Federal Energy Management Program

Battery Energy Storage System Evaluation Method

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Disclaimer

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Acknowledgments

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List of Symbols and Acronyms

η	Efficiency
A	Availability; (total time – downtime)/total time
ANSI	American National Standards Institute
BESS	battery energy storage system
CR	Capacity Ratio; "Demonstrated Capacity"/"Rated Capacity"
DC	direct current
DOE	Department of Energy
E	Energy, expressed in units of kWh
FEMP	Federal Energy Management Program
IEC	International Electrotechnical Commission
KPI	key performance indicator
NREL	National Renewable Energy Laboratory
O&M	operations and maintenance
P	Power, instantaneous power, expressed in units of kW
PV	photovoltaic
SAM	System Advisor Model

Executive Summary

This report describes development of an effort to assess Battery Energy Storage System (BESS) performance that the U.S. Department of Energy (DOE) Federal Energy Management Program (FEMP) and others can employ to evaluate performance of deployed BESS or solar photovoltaic (PV) +BESS systems. The proposed method is based on actual battery charge and discharge metered data to be collected from BESS systems provided by federal agencies participating in the FEMP's performance assessment initiatives. Long-term (e.g., at least one year) time series (e.g., hourly) charge and discharge data are analyzed to provide approximate estimates of key performance indicators (KPIs).

FEMP has provided an evaluation of the performance of deployed photovoltaic (PV) systems for over 75 Federal PV systems and compiled statistics regarding KPIs of PV system performance in the publication "Understanding Solar Photovoltaic System Performance: An Assessment of 75 Federal Photovoltaic Systems" https://www.nrel.gov/docs/fy22osti/80881.pdf. In that assessment, Performance Ratio and Availability were calculated using an hour-by-hour (or other time interval provided in the data such as 15-minute) comparison of metered PV system production data to an estimate of expected production developed using a PV system description and co-incident weather data in a computer model of the PV system. An hour-by-hour comparison does not provide reasonable results for systems including BESS, because the model estimate in any hour is not independent from the previous hours.

For battery systems, Efficiency and Demonstrated Capacity are the KPIs that can be determined from the meter data. Efficiency is the sum of energy discharged from the battery divided by sum of energy charged into the battery (i.e., kWh in/kWh out). This must be summed over a time duration of many cycles so that initial and final states of charge become less important in the calculation of the value. Efficiency can vary with temperature and charge rates, but as an approximation we use the single value for average efficiency calculated in the first step above in an estimate of battery capacity. Energy charged into the battery is added, while energy discharged from the battery is subtracted, to keep a running tally of energy accumulated in the battery, with both adjusted by the single value of measured Efficiency. The maximum amount of energy accumulated in the battery within the analysis period is the Demonstrated Capacity (kWh or MWh of storage exercised). In order to normalize and interpret results, Efficiency can be compared to rated efficiency and Demonstrated Capacity can be divided by rated capacity for a normalized Capacity Ratio.

The following steps are proposed for an assessment. For PV-only systems only step 1 applies; for BESS-only systems steps 2 and 3 apply; and for PV+BESS systems all three steps would apply.

1. Evaluate Performance Ratio and Availability of the PV array using the previously established methods of [Walker and Desai, 2022]
2. Evaluate Efficiency and Demonstrated Capacity of the BESS sub-system using the new method of this report.

3. Compare actual realized Utility Energy Consumption (kWh/year) and Cost ($/year) with Utility Consumption and Cost as estimated using NREL's REopt or System Advisor Model (SAM) computer programs.

FEMP is collaborating with federal agencies to identify pilot projects to test out the method.

The measured performance metrics presented here are useful in two respects:

1. Future feasibility studies will be better informed regarding realistic expectations of performance.
2. Owners of existing systems may compare KPIs measured in this assessment to benchmark values to identify the need for corrective action.

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1 Introduction

Federal agencies have significant experience operating batteries in off-grid locations to power remote loads. However, there are new developments which offer to greatly expand the use of batteries in both on-grid and off-grid applications, either alone or in combination with renewable energy such as PV:

1. New battery technologies have performance advantages which enable batteries to be practical and cost-effective in expanding applications (such as lithium ion compared to lead-acid)
2. PV systems are increasing in size and the fraction of the load that they carry, often in response to federal requirements and goals set by legislation and Executive Order (EO 14057).
    a. High penetration of PV challenges integration into the utility grid; batteries could alleviate this challenge by storing PV energy in excess of instantaneous load.
    b. Many utilities are discontinuing "net metering" policies and assigning much lower value to PV energy exported to the grid. Batteries allow the PV energy to be stored and discharged at a later time to displace a higher retail rate for electricity.
3. Utilities are increasingly making use of rate schedules which shift cost from energy consumption to demand and fixed charges, time-of-use and seasonal rates. Batteries are increasingly being used to reduce utility costs by:
    a. Peak shaving: discharging a battery to reduce the instantaneous peak demand .
    b. Load shifting: discharging a battery at a time of day when the utility rate is high and then charging battery during off-peak times when the rate is lower.
    c. Providing other services: source reactive power (kVAR), thus reducing Power Factor charges on a utility bill.
4. Resilience: batteries are used to provide continuous back-up power to critical loads such as network equipment.

FEMP seeks to help ensure that Federal agencies realize the cost savings and environmental benefits of battery or PV+BESS systems by providing an affordable and quick way to assess performance of these systems.

2 Background

Previously, FEMP developed an approach to evaluate the performance of solar photovoltaic (PV) systems at federal sites. The methodology was used to evaluate the performance of 75 federal PV systems and compile statistics regarding KPIs of PV system performance. A description of the methodology and results is provided in "Understanding Solar Photovoltaic System Performance: An Assessment of 75 Federal Photovoltaic Systems" www.nrel.gov/docs/fy22osti/80881.pdf. That method compared actual metered PV system energy delivery with that of a computer model. The computer model used was the National Renewable Energy Laboratory's (NREL's) System Advisor Model (SAM). The KPIs reported are Availability (% up-time) and Performance Ratio (PR). If the PV system output was zero or less than 5% of the model estimate, then the time interval was counted as "unavailable." For hours when the PV system was "available," the measured energy delivery was divided by a reference yield to calculate PR.

SAM was used to calculate the reference yield in the denominator of the PR because this is the most detailed, non-proprietary, and widely recognized performance assessment software (NREL 2021). For each hour of the analysis period, the reference yield was calculated based on the PV system description (number and type of PV modules, inverters, etc) and co-incident weather data as provided by a weather data service (for example nsrdb.nrel.gov).

For PV systems, this method provides a reliable estimate of Availability and Performance Ratio because the calculation in one hour is independent of the next hour. However, with BESS any error in the charge and discharge of the battery tends to accumulate so in terms of hour-by-hour time series data, the model of a BESS or PV+BESS system status quickly deviates from the measurements, and an hour-by-hour comparison of model to measured values is not meaningful. Because an hourly comparison cannot be made, Availability cannot be calculated as it can be for a PV system.

Thus, this new method is developed to assess KPIs for BESS and PV+BESS systems.

3 Methodology

The methodology is illustrated in Figure 1. For each BESS system, an agency would provide the record of time-series metered energy into and out of the battery for an analysis period. This data would be analyzed to calculate KPIs Efficiency and Demonstrated Capacity. The calculated Efficiency and Demonstrated Capacity are compared to rated values for the BESS as described in product literature and specifications. A report with the BESS system description, a photograph of the BESS, special assumptions made for the site, a graph of measured charge and discharge data, a table of KPIs with comparison to specifications, and links to battery O&M resources that might improve performance would be delivered to site and agency staff in an online briefing.

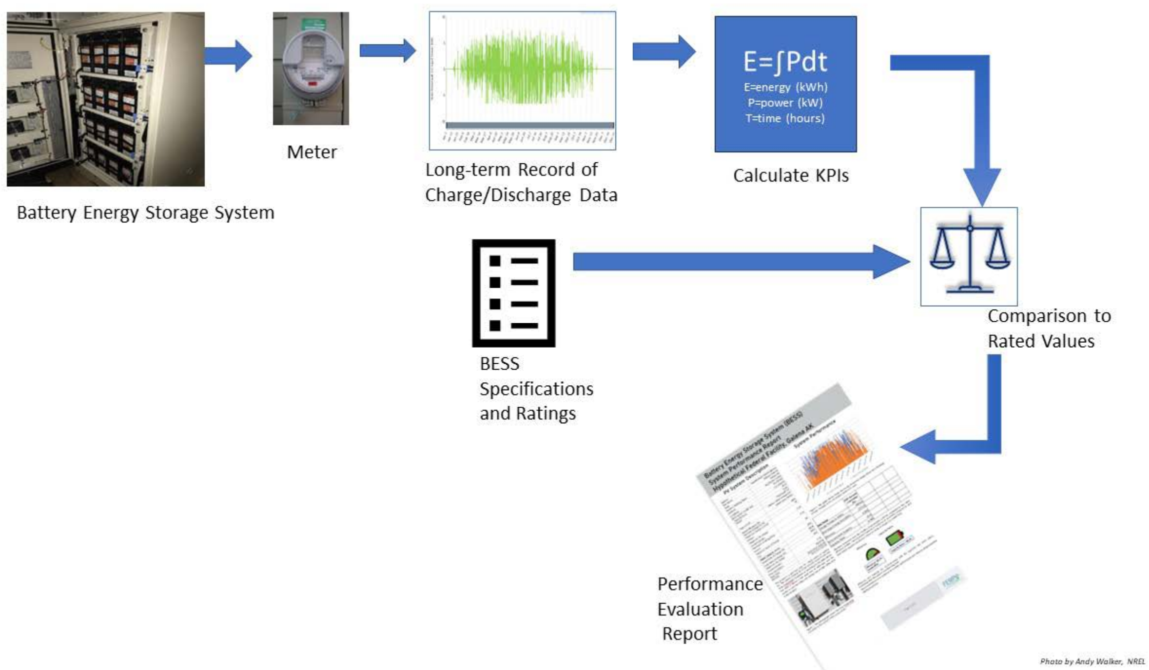

Figure 1. Methodology of the performance assessment to calculate key performance indicators from measured charge/discharge data and compare to battery specifications in a performance evaluation report

3.1 Data Collection

Data collected to perform each evaluation include a BESS system description, a record of meter data recording energy charge into and discharge out of the battery, and a photograph of the BESS system.

3.1.1 BESS System Description

A "BESS system description" is requested from each agency or subagency with information about each BESS system to provide a context of the system being evaluated and to provide benchmark values of efficiency and capacity to compare with the KPIs derived from the meter data.

BESS System Description includes:

- Agency and Facility Location (longitude and latitude), Agency Contact Information
- BESS System Manufacturer and Model Number
    - For each type of BESS unit (cell)
        - Type of cell
            - Lead Acid ($PbSO_4$)
            - Lithium iron phosphate (LFP)
            - Lithium nickel manganese cobalt oxide (NMC)
            - Lithium nickel cobalt aluminum oxide (NCA)
            - Lithium manganese oxide (LMO)
            - Lithium titanate (LTO)
        - Nominal Rated Capacity (kWh)
        - Rated Efficiency (%)
        - Nominal Voltage (V DC)
        - Maximum Charge Current (Amps)
        - Maximum Dis-charge Current (Amps)
        - Nominal A-h rating (Amp-hours)
        - Minimum State of Charge (%)
        - Initial State of Charge (%)
        - Final State of Charge (%)
- Photo of BESS System for inclusion in the report.

A photo of the BESS system is included in the report for context regarding the size and type of battery system under assessment.

3.1.2 Record of Charge and Discharge Data from BESS Meter.

In order to be assessed, the BESS system must be equipped with a meter measuring charge into the battery and a meter measuring discharge out of the battery, or a single meter that can record both.

- **Time-step duration:** If the BESS has a single meter to measure power in and out of the battery, then the time-step of the time series data must be short enough that battery "throughput" within the time-step (eg 1 hour) is minimal.

- **Analysis Period duration:** In order to render a calculation of battery round-trip efficiency and capacity of the battery from the charge/discharge data, at least one full charge/discharge cycle has to be included in the data set. A large number of complete charge/discharge cycles increases confidence in the result. Often a battery is charged whenever resources are available and discharged whenever load occurs without going through a complete charge/discharge cycle, so a long analysis period (e.g., 1 year) may be needed to capture when the battery is completely discharged (to minimum set point) and completely charged. As the initial state of charge and final state of charge of the battery are only approximately known, a long analysis period is needed to ensure that the initial and final energy content of the battery is small compared to the energy throughput of the battery over the analysis period.

Table 1. Example of BESS Charge and Discharge Data from Meter Record

Time	Battery Charge (kWh/h)	Battery Discharge (kWh/h)
7/6/2007 0:00	0	0.4788054
7/6/2007 1:00	0	0.476797
7/6/2007 2:00	0	0.4465869
7/6/2007 3:00	0	0.4303003
7/6/2007 4:00	0	0.2882934
7/6/2007 5:00	0	0.00195446
7/6/2007 6:00	0.7941279	0
7/6/2007 7:00	0.7950433	0
7/6/2007 8:00	0	5.515742
7/6/2007 9:00	0	3.269166
7/6/2007 10:00	3.685425	0
7/6/2007 11:00	7.415745	0
7/6/2007 12:00	0.09240728	0
7/6/2007 13:00	0	0
7/6/2007 14:00	0	0
7/6/2007 15:00	0	0
7/6/2007 16:00	0	0
7/6/2007 17:00	0	0
7/6/2007 18:00	0	0

Time	Battery Charge (kWh/h)	Battery Discharge (kWh/h)
7/6/2007 19:00	0	0
7/6/2007 20:00	0	0
7/6/2007 21:00	0	0
7/6/2007 22:00	0	0.1361371
7/6/2007 23:00	0	0.400444

Table 1 lists one day (July 6) of example battery discharge and charge rates (kWh/h, or average kW) for each timestep. Modeled data for a 1-year analysis period is shown in Figure 2.

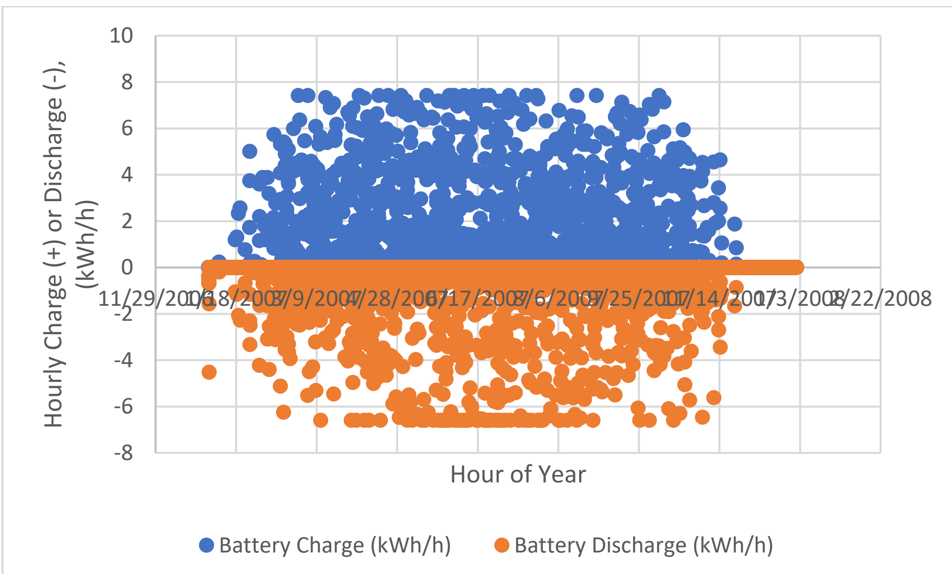

Figure 2. Charge (+) and discharge (-) data for each hour of a 1-year analysis period

3.2 Data Analysis

Data analysis seeks to evaluate uniform KPIs. In the case of BESS system potential KPIs include Availability, Efficiency, and Capacity. It is not possible to ascertain a value for Availability based on meter data alone because there are often hours with zero battery throughput even if the battery is operational. In order to evaluate Availability, additional information regarding the dispatch commands and the battery's response would be required. As a result, this analysis is focused on Efficiency and Demonstrated Capacity (Figure 3).

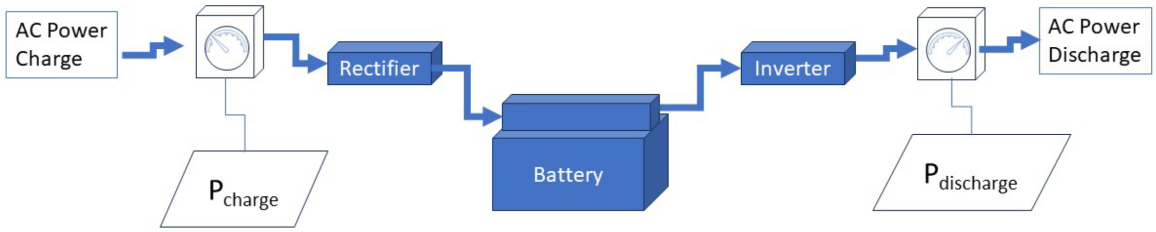

Figure 3. Battery energy storage system with terms identified in calculation of efficiency and demonstrated capacity

3.2.1 Data Analysis: Efficiency

Efficiency over any time period is defined as the energy discharged by the battery divided by the energy charged into the battery. This is a straightforward calculation if the battery is exercised in cycles that fully charge and then fully discharge the battery, but many applications involve charging and discharging that depends on random variations in solar resource and in load. As a result, a lengthy analysis period, T, may be required to capture several (or at least one) full charge-discharge cycle. An analysis period of one year is almost certainly sufficient, depending on how the battery is being used. Efficiency is calculated according to the following equation.

$$\eta = \frac{\int_{t=0}^{t=T} P_{discharge} dt}{\int_{t=0}^{t=T} P_{charge} \, dt} \; (equation\ 1)$$

The integrals of equation 1 are evaluated numerically, with a dt equal to the time-step of the time-series charging and discharging measurements from the meter. Within each time-step, P is the Power (kW or MW) charging or discharging from the battery which should be recorded separately to recognize that there could be both charging and discharging within a time-step.

3.2.2 Data Analysis: Capacity Ratio

The energy storage capacity, E, is calculated using the efficiency calculated above to represent energy losses in the BESS itself. This is an approximation since actual battery efficiency will depend on operating parameters such as charge/discharge rate (Amps) and temperature. Round trip efficiency determined in the previous step is partitioned equally between the charging and discharging steps, which is another approximation. Demonstrated Capacity is calculated using equation 2:

$$E_{demonstrated} = \int_{t=0}^{t=T} (P_{charge} * \sqrt{\eta} - P_{discharge}/\sqrt{\eta}\,)\, dt \; (equation\ 2)$$

The Demonstrated Capacity, $E_{demonstrated}$, of the battery is the largest amount of energy stored in the battery within the Analysis Period. This indicates the health of the battery and reflects the "Minimum State of Charge" (SOC_{min}) set in the battery controller as a reduction in Demonstrated

Capacity. SOC_{min} is a controller setpoint that leaves some charge in the battery at all times to extend battery life. We use a single parameter, so SOC_{min} would equal 20% for a battery that is cycled from 20% SOC to 100% SOC, or also for a battery that is cycled from 10% to 90% of rated capacity. For example, if SOC_{min}=20%, then a Demonstrated Capacity measured at 80% of rated capacity would confirm the rated capacity. To interpret Demonstrated Capacity, we define a Capacity Ratio, CR, as shown in equation 3:

$$CR = \frac{E_{demonstrated}}{E_{rated} * (1 - SOC_{min})} \ (equation\ 3)$$

E_{rated} is the rated capacity of the battery in kWh or MWh and is often estimated as the "Amp-hours" of the battery multiplied by the Nominal Voltage.

4 Report for Each PV System

Individual site assessments with these BESS KPI metrics will be provided to participating sites and agencies or subagencies, followed by online briefings to review results.

Each report would include:

- System description as provided by the agency (including photo if available) and assumptions, if any
- Graph displaying time-series data for BESS charging and discharging
- Charge Energy and Discharge Energy measured over the performance period
- Key performance indicators (i.e., Efficiency, Demonstrated Capacity and Capacity Ratio)
- Links to FEMP resources related to BESS deployment and O&M.

An example of the deliverable that may be provided for each site can be found in the Appendix. To inform future feasibility studies, data from the individual analyses can be aggregated and anonymized to calculate the key performance metrics of a sample of federal PV systems.

5 Limitations and Uncertainty

Identified sources of uncertainty and limitations of the method are described below.

5.1 Data Availability

Collecting metered charge and discharge data for BESS systems has been challenging. There have been only a limited number of BESS installations for utility cost savings in the Federal sector. Many battery systems have monitoring, but data might not be properly curated or might not be available to the study team.

5.2 Problems with the Charge Discharge Data

To calculate the KPIs, the data must include at least one full charge/discharge cycle and data regarding the initial and final state of charge of the battery. In one case where the battery was dispatched for research/demonstration purposes, the data appeared to indicate that the energy discharged from the battery exceeded that charging the battery, which is impossible, indicating the kind of error that can result from having incomplete and irregular battery dispatch within the Analysis Period. In one case data was only in the “discharge” column with no values in the “charge” column of the datasheet. The resulting recommendation is to not only install monitoring, but to check it frequently to ensure data quality.

5.3 Availability

An availability performance metric could not be calculated based only on BESS meter data. It was not possible to sort hours when the system was unavailable from hours where the battery was not being dispatched (zero charge or discharge).

5.4 Metering Accuracy

Meters employed for revenue purposes have a standard accuracy as described in American National Standards Institute (ANSI) Standard C12.20; meters may have accuracies of 0.1%, 0.2% or 0.5% depending on the class of meter (ANSI 2015). However, BESS metering systems may have varying accuracy. The most accurate meters on consumer-grade battery monitors have an accuracy less than ±1%, but less accurate power meters may vary ±3%. Tallying energy into a battery, the error of this power measurement will accumulate and determine the relative accuracy of the Efficiency and Demonstrated Capacity calculations. Accurate metering is required to measure the small difference between energy in and energy out of an efficient battery.

5.5 Low-Resolution Time-Series Data

Some sites may have only low-resolution (e.g., daily) measured BESS energy data. However, variations in both charge and discharge power levels that occur within one time-step could obscure overall BESS throughput and efficiency if the two are not recorded independently (often the two are averaged or summed over the time-step interval). Thus, a short time-step interval is needed were only one meter reports both charge and discharge data. For example, if the battery was charged 1 kWh and discharged 1 kWh within an hour, then the net energy averaged over the hour would be zero. Any energy lost in the intra-hour charging and discharging of the battery would be obscured from the calculation of efficiency. For many battery applications such as load shifting or solar energy storage, 1-hour time interval is probably sufficient since those phenomena result in a significant net change to a battery's charge level on an hourly basis. However, peak-shaving applications can modulate charging and discharging rapidly, thus hourly time-step data would not capture the efficiency fully. In off-grid applications, fluctuations in the solar resource and in the load can result in throughput that occurs with a one-hour averaging interval. If meter data integrates or averages energy in and out of the battery in a time-step then this intra-timestep through-put introduces error in the estimate of efficiency. Thus two measurements are ideal, one measuring all charge energy and the other measuring all discharge energy.

5.6 Sample Size Limitations

For the compiled statistics, it is hard to find a sample that is large and randomly selected—systems lacking good monitoring would be more likely to volunteer for the FEMP assessment. A small sample size increases the relative error. A limited sample size limits our ability to pinpoint specific BESS performance trends based on location and environmental conditions. The small sample size also makes it hard to draw statistical conclusions about the influence of BESS system type on performance.

6 Conclusion

A method has been developed to assess BESS performance that DOE FEMP and others can employ to evaluate performance of BESS or PV+BESS systems. The proposed method is based on information collected for the system under evaluation: BESS description (specifications) and battery charge and discharge metered data.

The method then processes the data using the calculations derived in this report to calculate Key Performance Indicators: Efficiency (discharge energy out divided by charge energy into battery); and Capacity Ratio: demonstrated capacity (kWh) divided by the Rated Capacity of the battery adjusted for minimum state of charge.

For combined PV+BESS systems, the following steps are proposed for an assessment:

1. Evaluate Performance Ratio and Availability of the PV Array using the previously established methods of [Walker and Desai, 2022]
2. Evaluate Efficiency and Demonstrated Capacity of the BESS subsystem using this report's methodology.
3. Compare actual realized Utility Energy Consumption (kWh/year) and Cost ($/year) with Utility Consumption and Cost as estimated using NREL's REopt or SAM computer programs.

FEMP is collaborating with federal agencies to identify pilot projects to test out the method.

The measured performance metrics presented here are useful in two respects: future feasibility studies will be better informed regarding realistic expectations of performance; and owners of existing systems may compare KPIs measured in this assessment performance to benchmark values to focus corrective action

7 References

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8 Appendix: Example BESS Performance Evaluation Report

The following pages provide an example of the report to be generated for each agency BESS system.

Battery Energy Storage System (BESS) System Performance Report Hypothetical Federal Facility, Galena AK

PV System Description

Agency	Hypothetical Federal Agency
Site Name	Galena Outpost
State	AK
System/ Building Name	HQ/Visitor Center
Latitude	64.420182
Longitude	-157.329643
BESS System Install Year	2013
Manufacturer	Tesla
Model	Powerwall 2.0
Type of Cell	Lithium nickel manganese cobalt oxide (NMC)
Rated Efficiency (%)	89%
Nominal Voltage (V DC)	50
Maximum Charge Current (Amps)	31.8
Maximum Discharge Current (Amps)	31.8
Nominal A-h rating (Amp-hours)	60
Minimum State of Charge (%)	20%
Rated Capacity (kWh)	**13.5**
Initial State of Charge (%)	100%
Final State of Charge (%)	20%
Maximum Discharge Current (Amps)	31.8
Time Resolution	Monthly
Start Date	2020-09-01 0:00:00
End Date	2022-07-01 0:00:00

The project is a grid-tied solar PV + BESS system in Galena AK. The system consists of 15 kW of roof-mount PV and one Tesla PowerWall 2.0 battery as described in the table above. The load is about 5 kW peak and 35 kWh/day, and the system is used for utility cost savings due to high utility rates in the location.

Figure 1. This photograph shows the Tesla PowerWall 2.0 which is the subject of the assessment.

System Performance

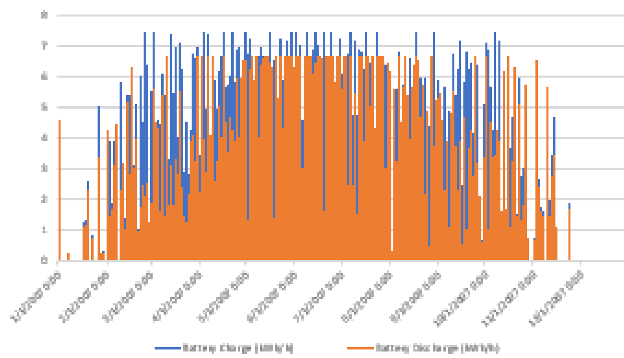

Figure 2. This graph above shows the hourly measured charge (blue) and discharge energy (orange) across an analysis period of 1 year.

Date Range	**2007 (January 1-December 31)**			
Charge Energy In (kWh)	3083.0			
Discharge Energy Out (kWh)	2753.9			
Efficiency	89.3%			
Demonstrated Capacity (kWh)	10.6			
Capacity Ratio	0.985			

Efficiency measured over the months of the analysis period is 89.3%, compared to the rated efficiency of 89%. Demonstrated Capacity is measured at 10.6 kWh, compared to 10.8 kWh Rated Capacity derated for 20% minimum state of charge (13.5 kWh*0.8).

Efficiency

Efficiency= 89.3% (rated 89%)

Capacity Ratio

Capacity Ratio = 98.5%

Efficiency and Capacity are commensurate with the expected and rated values, indicating that this system is preforming well.
Recommendation is to continue to monitor performance and observe all preventative O&M procedures.

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Battery Energy Storage System (BESS)
System Performance Report
Hypothetical Federal Facility, Galena AK

Next Steps & Resources:

While this report does not provide prescriptive measures for this specific BESS, the following next steps may help you optimize performance:

- FEMP BESS Technical Specifications : https://www.energy.gov/femp/articles/lithium-ion-battery-storage-technical-specifications
- Protocol for Uniformly Measuring and Expressing the Performance of Energy Storage Systems. Pacific Northwest National Labs and Sandia National Labs Report, 2016. https://www.sandia.gov/ess-ssl/publications/SAND2016-3078R.pdf

- **Procure professional O&M services.** FEMP has developed sample O&M contract templates
- **Use energy savings performance contracting to guarantee O&M.** The following resources can provide guidance: Energy Savings Performance Contract/Energy Sales Agreements ,Energy Savings Performance Contract Energy Sales Agreement Toolkit

Additional technical assistance *may* be available through FEMP. Please contact us.

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