Electrical Energy Storage Data Submission Guidelines, Version 2

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3002022119

SAND2021-8492

Technical Update, July 2021

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ACKNOWLEDGMENTS

Contributors from Sandia National Laboratories (SNL) were supported by the U.S. Department of Energy, Office of Electricity, Energy Storage Program under the direction of Dr. Imre Gyuk.

Pacific Northwest National Laboratory (PNNL), the Electric Power Research Institute's (EPRI) Energy Storage Integration Council (ESIC) participants, and Xanthus Consulting provided technical guidance, insight, and review during the development of this report. Sandia National Laboratories (SNL) and EPRI would like to acknowledge specifically the following personnel:

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This report describes research cosponsored by EPRI and SNL.

SNL and EPRI collaborated with PNNL in producing some of the material in the report. SNL and EPRI acknowledge that portions of the report might have been previously published by the Government and are now believed to be in the public domain.

This publication is a corporate document that should be cited in the literature in the following manner:

Electrical Energy Storage Data Submission Guidelines, Version 2. Electric Power Research Institute (EPRI) and Sandia National Laboratories (SNL): 2021. 3002022119.

ABSTRACT

Energy storage technologies are positioned to play a substantial role in power delivery systems. They have the potential to serve as an effective new resource to maintain reliability and allow for increased penetration of renewable energy. However, because of their relative infancy, there is a lack of knowledge about how these resources truly operate over time. A data analysis can help ascertain the operational and performance characteristics of these emerging technologies. Rigorous testing and a data analysis are important for all stakeholders to ensure a safe, reliable system that performs predictably on a macro level. Standardizing testing and analysis approaches to verify the performance of energy storage devices, equipment, and systems when integrating them into the grid will improve the understanding and benefit of energy storage over time from technical and economic vantage points.

Demonstrating the life-cycle value and capabilities of energy storage systems begins with the data that the provider supplies for the analysis. After a review of energy storage data received from several providers, some of these data have clearly shown to be inconsistent and incomplete, raising the question of their efficacy for a robust analysis. This report reviews and proposes general guidelines, such as sampling rates and data points, that providers must supply for a robust data analysis to take place. Consistent guidelines are the basis of a proper protocol and ensuing standards to (1) reduce the time that it takes for data to reach those who are providing the analysis; (2) allow them to better understand the energy storage installations; and (3) enable them to provide a high-quality analysis of the installations. The report is intended to serve as a starting point for what data points should be provided when monitoring. Readers are encouraged to use the guidance in the report to develop specifications for new systems, as well as enhance current efforts to ensure optimal storage performance. As battery technologies continue to advance and the industry expands, the report will be updated to remain current.

Keywords

Energy storage data
Storage controls
Storage performance

ACRONYMS

The following is a list of acronyms used in the report:

A	amperage
AC	alternating current
ANSI	American National Standards Institute
BMS	battery management system
CAES	compressed air energy storage
dBm	decibels referenced to milliwatts
DC	direct current
DER	distributed energy resource
EPRI	Electric Power Research Institute
ESIC	Energy Storage Integration Council
ESS	energy storage systems
EV	electric vehicle
HMI	human-machine interface
Hz	hertz
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
kVAR	kilovolt ampere reactive
kW	kilowatts
kWh	kilowatt-hour(s)
LVRT	low voltage ride through
ms	millisecond(s)
NIST	National Institute of Standards and Technology

O&M	operations and maintenance
PCC	point of common coupling
PCS	power conditioning system
PF	power factor
PNNL	Pacific Northwest National Laboratory
Psi	pounds per square inch
Pst	Perceptibility
RPM	revolutions per minute
SCADA	supervisory control and data acquisition
SNL	Sandia National Laboratories
SOC	state of charge
SOH	state of health
THD	total harmonic distortion
V	voltage

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1
OVERVIEW

As energy storage technologies promulgate, the need to accurately understand their reliability and performance has become paramount. Indications of storage performance are directly tied to performance warranties and grid reliability expectations. As storage becomes more prevalent, the grid will become more dependent on storage reliability to ensure overall grid reliability. When reviewing data from fielded energy storage systems (ESS), it quickly becomes clear that, despite the perceived best efforts and intentions from the provider, the data provided are not always sufficient or accurate enough to perform a robust reliability and performance analysis. Complete and accurate data are necessary to truly evaluate the ESS. The four main problems addressed by this report are (1) required data points, (2) sampling rates of the data, (3) importing data into a structured database that allows a complete analysis, and (4) managing data to ensure alarms and other pertinent data are acted upon appropriately by assigned personnel. Additionally, a new topic of power quality issues stemming from the DC side of systems is introduced.

If the provider of the information can supply data consistent with the following proposed guidelines, a robust analysis can be performed without the need to petition the provider for additional data. There also needs to be recognition that too much data may be inefficient and overwhelm acquisition, data transport, and subsequent analysis systems. Therefore, the points and sampling rates are described in a posture to optimize the amount of data needed.

This guideline will serve to define needed parameters. Many attributes of data collection will ultimately need to be addressed. These include:

- With valid amounts of data in place, it becomes possible to further understand system operation and allow an in-depth analysis on an independent basis of vendor performance claims. Numerous research efforts are underway to develop these independent techniques.
- It is also necessary, when prescribing data for reliability and performance assessment, to be cognizant of data that can be used for safety monitoring and allow export of relevant data to relevant parties.
- With cybersecurity, data collection must follow security best practices in collecting, accessing, and transmitting information.
- The data acquisition and the attendant optimal data set therefore need to be classified according to need, as follows:
  - Safety
  - Warranty and performance
  - Maintenance
  - R&D

- While standards can ultimately describe the data needed for a robust analysis of performance, the scope of implementing the needed sensors and systems needs to be detailed and assigned as the storage vendor, site owner, and system operator responsibilities.
- A typical storage system can employ numerous computer platforms that, in themselves, can process data and minimize the need to transport data upstream to a historian. Definition is needed on these downstream platforms and who supplies them and how they are operated.

2
INTEROPERABILITY, STANDARDS, AND GUIDELINES

The framework under which storage data are acquired, stored, and analyzed is an important consideration. Successfully performing a data analysis requires communication between numerous devices and other actors, such as system operators and analysts. Many of these devices communicate in different protocols. Storage components can use CANbus to internally communicate and SunSpec Modbus to communicate between modules or devices. Utility supervisory control and data acquisition systems typically operate using the IEEE 1815 (DNP3) protocol in the United States or IEEE 2030.5 in California, and International Electrotechnical Commission (IEC) 61850 internationally. In many cases in the United States, the DNP3 protocol uses the MESA specification, which maps the IEC 61850-7-420 distributed energy resources (DER) object model to DNP3 data points, as defined in the DNP3 Application Note (AN2018).

Standards that govern how ESS communicate are currently evolving to enable more complete interoperability. This standardization is based on the IEC 61850-7-420 data object standard that governs how data are defined, named, and structured. Some protocol standards then map these data objects directly (for example, IEC 61850-8-1, IEC 61850-8-2, and MESA), whereas others have a looser mapping (for example, IEEE 2030.5 and SunSpec Modbus).

This report aims to provide information on these existing and still-developing standards efforts in order to push a uniform stance on storage data and performance analysis, such as the MESA effort, which is currently being updated to reflect a better understanding of the communication requirements as utility-scale storage systems and combined photovoltaic (PV) plus storage systems are being implemented. Examples of standards under development that can be informed from the report include IEEE 1547.9 (Interconnection of ES-DER Guide) [1], P2686 (BMS Recommended Practice) [2], P2688 (ESMS Recommended Practice) [3], and the forthcoming ANSI C12.32-2021 standard, which is addressing DC metering.

Recent guidance from the North American Electric Reliability Corporation (NERC) is also touching on data availability and lack of uniformity [4]. A recent report, *Energy Storage: Impacts of Electrochemical Utility-Scale Battery Energy Storage Systems on the Bulk Power System*, highlighted the lack of uniformity seen in storage data.

Key findings and recommendations from the NERC report included [4]:

- *Data on battery storage tends to be non-uniform and lacking in consistency across reporting entities necessitating a need for better reporting mechanisms for BESS data.*
- *As regulators provide more incentives for the viability of battery storage to provide capacity and energy, system planners must adequately plan the system for a projected large increase in BESS, understanding the impact of size, location, and operating characteristics on maintaining the reliable operation of the grid.*

- *Entities that compile battery data information must enhance both their data collection methods as well as their reporting methods. As energy storage systems become more prolific, accurate and timely data will be essential for both system planners and operators. The Institute of Electrical and Electronics Engineers (IEEE) should update the IEEE Standards to reflect any implications of battery storage systems. The GADS Working Group should ensure that battery storage is accurately reflected in their data capturing protocols.*

The current report is therefore structured to provide guidance on energy storage resources, a subset of the DER classification. It will serve to inform further work on the MESA updated specifications, IEEE 1815 and 2686 and various other standards, guides and recommended practices, in part, as well as emerging market rules, guidance documents, and standard specification updates produced by the Electric Power Research Institute (EPRI) Energy Storage Integration Council (ESIC) and the Department of Energy.

3 DATA RESPONSIBILITY AND RELEVANCE

In framing the specific attributes of acquiring and analyzing data, it is important to create a structure that assigns responsibility for the different project phases and elements placed. This structure should be thoroughly developed early in the project to allow all stakeholders to understand roles, assignments, and system requirements in both the design and operational phases.

The following sample high-level responsibility matrix can serve as a template for this purpose.

Table 3-1
Data Responsibility Matrix

Project Deliverable	Equipment Vendor	Integrator	Operator	Maintenance	Analyst
Data System Design	X	X	X	X	X
Installation	X	X	X		
Commissioning	X	X	X	X	X
Operation		X	X	X	X
Analysis			X	X	X

As is evident in even a high-level approach, all parties need to be intricately involved in the design process as well as the commissioning effort. When the system is operable, the maintenance activities need to be well coordinated with data acquisition and subsequent analysis. Indeed, the analysis effort may, in itself, inform operational and maintenance activities [5].

The data and associated metrics of performance can also be classified in terms of relevance to specific project activities throughout the project life cycle in relation to business metrics. Figure 3-1 classifies metrics derived from sensors and related calculations to a continuum of business metrics.

Performance Metrics of Merit	Business Relevance: Planning	Design	Contracting	Operations	Asset Management
Roundtrip Efficiency (RTE): • How much charged energy can I expect to get back out of a system?	✓	✓	✓	✓	✓
State of Charge (SoC): • How much energy can a system charge or discharge in each moment?				✓	✓
Available energy capacity: • How much energy does 0% to 100% SoC truly represent?	✓		✓	✓	✓
State of Health (SoH) & Degradation: • How does available energy capacity change over time? How is the system degrading?	✓	✓	✓	✓	✓
Standby Losses: • How much energy is lost while the system is idle?	✓	✓	✓	✓	✓

Figure 3-1
Business Relevance of Storage Performance Metrics

4

OVERALL SYSTEM REQUIREMENTS

Before the data can be supplied, a system must be in place for effective data transfer. Figure 4-1 shows the overall high-level control architecture used for a larger system with an associated architecture for data collection.

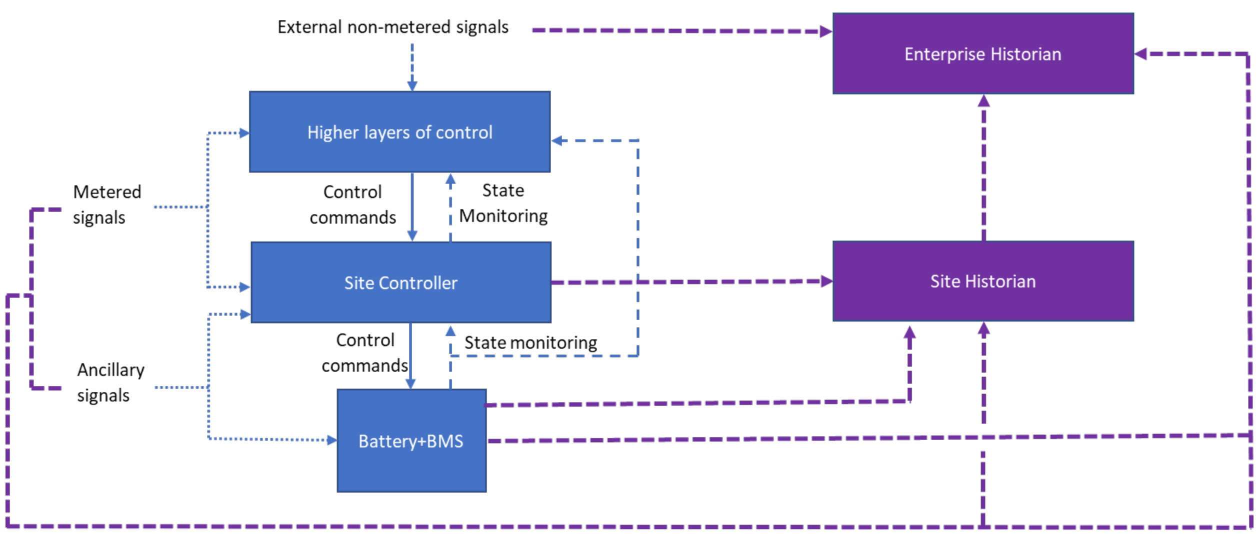

Figure 4-1
Data and Control Architectures

More detailed architectures are presented in Appendix A (Figure A-1) that point out the inherent complexity and numerous systems that are typically involved in storage operation.

In most cases, a sophisticated off-site data historian system is preferred due to the tools that can be used for a deep analysis. An on-site historian can be used to compile data for transport via alternative means or on an as-needed basis. The system can be broken down into the following elements to allow an understanding of requirements:

- **Battery (battery management system [BMS]) in the storage unit**. This includes all necessary points associated with the storage device(s), Power Conditioning System (PCS), metrology, and all installed power meters. Specific data points collected for the storage unit(s) are discussed in Section 6.
- **Master station site controller (DNP3 or IEC 61850-based outstation)**. The data collection device must also have a backup connection to the primary with a speed of at least 10 Mbps, less than 200 ms of latency, and less than 5% packet loss.

- **Data transport**. Primary link for the data collection to and from devices via high-speed wired or wireless connection with a speed of at least 10 Mbps for wired and 5 Mbps for wireless with less than 1% packet loss. Standard connections of this type include fiber optic, Category 6 or 5e ethernet, RS232, and/or cellular. It should be noted that higher upload speeds may be difficult to attain in certain cell coverage areas. Strategies for lower cellular transmission rates need to be researched further.
- **Off-site historian**. Data collection software, such as the historian, database, and operating system, must be the latest version and kept up to date throughout the project to ensure that data and cybersecurity policies are met. Data collection devices must have an onboard memory of at least 60 days with the same resolution of that being collected. Note that there may be more than one historian where an on-site historian can collect and analyze data and report out, lessening the burden on data transport. This could be coupled with an off-site historian that is connected to numerous systems.
- **Off-site control systems**. These are the utility or market participant control systems that ingest external or grid signals and instruct downstream control systems. This could include grid operations controls adapted to accommodate storage as a grid resource.

5
SAMPLING RATES OF DATA

For the system being monitored, there are typically three different kinds of sample rates. The first is the data acquisition system sample rate: the rate at which the system samples a specific data point. The second rate is the reporting sampling rate: the rate at which the logged data are to be transmitted to the analyst. The last sample rate is the rate at which the system collects data during a triggered event. Triggered events are identified using a set of boundaries for a given data point which, if violated, cause the system to collect the data at their highest resolution. The required resolution for particular triggered events will be addressed, in part, in later sections on alarm management and DC power quality.

The data acquisition sample rate can typically range from 1 second to 1 hour, and it is important to consider the optimal need, balancing the quantity of data needed against the bandwidth and data storage available. Many power-based values or basic voltages and currents are best obtained on a 1-second basis to understand subcomponent (battery cell) degradation and power characteristics. Energy-based values, such as kilowatt-hour(s) and measured temperatures, do not necessarily need to be collected at intervals smaller than 15 minutes. High resolution is typically performed in subcycle or greater than 180 Hz to capture waveform data, which can be stored and assessed locally.

6 GENERAL SYSTEM DATA POINTS

The following sections describe the data points that should be collected to ensure in-depth performance assessments for the entire ESS and specific technologies. See Section 7 for more discussion on the implications of collecting limited versus in-depth amounts of data. These data points need to be collected to evaluate the performance, safety, and longevity of the ESS. All data points need to be synchronously timestamped for accurate modeling and analysis.

6.1 Electrical AC

The AC data points are important as they inform the engineer/analyst of the amount of power coming in and out of the entire ESS. With these data points, they can find important system statistics that indicate what the system is putting back into the grid as well as overall round trip efficiencies (RTEs) and capacity fade. Auxiliary load data are also collected to understand the parasitic loads associated with various technologies. Below are the listed data points.

Note: It is important to designate charge versus discharge values for storage where the standard nomenclature is positive for *discharging*, negative for *charging* [1] [6].

6.1.1 Considerations

When designing the data acquisition system and the surrounding infrastructure, which will be used to collect and transmit the AC data, the following items should be considered:

- Ownership of meters and responsibility for programming, reporting, and maintaining data.
- Ability to capture events based on exceeding meter/parameter thresholds and how to transport, store, and analyze. Some meters are capable of recording events on a subcycle basis, and the quantity of data captured may be large. It may be best to store these events separately from the historian.
- Ability to host large data sets on site. If event recording is enabled, means to store the data (potentially in the recording device data buffer) need to be addressed. These files are typically not suited to communication protocols and are too large for data transport, unless fiber connections are in place.

6.1.2 Points Required

For all points calculating power parameters, such as kilowatt(s) and kilovolts ampere reactive, positive values denote that the ESS is discharging or pushing power from the PCS toward the electrical load. Negative values denote that the ESS is charging or absorbing power from the electrical grid through the PCS. If the ESS from where the data are being collected is a single-phase or split-phase system, all data will be collected from the line-to-neutral phase. Data points are described, as follows:

- **AC real power (kW)**. Provide three-phase values except during event triggered, denoting three-phase, line-to-line and line-to-neutral values.
- **AC reactive power (kVAR)**. Provide three-phase values except during event triggered, denoting each phase, line-to-line and line-to-neutral values..
- **AC power factor (PF)**. Provide single phase and, if applicable, three-phase values.
- **AC RMS voltage (V)**. Provide three-phase values except during event triggered, denoting each phase, line-to-line and line-to-neutral values. This will be used instead of RMS..
- **AC RMS current (A)**. Provide three-phase values except during event triggered, denoting each phase, line-to-line and line-to-neutral values. Instantaneous values will be used instead of RMS.
- **Total AC charge energy (kWh)**. This should be reported on a cumulative basis and ultimately have daily, monthly, annual, and lifetime sums for all energies available to compare with integrated instantaneous power measurements. This value will be reported for the three-phase system.
- **Total AC discharge energy (kWh)**. Similar to the total AC charge energy (kWh).
- **Auxiliary loads real power (kW)**. If applicable, provide three-phase values except during event triggered, denoting each phase, line-to-line and line-to-neutral values. If all auxiliary loads are single-phase or split-phase,
  the line-to-neutral value will be provided.
- **Auxiliary loads reactive power (kVAR)**. Similar to the auxiliary loads real power (kW).
- **Auxiliary loads RMS voltage (V)**. If applicable, provide three-phase values except during event triggered, denoting each phase, line-to-line and line-to-neutral values. This will be used instead of RMS.
- **Auxiliary loads RMS current (A)**. Similar to the auxiliary loads RMS voltage (V).
- **Relay status**. Provide status of relay (1 = Closed, 0 = Open).
- **Breaker status**. Provide status of breaker (1 = Closed, 0 = Open).

In addition to the previous data points, the listed points below should also be provided for their relation to AC as indicators of power quality:

- Flicker (Pst)
- System frequency (Hz)
- Total harmonic distortion (THD) (dBm)

6.2 Electrical DC

DC data points are collected at the DC side of the PCS. These data points allow insight into the performance of the energy storage technology behind the PCS, including items such as degradation and RTE. Without access to DC measurements, an accurate assessment of battery performance is not possible. There are ESS such as pumped hydro that may not have an electrical DC data point to collect and may ignore collecting the data points described in the following sections.

6.2.1 Considerations

When collecting DC data, the following items should be considered during the data acquisition design phase and collection:

- Number of points needed for cells in a module to accurately get average as well as maximum and minimum values, including temperatures. Number of points should accurately provide a representation of behavior of all cells for which data are not being collected. For large installations in which multiple ESS are being operated, sampling methods such as simple random, stratified random, or cluster sampling can be used. The sample set should be representative of all ESS in operation.
- Accuracy of sensors (see Section 8) and overarching BMS calculations.
- Processing that the BMS does, to potentially compile points, versus systems upstream, such as a site controller or historian-based analytic engine.
- Increasing interest in DC power quality. Recent focus has been placed on the potential for DC components, especially DC/DC converters, to introduce power quality issues, even on the AC side. Section 10 below further discusses DC power quality.

6.2.2 Points Required

Data points are described, as follows:

- **DC power (kW)**. This value should be collected at the output of the ESS and before the input of the PCS.
- **DC voltage (V)**. Depending on the technology being used, there may be numerous DC voltages measured within the system. For an electrochemical-based storage system, DC voltage needs to be acquired on all available levels, including string, underlying racks, underlying modules, and underlying cells in the modules. Figure 6-1 maps the potential

structure of an electrochemical ESS. For a 1-MW system, up to 40,000 cell measurements may be available; research indicates that only a subset of these would be needed for degradation analysis. Any deviation of any cell reading outside normal boundaries should be reported via an alert.

– Mapping the more granular points (those below Bank level) currently requires manually applying descriptors to identify specific strings and associated racks, modules, and cells. The excerpt used is a subset of a much larger listing of Battery Bank points in the DNP AN-2018 document. ESIC participants indicated the need for a software tool that applies required descriptors on a more automated basis.

- **DC current (A)**. All available current measurements should be acquired.
- **State of charge (%)**. In certain instances, the state of charge (SOC) is available on a whole system and subsystem basis. All available SOC measurements should be acquired.
- **State of health (SOH) (%)**. This value is generally available on a system or BMS level. This reported value is a very important indicator of remaining life and should be verified independently through rigorous analysis that uses subcomponent DC voltage, current, and internal temperature measurements.
- **Total DC discharge energy (kWh)**. This should be reported from startup on a cumulative basis and ultimately have daily, monthly, annual, and lifetime sums for discharge energies available to compare with integrated instantaneous power measurements.
- **Total DC charge energy (kWh)**. This should be reported from startup on a cumulative basis and ultimately have daily, monthly, annual, and lifetime sums for charge energies available to compare with integrated instantaneous power measurements.
- **Temperature (ºC)**. All temperatures available at the cell, module, rack, and system levels should be reported. Typically, temperatures are measured on the module level or higher.

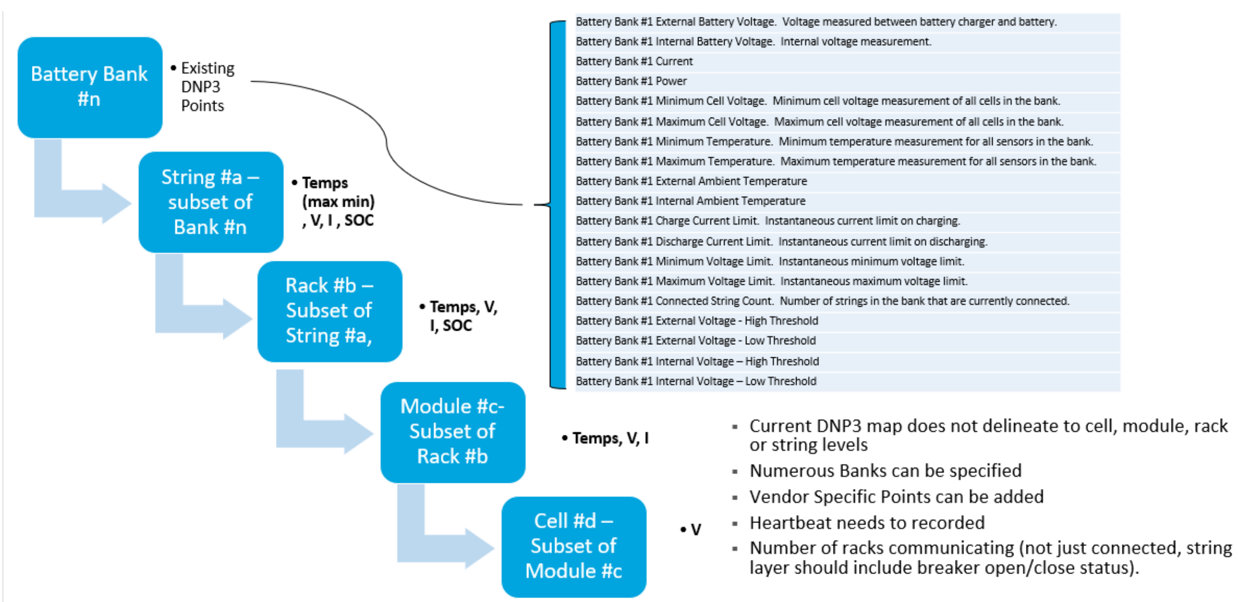

Figure 6-1
Flowchart for Battery Data Points

6.3 Conditional

Environmental and energy market points are useful because they allow the engineer to see the conditions the system is operating in and how these conditions affect the system. Financial market conditions like electricity price/cost are also included in this set because they help with the economic analysis of the system and its feasibility.

6.3.1 Considerations

The following are items that need to be considered when collecting conditional data:

- Setpoints may be required to allow further understanding relating to data analytics. These would be classified as *Analog Outputs* according to the DNP AN 2018 document.
- Temperature alerts are needed for safety concerns. Prioritization of alarms is available at three levels, and a thorough analysis needs to be given to thresholds and associated priority of alarms.
- Humidity measurements are also important in indicating the performance of environmental control systems. Both internal to system and ambient (outside) measurements are needed to ascertain internal conditions. Lack of proper control of internal humidity can lead to condensation of water vapor on surfaces that could lead to potential safety issues.

6.3.2 Points Required

Data points are described, as follows:

- **Outside temperature (°C)**. This measurement is intended for installations in which the ESS are installed outdoors.
- **Outside dew point (°C)**. Similar to the outside temperature—an indicator of humidity.
- **Internal temperature (°C)**. There can be numerous internal temperatures available. In an electrochemical system, temperatures should be available down to the module level (typically, two temperatures per module). All available internal temperatures should be acquired. Additionally, flags should be set to alarm if certain temperatures exceed safe operating limits.
- **Internal humidity (%)**. This sensor is located in the interior of the storage system, and attention needs to be paid to the accuracy of this sensor as it could serve as an indicator of condensation on interior surfaces.
- Precipitation (mm)
- Wind speed and direction (mph)
- **Electricity price/cost ($/kWh)**. If applicable and/or available, the electricity price will be provided if using time-of-use rates or real-time pricing.
- **Power request**. Real and reactive power command to the ESS.
- **Charge/discharge schedule**. If the ESS are on a pre-determined dispatch schedule, this schedule will be logged and provided.

- **Operating mode**. ESS have many modes of operations, which need to be collected to determine proper functionality and performance. This can include operating modes such as startup, standby, and load following.

6.4 Miscellaneous Data Logs, Signals and Alerts

6.4.1 Considerations

Points listed in Section 6.4.2 are equally as important for the analysis of the system as they let the operators know when and where there is a problem. Stakeholders can see how the associated data are affected by the problem and/or whether the data should be omitted. Some of the points in this section can be accessed through an analog or digital signal, whereas others are accessed through logs such as maintenance logs, highlighted in Section 6.4.3. The following is a list of considerations when determining other signals to collect for analysis:

- Prioritizing which alarms to send through for direct action and which alarms to send for condition monitoring. Alarm data may need to be filtered to limit the number of data points. See the alarm management discussion below (Section 9).
- There needs to be an indication to alarm recipients if the system has lost connectivity.
- Delivery of maintenance or other logs, either electronically or via hard copy, to the analysts needs to be discussed and determined.

6.4.2 Points Required

For event-triggered data, the data shall be collected at the highest sampling rate possible (subcycle minimum sampling) with a waveform capture one minute before and after the event was triggered.

- Events: errors, warnings, and faults alarms. This category can be composed of numerous points and prioritization of what is reported may be necessary.
- Maintenance logs and reports.
- Communication connectivity disruptions.

6.4.3 Maintenance Logs

The frequency and format for how these logs need to be delivered also need to be determined. Further research is being pursued on not only electronically capturing maintenance events, but also determining best operations and maintenance (O&M) practices through application of artificial intelligence to the database containing operational data. EPRI ESIC has published a tool available for public use to facilitate the collection of field O&M event data [16].

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6.5 Technology-Specific Points Required

The sections above provide guidance on which data points to collect for an agnostic energy storage technology and for evaluating its performance. Sections 6.5.1 through 6.5.5 provide guidance on data points that need to be collected for specific energy storage technologies. These data points will allow analysis to be performed on the energy storage technology and not the PCS and auxiliary loads. Additionally, depending on the energy storage technology, specific data points can be useful in evaluating the performance and safety concerns.

6.5.1 Cell-Based Battery

The solid-state battery technology is one that has solid electrodes immersed in an electrolyte, such as a lead acid or lithium-ion battery. Specific data to be collected for this technology are as follows:

- **Cell/module/string DC voltage (V)**. This can represent a significant amount of data, especially if every cell voltage were acquired (a 20 MW/10 MWh Li-ion system can have over 40,000 cells). A small subset of cell voltages, in this case, may be adequate to allow for a thorough performance assessment. These values may also be used for a safety assessment.
- **Cell/module/string DC current (A)**. Typically for electrochemical storage systems, current measurement is only available down to the module level. A small subset of cell/module currents in the case of a large ESS may be adequate to allow for a thorough performance assessment.
- **Cell/module/rack temperature (°C)**. A small subset of cell/module temperatures in the case of a large ESS may be adequate to allow for a thorough degradation assessment.
- **Cell resistance (ohm)**. A small subset of cell resistance measurements in the case of a large ESS may be adequate to allow for a thorough degradation assessment.
- **Cell/module or rack balancing indication**. This is a binary indication if balancing occurred. This indication may be important in identifying weak battery components.

6.5.2 Flow Battery

A flow battery is a type of rechargeable battery where rechargeability is provided by two chemical components dissolved in liquids contained within the system and most commonly separated by a membrane[2] [7]. Specific data to be collected for this technology are as follows:

- **Module/string DC voltage (V)**. This can represent a significant amount of data, especially if every cell voltage were acquired for a large system. A small subset of cell voltages, in this case, may be adequate to allow for a thorough performance assessment.
- **Module/string DC current (A)**. This can represent a significant amount of data, especially if every cell voltage were acquired for a large system. A small subset of cell currents, in this case, may be adequate to allow for a thorough performance assessment.
- **Temperature (°C)**. A small subset of cell temperatures in the case of a large ESS may be adequate to allow for a thorough degradation assessment.

- **Module/stack resistance (ohm)**. A small subset of cell/module/stack resistance in the case of a large ESS may be adequate to allow for a thorough degradation assessment.
- Anolyte flow(s) (L/min)
- Anolyte tank pressure(s) (psi)
- Anolyte tank(s) level (L)
- Catholyte flow(s) (L/min)
- Catholyte tank(s) pressure (psi)
- Catholyte tank(s) level (L)
- Stack SOC (%)
- Reported state of health (%)
- Converter (if applicable) input and output voltage (V) and current (I)

6.5.3 Flywheel

A flywheel is an ESS that consists of a spinning mass attached to a shaft that converts mechanical energy into electrical energy. Specific data to be collected for this technology are as follows:

- Speed of flywheel (RPM)
- Vacuum pressure (psi)
- System temperatures (°C)
- Vibration sensor (m/s^2)

6.5.4 Compressed Air

Compressed air energy storage (CAES) consists of storing energy in the form of air and releasing the air into a turbine connected to a generator producing electricity. As these are rather complex systems, the number of sensed points can be quite large. Publicly available reports such as EPRI's *Reference Design Description and Cost Evaluation for Compressed Air Energy Storage Systems* (1021939) [8] detail typical system designs and illuminate the potential complexity of these types of systems. General data to be collected for this technology are as follows:

- Inlet air pressure (psi)
- Outlet air pressure (psi)
- Speed of turbine (RPM)
- System and ambient temperatures (°C)
- System fuel consumption (MMBtu/kWh or similar)
- **System emissions data (ppm)**. This value is the cumulative emission in ppm between samples. This can be many points depending on the various types of emissions that are produced.

6.5.5 Pumped Hydro

Pumped hydro is typically found at the utility scale. It consists of pumping water from one reservoir to another reservoir at a high altitude and then releasing the water from the higher reservoir through a turbine and generator to produce electricity. Like CAES, these systems can be quite large with numerous points requiring monitoring. General data to be collected for this technology are as follows:

- Reservoir water height (m)
- Water flow from higher reservoir to lower reservoir (L/min)
- Water pressure from higher reservoir to lower reservoir (psi)
- Water flow from lower reservoir to higher reservoir (L/min)
- Water pressure from lower reservoir to higher reservoir (psi)
- Water pump speed (RPM)
- System temperatures (°C)
- Turbine inlet pressure (psi)
- Turbine outlet pressure (psi)

6.6 Sample Points List—General Energy Storage Three-Phase System

For the stated minimums in Table 6-1 and Table 6-2, if the report out can be provided at a faster rate, the faster rate is desired, and the provider shall provide the data at that rate.

Table 6-1
System Data Points

Data Point	Units	Sample Rate Minimum	Power Application Report Out Minimum	Energy Application Report Out Minimum	Values
AC Real Power	kW	≥1 Sample/Second	≥1 Sample/Second	≥1 Sample/15 minutes	Value, max, min, avg
AC Reactive Power	kVAR	≥1 Sample/Second	≥1 Sample/Second	≥1 Sample/15 minutes	Value, max, min, avg
AC Power Factor		≥1 Sample/Second	≥1 Sample/Second	≥1 Sample/15 minutes	Value, max, min, avg
AC RMS Voltage	VRMS	≥1 Sample/Second	≥1 Sample/Second	≥1 Sample/15 minutes	Value, max, min, avg
AC RMS Current	IRMS	≥1 Sample/Second	≥1 Sample/Second	≥1 Sample/15 minutes	Value, max, min, avg
Total AC Discharge Energy	kWh	≥1 Sample/Second	≥1 Sample/Second	≥1 Sample/15 minutes	Value, max, min, avg
Total AC Charge Energy	kWh	≥1 Sample/Second	≥1 Sample/Second	≥1 Sample/15 minutes	Value, max, min, avg
Auxiliary Load Real Power	kW	≥1 Sample/Second	≥1 Sample/Second	≥1 Sample/15 minutes	Value, max, min, avg
Auxiliary Load Reactive Power	kVAR	≥1 Sample/Second	≥1 Sample/Second	≥1 Sample/15 minutes	Value, max, min, avg
Auxiliary Load RMS Voltage	VRMS	≥1 Sample/Second	≥1 Sample/Second	≥1 Sample/15 minutes	Value, max, min, avg
Auxiliary Load RMS Current	IRMS	≥1 Sample/Second	≥1 Sample/Second	≥1 Sample/15 minutes	Value, max, min, avg
Relay Status	Binary	≥1 Sample/Second	≥1 Sample/Second	≥1 Sample/15 minutes	1 = Closed 0 = Open

Table 6-1 (continued)
System Data Points

Data Point	Units	Sample Rate Minimum	Power Application Report Out Minimum	Energy Application Report Out Minimum	Values
Breaker Status	Binary	≥1 Sample/Second	≥1 Sample/Second	≥1 Sample/15 minutes	1 = Closed 0 = Open
Flicker	Pst	≥500 Samples/Second	≥1 Sample/Second	≥1 Sample/15 minutes	Value, max, min, avg
System Frequency	Hz	≥1 Sample/Second	≥1 Sample/Second	≥1 Sample/15 minutes	Value, max, min, avg
THD	dBm	≥500 Samples/Cycle	≥1 Sample/Second	≥1 Sample/15 minutes	Value, max, min, avg
DC Power	kW	≥1 Sample/Second	≥1 Sample/Second	≥1 Sample/15 minutes	Value, max, min, avg
DC Voltage	V	≥1 Sample/Second	≥1 Sample/Second	≥1 Sample/15 minutes	Value, max, min, avg
DC Current	I	≥1 Sample/Second	≥1 Sample/Second	≥1 Sample/15 minutes	Value, max, min, avg
State of Charge	%	≥1 Sample/Second[2]	≥1 Sample/Second	≥1 Sample/15 minutes	Value, max, min, avg
State of Health	%	≥1 Sample/Second	≥1 Sample/Second	≥1 Sample/15 minutes	Value, max, min, avg
Total DC Discharge Energy	kWh	≥1 Sample/Second	≥1 Sample/Second	≥1 Sample/15 minutes	Value, max, min, avg
Total DC Charge Energy	kWh	≥1 Sample/Second	≥1 Sample/Second	≥1 Sample/15 minutes	Value, max, min, avg

Table 6-1 (continued)
System Data Points

Data Point	Units	Sample Rate Minimum	Power Application Report Out Minimum	Energy Application Report Out Minimum	Values
Outside Temperature	ºC	≥1 Sample/Minute	≥1 Sample/Minute	≥1 Sample/15 minutes	Value, max, min, avg
Outside Dew Point	ºC	≥1 Sample/Minute	≥1 Sample/Minute	≥1 Sample/15 minutes	Value, max, min, avg
Internal Enclosure Temperature	ºC	≥1 Sample/Minute	≥1 Sample/Minute	≥1 Sample/15 minutes	Value, max, min, avg
Internal Enclose Humidity	%	≥1 Sample/Minute	≥1 Sample/Minute	≥1 Sample/15 minutes	Value, max, min, avg
Precipitation	mm	≥1 Sample/Minute	≥1 Sample/Minute	≥1 Sample/15 minutes	Value, max, min, avg
Wind Speed and Direction	(mph, cardinal direction)	≥1 Sample/Second	≥1 Sample/Second	≥1 Sample/15 minutes	Value, max, min, avg
Electricity Price/Cost	$/kWh	Sample rate associated with price data	Sample rate associated with price data	Sample rate associated with price data	Value
Power Request	(kW, kVAR, kVA)	≥1 Sample/Second	≥1 Sample/Second	≥1 Sample/15 minutes	Value, max, min, avg
Charge/Discharge Schedule	(Time vs. kW)	≥1 Sample/5 Minute	≥1 Sample/5 Minute	≥1 Sample/15 minutes	Schedule
Operating Mode	Integer	≥1 Sample/5 Minute	≥1 Sample/5 Minute	≥1 Sample/15 minutes	Integer value related to operating mode

Table 6-1 (continued)
System Data Points

Data Point	Units	Sample Rate Minimum	Power Application Report Out Minimum	Energy Application Report Out Minimum	Values
Events: Errors, Warnings, and Faults		≥1 Sample/Second	≥1 Sample/Second	≥1 Sample/15 minutes	Value
Maintenance Logs		Per manufacturer	Monthly	Monthly	Tablature report
Communication Conductivity Disruptions	Integer	≥1 Sample/Second	≥1 Sample/Second	≥1 Sample/15 minutes	1 = Online 0 = Offline

Table 6-2
Technology-Specific Data Points

Data Point	Units	Sample Rate Minimum	Power Application Report Out Minimum	Energy Application Report Out Minimum	Values
Cell-Based Battery					
Cell/Module/String DC Voltage	V	≥1 Sample/Second	≥1 Sample/Second	≥1 Sample/15 minutes	Value, max, min, avg
Cell/Module/String DC Current	I	≥1 Sample/Second	≥1 Sample/Second	≥1 Sample/15 minutes	Value, max, min, avg
Cell/Module/Rack Temperature	ºC	≥1 Sample/Second	≥1 Sample/Second	≥1 Sample/15 minutes	Value, max, min, avg
Cell Resistance	Ohms	≥1 Sample/Second	≥1 Sample/Second	≥1 Sample/15 minutes	Value, max, min, avg
Flow Battery					
Cell/Stack/String DC Voltage	V	≥1 Sample/Second	≥1 Sample/Second	≥1 Sample/15 minutes	Value, max, min, avg
Cell/Module/String DC Current	I	≥1 Sample/Second	≥1 Sample/Second	≥1 Sample/15 minutes	Value, max, min, avg
Cell Temperature	ºC	≥1 Sample/Second	≥1 Sample/Second	≥1 Sample/15 minutes	Value, max, min, avg
Cell/Module/Stack Resistance	ohm	≥1 Sample/Second	≥1 Sample/Second	≥1 Sample/15 minutes	Value, max, min, avg
Anolyte Flow(s)	L/min	≥1 Sample/Second	≥1 Sample/Second	≥1 Sample/15 minutes	Value, max, min, avg
Anolyte Tank Pressure(s)	psi	≥1 Sample/Second	≥1 Sample/Second	≥1 Sample/15 minutes	Value, max, min, avg
Anolyte Tank Level(s)	L	≥1 Sample/Second	≥1 Sample/Second	≥1 Sample/15 minutes	Value, max, min, avg

Table 6-2 (continued)
Technology-Specific Data Points

Data Point	Units	Sample Rate Minimum	Power Application Report Out Minimum	Energy Application Report Out Minimum	Values
Flow Battery (continued)					
Catholyte Flow(s)	L/min	≥1 Sample/Second	≥1 Sample/Second	≥1 Sample/15 minutes	Value, max, min, avg
Catholyte Tank Pressure(s)	psi	≥1 Sample/Second	≥1 Sample/Second	≥1 Sample/15 minutes	Value, max, min, avg
Catholyte Tank Level(s)	L	≥1 Sample/Second	≥1 Sample/Second	≥1 Sample/15 minutes	Value, max, min, avg
DC Converter output voltage	V	≥1 Sample/Second	≥1 Sample/Second	≥1 Sample/15 minutes	Value, max, min, avg
DC Converter input voltage	V	≥1 Sample/Second	≥1 Sample/Second	≥1 Sample/15 minutes	Value, max, min, avg
Flywheel					
Speed of Flywheel	rpm	≥1 Sample/Second	≥1 Sample/Second	≥1 Sample/15 minutes	Value, max, min, avg
Vacuum Pressure	psi	≥1 Sample/Second	≥1 Sample/Second	≥1 Sample/15 minutes	Value, max, min, avg
System Temperature(s)	ºC	≥1 Sample/Second	≥1 Sample/Second	≥1 Sample/15 minutes	Value, max, min, avg
Vibration Sensor	m/s^2	≥1 Sample/Second	≥1 Sample/Second	≥1 Sample/15 minutes	Value, max, min, avg

Table 6-2 (continued)
Technology-Specific Data Points

Data Point	Units	Sample Rate Minimum	Power Application Report Out Minimum	Energy Application Report Out Minimum	Values
Compressed Air					
Inlet Air Pressure	psi	≥1 Sample/Second	≥1 Sample/Second	≥1 Sample/15 minutes	Value, max, min, avg
Outlet Air Pressure	psi	≥1 Sample/Second	≥1 Sample/Second	≥1 Sample/15 minutes	Value, max, min, avg
Speed of Turbine	rpm	≥1 Sample/Second	≥1 Sample/Second	≥1 Sample/15 minutes	Value, max, min, avg
System Temperature(s)	ºC	≥1 Sample/Second	≥1 Sample/Second	≥1 Sample/15 minutes	Value, max, min, avg
System Fuel Consumption	(MMBtu/kWh)	≥1 Sample/Second	≥1 Sample/Second	≥1 Sample/15 minutes	Value, max, min, avg
System Emission Data	ppm	≥1 Sample/15 Minutes	≥1 Sample/15 minutes	≥1 Sample/hour	Value, max, min, avg
Pumped Hydro					
Reservoir Height	m	≥1 Sample/Second	≥1 Sample/Second	≥1 Sample/15 minutes	Value, max, min, avg
Water Flow from High Reservoir to Low Reservoir	L/min	≥1 Sample/Second	≥1 Sample/Second	≥1 Sample/15 minutes	Value, max, min, avg
Water Pressure from High Reservoir to Low Reservoir	psi	≥1 Sample/Second	≥1 Sample/Second	≥1 Sample/15 minutes	Value, max, min, avg
Water Flow from Low Reservoir to High Reservoir	L/min	≥1 Sample/Second	≥1 Sample/Second	≥1 Sample/15 minutes	Value, max, min, avg

Table 6-2 (continued)
Technology-Specific Data Points

Data Point	Units	Sample Rate Minimum	Power Application Report Out Minimum	Energy Application Report Out Minimum	Values
Pumped Hydro (continued)					
Water Pressure from Low Reservoir to High Reservoir	psi	≥1 Sample/Second	≥1 Sample/Second	≥1 Sample/15 minutes	Value, max, min, avg
Water Pump Speed	rpm	≥1 Sample/Second	≥1 Sample/Second	≥1 Sample/15 minutes	Value, max, min, avg
System Temperature(s)	ºC	≥1 Sample/Second	≥1 Sample/Second	≥1 Sample/15 minutes	Value, max, min, avg
Turbine Inlet Pressure	psi	≥1 Sample/Second	≥1 Sample/Second	≥1 Sample/15 minutes	Value, max, min, avg
Turbine Outlet Pressure	psi	≥1 Sample/Second	≥1 Sample/Second	≥1 Sample/15 minutes	Value, max, min, avg

Figure 6-2 summarizes an assessment of points required, mapped to various applications.

Data Group	Data Points	PV Smoothing	Volt/Var	Renewable Firming	Power Quality	Frequency Control	Peak Shaving	Frequency Regulation	Microgrid Stability
AC	P (W)	x	x	x	x	x	x	x	x
	Q (VAR)	x	x	x	x	x	x	x	x
	Vrms (V)	x	x	x	x	x	x	x	x
	Irms (A)	x	x	x	x	x	x	x	x
	Discharge Energy (Wh)	x	x	x	x	x	x	x	x
	Charge Energy (Wh)	x	x	x	x	x	x	x	x
	Power Factor (pf)				x	x			x
DC	P (W)	x	x	x	x	x	x	x	x
	V (V) for Cell/Module/Rack/String	x	x	x	x	x	x	x	x
	I (A) for Cell/Module/Rack/String	x	x	x	x	x	x	x	x
	SOC (%)	x	x	x	x	x	x	x	x
	SOH (%)	x	x	x	x	x	x	x	x
	Discharge Energy (Wh)	x	x	x	x	x	x	x	x
	Charge Energy (Wh)	x	x	x	x	x	x	x	x
	Discharge Capacity (Ah)	x	x	x	x	x	x	x	x
	Charge Capacity (Ah)	x	x	x	x	x	x	x	x
	DoD Count	x	x	x	x	x	x	x	x
	Temperature Cell/Module/Rack (Degrees (	x	x	x	x	x	x	x	x
Auxiliary AC or DC	P (W)	x	x	x	x	x	x	x	x
	Q(VAR)	x	x	x	x	x	x	x	x
	Vrms (V)	x	x	x	x	x	x	x	x
	Irms (A)	x	x	x	x	x	x	x	x
Status	Relay	x	x	x	x	x	x	x	x
	Breaker	x	x	x	x	x	x	x	x
	Faults/Alarms	x	x	x	x	x	x	x	x
Power Quality	Flicker (Pst)		x		x				x
	Frequency (Hz)				x	x			x
	THD (dBm)		x		x	x			x
Conditional	Outside Temperature (Degrees Celsius)	x	x	x	x	x	x	x	x
	Outside Dew Point (Degrees Celsius)	x	x	x	x	x	x	x	x
	Internal Temperature (Degrees Celsius)	x	x	x	x	x	x	x	x
	Internal Humidity (%)	x	x	x	x	x	x	x	x
	Precipitation (mm)	x	x	x	x	x	x	x	x
	Wind Speed and Direction (mph)	x		x					x
Operational / Economics	Electricity Price/Cost ($/kWh or $/gal)	x		x	x	x	x	x	x
	Power Request (W and/or VAR)	x	x	x	x	x	x	x	x
	Operating Mode	x	x	x	x	x	x	x	x

Figure 6-2
Data Points Mapped to Storage Functions

A list of the DER autonomous functions that a storage system can provide is shown in Table A-1 of Appendix A. As storage system assume numerous duties it is increasingly important to uniformly label the duties being enabled and or executed to ensure correct understanding of which control mode was enabled and pursued, especially if numerous modes of operation are being pursued. It displays these functions mapped to overarching and regional standards.

7
DATA QUALITY AND TRANSMISSION

7.1 Overview

After the data are measured and logged, they shall be sent to the analyst by the provider in 24 hours or less. If the data from a time period are aggregated into a single file, like daily data, the provider should have 24 hours from the last sample to make the data available for the analyst.

When the data are transmitted, they should be sent in a timestamped row-column format where one of the columns documents each row's unique timestamp with all other columns relaying measurements and status values for the corresponding timestamp.

It may be necessary to create multiple files for logging data within a given interval. Each file may logically represent a subsystem within the larger storage system (for example, data from controllers, meteorological stations, containers, racks, modules, cells). The files should abide by an intuitive naming scheme. For instance, each file name should contain the date, a short descriptor for what subsystem it represents, and, if there are numerous files produced in a day, a number designating which file it is for that day. An example for a group of files under this naming scheme might look like the following:

- Bank1_20190111_1.csv
- Bank1_20190111_2.csv
- Bank1_20190111_3.csv

A "data details" document should accompany the first data set (and any subsequent changes to the reported data) and should provide the following information to support the interpretation, storage, and analysis of the data. This includes:

- A short description of the data in each column
- Corresponding units
- All possible values with a description of what the values represent, if the data point is an enumerated type

If a software/firmware update will in any way affect the way data are logged by the system, the vendor must alert the operator of the expected changes. If new data points will be added to the log files, the columns should be appended to the end of the file. A new "data details" document should also be provided by the vendor for added visibility into the changes.

To ensure privacy and protection of proprietary information, a possible non-disclosure agreement can be signed between the analyst and the provider of data. This, combined with the read-only access for the analyst, will ensure that data will not be shared with anyone else, and the provider can remain confident that the information will remain private.

If the provider, upon review, finds that the data quality is compromised due to any planned or unplanned outages, the provider should request or initiate repair of the system within 24 hours to ensure the smallest downtime. In addition, the provider should tag the data loss interval in a log provided to the engineer. To combat data loss due to network issues or outages, the vendor shall implement on site data storage from where compiled data can be pulled later once connection is reestablished.

The system also needs to account for daylight savings time in cases where revenue meters automatically adjust. Data should be timestamped using methods such as Universal Time Coordinated or similar.

7.1.1 Data Resolution Considerations from Fielded ESS

The safe and effective operation of an ESS requires the continuous collection and processing of a vast amount of data from the components throughout a system (for example, cells, racks, safety equipment, thermocouples, thermal management subsystems, inverters). These data streams are used by different levels of a battery's controls hierarchy to make decisions about how the system should/can be operated given its current state.

In most cases, a majority of these data are not visible or accessible externally. In some cases, these data may be either logged for later analysis (by the vendor or an external stakeholder) or is made directly visible in real time through some communication protocol (for example, Modbus) to facilitate real-time data collection. There is no standard for what, if any, data should be made externally available; the data that are available from commercial ESS can differ between vendors.

Due to the variety of data reporting practices, individual products' reported data sets can be classified as existing somewhere on a spectrum between "robust" and "sparse." As visualized in Figure 7-1, the robustness of a system's data refers to both the spatial resolution (that is, at what physical level data are reported from components throughout the system) and temporal resolution (that is, at what time interval these measurements are reported).

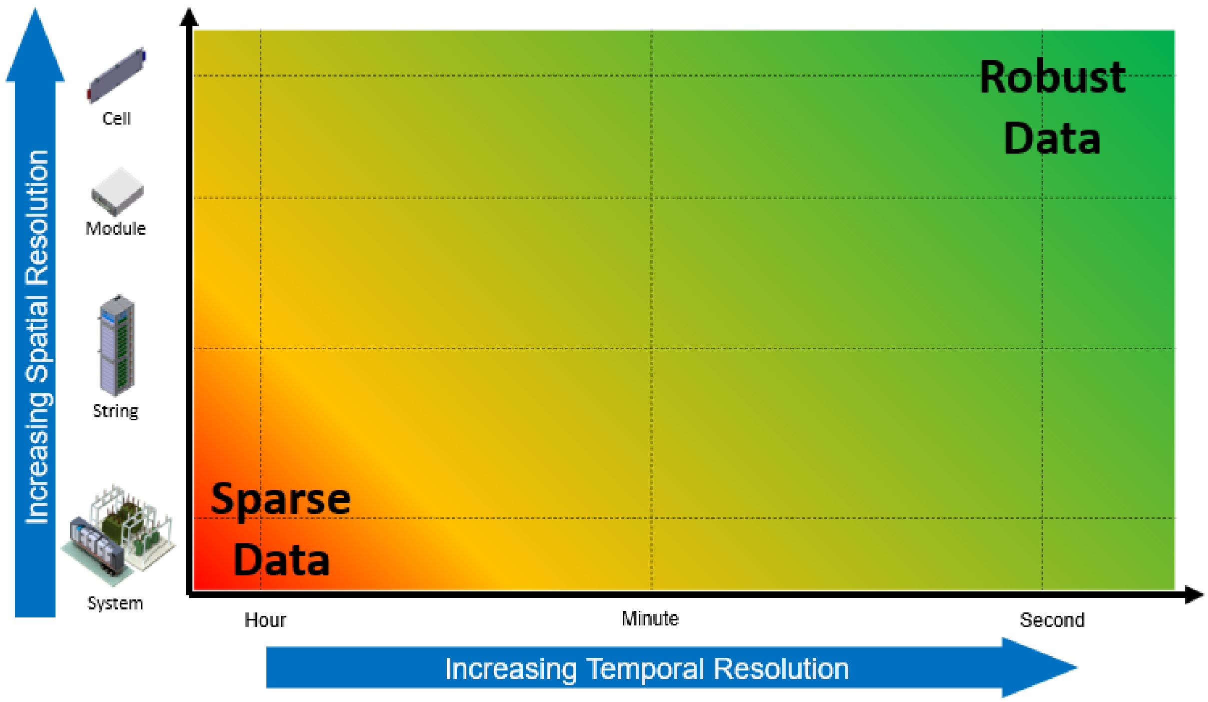

Figure 7-1
Sparse and Robust Data Sets Versus Temporal Resolution

A relatively sparse data system may only report AC-level power and a handful of battery-specific details like SOC and operating mode every minute, while a robust system may report data at the point of interconnection, at all major DC junctions, and for all cells each second. These data can include both direct measurements (for example, power, temperatures, voltages, currents, SOC, state of health), control information (for example, setpoints), and statuses (for example, errors, warnings, setpoints), which extend the realm of possibilities for robust data systems. Unless specified on the project inception, the owner and operators may not have access to the data needed for an independent performance assessment.

An important consideration on specifying storage systems and associated data requirements is the level of knowledge of performance needed. Systems with sparse data can be gauged at some level over time on coarse measurements like efficiency and standby losses, and these approaches have to be calibrated for many conditions (thermal and operational modes). Systems with robust levels of data can be assessed for many more attributes, such as independent assessments of SOH and SOC, to allow verification of warranties, indication of premature aging, and indication of potential problems.

8
SENSOR AND COMPUTATIONAL ACCURACY

Inaccurate sensors lead to poor quality data and hence inaccurate analysis and misleading representation and calculated metrics of system condition. Inaccuracies can also be introduced through calculation routines where significant digits are truncated, or the equations used are inaccurate in themselves. Lack of clarity on proprietary algorithms can further obfuscate a firm understanding of storage performance.

8.1 SOC Accuracy

Recent focus has been placed on the accuracy of one of the most important performance metrics: SOC. SOC is an important value in an efficient and reliable dispatch. However, in many technologies, SOC is an estimate of an unobservable quantity, such as the average concentration of lithium in the anodes of thousands of individual battery cells. For these technologies, there is no way to calculate the accuracy of the SOC given that there is no way to measure its underlying true value (except at specific operating points). This topic is receiving attention in emerging standards, namely IEEE 1547.9 [9], and has been addressed in recent NERC-issued guidelines [10]. Substantial differences between vendor-reported and independently calculated values, as well as physically impossible reported values, have been noted in field performance assessments. This seemingly irrational system behavior causes problems for control systems and confusion for operators. Considering its practical usage, there are some best practices for the calculation and reporting of SOC:

- The term *operational state of charge* can be used to distinguish the practical, system-level value from the electrochemical property estimate reported by an individual BMS.
- The operational SOC should be reported as a percentage of the real-time operational capacity. Operational capacity can change over time due to both environmental factors and degradation.
- The operational SOC should never be allowed to fall below 0% or exceed 100%. If there is an internal calculation that needs to use an SOC-like value outside of this range (for example, lead acid batteries undergoing an equalization charge), it should be tracked separately from the operational SOC.
- The operational SOC estimation algorithm should be well tuned over its whole range. Estimation algorithms often use parameters that are dependent on SOC or temperature (for example, cell resistance or open-circuit voltage) and so they should be configured to update these calculation parameters based on the current conditions.
- The operational SOC should be smooth, meaning that the maximum difference between sequential estimates should be limited by the maximum theoretical change in SOC between time steps. Smoothness can be relaxed when an algorithm first starts or when capacity is added to or removed from the estimate.

- The operational SOC and operational capacity calculations, along with their parameters, should be made available to the device owner through the procurement process. This calculation should specify whether it uses values reported by a device management system whose algorithms are proprietary or unknown.

8.1.1 Meter Accuracy Standards

Also of interest is the accuracy of the electrical metering. The key data elements are associated with performance analysis center on these meters. Temperature measurements are also important, but the accuracy requirements may not be as arduous. Revenue grade accuracy has been the traditional nomenclature used to describe the accuracy of meters used in utility settings. These levels of accuracy should be used for storage performance measurement, though the level of revenue grade accuracy needs to be established for a given project. Standards that govern the accuracy of electric meters follow:

8.1.1.1 New Standard: ANSI C12.32-2021, Electricity Meters for the Measurement of DC Energy

This new standard is due to be published in 2021 and is poised to establish performance criteria for revenue grade DC watt-hour meters and demand meters. It is also slated to target, similar to ANSI AC meter standards, various accuracy and current classes and other similar attributes. This new standard should be integral in understanding DC power and energy measurements.

8.1.1.2 U.S.-Based

- ANSI C12.1-2014 – National Standard for Electric Meters – Code for Electricity Metering which covers the testing and installation of the meter [11] [3].
- ANSI C12.20-2015 – American National Standard for Electric Meters for Electricity Meters – 0.1, 0.2, and 0.5 Accuracy Classes. This revision introduced a new 0.1 accuracy class. Previous versions had a 0.5 accuracy (error rate <0.2%) and 0.2 accuracy (error rate <0.1%). The new 0.1 accuracy class dictates an error rate of <0.05% [12, 13].

8.1.1.3 International

Similar to the ANSI Class structure, the IEC standards applicable to meter accuracy include: (1) IEC 62053-21 Class 1 and (2) IEC 62053-22 Class 0.5, 0.2, and 0.1 (ed. 2) [14, 15].

8.1.2 Temperature and Humidity Sensors

The National Institute of Standards and Technology (NIST) lists numerous standards that govern the accuracy for a variety of thermocouple configurations. Of key importance is the calibration of thermocouples that is required after certain time durations. NIST Special Bulletin 250-35 details techniques for recalibration. As storage systems age, it is necessary to understand that temperature sensor accuracy may deteriorate and require recalibration or replacement.

There are a variety of humidity sensors available with a wide range of accuracy. It is important to understand not only the needed accuracy, but also any drift that may be experienced over time. In containerized systems, understanding humidity may be important with respect to the prevention of condensation on surfaces that are cooler than the dew point of the surrounding air. This should be a key consideration in humid environments with regard to O&M practices and when open doors can introduce humid air.

8.1.3 Impacts of Various Accuracies on Energy Measurement

It should be noted that RTE may be independent of meter accuracy since any error that scales with the power reading will not affect RTE calculations, because it will reduce/increase the charging energy as much as the discharging energy. Other important measurement parameters can be affected through differences in accuracy and the incumbent error introduced into the measurement. Figure 8-1 highlights the cumulative difference or error that could be presented over 10 years for cumulative energy discharged from a system rated at 1 MW/2 MWh and discharging an expected 50 MWh/year.

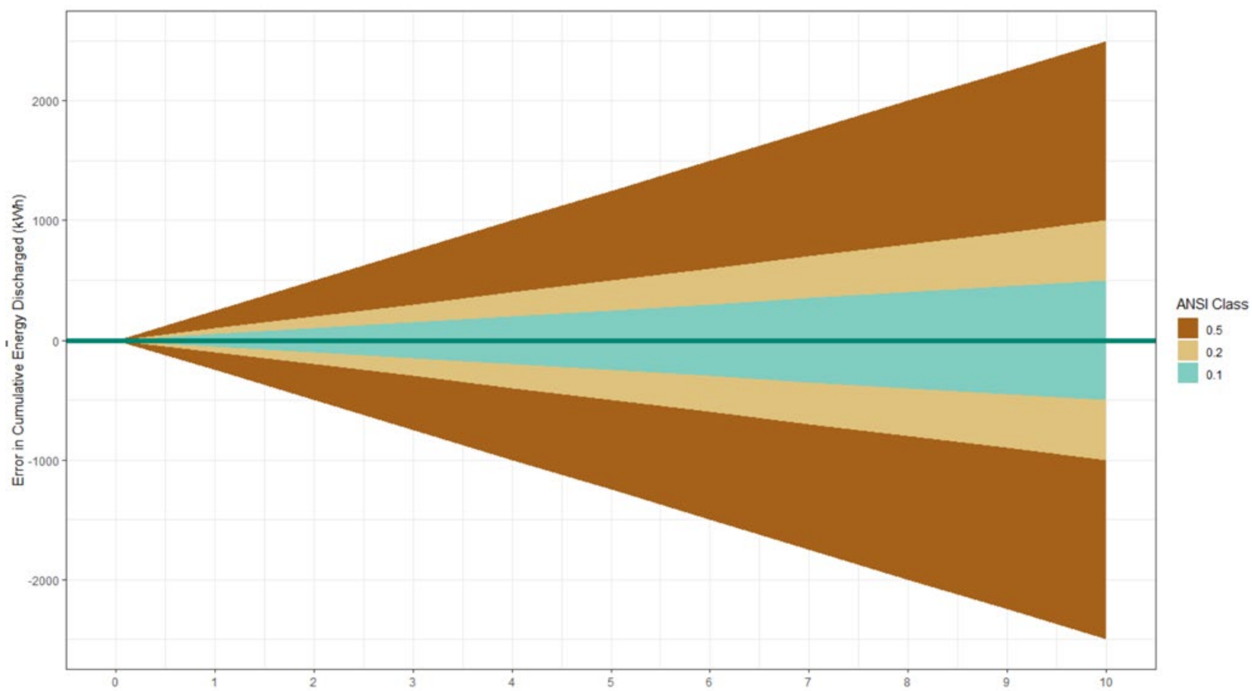

Figure 8-1
A 50-MWh/Year Cumulative Energy Error for ANSI 0.1, 0.2, and 0.5 Class Meters

The relative expanse of the error experienced in Figure 8-1 would be expected to broaden significantly with the use of less-than-revenue-grade metering.

9
ALARM MANAGEMENT

9.1 Framework to Identify Needed Alarms/Indicators

As indicated in Section 6, there is a multitude of sensors associated with storage systems and for larger systems, the number of monitoring points can easily reach in the tens of thousands. Alarm management involves not only prioritizing key sensors that indicate potential safety issues, but also ensuring the correct action is taken if these sensors indicate off-normal status.

System design documents and failure modes and effects analysis (FMEA) or other systematic methodologies can serve as a basis to structure an approach to alarm management. ANSI/ISA-18.2-2016, “Management of Alarm Systems for the Process Industries,” is one source that can serve to inform alarm management.

The content included in this section is currently focused on Li-ion systems as the predominant system type in deployment today. The development of alarm type, content, and management approach for a non-Li-ion system can be done using a similar structured methodology and referencing the alarms noted here and the data monitoring details in Section 6.

9.2 Alarm Responsibilities and Roles

Similar to the Data Responsibility Matrix presented in Section 3, Table 3-1, responsibility with respect to management of sensors producing alarms and response to alarms needs to be explicitly defined.

The site *operator* oversees control of the ESS and has authority to energize or de-energize the system. This role is often employed by the site owner. While the operator may work on-site or remotely, the operator may have the first access to alarms and may be the first responder to an incident.

Several *vendors*, or suppliers, may continue to be involved in an ESS long after project commissioning to provide service or satisfy warranties and performance guaranties. Many vendors require ongoing data access to a site and may have visibility into alarms (in real-time, in review of periodic data transfers, or even after specific events during forensic activities).

NFPA 855 includes a requirement for a *subject matter expert (SME)* to be available at all times. In the event of an emergency, the SME may be called to advise first response activities or system status.

Depending on the ESS site, several *site employees* may have access (physically, or at least visually) to a site. They may identify or be able to initiate alarms and also may act as first responders. Their education and training regarding ESS guidelines can support safe and continuous operations. The *general public* may also have access to a site and present the same opportunities (and risks) as *site employees*. Robust and clear signage can help communicate alarm acknowledgment and response to this group.

The *fire service* is trained in general emergency response, though may be unaware of ESS-specific issues, and may be volunteers. Specific training should be conducted with respect to response to ESS incidents, and the training should be periodically repeated to address any turnover or staff changes.

An *alarm management team* can be helpful to periodically review alarms for validity and importance. The team can include participants from each of the above roles and develop guidance for alarm communications and responses.

9.3 Hazard Indicators

The following list offers potential sources of hazard indicators but should not be considered exhaustive. The framework documents mentioned previously, such as FMEAs, should detail actual sources and identify key data labels for mapping to proper communication channels.

- Voltage (AC and DC)
- Temperature
- Smoke
- Gas detectors
- Infrared and heat
- Ground fault detectors
- Flow rate and fluid level sensors, leak detectors
- Fuse and circuit breaker auxiliary contacts
- Site security—door status
- Abnormal ancillary load operation

9.4 Alarm Communication

Alarms are typically communicated on site and externally via a communication channel. On-site alarm communication typically includes:

- Horn/strobe installation
- Fire panel human-machine interface (HMI)
- Battery management HMI
- Power conditioning HMI
- Site controller HMI

External screens can be used to display alarms to appropriate personnel, including:

- Grid operators
- Site operators
- Local emergency response
- Equipment vendor operations

In most cases, these external platforms need 24/7 attendance and/or automated callout features.

9.5 Potential Alarm Categories

The alarm management framework can center on distinct categories of sensor data for which oversight can be assigned to appropriate operations personnel.

- Temperature (cell, module, ambient, coolant)
- Voltage (cell, module, string, array)
- Overcurrent
- Relative humidity
- Smoke detection
- Distribution of gases (range/delta)
- Distribution of temperature (range/delta)
- Trend monitoring (for temperature, voltage, current, and so forth)
- Breaker status (open/close/trip)
- Communication status (heartbeat)
- Communication status (other than heartbeat, for example, WiFi signal presence)
- Gas levels—H_2, hydrocarbons, O_2, CO
- Door/intrusion/motion detection
- Ventilation/deflagration vent status
- Insulation/isolation faults (ground faults)
- Uninterruptible power supply availability
- Low SOC/remaining duration
- Balancing (SOC, rate of balancing)
- BMS errors (read errors, comms loss)
- PCS temperature
- PCS connection/mode
- Suppression release
- Trouble status

9.6 Alarm Response

Combining the roles and possible scenarios created in a typical framework yields a sample matrix that starts with possible actions that stem from a hazard indication to the possible responses and justification for the response, as shown in Table 9-1. It should be noted that this matrix is for information purposes only.

Table 9-1
Alarm Management Matrix

	Possible Responder						Possible Response						
Action	Operator	Vendor	SME	General Public	Site Employee	Fire Service	Automated	Manual Remote	Manual Local	Design Consideration	Benefit	Concern/Hazard	When to Use
Pause Operations - terminate discharge or charge, exit any bidding process, place BESS in 'standby'	X						X	X	X	A prominent 'suspend service' or 'standby' button or switch could be made available in the site controller HMI. Exact solution could be implemented differently depending on site hardware and software	Situational Awareness, "Size-up situation"	Loss of revenue or service	Alarm condition identified, prior to presence of hazard
Review Data - Manually analyze an event or performance anomaly that poses concern	X	X	X		X	X		X	X	Sufficient data resolution, frequency, and history should be logged. Database should be large enough and flexible enough to quickly poll results as discussed in the Data Guide	Situational Awareness, "Size-up situation"	Anomalies may be overlooked, or pattern may appear when not actually correlated	Continuously, and especially when operations are paused due to anomaly
Soft Shutdown - Execute an automated sequence that ramps delivered power to zero and opens key power disconnects, breakers, and contactors	X				X		X	X	X	A separate button or switch could be made available in the site controller HMI to ramp power to zero and initiate proper shutdown sequences.	Controlled de-energization of the cables, bus work, inverters, and switchgear; removal of hazard from electricity alone	Controls may be inoperable, or alarm condition may be too urgent to wait; hazard may be present even without electrical connection	Alarm condition is identified but before personnel or equipment are exposed to immediate danger

Table 9-1 (continued)
Alarm Management Matrix

Stand Back - evacuate all personnel to a predefined distance from the alarming equipment	X	X	X	X	X	X			X	Hazard assessments and test results should inform safe distances. Bollards, fences, barriers, or other markers could be placed at known safe distances. Signs with maps may provide wayfinding to muster points or other general points of interest.	Remove personnel from exposure to hazard(s)	Manual intervention may be needed to avoid loss of equipment	Hazard is present or imminent, posing risk of exposure to personnel - several radii as well as a separate muster point may be defined to address varying hazards
Alert Vendor - contact supplier of equipment suspected at the root of the alarm condition	X		X			X	X	X	X	Databases could be designed for efficient selection and export of key data to inform vendor, per their recommended data requirements. Contact information could be located in signage at strategic site locations.	Seek product-specific technical information	Vendor may be unaware of site-specific conditions or unable to help in the desired timeframe	Alarm condition is identified but before personnel or equipment are exposed to immediate danger. Often used in conjunction with SME contact.
Alert SME - contact the resident subject matter experts as prescribed in NFPA 855 or other site-applicable code	X				X	X	X	X	X	Databases could be designed for efficient selection and export of key data to inform SME, per their recommended data requirements. Database access could be provided to SME. Contact information could be located in signage at strategic site locations.	Seek project or site-specific technical information	N/A	Alarm condition is identified but before personnel or equipment are exposed to immediate danger. Often used in conjunction with Vendor contact.

Table 9-1 (continued)
Alarm Management Matrix

Emergency Shutdown - actuate the control power disconnect or other "Emergency Power Off (EPO)" button	X			X		X			X	Hardwired trip signals could be wired to externally (and possibly, remotely) accessible emergency power off buttons installed at strategic locations (physical or via HMI) to immediately open primary power interconnections as well as auxiliary power loads. Backup power (UPS) should be considered for communications and critical support systems to maintain site awareness.	Immediate de-energization of the cables, bus work, inverters, and switchgear; removal of hazard from electricity alone.	Usually involves opening breakers, which may result in temporary surges or additional power electronics alarm or 'trouble' conditions; may remove power from critical communications systems	Hazard is present or imminent, posing risk of exposure to personnel - several radii as well as a separate muster point may be defined to address varying hazards
Fire Suppression - actuate internal fire suppression system or external manual application of suppressant	X					X	X	X	X	Fire suppression systems should be installed and maintained to code. Externally (and possibly, remotely) accessible fire suppression system actuation buttons could be installed at strategic locations (physical or HMI) with time delay to avoid nuisance triggers. Consideration should also be given to exhaust ventilation systems to reduce explosion risk based on updated codes and standards guidance	Removal of heat, oxygen, and/or flame to inhibit continued fire	Some suppressants are conductive and may contribute to electrical faults; some suppressants may be insufficient to address thermal runaway fires	Incipient fire is identified (smoke, heat, IR detection) and 'letting it burn' is not an option
Alert Local First Responders - contact local emergency services (Fire Service/Rescue/911)	X			X	X			X	X	Fire panels could be networked to each other and to auto dialer or pre-programmed phones ("red phones"). Signage could include key points of contact at local authorities.	Seek fire, explosion, and/or HAZMAT-trained personnel to conduct prevention and mitigation activities	Local first responders may not be familiar with site specific hazards	Hazard is present or imminent, fire is visible, or personnel are either in danger or have been exposed to hazard.

9.7 Prioritization

Prioritization of alarms requires a thorough assessment through the alarm management framework and may be further refined using the MESA architecture. This carries three levels of priority, and embedded sensors or indicators can be mapped as an option to these priority points.

Relying on sensors alone may not be sufficient to detect hazardous situations. It is important to note the difference between monitoring discrete sensors versus monitoring trends that may be computationally derived. These trends can potentially indicate situations that can be ameliorated before a hazard situation arises. This would include off-normal temperature and voltage and current fluctuations, as well as higher-than-normal cell balancing.

10
DC POWER QUALITY

Traditionally, solar or ESS have been composed of a solar array or battery coupled directly to an inverter. While AC power quality concerns did and do occur with these arrangements, DC power quality concerns have not typically been considered in such systems due to PV modules or batteries presenting a relatively constant impedance to the inverter.

However, improved efficiency, lower interconnection costs, and regulatory considerations have driven some integrators toward DC-coupled topologies where more than one source is coupled to a single inverter, generally using one or more DC:DC converters. Increasing utilization of DC coupling for some flow-based storage or hybrid ESS, such as solar plus storage, is creating greater complexity. DC coupling is also becoming prevalent in electric vehicles (EVs) and other industries.

Solar or storage inverters are power converters that have not historically been designed to interface with active sources such as DC:DC converters. Typically, inverters have been connected to passive components such as PV modules on one side and a transformer with known impedance on the other. But where converters are coupled and regulated, they become constant power loads and may present negative impedance characteristics that can destabilize control functions and lead to resonance. As a result, negative impedance instability or other resonances can occur where converters are connected. Interactions between converters can occur in multi-converter renewables architectures and industrial motor drives but perhaps are best known in the EV space.

Undesirable resonances in multi-converter DC systems are, at their core, stability issues. In some cases, these issues may lead to instability, in which case the magnitude of oscillation increases until hardware or firmware limits are exceeded. This can result in equipment damage and/or nuisance tripping. Perhaps more problematically, resonant behaviors may lead to a marginally stable state in which oscillation persists at a constant magnitude. If the magnitude of the resonance never reaches the trip threshold of protective devices, these issues may remain permanently undetected. High-frequency oscillations reduce system efficiency and decrease component reliability. Additionally, these resonances can propagate to or from the AC side connection of a system, negatively impacting grid power quality. Such issues may remain undetected in commercial systems if inverter tripping does not occur, but may yield lower than expected efficiency, reduced component life, and undesirable grid power quality.

The underlying phenomena responsible for stability issues in multi-converter DC systems are well-known in the specific power quality arena, and a variety of effective strategies for mitigating their influence are available in the literature. Impedance-based stability criteria are a well-established family of methods for predicting, describing, and mitigating undesirable interactions between converters.

Despite the maturity in this area of DC system stability theory, addressing emergent stability issues in the field remains challenging. Accurate knowledge of converter and system impedances, obtained either from model-based expressions or empirical measurements, is required to apply impedance-based stability criteria. These criteria are most easily employed when, for example, a multi-converter system is being designed from the ground up with full knowledge of constituent converter topologies, control structures, and gain parameters. In practice, this depth of information is not always available. This is particularly true in the emerging area of DC coupled systems for grid-tied storage and distributed resources, where complex multi-converter structures are assembled from general purpose power conversion devices by a system integrator. When problematic interactions appear during integration, their root cause is often obscured by a “black box” representation of the converters, complicating the diagnosis of the issue.

New tools, both in terms of instrumentation and computational methods, are needed to support the detection, identification, and resolution of DC power quality issues in the field. Because resonant behaviors commonly involve high frequency modes of oscillation, detecting and understanding these issues require very granular data capture, large amounts of data storage capability, and powerful analytic tools.

Oscilloscopes are typically used to troubleshoot and understand issues with electronics and power systems. The high sampling rate offered by oscilloscopes (and some high-end meters) enables viewing of very granular data. However, this sampling rate produces data at a much higher rate than can be transferred by Modbus or other traditional meter data transmission protocols.

Additionally, traditional data logging solutions simply collect and transmit time-averaged data back to an enterprise location where post-processing may take place using database and other tools. Oscilloscopes often conduct data storage and processing within the oscilloscope tool itself but are not typically designed for permanent installation and long-term data capture or export to traditional field data logging systems. Due to the high data bandwidth resulting from high sampling rates of numerous channels, it may be advisable to process this data output on site and transmit only desired segments and post-processing data.

To address emerging DC power quality measurement needs in a cost-efficient and effective manner, EPRI is investigating an array of new components that can be permanently field-placed and allow for ongoing analysis as compared to relatively expensive and temporary placement of traditional oscilloscopes. These components include novel, very compact meters designed for advanced and high-resolution power quality measurement with an open-source web interface that can provide substantial post-processing.

Additionally, fast Fourier transformation (FFT) on-site analysis can save transmitted data bandwidth. This technique can help analyze ripple on DC circuits or harmonics on AC circuits at the site without burdening outgoing communication channels. FFT functionality is currently available from inexpensive hardware, and open-source software already exists. Another application of FFT is the capture and analysis of current steps that permit impedance calculations for cell degradation evaluation. With on-site processing, only limited indicators need to be exported to remote operators who can then trigger on-site manual downloads of detailed data. These low-cost approaches to detection and on-site processing are being investigated for ease of incorporation into distributed resource control panels, accuracy, and cost-efficiency.

An alternative approach is to integrate system identification and adaptive control capabilities into power converter firmware. All modern utility-scale power converters perform high-speed local voltage and current sensing as part of a feedback path for closed-loop control systems. These measurements provide all the information necessary to accomplish permanent on-site power quality monitoring without requiring any additional hardware. Additionally, this approach would empower the converter to adjust its control parameters on-line in response to developing power quality issues. This could be as simple as changing controller gains to manipulate closed-loop output impedance or engaging an active damping control scheme to suppress current and voltage oscillations. However, if the vendor does not allow access to these data, independent measurement and analysis may be necessary.

11 CONCLUSION

While this proposed procedure for providing data does not guarantee a perfect analysis, it serves as a starting point to enable quality data analysis of ESS. Ultimately, if the data are collected in a consistent manner across a large number of storage systems, accurate evaluation and comparison will be possible and allow for even more efficient integration of energy storage technologies.

Robust data, provided via these guidelines, can benefit all stakeholders and facilitate meaningful analysis and independent verification of storage performance. This analysis capability can lead to impactful conclusions that help improve the performance of ESS as well as improve O&M practices. As noted throughout this guideline, there are numerous areas that need more research. Numerous activities will help inform subsequent versions, including sessions under the auspices of EPRI's ESIC and IEEE Energy Storage and Stationary Battery (IEEE ESSB) Committee. These forums are open to all, and information on participation can be found at www.epri.com/esic or www.ieee.org.

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A

DER FUNCTIONS

A.1 Table

A list of the most common DER operational functions is shown in Table A-1. The table also indicates where the operational functions are described in the EPRI Common Functions report and the current edition of IEC 61850-7-420. In addition, it indicates which operational functions are mandatory in different jurisdictions.

Table A-1
DER Operational Functions from the Second Edition of IEC 61850-7-420 (Pending Release)

#	Operational Function	Description and Key Parameters	IEEE 1547: 2018	EN 50549 (Europe)	IEC 61850-7-420
	Basic Capabilities				
1.	**Retrieve Nameplate Values**	Nameplate values from the factory are retrievable	Included		
2.	**Retrieve and Update Operational Settings**	Operational settings, based on installed configurations and on all operational changes, are retrievable. If authorized, operational settings may also be updated.	Included		
3.	**Monitoring Function** The DER provides nameplate, configuration, status, measurements, and other requested data	The DER provides status, measurements, alarms, logs, and other data as authorized and requested by users. Examples include connect status, updated capacities, real and reactive power output/consumption, state of charge, voltage, and other measurements. Also of interest are forecast status and expected measurements.	Communications capability mandated for all DER (not necessarily implemented in all DER) Monitoring where needed is mandatory		
	Grid Code Operational Functions				
4.	**Disconnect/Connect Function** Disconnect or connect the DER from the grid at its ECP	The disconnect command initiates the galvanic separation (usually via switches or breakers) of the DER at its ECP or at the PCC. There may be a time delay between receiving the command and the actual disconnect The connect command initiates or allows the reconnection of the DER at its ECP or at the PCC. A permission to reconnect may also be issued.	Either galvanic disconnect or cease-to-energize	All Types of DER For type A, only an interface is requested for disconnection	LN **DGEN,** LN **DSTO,** LN **DLOD** and/or LN **CSWI** LN **XCBR** LN **XSWI**

Table A-1 (continued)
DER Operational Functions from the Second Edition of IEC 61850-7-420 (Pending Release)

#	Operational Function	Description and Key Parameters	IEEE 1547: 2018	EN 50549 (Europe)	IEC 61850-7-420
	Grid Code Operational Functions (continued)				
5.	**Cease-to-energize and Return to Service** The DER ceases all active power output Allow active power output at the PCC	"Cease-to-energize" is a different function from disconnect/connect. The (draft) definition is "the DER shall not export active power during steady-state or transient conditions. Reactive power exchange (absorb or supply) shall be less than x % of nameplate DER rating and shall exclusively result from passive devices.". There may be a time delay between receiving the command and the actual cease-to-energize. "Return to service" allows current flow at the PCC. A permission to return to service may also be issued.	Either galvanic disconnect or cease-to-energize at the PCC	Type A and B only of DER – cease active power output within 5 seconds, following an instruction being received at the input port Type A may disconnect randomly	LN **DCTE**
6.	**High/Low Voltage Ride-Through Operational Function** The DER rides through temporary fluctuations in voltage	The DER follows the utility-specified voltage ride-through parameters to avoid tripping off unnecessarily. The function would block tripping within the fault ride-through zones. Although normally enabled by default, this ride-through operational function may be updated, enabled, and disabled.	H/LVRT is mandatory for all DER	Fault ride-through is mandatory for all generators starting type B and larger generators,	LN **DVHT**, LN **DVLT** LN **PTOV**, LN **PTUV**, LN **PTRC**
7.	**High/Low Frequency Ride-Through Operational Function** The DER rides through temporary fluctuations in frequency	The DER follows the utility-specified frequency ride-through parameters to avoid tripping off unnecessarily. The function would block tripping within the fault ride-through zones. Although normally enabled by default, this ride-through operational function may be update, enabled, and disabled.	H/LFRT is mandatory for all DER	no mention, except the fact that facilities must remain operational within an "extended" frequency range from 47 to 52 Hz (exact range may depend on European synchronous zone)	LN **DFHT**, LN **DFLT**, LN **PTOF**, LN **PTUF**, LN **PTRC**
8.	**Dynamic Reactive Current Support Operational Function** The DER reacts against rapid voltage changes (spikes and sags) to provide dynamic system stabilization dV/dt	The DER provides dynamic reactive current support in response to voltage spikes and sags, similar to acting as inertia against rapid changes. This operational function may be focused on emergency situations or may be used during normal operations. When the dynamic reactive current support operational function is enabled, the DER monitors the voltage at the Referenced ECP and responds based on the parameters.	Is included as optional but may become mandatory	No direct mention Synthetic inertia is requested starting Class C. Reactive power injection in case of grid fault is requested starting class B, upon TSO request. Also requested for transmission connected facilities	LN **DRGS**

Table A-1 (continued)
DER Operational Functions from the Second Edition of IEC 61850-7-420 (Pending Release)

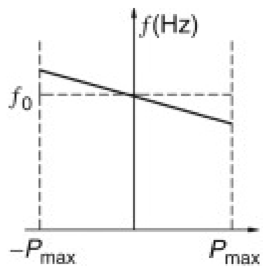
#	Operational Function	Description and Key Parameters	IEEE 1547: 2018	EN 50549 (Europe)	IEC 61850-7-420
	Grid Code Operational Functions (continued)				
9.	**Frequency-Droop Operational Function (Primary Frequency Control)** The active power output of a generator decreases (increases as the line frequency increases (decreases) from nominal frequency	Droop is a control mode used for generators to maintain the frequency within the normal operating zone, focused on returning the frequency to its nominal value. Specifically, the active power output of a generator reduces as the line frequency increases above nominal frequency, and vice versa, based on a curve such as illustrated below. 	Mandatory for all DER		LN **DHFW,** LN **DLFW**
10.	**Volt-Watt Operational Function** The DER responds to changes in the voltage at the Referenced ECP by changing its production or consumption rate	The DER is provided with voltage-watt curves that define the changes in its watt output based on voltage deviations from nominal, as a means for countering those voltage deviations. When the volt-watt operational function is enabled, the DER receives the voltage measurement from a meter (or another source) at the Referenced ECP. The DER adjusts its production or consumption rate to follow the specified volt-watt curve parameters.	Mandatory for all DER		LN **DVWC**
11.	**Fixed (Constant) Power Factor Operational Function** The DER power factor is set to a fixed value.	The DER power factor is set to the specified power factor. A leading power factor is positive and a lagging power factor is negative, as defined by the IEEE or IEC sign conventions.	Mandatory for all DER	For Type C & D DER, the ability to adjust reactive power, automatically by either voltage control operational function, reactive power control operational function or power factor	LN **DFPF**

Table A-1 (continued)
DER Operational Functions from the Second Edition of IEC 61850-7-420 (Pending Release)

#	Operational Function	Description and Key Parameters	IEEE 1547: 2018	EN 50549 (Europe)	IEC 61850-7-420
	Grid Code Operational Functions (continued)				
12.	**Fixed (Constant) Reactive Power Operational Function** The DER is requested to provide a fixed amount of reactive power	The DER is requested to provide a fixed amount of reactive power	Mandatory for all DER		LN **DVAR**
13.	**Volt-VAr Control Operational Function** The DER responds to changes in voltage at the Referenced ECP by supplying or absorbing reactive power in order to maintain the desired voltage level	The DER is provided with voltage-var curves that define the reactive power for voltage levels. When the volt-var operational function is enabled, the DER receives the voltage measurements from a meter (or another source) at the Referenced ECP. The DER responds by supplying or absorbing reactive power according to the specified volt-var curve in order to maintain the desired voltage level.	Mandatory for all DER	For Type C & D DER, the ability to adjust reactive power, automatically by either voltage control operational function, reactive power control operational function or power factor	LN **DVVR**
14.	**Watt-VAr Operational Function** The DER responds to changes in power at the Referenced ECP by changing its reactive power	The DER is provided with watt-var curves that define the changes in its reactive power-based changes of power. When the watt-var operational function is enabled, the DER modifies its reactive power setting in response to the power level at the Referenced ECP.	Mandatory for all DER	German LV Grid Codes VDE-AR-N4105	LN **DWVR**
15.	**Watt-PF Operational Function** The DER responds to changes in power at the Referenced ECP by changing its power factor	The DER is provided with watt-PF curves that define the changes in its power factor-based changes of power. When the watt-PF operational function is enabled, the DER modifies its PF setting in response to the power level at the Referenced ECP.			LN **DWPF**
16.	**Set Active Power Operational Function** Set the DER to generate or consume energy as a percentage of maximum capability	The DER is set to a percentage of maximum generation or consumption rate. A positive value indicates generation, negative means consumption.			LN **DWGC**

Table A-1 (continued)
DER Operational Functions from the Second Edition of IEC 61850-7-420 (Pending Release)

#	Operational Function	Description and Key Parameters	IEEE 1547: 2018	EN 50549 (Europe)	IEC 61850-7-420
	Grid Code Operational Functions (continued)				
17.	**Limit Active Power Production or Consumption Operational Function** Limits the production and/or consumption level of the DER based on the Referenced ECP	The production and/or consumption of the DER is limited at the Referenced ECP, indicated as absolute watts values. Separate parameters are provided for production or consumption limits to permit these to be different.	Mandatory for all DER		LN **DWMN**, LN **DWMX**
18.	**Frequency-Active Power Operational Function (Frequency Sensitivity)** The DER responds to frequency excursions beyond the normal frequency range by changing its production or consumption rate	The frequency sensitivity function responds to abnormal events when the frequency exceeds its normal range. events by following frequency-active power curves that define the changes in its active power output. Its purpose is to bring abnormally high or low frequency back within the normal range.	Expected for larger DER but not mandatory	Over frequency "Frequency Sensitive Operational function (FSM)" is mandatory for all DER types. Underfrequency is requested starting class C Maximum power decrease in case of frequency decrease is specified and should be respected by all DER	LN **DHFW**, LN **DLFW**
19.	**Low Frequency-active power Emergency Operational Function** for demand side management (fast load shedding)	Enable automatic *low frequency* disconnection of a specified proportion of their demand (in stages) in a given time frame.	Not mentioned explicitly in IEEE 1547 which does not cover loads, but expected to be available		---
20.	**Low Voltage-Watt Emergency Operational Function** for demand side management	Provide capabilities to … enable automatic or manual load tap changer blocking and automatic *low voltage* disconnection.	Not mentioned explicitly in IEEE 1547 which does not cover loads, but expected to be available		---
21.	**Scheduling of Power Settings and Operational Functions**	The DER follows the schedule which consists of a time offset (specified as a number of seconds) from the start of the schedule and is associated with: a power system setting the enabling/disabling of a function a price signal	Becoming important for California and Hawaii, but not mandatory		LN **FSCH** LN **FSCC**

Table A-1 (continued)
DER Operational Functions from the Second Edition of IEC 61850-7-420 (Pending Release)

#	Operational Function	Description and Key Parameters	IEEE 1547: 2018	EN 50549 (Europe)	IEC 61850-7-420
	Non-Grid Code Operational Functions				
22.	**Peak Power Limiting Operational Function** The DER limits the load at the Referenced ECP after it exceeds a threshold target power level	The active power output of the DER limits the load at the Referenced ECP if it starts to exceed a target power level, thus limiting import power. The production output is a percentage of the excess load over the target power level. The target power level is specified in absolute watts.			LN **DPKP**
23.	**Load Following Operational Function** The DER counteracts the load by a percentage at the Referenced ECP, after it starts to exceed a threshold target power level	The active power output of the DER follows and counteracts the load at the Referenced ECP if it starts to exceed a target power level, thus resulting in a flat power profile. The production output is a percentage of the excess load over the target power level. The target power level is specified in absolute watts.			LN **DLFL**
24.	**Generation Following Operational Function** The consumption and/or production of the DER counteracts generation power at the Referenced ECP.	The consumption and/or production of the DER follows and counteracts the generation measured at the Referenced ECP if it starts to exceed a target power level. The consumption and/or production output is a percentage of the excess generation watts over the target power level. The target power level is specified in absolute watts.			LN **DGFL**
25.	**Dynamic Active Power Smoothing Operational Function** The DER produces or absorbs active power in order to smooth the changes in the power level at the Referenced ECP. Rate of change of power – dW/dt	The DER follows the specified smoothing gradient which is a signed quantity that establishes the ratio of smoothing active power to the real-time delta-watts of the load or generation at the Referenced ECP. When the power smoothing operational function is enabled, the DER receives the watt measurements from a meter (or another source) at the Referenced ECP. New data points are provided multiple times per second.			LN **DWSM**

Table A-1 (continued)
DER Operational Functions from the Second Edition of IEC 61850-7-420 (Pending Release)

#	Operational Function	Description and Key Parameters	IEEE 1547: 2018	EN 50549 (Europe)	IEC 61850-7-420
	Non-Grid Code Operational Functions (continued)				
26.	**Automatic Generation Control (AGC) Operational Function (Secondary Frequency Control)** The DER responds to raise and lower power level requests to provide frequency regulation support	When AGC operational function is enabled, the DER responds to signals to increase or decrease the rate of consumption or production every 4 to 10 seconds, with the purpose of managing frequency.			LN **DAGC**
27.	**Operating Reserve (Spinning Reserve) operational function (Tertiary Frequency Control)** The DER provides operating reserve	The DER can provide reserve power that is available within about 10 minutes			—
28.	**Synthetic or Artificial Inertia Frequency-Active Power Operational Function** The DER responds to the rate of change of frequency (ROCOF) by changing its active power production (or consumption) to counteract rapid changes (spikes and sags) df/dt	The DER responds to the rate of change of frequency (ROCOF) by changing its active power production (or consumption) to counteract rapid changes. Its purpose is to smooth (spikes and dips) based on df/dt. It does not act to return the frequency to nominal frequency.			LN **DHFW,** LN **DLFW**
29.	**Coordinated Charge/Discharge Management Operational Function** The DER with storage capability determines when and how fast to produce or consume energy so long as it meets its target state of charge (SoC) obligation by the specified time	The DER is provided with a target state of charge and a time by which that SoC is to be reached. This allows the DER to determine when to charge or discharge based on price or other considerations. The DER takes into account not only the duration at maximum consumption / production rate, but also other factors, such as that at high SoC the maximum consumption rate may not be able to be sustained, and vice versa, at low SoC, the maximum discharge rate may not be able to be sustained			LN **DTCD**

Table A-1 (continued)
DER Operational Functions from the Second Edition of IEC 61850-7-420 (Pending Release)

#	Operational Function	Description and Key Parameters	IEEE 1547: 2018	EN 50549 (Europe)	IEC 61850-7-420
	Non-Grid Code Operational Functions (continued)				
30.	**Power Factor Limiting (Correcting) Operational Function** The DER supplies or absorbs Reactive power to hold the power factor at the Referenced ECP within the PF limit	When the PF limiting (correcting) operational function is enabled, the DER is provided with the target PF. The DER supplies or absorbs reactive power in order to maintain the PF at the Referenced ECP within the limits of the target PF.			LN **DPFC**
31.	**Delta Power Control Function** Decrease active power output to ensure there remains spinning reserve amount that was bid into the market	Decrease active power output to ensure there remains spinning reserve amount that was bid into the market			—
32.	**Power Ramp Rate Control** The power increases and decreases are limited by specified maximum ramp rates	Manage active power ramp time, when the active power should be at the required power level by the end of the ramp time. It may reach the required power level earlier, but not later.			—
33.	**Dynamic Volt-Watt Function** Dynamically absorb or produce additional watts in proportion to the instantaneous difference from a moving average of the measured voltage	Dynamically absorb or produce additional watts in proportion to the instantaneous difference from a moving average of the measured voltage. This function utilizes the same basic concepts and settings as the Dynamic Reactive Current function but uses active power as an output rather than reactive current.			—
	Non-Functional Capabilities				
34.	**Collect and Provide Historical Information**	Collect and provide detailed measurement and performance data which may be valuable to record in an operational historian			LN **MMXU** plus PV, Wind, CHP, Fuel Cell, Battery detailed LNs
35.	**Establish Different Ramp Rates for Different Purposes**	In addition to the default ramp rate, the DER may support multiple ramp rates that reflect different conditions. This function was defined in California's Rule 21 Phase 1 requirements.	Relevant ramp rates or ramp times are included in each operational function		Per function

Table A-1 (continued)
DER Operational Functions from the Second Edition of IEC 61850-7-420 (Pending Release)

#	Operational Function	Description and Key Parameters	IEEE 1547: 2018	EN 50549 (Europe)	IEC 61850-7-420
	Non-Functional Capabilities (continued)				
36.	**Soft-Start Return to Service**	Use ramp rate and/or random time within window when reconnecting. This function was defined in California's Rule 21 Phase 1 requirements.	Using open loop response times rather than ramp rates	"Ensuring appropriate reconnection", including random reconnect time windows	LN **DCTE**
	Capabilities Not Yet Fully Defined				
37.	**Microgrid Separation Control (Intentional Islanding)**	Process for normal separation, emergency separation, and reconnection of microgrids. These microgrids could be individual facilities or could be multiple facilities using Area EPS grid equipment between these facilities.	Separation requirements are identified, but not fully described for intentional (microgrid) and unintentional islanding	Type C & D shall be capable of taking part in island operation if required by the relevant system operator	—
38.	**Microgrid Management**	Planning for and managing islanded microgrids with grid forming and grid following DER			—
39.	**Provide Black Start Capability**	Ability to start without grid power, and the ability to add significant load in segmented groups		Not mandatory, but requirements are expected to be discussed	—
40.	**Provide Backup Power**	Ability to provide power automatically to local loads after an outage or when these loads are not connected to the grid. In common configurations, backup power might consist of an Uninterruptible Power System (UPS) plus diesel generator. In more modern configurations, backup power might consist of PV+storage systems.			—

A.2 Control and Communication Architectures

Figure A-1 is an overall diagram of DER architecture, including all the possible communication interactions with different stakeholders. It highlights the numerous stakeholders and systems that need data, particularly if storage is just one DER within a facility or microgrid.

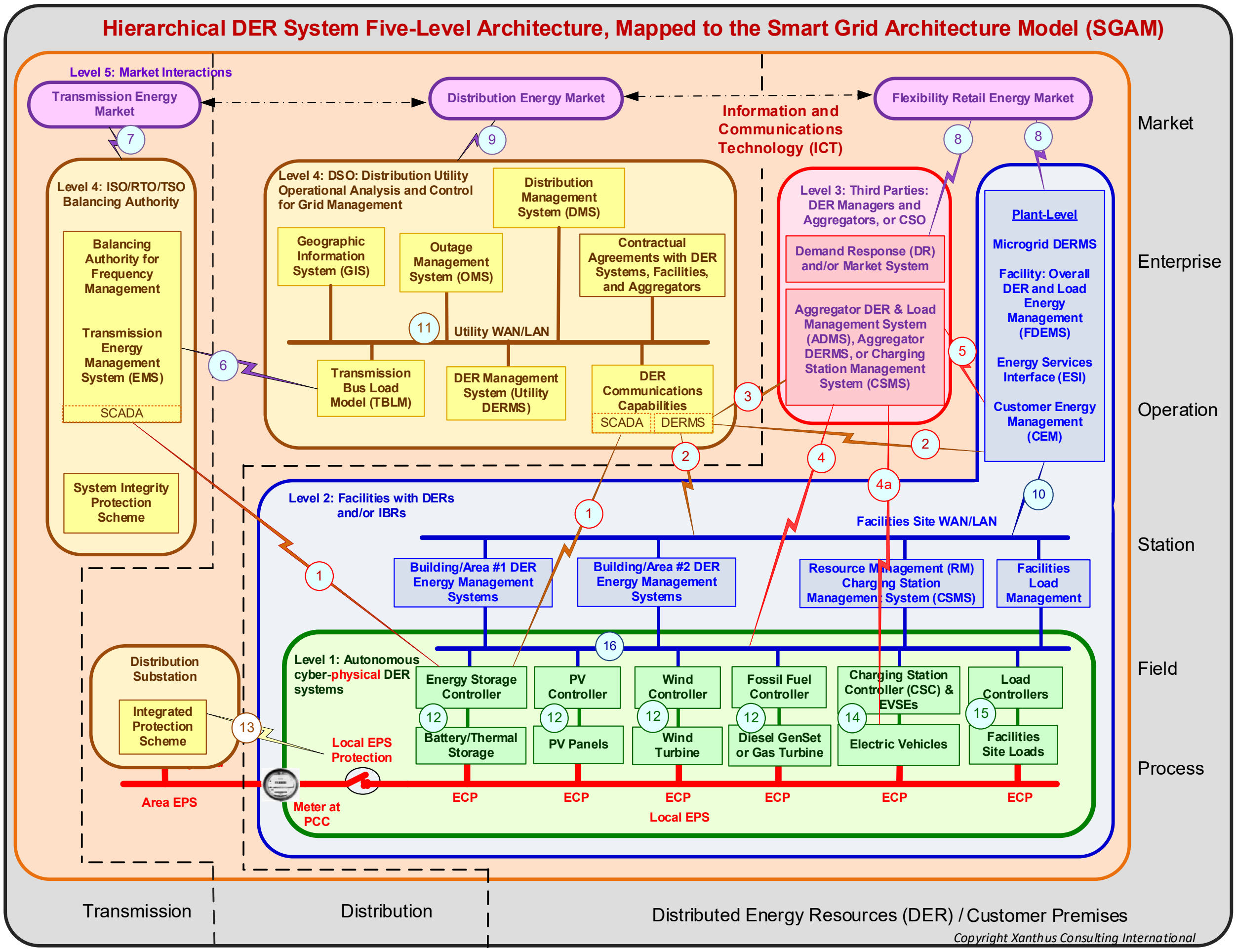


Figure A-1
Detailed Data and Control Architectures

Figure A-2 is an overview of the MESA "de facto" standard, built on IEC 61850, DNP3, and SunSpec Modbus. There are hundreds of data points in the MESA-DER and SunSpec Modbus device models.

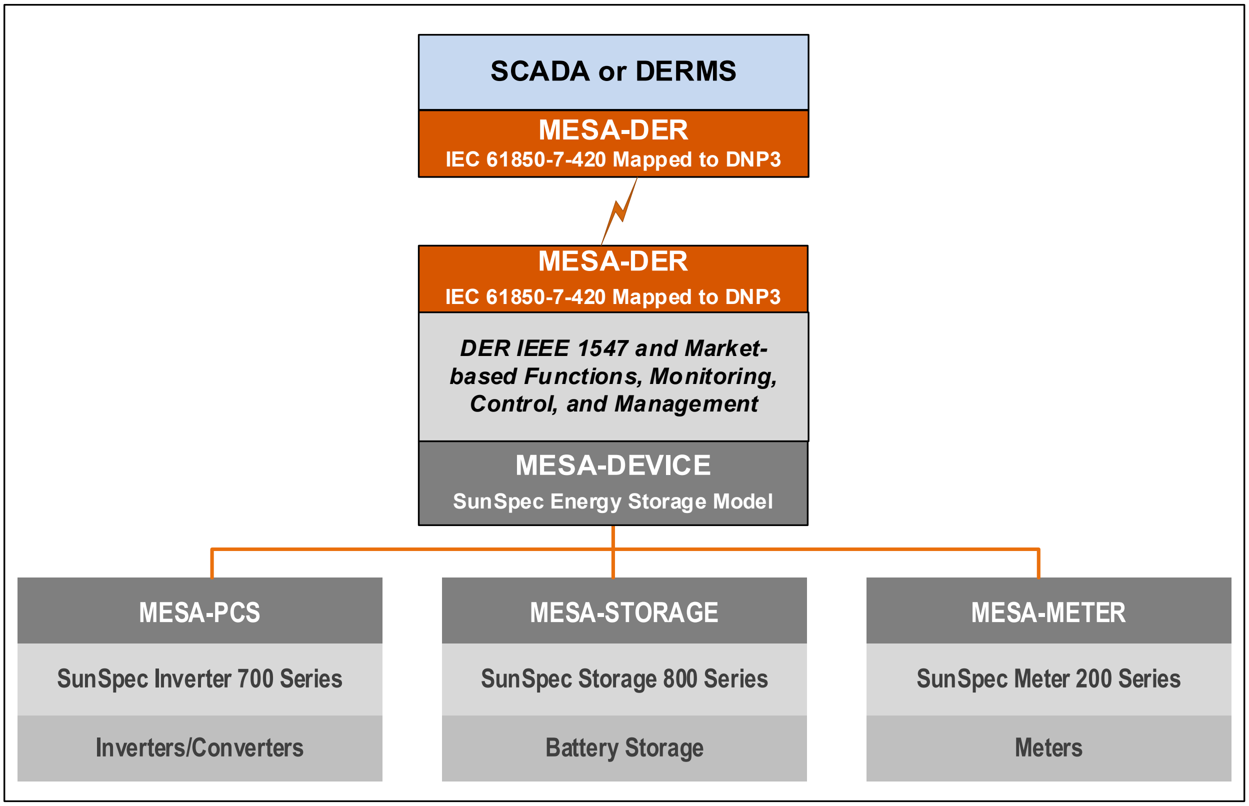


Figure A-2
MESA Standard

The Electric Power Research Institute, Inc. (EPRI, www.epri.com) conducts research and development relating to the generation, delivery and use of electricity for the benefit of the public. An independent, nonprofit organization, EPRI brings together its scientists and engineers as well as experts from academia and industry to help address challenges in electricity, including reliability, efficiency, affordability, health, safety and the environment. EPRI also provides technology, policy and economic analyses to drive long-range research and development planning, and supports research in emerging technologies. EPRI members represent 90% of the electricity generated and delivered in the United States with international participation extending to nearly 40 countries. EPRI's principal offices and laboratories are located in Palo Alto, Calif.; Charlotte, N.C.; Knoxville, Tenn.; Dallas, Texas; Lenox, Mass.; and Washington, D.C.

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3002022119

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