efficiencies at lower temperatures, but this may be due to spending more time at higher SOCs.

5. The BESS's efficiency is affected by its temperature and how much time is spent at low SOC.

6. The BESS does not seem to follow a rapidly changing signal well; however, it was installed for energy-intensive applications, so this may not be an issue. Also, it was hard to judge signal following performance with time resolution of 1 minute, reducing the number of observations we could analyze from 21,600 to 1,440.

7. No tapering of power was observed outside the region of 20% to 74% SOC. Full discharge power could be provided in the entire 20% to 100% SOC range. Full charge power was only observed up to the 74% SOC range. However, this may be due to the charge steps reducing the power, as the priority during these steps was set to SOC (which tapers power) rather than power (which keeps full requested power until the target SOC is reached).

8. Data was available for individual strings, allowing for analysis of variation in stack performance. This analysis does not appear in this report, however.

9. The auxiliary power mostly seems to vary with temperature, increasing at higher temperatures, presumably to cool the system.

3.2 Lessons Learned in Design of Data Transfer

1. No programmatic method for obtaining data was available. Each individual day of data had to be downloaded separately after logging into the site. PNNL wrote a Selenium script to scrape the data from the site.

2. Options for a time resolution finer than 60 seconds would have allowed for better analysis of the tests with a rapidly changing signal, such as the pulse tests and frequency regulation tests.

3. Testing was paused for a few months as an option was not available to upload a power signal. Due to a large number of steps, manual entry was impractical. Support from Powin allowed PNNL to upload CSV files to containing power signals for the duty cycles, and the 22k step frequency regulation test was run by remoting in to the BMS and running a Python script to control the BESS.

4. The SOC had a resolution of 1%. Although for such big data sets it is important to round numbers to save hard disk space, the SOC is a vital part of analyzing BESS performance, and increased resolution would have allowed for greater accuracy. This BESS has very high efficiency, so accurately knowing the SOC at the start and end of the test is vital for quantifying accurately the charge and discharge energy corresponding to the operating SOC range. We recommend a resolution of 0.01% if possible. As SOC is not directly measured and is calculated from voltage and current, avoiding rounding error can be important.

5. Auxiliary meter was not available separately – this would have been useful for analytics. The auxiliary loss trend was deduced by the difference between the power at the PCS and the power at the BESS, but this added some noise to the analysis.

3.3 Lessons Learned in Design of Test Setup

1. A recharger app was enabled for the baseline performance tests, which started automatically recharging the BESS at SOC less than 50%. This complicated analysis of the test results, as the BESS started recharging when it was not expected. This was not discovered until the first round of use case tests and took some time to troubleshoot. We will check for these sorts of apps in the future to ensure tests are not affected.

3.4 Lessons Learned from Site-Related Issues

1. A recharger app was enabled for the baseline performance tests, which started automatically recharging the BESS at low SOCs. This complicated analysis of the tests, as the BESS started recharging when it was not expected. This was not discovered until the first use case began and took some time to troubleshoot.

2. A power outage caused the BESS to fault and go offline on 2022-04-05, requiring a manual reset. This resulted in reporting artificial SOC of 0%. The manual reset affects the data received.

3. Human-machine interface resets required manual trips to Decatur Island to reset the PC.

4.0 Novel Findings

4.1 Performance Model

Over the course of testing, a predictive model was developed to help predict how the SOC changed as a function of power and SOC. This predictive modeling was vital for adjusting the duty cycles as we obtained more data on the BESS.

This model is made by regressing the rate of SOC change against the SOC, the power, and various combinations thereof. The data points used in the regression are weighed by the SOC change of each charge or discharge cycle. To avoid overfitting, the elasticnet algorithm is used, with the regularization parameters used to minimize predictive error. To validate and estimate out-of-sample predictive error, the data was split into test and train sets, with one split for each cycle (each cycle was used once as a test set, with the train set composed of all previous cycles).

The resulting formula for the rate of SOC change is given as follows:

$$\frac{dSOC}{dt} = (3.50e - 4\ kW^{-1}h^{-1})P_{chg} + (-3.54e - 4\ kW^{-1}h^{-1})P_{dis} + (-1.13e - 5kW^{-1}h^{-1})P\ SOC + (-4.72e - 6\ kW^{-1}h^{-1})\frac{P}{SOC}$$

This model can be used to consistently predict the BESS’s performance for duty cycles. The predicted rate of change of SOC is plotted in Figure 4.1 as a function of power and SOC.

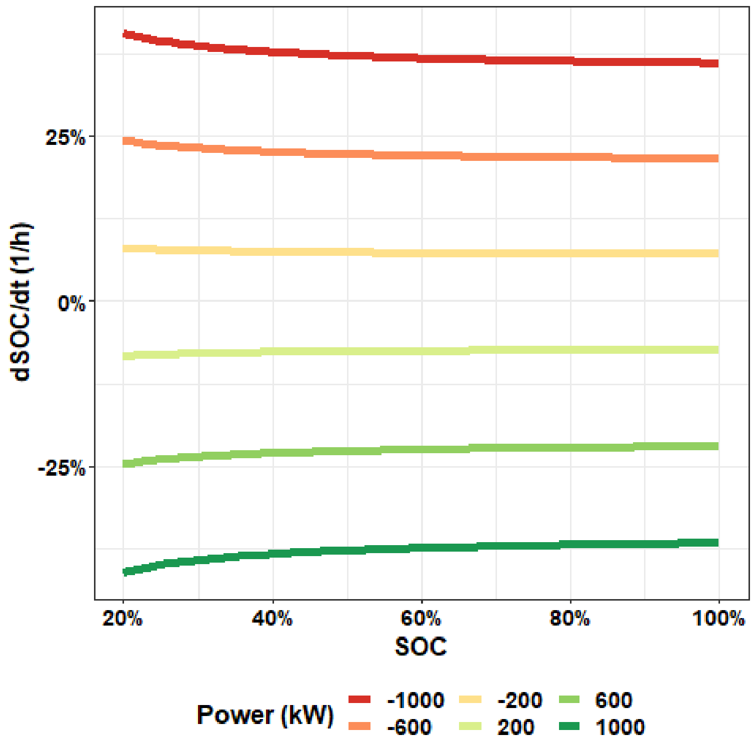

Figure 4.1. BESS performance model.

Figure 4.2 shows the cumulative out-of-sample performance error of the model. Each cycle's SOC is predicted using data from the previous cycles, so this shows the true predictive capability of the model. The cumulative error decreases over time as the model learns from more data. At the end of testing, the error flatlines, indicating that this model will only marginally improve with further data. However, more data may be useful for showing how the performance degrades over time. It took approximately 80 days of testing to go from the initial out-of-sample RMSE of 5% to a consistent RMSE of 0.7%.

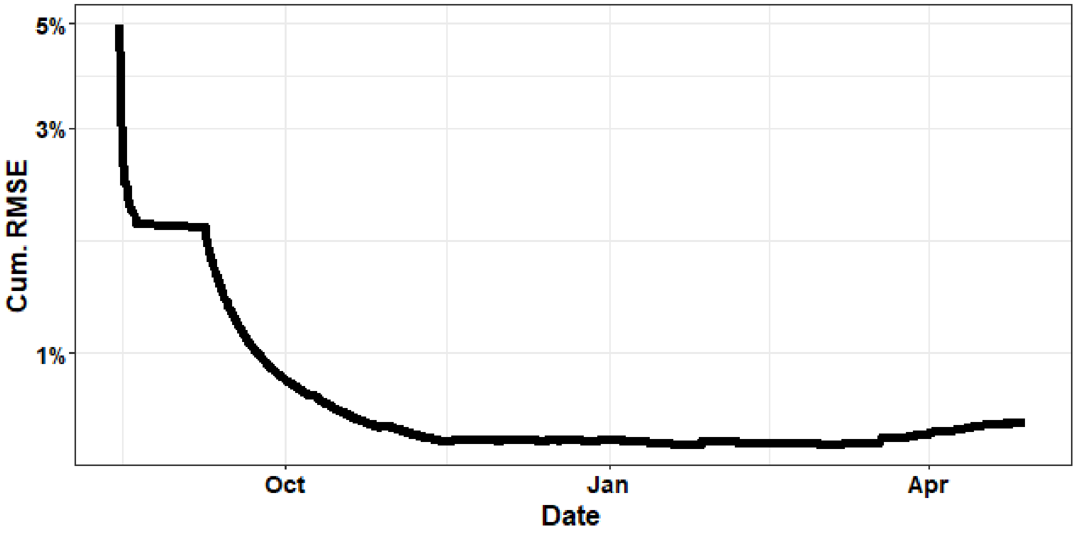

Figure 4.2. BESS performance model performance over time.

4.2 Temperature Model

To calculate the effect of power on the rate of temperature change, the rate was regressed against a second degree polynomial of power. The reason for this is we can reasonably assume the reversible heat loss from operating a battery is proportional to the power and the irreversible heat is proportional to the square of the power, with power serving as a proxy for current. The result is that the irreversible heat term seems to dominate, with the battery temperature increasing during charge and discharge. The battery heats up slightly faster during charge, implying that the charge reaction is exothermic and the discharge reaction is endothermic. A similar trend was observed when performing the same analysis on a previous utility's LFP battery, along with similar magnitudes of temperature change (Crawford 2019). The temperature model is given in Figure 4.3.

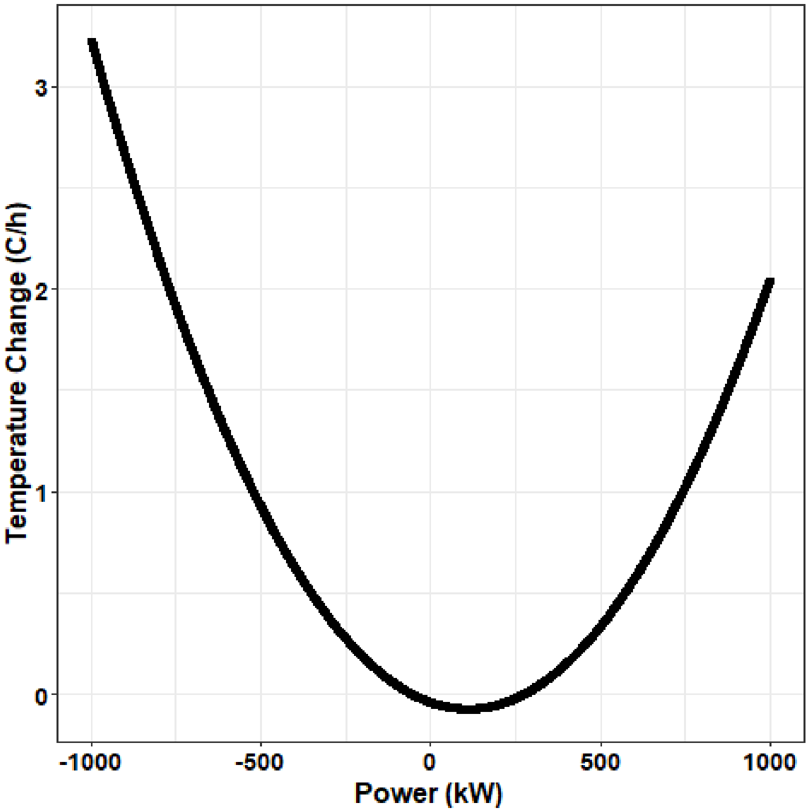

Figure 4.3. BESS thermal model.

5.0 Conclusions

This report documents the testing results and performance assessment of the Decatur Island BESS through actual field operations. RPTs were performed to collect data to assess the general technical capability of the BESS, including the stored energy capacity, ramp rate performance, ability to track variable charge/discharge commands, and DC battery internal resistance. Use case tests were performed to examine the performance of the BESS engaged in a specific use case. The analyses of the BESS tested performance confirm that the technical characteristics (e.g., capacity) and performance (e.g., response rate) of the Decatur Island BESS are generally compatible with the range of use cases investigated earlier in this project.

The findings presented in this report will help OPALCO understand the performance of the BESS in its current state and design appropriate operational strategies for this and other BESSs over the long term. The results and lessons presented herein would also be beneficial in general for any task or effort that needs technical assessment on similar types of BESSs based on field deployment results.

Specific conclusions include the following:

1. Of the system rated energy of 2000 kWh, the equivalent of 1990 kWh was discharged during the capacity tests using the 20% to 95% SOC range.
2. The estimated energy content corresponding to ΔSOC of 100% is 2650 kWh of discharge capacity.
3. In general, increasing the BESS’s power decreased its efficiency by decreasing both available discharge energy and the subsequent charge energy.
4. The BESS’s efficiency varied a lot with SOC, with the highest efficiencies observed in the 40% to 90% SOC range.
5. For energy-intensive applications, the BESS RTE was consistently within the range of 89% to 97%.
6. Due to the BESS’s high efficiency, the SOC resolution of 1% presented challenges and introduced errors in estimating the RTE.
7. The loss of PCS conversion ranged from 23 kW at for charge at rated power to 17 kW for discharge at rated power.
8. The auxiliary power was not directly available, but was estimated using the temperature dependent difference between power measured at the PCS and at the array. The estimated auxiliary power depends on battery temperature, increasing from 4 kW at 20°C to 11 kW at 35°C, presumably due to active cooling.
9. In standby mode, the BESS’s SOC decreased by 0.03% (about 0.8 kWh) per hour.
10. The calculated DC cell resistance was 1.0 mΩ, with no noticeable difference between baseline and post cycle resistance. This is a significant underestimation of actual

resistance, since the ΔV is expected to be << the actual delta V at the end of pulse, due to voltage relaxing to the value just prior to the start of pulse.

11. With the 1-minute measurement data, the exact BESS response time and rate cannot be quantified. However, the response time was < 1 min, corresponding to a ramp rate of > 1 MW/min.

12. No degradation in state of health was observed during testing, with the capacity tests showing no decline in performance.

13. The signal tracking performance was poor, with an RMSE of 81 kW, or 8% of the rated power. This was attributed to signal being applied at the PCS level, while the response was gathered at the BESS level.

6.0 References

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Appendix A – Additional Battery Design and Performance Information

A.1 Duty Cycles

These duty cycles are slightly different from what was provided in the test plan. This is because over the course of testing, the duty cycles were updated to account for the observed battery energy storage system performance. Duty cycles were modified to keep the state of charge within acceptable bounds.

Table A.1. Duty cycle time series for demand charge, load shaping, outage mitigation, and transmission deferral

	Power Signal (kW)			
Hour	Demand Charge	Load Shaping	Outage Mitigation	Transmission Deferral
1	0	0	0	0
2	0	0	0	0
3	0	0	0	0
4	-45	0	0	0
5	-464	0	0	0
6	-464	0	0	0
7	433	0	0	0
8	500	0	0	500
9	0	0	99	500
10	0	0	127	0
11	0	0	0	0
12	0	0	0	0
13	0	0	0	-146
14	0	0	0	-450
15	0	0	0	-450
16	0	0	0	0
17	0	0	0	0
18	0	0	0	500
19	0	-394	-125	500
20	0	-394	0	0
21	0	-128	0	-450
22	0	0	0	-450
23	0	0	0	-180
24	0	0	0	0
25	0	0	0	0
26	0	0	0	0
27	0	0	0	0
28	-45	0	0	0
29	-464	400	0	0
30	-464	400	0	0

	Power Signal (kW)			
Hour	Demand Charge	Load Shaping	Outage Mitigation	Transmission Deferral
31	433	400	0	0
32	500	400	0	500
33	0	0	0	500
34	0	0	0	0
35	0	0	0	0
36	0	0	0	-360
37	0	0	0	-360
38	0	0	0	0
39	0	0	0	0
40	0	0	0	0
41	0	0	0	0
42	0	0	69	500
43	0	0	229	500
44	0	0	0	0
45	0	0	0	0
46	0	-394	0	0
47	0	-394	0	0
48	0	-394	0	-264
49	0	-394	0	-405
50	0	0	0	-405
51	0	0	0	-162
52	-41	0	-86	0
53	-417	0	-176	0
54	-417	0	0	0
55	433	400	0	56
56	500	400	0	500
57	0	400	0	500
58	0	400	0	-162
59	0	0	0	0
60	0	0	0	0
61	0	0	304	0
62	0	0	281	-243
63	0	0	284	-243
64	0	0	0	0
65	0	0	0	0
66	0	0	0	500
67	0	0	0	500
68	0	0	0	0
69	0	0	-382	0
70	0	-425	-353	-405
71	0	-425	-220	-405
72	-450	-425	208	-405
73	0	-425	187	-243

Hour	Power Signal (kW)			
	Demand Charge	Load Shaping	Outage Mitigation	Transmission Deferral
74	0	0	171	0
75	0	0	165	0
76	-41	0	175	0
77	-417	400	166	0
78	-417	400	0	0
79	433	400	0	0
80	500	300	0	500
81	0	0	0	500
82	0	0	0	0
83	0	0	0	0
84	0	0	0	0
85	0	0	0	-324
86	0	0	0	-202
87	0	0	0	0
88	0	0	0	0
89	0	0	0	0
90	0	0	0	500
91	0	0	0	500
92	0	0	0	0
93	0	0	-440	0
94	0	-394	-440	0
95	0	-394	-352	0
96	0	-394	197	-264
97	0	-394	226	-405
98	0	0	229	-405
99	0	0	209	-405
100	-41	0	210	0
101	-417	400	220	0
102	-417	400	0	0
103	433	400	0	0
104	500	300	0	500
105	0	0	-264	500
106	0	0	-176	0
107	0	0	290	0
108	0	0	0	0
109	0	0	0	-324
110	0	0	0	-202
111	0	0	0	0
112	0	0	0	0
113	0	0	0	0
114	0	0	0	500
115	0	0	0	500
116	0	0	-220	0

Hour	Power Signal (kW)			
	Demand Charge	Load Shaping	Outage Mitigation	Transmission Deferral
117	0	0	-220	0
118	0	0	-220	0
119	0	0	-220	0
120	0	0	-88	-264
121	0	-394	-176	-405
122	0	-394	0	-405
123	0	-394	0	-405
124	-41	-394	0	-81
125	-417	0	0	0
126	-417	0	0	0
127	433	0	0	0
128	500	0	0	500
129	0	0	0	500
130	0	0	0	0
131	0	0	0	0
132	0	0	0	0
133	0	0	0	-202
134	0	0	304	-202
135	0	400	281	0
136	0	400	284	0
137	0	400	0	0
138	0	300	0	500
139	0	0	0	500
140	0	0	0	0
141	0	0	0	0
142	0	-394	-382	0
143	0	-394	-353	0
144	0	-394	-264	-264
145	0	-394	208	-405
146	0	0	187	-405
147	0	0	171	-405
148	-41	0	165	-122
149	-417	400	175	0
150	-417	400	166	0
151	433	400	0	0
152	500	300	0	500
153	0	0	0	500
154	0	0	0	0
155	0	0	0	0
156	0	0	0	0
157	0	0	0	-202
158	0	0	0	-202
159	0	0	0	0

	Power Signal (kW)			
Hour	Demand Charge	Load Shaping	Outage Mitigation	Transmission Deferral
160	0	0	0	0
161	0	0	0	0
162	0	0	0	500
163	0	0	0	500
164	0	0	-132	0
165	0	0	-352	0
166	0	-394	-352	0
167	0	-394	-352	0
168	0	0	0	0
93	0	0	-440	0
94	0	-394	-440	0
95	0	-394	-352	0
96	0	-394	197	-264
97	0	-394	226	-405
98	0	0	229	-405
99	0	0	209	-405
100	-41	0	210	0
101	-417	400	220	0
102	-417	400	0	0
103	433	400	0	0
104	500	300	0	500
105	0	0	-264	500
106	0	0	-176	0
107	0	0	290	0
108	0	0	0	0
109	0	0	0	-324
110	0	0	0	-202
111	0	0	0	0
112	0	0	0	0
113	0	0	0	0
114	0	0	0	500
115	0	0	0	500
116	0	0	-220	0
117	0	0	-220	0
118	0	0	-220	0
119	0	0	-220	0
120	0	0	-88	-264
121	0	-394	-176	-405
122	0	-394	0	-405
123	0	-394	0	-405
124	-41	-394	0	-81
125	-417	0	0	0

	Power Signal (kW)			
Hour	Demand Charge	Load Shaping	Outage Mitigation	Transmission Deferral
126	-417	0	0	0
127	433	0	0	0
128	500	0	0	500
129	0	0	0	500
130	0	0	0	0
131	0	0	0	0
132	0	0	0	0
133	0	0	0	-202
134	0	0	304	-202
135	0	400	281	0
136	0	400	284	0
137	0	400	0	0
138	0	300	0	500
139	0	0	0	500
140	0	0	0	0
141	0	0	0	0
142	0	-394	-382	0
143	0	-394	-353	0
144	0	-394	-264	-264
145	0	-394	208	-405
146	0	0	187	-405
147	0	0	171	-405
148	-41	0	165	-122
149	-417	400	175	0
150	-417	400	166	0
151	433	400	0	0
152	500	300	0	500
153	0	0	0	500
154	0	0	0	0
155	0	0	0	0
156	0	0	0	0
157	0	0	0	-202
158	0	0	0	-202
159	0	0	0	0
160	0	0	0	0
161	0	0	0	0
162	0	0	0	500
163	0	0	0	500
164	0	0	-132	0
165	0	0	-352	0
166	0	-394	-352	0
167	0	-394	-352	0
168	0	0	0	0

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