GMLC Survey of Distributed Energy Resource Interconnection and Interoperability Standards

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Abstract

This document reports on the Grid Modernization Laboratory Consortium effort to identify gaps in standards for the interconnection and interoperability of distributed energy resources (DERs). The project extended over a 3-year period from 2017 to 2019. Under the work plan, the team identified standards and test procedures related to interconnection and interoperability grouped under the broad headings of the primary applicable technology domain: automotive, responsive loads, photovoltaic inverters, inverter-based energy storage, machine-based DERs, and microgrids. The team then conducted a gap analysis by comparing the current standards to the expected future requirements needed for specific grid services. Overall, gaps could be any activity needed to harmonize requirements among standards development organizations, to minimize conflicting requirements among technology domains, or to streamline conformance test procedures.

Summary

A modern grid requires robust levels of device and system interconnectivity through predictable integration that is supported by reliable methods of testing and product certification. Distributed energy resources (DERs)—including generation, storage, and connected responsive loads—must provide a range of services as part of an integrated architecture that supports the physical grid architecture. The use of open, standard, and highly interoperable communications protocols is essential to the effective deployment of these devices. These standards also help support and enable various technologies to interact with each other and the grid to optimize solutions among multiple objectives. There is a desire to make the grid more reliable, resilient, and secure. This includes the ability to have faster recovery after a storm and to serve customer needs even if a key resource goes offline because of a failure or a cyber-physical attack.

Many definitions of DERs exist in the current literature. Typically, these refer to well-known power generation and storage, such as utility-scale[1] wind and solar power plants as well as rooftop residential solar photovoltaic (PV) systems and batteries. For this study, DERs include these as well as any loads whose energy consumption can be modulated (i.e., "responsive loads"). For example, electric vehicles (EVs); heating, ventilating, and air-conditioning systems; lighting; and household appliances are included because they all have the potential to provide grid services. The other commonality among all these devices is that DERs are connected at the local electric distribution level rather than to the subtransmission or transmission network. Most small- to moderate-sized DERs are not typically controlled or dispatched from the central grid operator but instead provide or consume power at the point of common coupling to the grid. The result is a grid architecture that is evolving from the original central-station design and is becoming increasingly challenging to manage.

The emergence of DERs requires revising the old model of grid dispatch and control to allow for coordination of these additional assets to deliver grid services. Innovations introduced by information and communications technologies can enable future electric grids to be more flexible in operation, to connect resources, and to provide a series of new services. Proper integration and coordination are expected to result in the more effective use of grid-connected assets and lead to improved reliability and reduced capital and operating costs. For example, an integrated and controlled grid could allow for a distribution network to better manage the variability of solar and wind plants, thus enabling the effective use of existing resources, a reduced need for building new resources, and fewer spinning reserves.

Much work has been done to develop interconnection and interoperability standards and to define how to connect devices to form a "smart" or "modern" grid. A major challenge is that standards are typically developed within each technology domain and without a complete vision for how the parts must interact from one end to another to deliver grid services. On their own, standards could be technically robust and meet the needs within a domain, but they might not support the emerging grid services to enable these services to be cost-effective, reliable, and interoperable.

[1] Note: The term *utility-scale* is not clearly defined. The intent here is to illustrate that DER capacity could range from a few kilowatts to many megawatts.

This Grid Modernization Laboratory Consortium (GMLC) project aimed to evaluate key standards across multiple domains and considered the challenges posed by the interconnection, interoperability, and testing of DERs. A project goal was to identify gaps that prevent the effective management of DER grid services. Overall, gaps could be any activity needed to harmonize requirements among standards development organizations, to minimize conflicting requirements among technology domains, or to streamline conformance test procedures. The project team then mobilized to help fill the gaps by assisting in the development and validation of needed interconnection and interoperability standards and test procedures for these DERs to perform certain key grid services either individually or collectively.

Project team members provided direct input to standards development efforts under various working group efforts across multiple standards development organizations.

Grid services are high-level functions provided at the distribution and transmission grid interface. To provide these higher level functions, different technology types could be aggregated so that they are collectively performing the same core function at an optimum level of performance at the total overall cost. At the lowest level of local devices, the desired grid service must be mapped to specific lower level functions (e.g., increase or decrease active power).

New grid services are being considered to create a more flexible and resilient system that allows for better the integration of renewables, responsive loads, and other distributed resources and increases flexibility between the grid and its connected loads. This project used a subset of grid services from GMLC project 1.4.2, “Definitions, Standards, and Test Procedures for Grid Services from Devices.”

Energy-Related Grid Services (Peak Load Management, Energy Cost, Supply Capacity)

These services reduce the net load when prices are high, and any associated increases in net load take place when prices are low. To perform any of these services, distributed generation and storage will increase or reduce active power being provided to the grid, EVs will increase or reduce their charging rate, and building loads (or their energy management systems) will change set points to increase or decrease energy consumption.

Regulation-Related Grid Services (Frequency Regulation, Spinning Reserve, Ramping)

Regulation-related grid services are energy products that are used to help maintain grid stability and reliability. At present, there are four types of regulation-related grid services products: regulation up, regulation down, spinning reserve, and non-spinning reserve. Ramping (load following) is a newer service developed to address renewables’ variability on the grid, representing steep ramps, either up or down. To perform any of these services, distributed generation and storage will increase or reduce active power being provided to the grid, EVs will increase or reduce their charging rate, and building energy management systems will change set points to increase or decrease energy consumption by any connected loads or generation. For these scenarios, the devices generally must respond faster than in energy-related grid services.

Distribution Voltage Regulation

The objective of this service is to maintain distribution system voltage within the normal range. To perform this service, distributed generation and storage will adjust functions such as volt/volt ampere reactive (VAR), power, fixed power factor, and volt-watt; EVs will adjust functions for volt-watt or volt/VAR; and building energy management systems will change set points to increase or decrease energy consumption by any connected loads or generation.

Inertial Response Grid Services

Traditional rotating machines help to stabilize bulk power system frequency and voltage by working together to serve the connected load. Changes in power demand will affect the rotating machine by causing a slight change in its speed. Load increase will decrease the machine's speed, and load decrease will increase the machine's speed. Changes in speed affect the bulk system frequency. Inertia helps to counteract the effect of variation in load. "Artificial" inertia is used to describe a capability of DERs that do not contain rotating machines to inherently provide inertia. An application of this service is to slow and arrest the otherwise precipitous change in frequency that begins instantly when a large grid asset (e.g., power plant or transmission line) or a similar load suddenly and unexpectedly trips offline and creates a large imbalance between supply and demand (Widergren et al. 2017). To create inertial response, nonrotating machine DERs will adjust functions such as frequency-watt, and building energy management systems will change set points to increase or decrease energy consumption by any connected loads or generation and adjust any variable-frequency motors.

Communications Framework

To provide a framework for discussing the functionalities referenced in the standards, the team has relied on the Open Systems Interconnection model and the "GWAC Stack," which is an extended communications protocol stack defined by the GridWise Architecture Council (GWAC) (GridWise 2019) and used by both the Smart Grid Interoperability Panel and the National Institute of Standards and Technology (NIST). To accommodate interconnection standards, a physical interconnection layer has been added to the GWAC Stack to represent the physical interconnection to an electric power system.

The NIST Smart Grid Interoperability Reference Model (NIST 2014) and the Institute of Electrical and Electronics Engineers (IEEE) Standard 2030-2011, *IEEE Guide for Smart Grid Interoperability of Energy Technology and Information Technology Operation with the Electric Power System (EPS), End-Use Applications, and Load*, were used as tools for identifying actors, devices, and possible communications paths that could be used in performing needed grid services.

Gap Prioritization for the Grid Modernization Laboratory Consortium Team

Given the breadth of technology areas and the multitude of related standards, a methodology to prioritize the identified gaps was developed by the GMLC team in the early stages of the project. A score that was based on four areas was determined: opportunity for impact, time to fill gap, locational urgency plus resource relevance, and technical difficulty. These areas were given a relative weight. The gap priority score was meant to show the higher relative short-term priorities. A higher score indicates a priority gap that should be addressed first and that:

- The opportunity for impact is large within 3–5 years.
- The time to fill the gap is very short (3–5 years).
- The locational urgency is great, and the resource is highly relevant to providing the required grid services.
- There are no technical barriers to overcoming the identified gaps.

Upon review, the GMLC team concluded that certain technologies had dependencies not only on these scoring criteria but also on the market development trajectory. This market development trajectory affects the rate that the standards gaps are closed (e.g., how much consumers are willing to pay for specific grid-service-related features in EVs). State and federal policies and regulations also have a direct impact on these market and technology trajectories. These factors were not directly considered in the gap analysis and did not contribute to the scoring criteria.

The prioritization exercise suggested that focusing efforts on the areas of inverter-based systems for energy, frequency regulation, ramping, and voltage management was the top priority, followed by grid-connected microgrids. To date, the use of responsive loads for these grid services has not reached its full potential. The use of EVs and EV supply equipment also could have high potential; however, this is still in the nascent stages of commercialization. The analysis presented here includes recommendations for how to consolidate or make equivalent interconnection and interoperability standards among all technologies. These recommendations could be used to inform organizations and working groups that are responsible for maintaining and updating the specified standards.

Much of the work needed to develop standards for moving to a modernized, smarter grid with broad support for grid services is already underway. The intent of this project was to support these developments through an intensive effort by multiple national laboratories.

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Acronyms and Abbreviations

ANSI	American National Standards Institute
CTA	Consumer Technology Association
DER	distributed energy resource
DERMS	distributed energy resource management system
DG	distributed generation
DNP3	Distributed Network Protocol 3
DOE	U.S. Department of Energy
DSO	distribution system operator
EIA	U.S. Energy Information Administration
EMCS	energy management and control system
ESI	energy services interface
ESI	energy services interface
ESS	energy storage system
EV	electric vehicles
EVSE	electric vehicle supply equipment
FERC	Federal Energy Regulatory Commission
FSGIM	Facility Smart Grid Information Model
FSGIM	Facility Smart Grid Information Model
GMLC	Grid Modernization Laboratory Consortium
GWAC	GridWise Architecture Council
HAN	home area network
HVAC	heating, ventilating, and air conditioning
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IP	Internet Protocol
ISO	independent system operator
MDMS	meter data management system
MESA	Modular Energy Storage Architecture
MESA-ESS	Modular Energy Storage Architecture-Energy Storage System
MESA-ESS	Modular Energy Storage Architecture-Power Conversion System
NAN	neighborhood area network
NEMA	National Electrical Manufacturers Association
NERC	North American Electric Reliability Corporation
NIST	National Institute of Standards and Technology
OASIS	Organization for the Advancement of Structured Information Standards
OpenADR	Open Automated Demand Response
OpenFMB	Open Field Message Bus
OSI	Open Systems Interconnection
PEV	plug-in electric vehicle
PV	photovoltaic
RTO	regional transmission organization
SAE	Society of Automotive Engineers
SEPA	Smart Electric Power Alliance
TCP	Transmission Control Protocol

V2G	vehicle-to-grid
VAR	volt ampere reactive

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1.0 Introduction

The North American electric grid architecture has evolved during many decades. Fundamentally, the grid has relied on large generating plants that are connected to a transmission network to provide power—often over great distances and at high voltages. The transmission network is then connected to local distribution networks that branch out and provide power to homes, businesses, and industry at various lower voltages. Consumers use power as desired, and grid operators manage the system to ensure that capacity is adequate and delivered at the proper voltage and frequency.

Over time, the grid has become more complicated. This started with interconnections among utilities at the transmission level, which allowed for the development of regional grids. These larger grids provided increased capacity, flexibility, and redundancy, and they allowed for power trading at the bulk level. Improvements in reliability have been engineered into local distribution networks as well.

Recently, there has been a large-scale emergence of distributed energy resources (DERs). There are many types of well-known DERs, such as wind and solar power plants, but by making loads in buildings (i.e., water heaters; heating, ventilating, and air-conditioning [HVAC] systems; lighting) controllable, they can also support the electric power system. DERs based on renewable resources (without battery storage) tend to have variable output and provide power only when the sun shines or the wind blows. Because most DERs are small and are not connected to the transmission network, they are not typically controlled or dispatched from the central grid operator; instead, they inject power at their point of common coupling to the grid. The result is a grid architecture that has evolved from the original central-station design and has become more challenging to manage reliably.

There is a desire to make the grid more reliable, resilient, and secure. This includes the ability to have faster recovery after a storm and to be able to serve customer loads even if a key resource goes offline because of a failure or other problem. In the future, it is anticipated that new technologies, including energy storage and distributed generation, will increase and that most of them will be deployed on the distribution network.

All these issues are key drivers for grid modernization, and they are key tasks being addressed by the Grid Modernization Laboratory Consortium (GMLC). One goal of the GMLC is to help define an improved electric grid that includes changes to the physical architecture and incorporates a data and communications architecture that will allow for improved management of this future grid.

1.1 Background on the Grid Modernization Lab Consortium

A modern electric grid is vital to the security, economy, and even the way of life of the United States, providing the foundation for essential services that Americans rely on every day. The U.S. Department of Energy (DOE) Grid Modernization Initiative represents a comprehensive effort to help shape the future of the U.S. grid and to solve the challenges of integrating conventional and renewable resources with energy storage and smart buildings while ensuring that the grid is resilient and secure to withstand future challenges.

This project is a part of the Foundational Platform Activities of the GMLC, which includes collaboration among the National Renewable Energy Laboratory, Pacific Northwest National Laboratory, Lawrence Berkeley National Laboratory, Sandia National Laboratories, Argonne National Laboratory, Oak Ridge National Laboratory, and Idaho National Laboratory in undertaking a 3-year project to review and develop standards and test procedures for interconnection and interoperability in the electricity sector with a focus on the distribution level. The primary objective of this project is to build on prior efforts and leverage existing activities spanning multiple DOE programs that are developing interconnection and interoperability standards and test procedures to:

- Harmonize requirements among standards development organizations
- Minimize conflicting requirements among technology domains
- Fully streamline conformance test procedures.

As an initial part of this effort, the project team investigated current interconnection and interoperability standards and test procedures to identify whether additional work should be undertaken to update these standards and test procedures to address the needs of the emerging grid.

1.2 Objectives and Scope

This project's overarching goal was to help develop and validate needed interconnection and interoperability standards and test procedures for existing and new electrical generation, storage, and loads. The project also aims to ensure cross-technology compatibility and harmonization of requirements among different organizations. Ultimately, this will enable significant deployment levels of renewable generation and energy-efficient technologies on distribution systems while maintaining grid reliability, resilience, and security. These standards also help to support and enable various technologies to interact with each other and the grid to optimize solutions among multiple objectives, including providing a range of grid services.

Grid devices must be able to provide services as part of an integrated software architecture that supports the physical grid architecture. Interconnection and communications standards are needed for the safe and reliable connection of DERs to the grid. The use of open, standard, and highly interoperable communications protocols is essential to the effective deployment of these devices. A smart, modern grid requires robust levels of device and system connectivity through simple and predictable integration that is supported by reliable methods of testing and product certification.

The goal of the initial phase of this research was to first provide an accurate summary of the relevant standards for interconnection and interoperability grouped by technology domains and then to identify any potential gaps in these standards that limit the effectiveness of these resources. This activity included outreach to industry and various standards organizations to collaborate on the standards processes to support the development of necessary changes and demonstrations of selected sets of integrated services. Such efforts are intended to help the United States develop and advance common platforms—especially data formats and communications protocols—which are necessary for a modernized and more flexible, reliable, and efficient electric grid.

1.3 Project Background, Scope, and Approach

Under this project, DOE national laboratories developed a work plan that included laboratory development and validation as well as working directly with industry through standards development organizations to accelerate the establishment and revision of standards and test procedures for grid-connected devices and systems.

Through this effort, the national laboratories collaborated with key stakeholders to promote standards harmonization among organizations and technologies in recognition that the grid is a single interconnected system and that factors such as policy and market drivers also impact successful harmonization efforts. During the 3-year time frame of this work, each national laboratory on the team focused on areas relevant to its strengths. Year 1 focused on identifying gaps and coordination with standards organizations. Years 2 and 3 continued the coordination necessary for the development of standards and test procedures to address the gaps.

Typically, national and international consensus-based standards-making bodies create and revise codes and standards on different revision cycles (usually many years). Standards-making entities include, for example, the American Society of Mechanical Engineers, the Institute of Electrical and Electronics Engineers (IEEE), the International Electrotechnical Commission (IEC), the National Electrical Code, and the Society of Automotive Engineers (SAE). The consensus process brings together stakeholders from utilities and grid operators, product vendors, national laboratories, and others to formulate requirements for a particular technology. These standards generally are not enforceable until a state or another authority having jurisdiction adopts the code or standard.

Under this project, team members worked directly with various standards development organizations to harmonize specific technical requirements across standards. Figure 1 summarizes team members and standards-related activities.

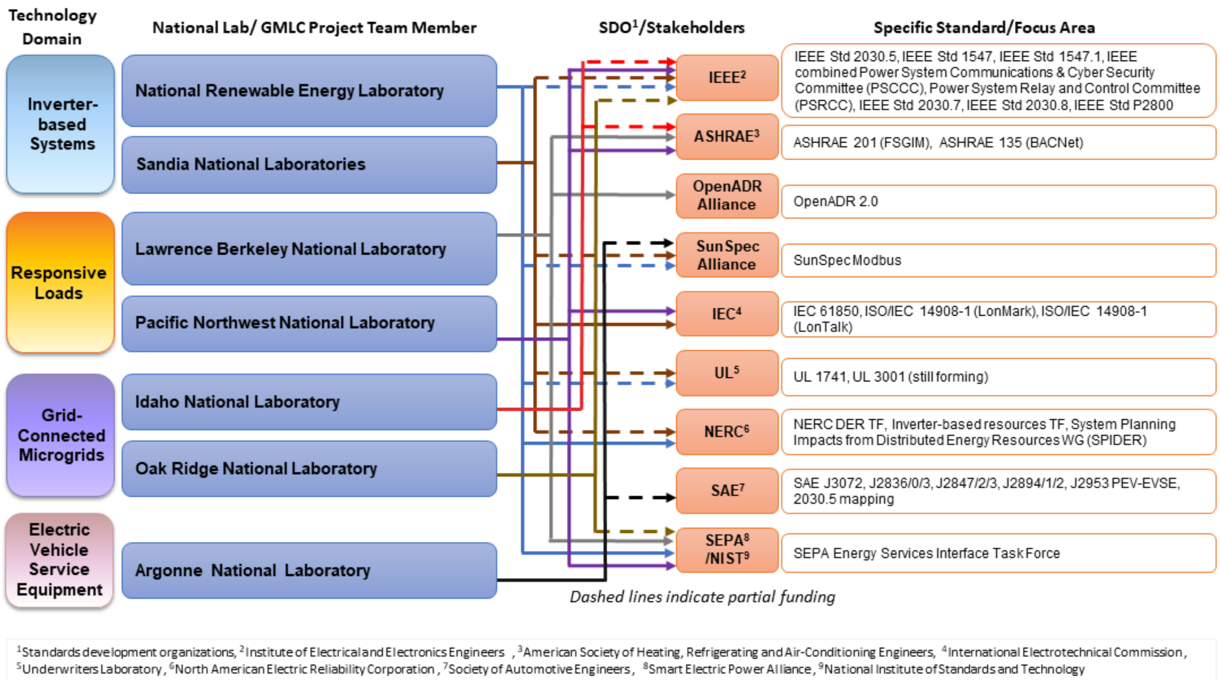

Figure 1. GMLC 1.4.1 team contributions to standards-related activities

Figure by the National Renewable Energy Laboratory

There are different types of national and jurisdictional codes and standards in the United States. In this document, the team focused on interconnection and interoperability performance and testing standards and codes.

Interconnection performance standards specify functional requirements for equipment to intertie to the electric grid. *Interconnection testing standards* are a sequence of experiments and associated performance requirements for equipment to become compliant to an interconnection code. The GMLC team focused on national standards related to interconnection.[1]

Interoperability performance standards define the requirements for exchanging information among communications-enabled entities. *Interoperability testing specifications* are the testing procedures used to verify that devices are compliant to an interoperability standard. The GMLC team focused on national standards related to interoperability.

Standards and codes related to equipment certification or safety are critical to the sound installation, operation, and maintenance of all technologies, but these are not the focus of this report.

[1] Because of the dynamic nature of the market uptake and regulatory needs, some jurisdictions have developed interconnection and interoperability rules to address their specific needs. These were not included in the gap analysis under this GMLC project.

In this report, the GMLC team considered the supply of some of these grid services from DERs or aggregated DERs, specifically energy- and capacity-related grid services, regulation-related grid services, inertial response, and distribution voltage management.

Grid services can be considered high-level functions provided at the grid interface. To provide these higher level functions, different DER technology types can be aggregated so that they collectively perform the same core function. At the lowest level of local devices, the desired grid service must be mapped to specific lower level device functions (e.g., an increase or decrease in active power). Figure 2 shows this progression from lower level device functions to higher grid services.

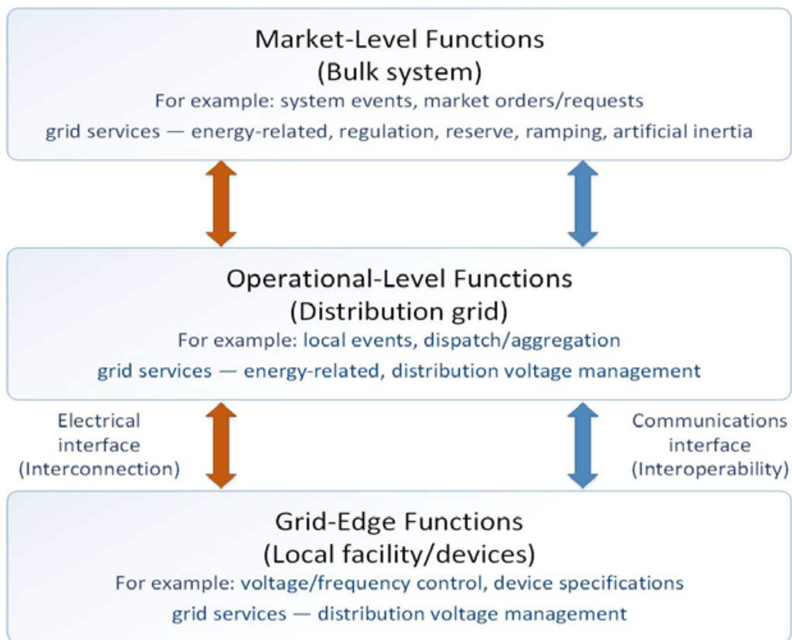

Figure 2. Progression from lower level functions to grid services

Figure by the National Renewable Energy Laboratory

For the grid services considered in this analysis, DERs or the DER controller must perform certain functions at the device level to change the power or voltage profile of the DERs. Table 1 provides a summary of the required functions by type of grid service and DER technology.

Table 1. Summary of DER Device or DER Controller-Level Functions Required for Grid Services

Type of Grid Service	**Inverter-Based DERs (PV, energy storage)**	**EVs** (or EV service equipment)	**Responsive Loads** (or Building Energy Management Systems)	**Grid-connected Microgrids** (or Microgrid Controllers)
Energy	Increase or reduce active or reactive power output (for energy storage, charging, or discharging)	Change charge or discharge rate	Change set points to increase or decrease active or reactive loads	Change set points for energy import and export
Regulation	Increase or reduce active power input	Reduce active power charging rate	Change set points to increase or decrease loads	Change set points of active and reactive power consumption
Distribution voltage management	Volt/VAR reactive power; fixed power factor; volt-watt	Volt-watt volt/VAR	Modify set points that change loading for various devices	Modify the import and export set points for power exchanges
Inertial response	Frequency-watt	Frequency-watt	Device on/off, adjust variable-frequency motors	Not yet fully defined

2.0 Grid Services at the Electric Transmission Level

The term *grid service* as used in this report includes use of DER capabilities at both the local distribution level and the bulk power transmission level. Note that the provision of grid services at these two levels falls under separate jurisdictions and will be subject to different interconnection and market rules and requirements. Following is a high-level review of how the bulk power system is structured and managed.

At the highest level, the North American bulk power system is structured as four large electrical islands called "interconnections"[2] that are operated independently but coordinated (shown in Figure 3).

Figure 3. North American interconnections

Figure adapted from (Gevorgian et al. 2019)

At the bulk power system level, the Federal Energy Regulatory Commission (FERC) has overall regulatory authority over rates and services for interstate electric transmission by public electric utilities. FERC also has responsibility for the reliability and security of the bulk power system and certified the North American Electric Reliability Corporation (NERC) as its delegate[3] to

[2] An interconnection is defined by FERC as "a geographic area in which the operation of the electric system is synchronized" (FERC 2018).

[3] FERC certification of NERC as the electric reliability organization in the United States

develop and enforce mandatory reliability and security standards for the bulk power system (Greenfield 2018). To carry out its responsibility, NERC, in turn, delegated its authority to monitor and enforce compliance with reliability standards to six regional entities, which are shown in Figure 4.

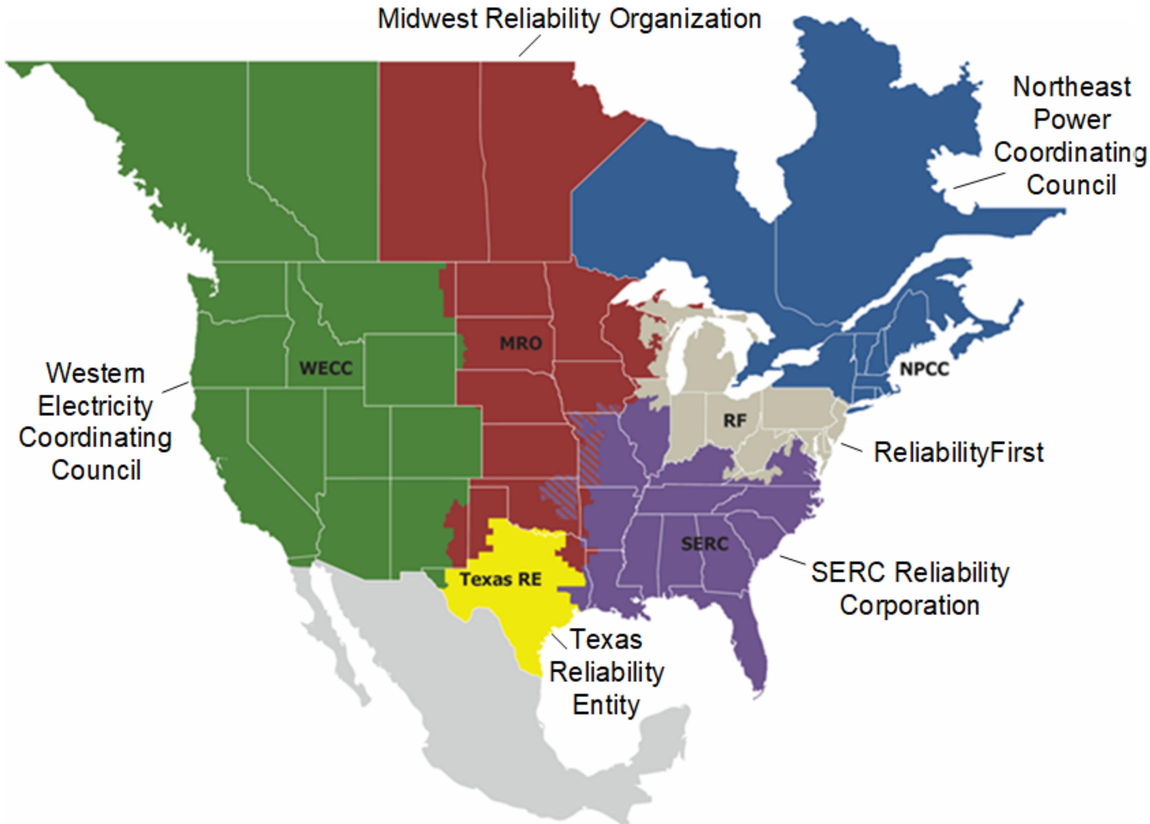

Figure 4. Regional reliability entities designated by NERC

Figure adapted from (NERC 2019a). Used with permission.

The regional entities coordinate the bulk power system reliability in their regions and have NERC-delegated authority to enforce compliance to NERC standards. Regional reliability entities work with balancing authorities in the region to perform several balancing authority area services—including balancing generation with energy demand (generation imbalance service, energy imbalance service, operating reserves—spinning reserves, operating reserves—supplemental reserves), controlling frequency and time error—and to implement interchange transactions.

There are 66 balancing authorities in the United States. Balancing authorities can be operated by the wholesale market operator, which is typically a regional transmission organization (RTO) or an independent system operator (ISO). Or the balancing authority can be delegated to large utilities. Figure 5 shows balancing authorities .

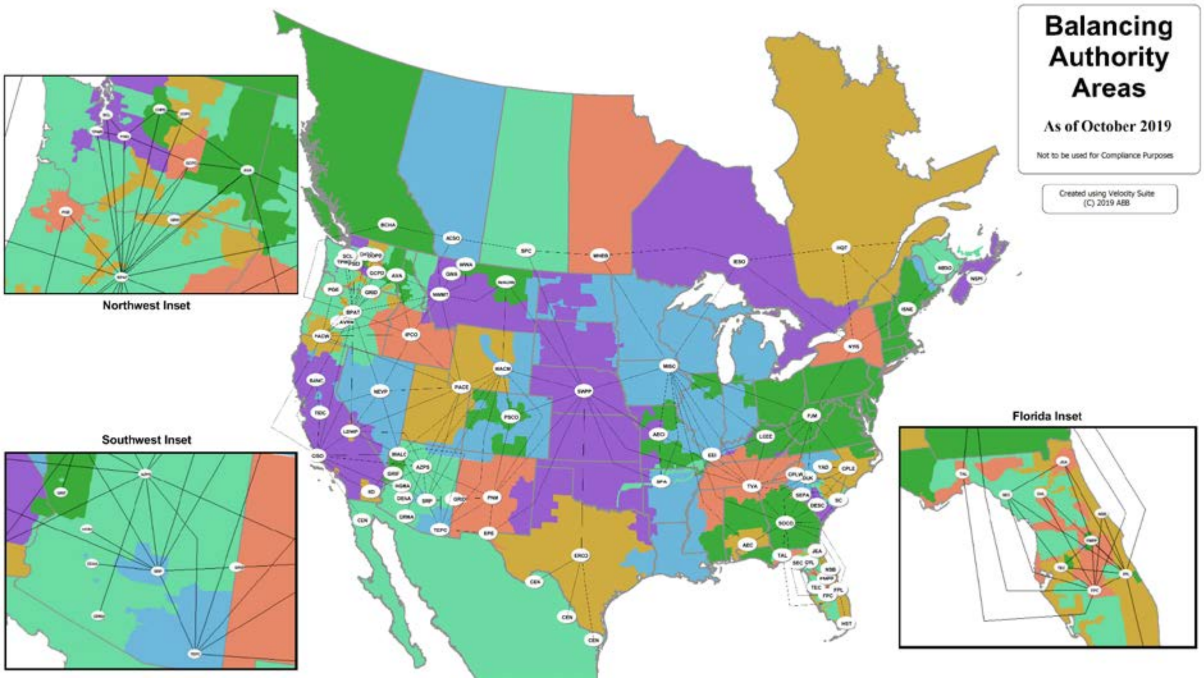

Figure 5. NERC balancing authorities and areas (shown as white ovals)

Figure from (NERC 2019b). Used with permission.

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Regional reliability entities also work with RTOs and ISOs to manage regional bulk electric power flows and markets. Figure 6 shows RTOs and ISOs. As noted, RTOs or ISOs can also be the balancing authority.

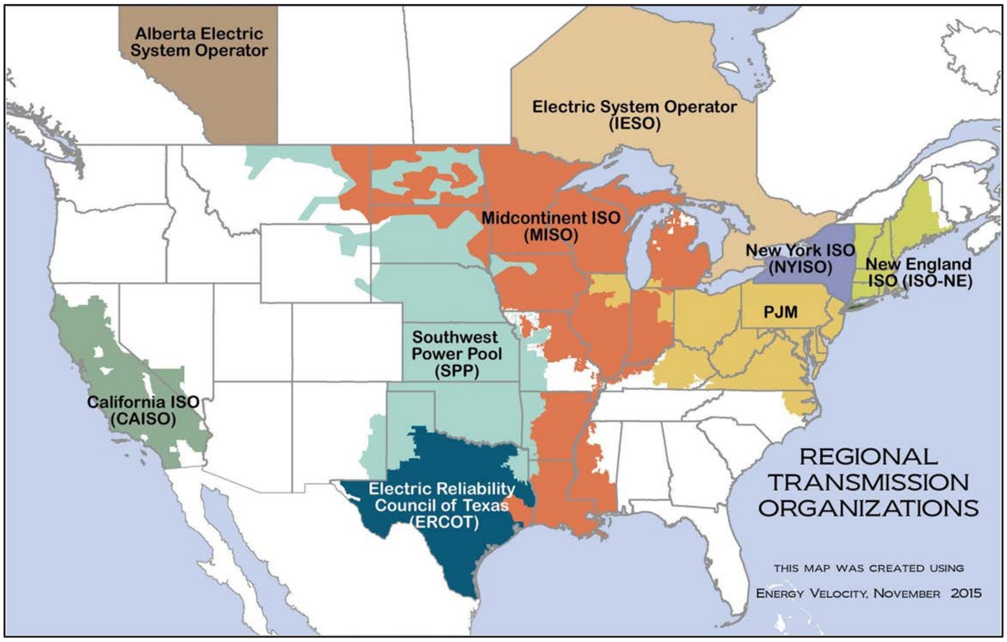


Figure 6. Regional transmission organizations

Image source: (FERC 2015). Used with permission

At the transmission level, grid services can also be referred to as "ancillary services," defined by FERC as "those services that are necessary to support the transmission of capacity and energy from resources to loads while maintaining reliable operation of the Transmission Provider's Transmission System in accordance with Good Utility Practice" (FERC 1996).

In FERC Order No. 888, issued in 1996, six ancillary services were identified by FERC as necessary for providing reliable transmission service within and among control areas (FERC 1996): (1) scheduling, system control, and dispatch; (2) reactive supply and voltage control from generation sources; (3) regulation and frequency response; (4) energy imbalance; (5) operating reserve—spinning; and (6) operating reserve—supplemental.

In the same order, FERC also noted that other services could be provided to serve the needs of a specific transaction or agreement (such as restoration service, also referred to as black start). These ancillary services have become embedded in bulk energy markets and operations. Ancillary services are required at varying timescales depending on the need. Many ancillary services are used to mitigate frequency disturbances, as shown in Figure 7.

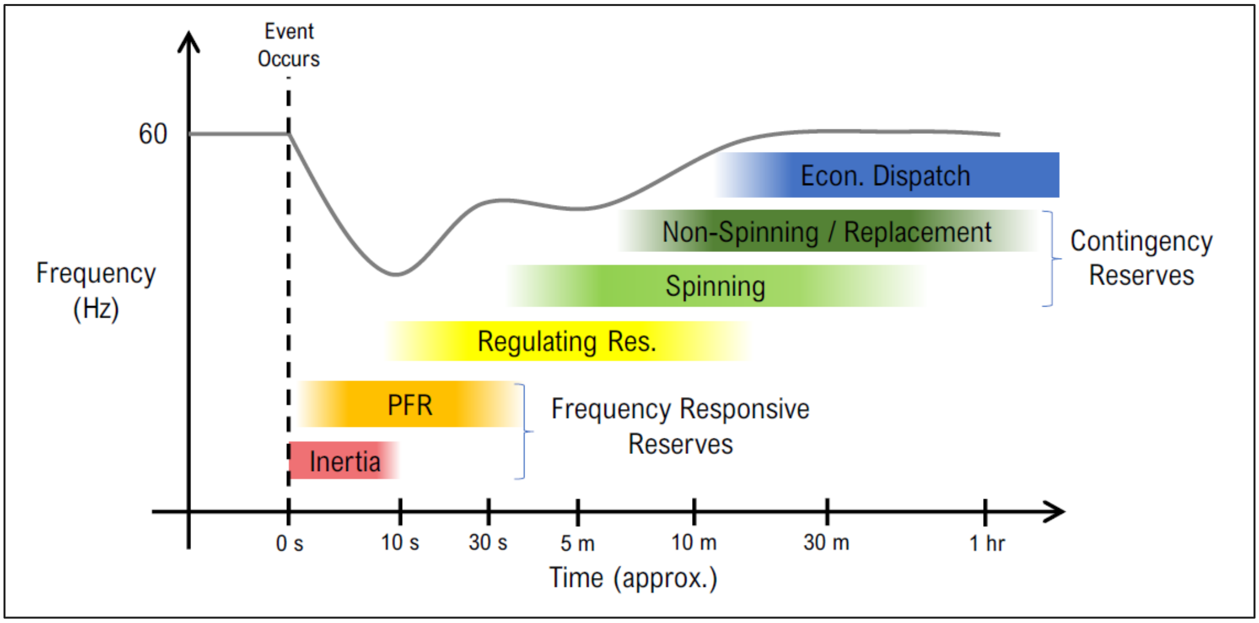


Figure 7. Ancillary services deployed at varying timescales

Figure from (Denholm, Sun, and Mai 2019)

2.1 Balancing Energy and Capacity to Customer Load

A major responsibility for transmission grid operators is to procure an adequate supply of generation to meet consumer energy demand. At the transmission level, this function is managed in two markets: a day-ahead market and a real-time balancing market. In the day-ahead market, generation owners offer bids for hourly energy costs for the following day.

Daily loads are generally considered to be predictable based on seasonal patterns; however, random disruptions of daily patterns can be caused by weather conditions, plant outages, shortages in output from renewable generation, or unusual wholesale market conditions. To manage random disruptions, transmission grid operators also balance in real time, and this correlates to a real-time market that is calculated in 5-minute intervals (PJM 2020c).

In some regional markets (such as PJM), consumers, including residential and small commercial customers, can participate in the real-time energy market by changing their energy use pattern in response to power system needs or hourly electricity costs. In the PJM wholesale electricity market, this is called price responsive demand (PJM 2017).

Looking beyond the real-time and day-ahead generation resource adequacy requirements, RTOs also have responsibility to obtain the generation capacity needed for the future. RTOs have set up capacity markets that include long-term price signals to spur needed investments in capacity resources (PJM 2020a). Capacity might also be needed and supplied in a grid emergency. Capacity resources can include new and existing generators, upgrades for existing generators, demand response, and energy storage.

For this analysis, peak load management, energy market price response, and capacity market were combined into a single category because technologies must provide the same basic functions for these services: distributed generation and storage will increase or reduce active power being provided to the grid, electric vehicles (EVs) will increase or reduce their charging rate, and responsive loads[4] will change set points to decrease energy consumption or increase on-site generation.

2.2 Frequency Control and Regulation

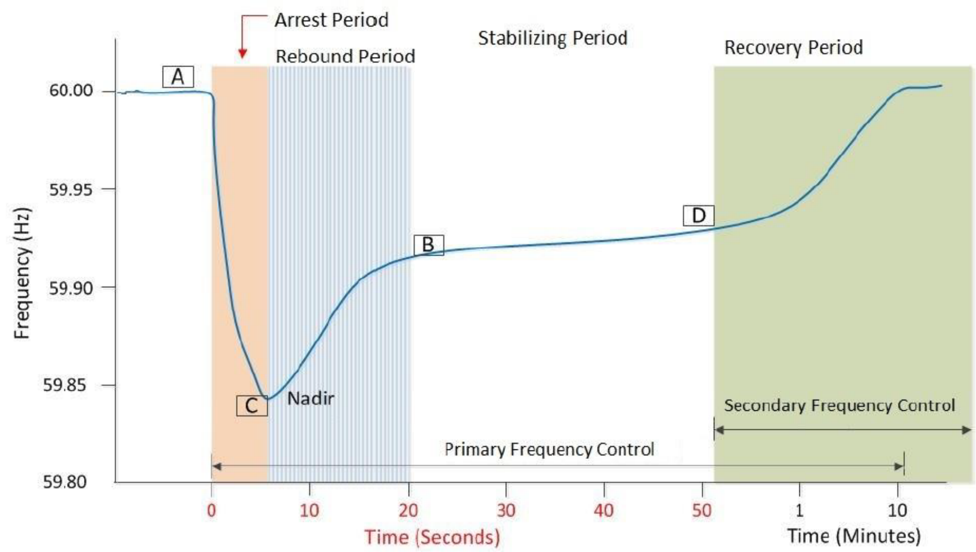
Frequency regulation is needed to correct for short-term fluctuations in electricity demand and generation, which helps to maintain a system frequency of nominal 60 Hz. Regulation resources respond to automatic control signals to increase or decrease their electricity generation or consumption and have historically included traditional generators, energy storage, or demand response. Balancing authorities can generate several types of control signals, and there can be different types of regulation depending on desired effect. For example, in the PJM territory, Regulation D is a dynamic signal requiring real-time (almost instantaneous) response, and Regulation A is a slower signal intended to recover from larger and longer fluctuations. A specific DER's ability to follow Regulation D or Regulation A depends on the DER's inherent capabilities (PJM 2020b).

Frequency control is illustrated in Figure 8, which shows an example a frequency disturbance and the types of responses needed to recover from the disturbance and return the power system to a stable frequency. As shown, primary frequency control (also known as frequency response) is exercised by local devices and control systems within the first few seconds following the disturbance.

Primary frequency control is provided automatically by traditional electric generators (rotating machines) through governors. In addition, primary frequency control can be obtained by adjusting the connected load; to some extent, this could occur naturally because the change in frequency during the disturbance causes a proportional change in the speed of motors (and a corresponding change in energy draw). Load changes can also result from exercise of contracts for demand response or ancillary services. If these measures do not produce the desired response, operation of underfrequency load-shedding schemes can be exercised. Primary frequency response is designed only to stabilize frequency—that is, to stop a precipitous increase or decrease (NERC 2011).

[4] Behind-the meter loads and generation can be controlled through a building energy management system.

Point A is defined as the predisturbance frequency; Point C or Nadir is the maximum deviation due to loss of resource; Point B is defined as the stabilizing frequency and; Point D is the time the contingent Balancing Authority begins the recovery from the loss of resource.



Note: Some Secondary Frequency Control may begin earlier or later than illustrated. Also, some Primary Frequency Control may end earlier than illustrated due to governor deadband.

Figure 8. Components of frequency control

Figure from (NERC 2015). Used with permission.

To restore the frequency to nominal, secondary frequency control, also known as regulation, is exercised in the minutes following a frequency disturbance. Secondary control is typically managed by the balancing authority and can use a number of tools, including both and non-spinning reserves, through exercising automatic generation control and manual dispatch (NERC 2011).

Additional types of control might be required during longer time frames. These are called tertiary control and time control services. Table 2 shows a summary of time frames for control and ancillary services.

Table 2. Time Frames for Types of Ancillary Services and Control

Type of Control	Ancillary Service[a]	Response Time Frame
Primary control	Frequency response	10–60 seconds
Secondary control	Regulation	1–10 minutes
Tertiary control	Imbalance/reserves	10 minutes–hours
Time control	Time error correction	Hours

[a] These types of control services are also known as interconnected operations services.

Table adapted from (NERC 2011)

DERs participate in these grid services by delivering the necessary active power to provide either voltage or frequency regulation of the grid. These regulation services can be combined to represent regulation services for each device class because each regulation service is invoked through conditions on the electric power system or through communications. The regulation market, which represents both voltage and frequency regulation services, is used to signify the capabilities of the device class, and it can be used for either regulation service.

2.3 Reserves

Reserves account for system imbalances and are typically needed within 10 minutes and could be in effect for up to several hours depending on the cause of the imbalance. Table 3 shows the NERC definitions of reserves used in this report.

Table 3. Types of Operating and Planned Reserves

<table>
<tr><th></th><th colspan="2">Operating Reserves[a]</th><th colspan="2">Planned Reserves</th></tr>
<tr><th></th><th>Deployable Within 10 Minutes</th><th>Deployable Within 10–60 Minutes</th><th>Deployable Within Hours to Days</th><th>Deployable Within Weeks to Years</th></tr>
<tr><td rowspan="2">Online</td><td>Regulating reserve[b]</td><td rowspan="2">Other online reserve</td><td rowspan="3">Operations planning/
unit commitment</td><td rowspan="3">System planning/
resource installation</td></tr>
<tr><td>Spinning reserve[c]</td></tr>
<tr><td>Off-line</td><td>Non-spinning/
supplemental
ʳeserve[d]</td><td>Other off-line reserve</td></tr>
</table>

Key definitions associated with terms related to reserves come from NERC (NERC 2011):

[a] Operating reserve: “that capability above firm system demand required to provide for regulation, load forecasting error, equipment forced and scheduled outages, and local area protection.”

[b] Regulating reserve: “an amount of spinning reserve responsive to Automatic Generation Control, which is sufficient to provide normal regulating margin.”

[c] Spinning reserve: “unloaded, synchronized, resource, deployable in 10 minutes.”

[d] Non-spinning/supplemental reserve: “additional capacity from electricity generators that can be used to respond to a contingency within a short period, usually ten minutes.” Examples are interruptible load and fast-start generation. Other types of off-line reserves include curtailable load and off-line generating units.

Interruptible load is defined as “load under direct control of an operator that can be interrupted within 10 minutes.”

Curtailable load is defined as “load that can be disconnected from the system with assurance in less than one hour”

2.4 Inertial Response

Traditional rotating generators and motors interconnected and synchronized to the power system store kinetic energy. When a disturbance occurs, such as the loss of one a generator, the stored kinetic energy is immediately withdrawn from the remaining generators as they compensate for the added load placed on them in an attempt to maintain balance between energy generation and demand. As the kinetic energy is withdrawn, generator speed slows, which decreases the system frequency. The rate at which system frequency decreases depends on the amount of stored kinetic energy available at the time of the disturbance (known as the synchronous inertial response) of the system (NERC 2016). Figure 9 shows inertial response from synchronous machines.

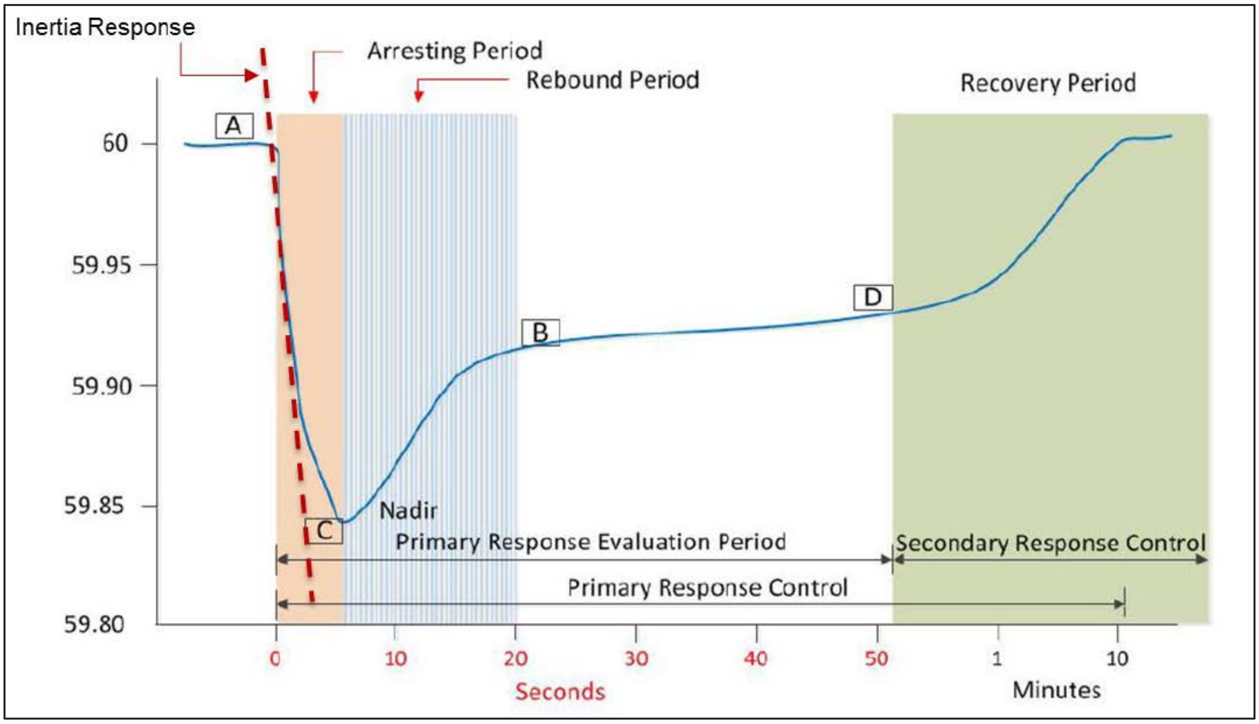


Figure 9. Inertial response from synchronous machines

Figure from (NERC 2016). Used with permission.

As the power system increases the use of nonsynchronous generation displacing traditional generators with their rotating machines, the level of inertial response will decrease unless the new generators provide some form of frequency response similar to inertia.

This type of inertial response[5] is a new capability that can be provided by modern, electronically coupled, inverter-based DERs. One term that describes this capability is *fast frequency response*, defined by NERC as "active power injection automatically deployed in the arresting phase of a frequency event aimed at providing full response before the frequency nadir is reached" (NERC 2016). This fast frequency response supplements traditional primary frequency response to slow down the rate of change of frequency.

Fast frequency response can also be obtained from frequency-responsive loads, which can include large industrial loads, heat pumps, industrial refrigerator loads, or storage devices (NERC 2016).

Today's inverter-based DERs include a function for synthesizing a rotating machine's inertia. This is accomplished with a simulated frequency-droop function. The frequency-watt functions enable the DERs to operate at a rated level or at an active power level that corresponds to the

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[5] NERC also identifies the term *synthetic inertia* as another example of fast frequency response from Type 3 and Type 4 wind turbines based on extracting kinetic energy from the rotating mass of the wind turbine (NERC 2016).

input resource when the frequency is operating at near-nominal conditions. When the frequency varies from nominal (increases), the output power of the DERs can be reduced, simulating a frequency-droop function. Because the slope of the frequency-watt function is adjustable and because the deadband—which allows the DERs to continue operating without a reduction of output active power—is also adjustable, a communications-based implementation of this function is advantageous. Through communications, the functions can be enabled and adjusted to help meet the needs of both the electric power system and the system owner.

For inverter-based DERs, a PV inverter can override an active power curtailment and increase active power generation during a frequency dip event, but active power can also decrease because of irradiance conditions, which is an undesired operation. For a battery-based inverter, the DER output is much more controlled. A decrease can be ramped as requested, and the decreases does not need to follow a decrease in irradiance. In IEEE Std 1547-2018, the frequency-droop capability is a requirement to provide ride-through during abnormal situations such as low or high frequency. A further application of this capability could result in the frequency-watt capability.

3.0 Grid Services at the Electric Distribution Level

To date, the provision of grid services at the distribution level has been largely one-way: from the utility to the customer. Some mechanisms to engage DERs for grid services, such as direct-control demand response, are fairly mature.[6] Recent advances in DER capabilities and revisions to grid codes to allow the use of the new capabilities has accelerated the use of DERs to provide grid services at the distribution level.

This study focused on distribution voltage management grid services because they are the most mature; however, other types of services at the distribution level also are being actively researched.

3.1 Distribution Voltage Management Grid Services

The objective of this service is to provide response that maintains distribution system voltage within the acceptable operating range under a variety of operating conditions, including response to rapid changes in net demand for power or variability of energy supply. In addition to the rapid response, there can also be a slower response that assists in coordinating reactive power output with distribution voltage management systems (transformer tap changers, voltage regulators, and capacitor banks), either on command or autonomously based on self-sensed voltage fluctuations (Widergren et al. 2017).

DER resources providing this grid service must sense when the distribution voltage fluctuates and act instantly and autonomously to adjust either load or generation reactive and active power components.

Inverter-based DERs are being developed to assist the grid in meeting voltage regulation requirements. The functions under development monitor the voltage at the DER's terminals, point of common coupling, and other locations; and they can provide reactive power to compensate for voltages outside of a predetermined set point. This capability is required[7] for all DERs seeking interconnection with the grid (as specified in IEEE Std 1547-2018) .

One method for implementing voltage-regulating capabilities is through preprogrammed power factor profiles, wherein the power factor generated by the DERs can be programmed at a particular level at a corresponding time of day according to voltage profiles on record. Because DERs are typically programmed to operate at unity power factor, site-specific adjustments are required for this to be implemented correctly. This is a somewhat inelegant yet effective manner of achieving voltage regulation from DERs, which can be augmented through communications

[6] Nascent concepts, such as transactive energy, are the active topic of research within the GMLC and in industry. For example, GMLC 1.4.02, "Definitions, Standards, and Test Procedures for Grid Services" (GMLC 2019), has been focusing on the response of various DERs and responsive loads to different grid service requests. GMLC 1.4.02 developed a battery-equivalent model for different DERs and commercial responsive loads (e.g., battery inverters, PV, EVs, electrolyzers, fuel cells, air conditioners, refrigeration units, and water heaters). New grid services are being considered for a more flexible and resilient system that enables better integration of renewables, responsive loads, and other distributed resources and provides more flexibility between the grid and connected loads. A master list of grid services is available from GMLC 1.2.01, "Grid Architecture" (GMLC 2017).

[7] Note that the IEEE standard specifies that all DERs must have this capability. Use of this capability is determined by the local authority.

that allow the power factor function to be enabled/disabled or adjusted to meet present voltage conditions.

Another method of voltage regulation is through the implementation of the reactive power function. The volt/volt ampere reactive (VAR) function is the type of voltage-regulating algorithm that can be implemented autonomously, and the deadband of the function allows for the DERs to deliver active power as normal when the line voltage is operating near normal. If the voltage moves beyond near normal and beyond the preprogrammed deadband, the function will deliver reactive power relative to how far the voltage varies from near normal.

Communications can be used to remotely adjust the parameters of the voltage regulation function by varying the slope of the volt/VAR delivery and by adjusting the available VAR percentage. Communications can also invoke an adjustable reference voltage set point that will respond to local voltage levels. If this function does not provide enough reactive power to maintain an operating voltage level within American National Standards Institute (ANSI) requirements, the volt-watt function can be enabled via communications, and this function will reduce active power generation as voltage continues to move away from nominal voltage and violates ANSI voltage requirements.

4.0 Photovoltaic Generation and Related Standards

Distributed energy has seen an increased rate of adoption in the United States. The most common type of DER is an inverter-based PV system. The declining cost of PV has resulted in substantial deployment across the country. According to a study conducted by Greentech Media, the installed capacity is projected to increase from 46.4 GW (2017 installed capacity) to 104 GW by 2023 (St. John 2018). Figure 10 illustrates the installed DER capacity in the United States by state. Among the states leading the development of distributed PV systems, California has installed approximately 8,000 MW of behind-the-meter solar capacity (California Energy Commission 2018).

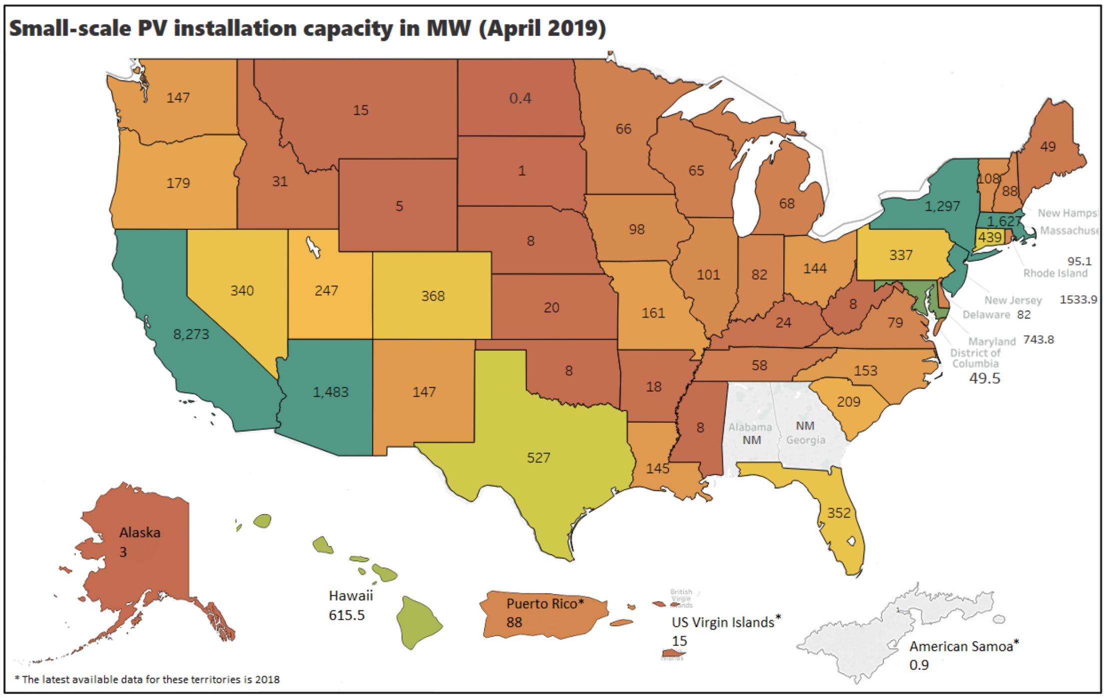

Figure 10. Small-scale PV installation capacity in the United States

Data source: EIA 2019b. Figure by the National Renewable Energy Laboratory

Figure 11 shows, however, that there are zones throughout the country with significant potential for roof-mounted PV. These pockets are smaller and denser in the East, and they are wider and relatively sparse in the West.

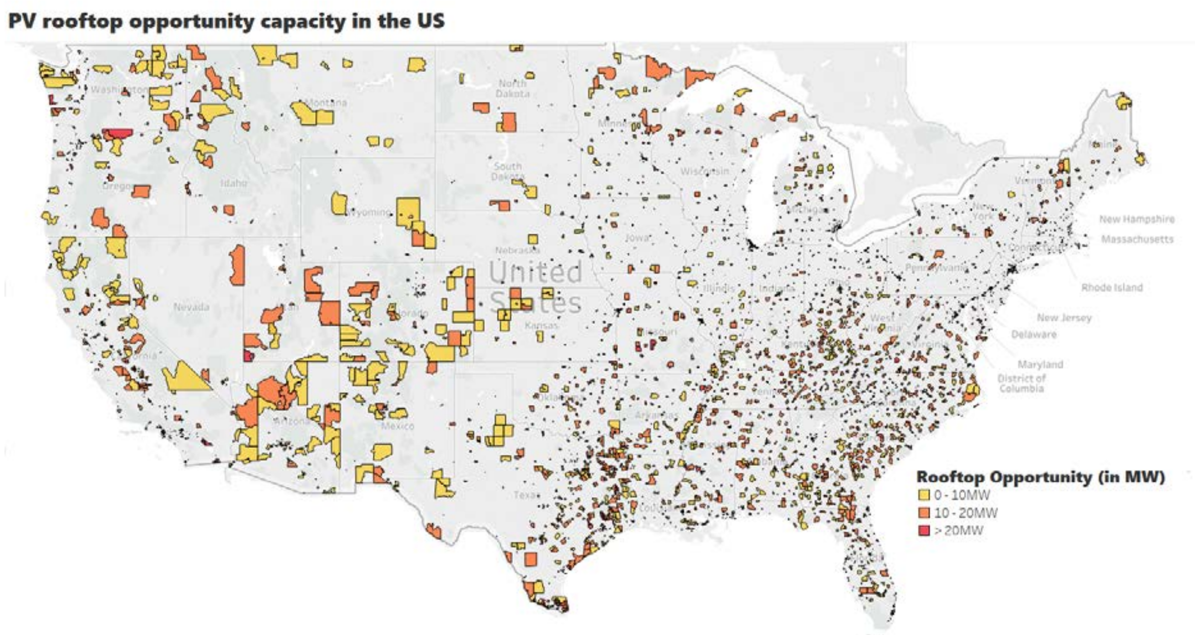

Figure 11. PV rooftop capacity opportunity in the United States

Data source: EIA 2019b. Figure by the National Renewable Energy Laboratory

Inverter-based distributed generation includes a range of technologies, including PV, fuel cells, energy storage, and microturbines. The majority of inverter-based DERs are currently PV systems, and the main interconnection standards for these technologies is IEEE Std 1547. This standard is intended to be used with other standards, as shown in Figure 12.

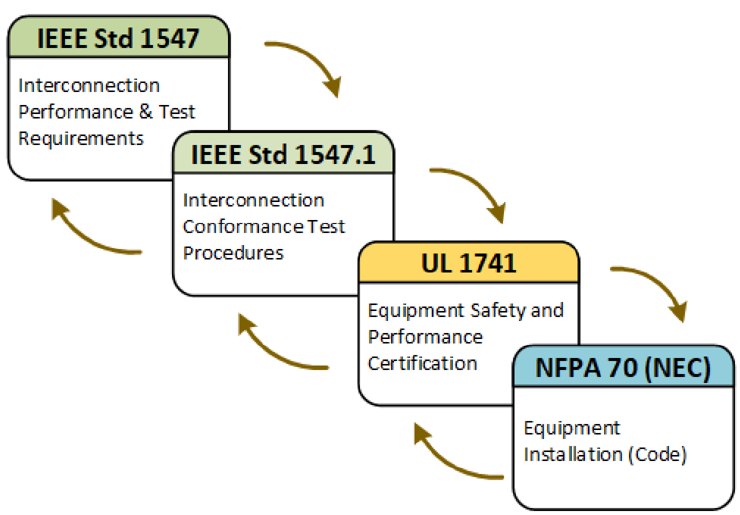

Figure 12. Intended use and relationship of IEEE Std 1547 to related standards and codes

Figure by the National Renewable Energy Laboratory

Interoperability standards for inverter-based distributed generation are evolving, with a view toward harmonization of the communications requirements. Efforts are ongoing to unify the object models and communications structures under IEC 61850-90-7 and IEC 61850-7-420.

Further efforts are ongoing by SunSpec Alliance to translate these object models from IEC 61850-7-420 to various other protocols to provide utilities, aggregators, and users direct control of PV inverters. All these efforts have critical gaps in terms of harmonizing the function types, function parameters, and monitoring points. An additional critical gap exists in terms of the standardized testing of these communications-based operations to determine their interoperability and their ability to provide proper interconnection functionality.

New system-level communications standards such as Open Field Message Bus (OpenFMB) and IEEE Std 2030.5 are discussed here because they will be pertinent to the interoperability of PV inverters to other DERs and loads in the future. In 2016, IEEE Std 2030.5 was chosen by the California Public Utilities Commission as the "default" communications protocol for DER grid integration in California.

4.1 IEEE Std 1547

IEEE Std 1547, *IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces*, is mandated by the Energy Policy Act of 2005 to be considered for the interconnection of DERs to electrical distribution systems. This standard is the primary U.S. interconnection standard for DERs. It was first published in 2003, reaffirmed in 2008 and 2013, and amended in 2014. It completed a full revision in April 2018 to include features for managing high penetrations of DERs on distribution feeders and to support the grid under normal and abnormal conditions.

The term *interoperability* is a new addition to IEEE Std 1547-2018. The standard now recognizes DERs as having both an electrical (interconnection) interface and a communications (interoperability) interface (IEEE 2018). Moving forward, DERs shall be capable of responding to external inputs (via manual DER control panel or through a local DER communications interface). IEEE Std 1547-2018 is now mapped to four communications standards in IEEE 1547.1: IEEE 2030.5, Distributed Network Protocol 3 (DNP3), SunSpec Modbus, and IEC 61850-7-420.

The new standard also includes various advanced grid-support functions, such as active power control, dynamic voltage, and frequency regulation through the volt/VAR and frequency-watt functions and voltage/frequency ride-through. A few new capabilities for supporting grid services that are enabled in IEEE Std 1547-2018 include the following:

- **Distribution voltage management:**
  The provision of key performance capabilities to support distribution grid voltage is specified in the revised standard. Distribution voltage management is one grid service emphasized in the GMLC 1.4.1 project on gap analysis as having a high priority. In the revised standard, DERs shall be capable of providing[8] several modes that regulate voltage by reactive power control (and active power control for certain DERs). Modes include:
    - **Constant power factor mode**: In this mode, the DER operates at a constant power factor. At unity power, this mode is the default factory-setting mode. This mode is highlighted in the GMLC 1.4.1 project on gap analysis as a key function.

[8] DERs might have different capabilities based on a DER performance category for normal and abnormal conditions.

- **Voltage-reactive power mode (volt/VAR)**: In this mode, the DER actively controls its reactive power output as a function of voltage. *This mode is highlighted in the GMLC 1.4.1 project on gap analysis as a key function.*
- **Active power-reactive power mode (watt-VAR)**: In this mode, the DER actively controls its reactive power output as a function of the active power output.
- **Constant reactive power mode**: In this mode, the DER maintains a constant reactive power output. *This mode is highlighted in the GMLC 1.4.1 project on gap analysis as a key function.*
- **Voltage-active power mode (volt-watt)**: In this mode, the DER actively limits its active power as a function of the voltage. *This mode is highlighted in the GMLC 1.4.1 project on gap analysis as a key function.*

- **Energy/capacity:**
  The standard supports energy-related grid services with the requirement that the DERs shall be capable of limiting active power as a percentage of the nameplate active power rating. This function could be used to provide additional (positive) active power through consideration of the "default" active power setting and can be coupled with energy storage to provide additional capacity.
- **Regulation and inertial response:**
  The function for limiting active power can also support certain regulation needs at the bulk power system level. Depending on the DER's abnormal performance category, the standard specifies frequency-watt (frequency-droop) operation during temporary frequency disturbances. The standard does not require but allows inertial response (a function during which the DERs active power is varied in proportion to the rate of change of frequency).
- **More information:**
  - https://standards.ieee.org/standard/1547-2018.html
  - http://sites.ieee.org/sagroups-scc21/standards/1547rev/.

4.2 IEEE Std 1547.1[9]

IEEE Std 1547.1, *IEEE Standard Conformance Test Procedures for Equipment Interconnecting Distributed Resources with Electric Power Systems*, was published in 2005, reaffirmed in 2010, and amended in 2015. IEEE Std 1547.1 is the standard for testing the compliance of DERs to the IEEE Std 1547 requirements, and UL 1741 is the certification standard for PV inverters (and other DER inverters).

IEEE Std 1547.1 was revised in 2020. The revisions addressed the tests needed to verify IEEE Std 1547-2018 requirements; however, some important items were not included because they are outside the scope of the standard, such as interaction among multiple inverters providing grid support and modeling and simulation requirements.

- **More information:**
  - https://standards.ieee.org/project/1547_1.html.

[9] The full revision to IEEE 1547.1 was published in May 2020.

4.3 UL 1741

UL 1741, *Standard for Safety—Inverters, Converters, Controllers, and Interconnection System Equipment for Use With Distributed Energy Resources*, is tightly coupled with IEEE Std 1547.1. UL 1741 contains tests and verifications to confirm two aspects of inverters:

- Safety aspects such as shock and fire prevention
- Grid interconnection performance.

To verify grid interconnection performance, UL 1741 historically simply referenced the type tests in IEEE Std 1547.1. With the emergence of high levels of DERs in California and Hawaii, an amendment to UL 1741 was developed and published in 2016: UL 1741 Supplement A (UL 1741 SA). UL 1741 SA contains test procedures to verify that inverters can perform the following grid-support functions:

- Voltage and frequency event ride-through
- Volt/VAR control
- Frequency-watt control
- Volt-watt control
- Anti-islanding with ride-through and other grid-support functions active
- Fixed power factor operation
- Normal ramp-rate control and soft-start ramp-rate control.

The ranges of inverter control parameters to be evaluated for each function are not specified in UL 1741 SA. Instead, the inverter manufacturer must specify a source requirements document containing ranges of settings for each function, typically supplied by the utility where the inverter would be installed. Only a few progressive utilities with high levels of DERs require testing to UL 1741 SA.

It is expected that UL1741 will be updated to reflect the revisions in IEEE Std 1547.1-2020.

4.4 IEC TR 61850-90-7/IEC 61850-7-420

IEC TR 61850-90-7, *Communication Networks And Systems For Power Utility Automation – Part 90-7: Object Models For Power Converters In Distributed Energy Resources (DER) Systems*, published in February 2013, is a technical report that defines an information model for DER devices to provide grid-support services (e.g., volt/VAR, frequency-watt). This technical report was updated and converted to IEC 61850-7-420.

IEC 61850-7-420 was updated in May 2018 to reflect new functions and DER grid codes, including California's Rule 21, IEEE Std 1547-2018, and the European Network of Transmission System Operators for Electricity grid codes of May 2016. The working group also added functions that are not specifically grid codes but will be used by DERs (including voltage and frequency regulation functions, such as inertial response). Aspects of energy storage systems (ESS) are included, such as charging aspects. Another update (Edition 2) is expected to be released in mid-2020.

- **More information:**

- IEC TR 61850-90-7, https://webstore.iec.ch/publication/6027, *Communication Networks and Systems for Power Utility Automation—Part 90-7: Object Models for Power Converters in Distributed Energy Resources (DER) Systems*
- IEC 61850-7-420, https://webstore.iec.ch/publication/6019, *Communication Networks and Systems for Power Utility Automation—Part 7-420: Basic Communication Structure—Distributed Energy Resources Logical Nodes*.

4.5 Smart Electric Power Alliance/North American Energy Standards Board Open Field Message Bus

The North American Energy Standards Board OpenFMB is a communications framework and reference architecture designed to enhance interoperability among proprietary devices on the electric grid. The framework is based on existing standards.

The OpenFMB reference architecture specifications were ratified in March 2016 by the North American Energy Standards Board. The current Smart Electric Power Alliance (SEPA) project's focus is to develop use cases and requirements, determine semantic model needs, and develop adapters and applications as well as test beds. An OpenFMB demonstration on use case functionality took place at the 2016 Grid Modernization Summit (November 7–10, 2016).

- **More information:**
  - https://openfmb.github.io/
  - https://www.naesb.org/
  - https://openfmb.ucaiug.org/Pages/Overview.aspx?#naesb.

4.6 SunSpec Alliance Photovoltaic Models

The SunSpec Alliance provides information monitoring and advanced DER function models (e.g., direct control functions, volt/VAR, frequency-watt, watt-power factor) from IEC 61850-7-420. The SunSpec Alliance PV models have been ratified through a consensus process with members of the SunSpec Alliance. These models are undergoing a review for updates.

- **More information:**
  - http://sunspec.org/about-sunspec-specifications/.

4.7 IEEE Std 2030.5

IEEE Std 2030.5-2018, *IEEE Standard for Smart Energy Profile Application Protocol*, is a communications protocol (information model) that originated from the Smart Energy Profile. IEEE Std 2030.5 is currently being revised to include DER advanced inverter functions included in IEC 61850 (information models), California Rule 21 (grid code), Hawaii Rule 14H (grid code), and UL 1741 (certification protocol). IEEE Std 2030.5 was revised for DERs, with the latest version published in May 2018.

Quality Logic developed a set of tools for testing IEEE Std 2030.5 and related services. These are available at https://www.qualitylogic.com/what-we-test/smart-energy-standards/ieee-2030-5-test-tools-qa-services/.

- **More information:**

    - https://standards.ieee.org/standard/2030_5-2013.html.

4.8 Modbus

Modbus is a serial communications protocol used to establish leader/follower client/server communications among intelligent devices. It is an open standard that is available without royalties with variants for serial ports (Modbus RTU) and Ethernet (Modbus Transmission Control Protocol [TCP]/Internet Protocol [IP]). Modbus is a de facto standard in the electrical and industrial manufacturing environment, and it has been implemented by hundreds of vendors on thousands of different devices to transfer discrete/analog input/output and register data among control devices. It is widely used by many DER equipment manufacturers, including PV inverters, energy storage, on-site generators, and microgrid switchgear equipment. Industry analysts have reported more than 7 million Modbus nodes located in North America and Europe alone.

Modbus is used as the base protocol for the Modular Energy Storage Architecture (MESA)-Device interfaces; MESA-PCS (power conversion systems), and MESA-Power Meter (MESA 2018). MESA device specifications are based on previous work at the SunSpec Alliance and extended through collaboration with SunSpec Alliance (MESA 2014a). A MESA-compliant device implements a specific set of SunSpec models.

- **More information:**
    - http://www.modbus.org/.
    - http://mesastandards.org/mesa-device/
    - http://sunspec.org/wp-content/uploads/2015/06/SunSpec-Meter-Models-12023.pdf.

4.9 SunSpec Modbus

SunSpec Modbus is a communications protocol intended to enable interoperability among DER system components, and it one of three communications protocols referenced in IEEE Std 1547-2018. The specification defines common parameters and settings for the monitoring and control of DERs. The specification includes services for exercising advanced DER functions, such as voltage regulation, changing power factor, and limiting power export. The SunSpec Modbus specification is built on the existing Modbus protocol.

- **More information:**
    - https://sunspec.org/sunspec-modbus/
    - http://www.modbus.org/specs.php.

4.10 IEEE Std 1547.3

IEEE Std 1547.3, *IEEE Guide for Monitoring, Information Exchange, and Control of Distributed Resources Interconnected with Electric Power Systems*, published in 2007, provides guidance for monitoring, information exchange, and control aspects of DERs connected to the electric power system. The guide discusses interoperability, configuration management, communications protocols, and security guidelines.

- **More information:**

- https://standards.ieee.org/findstds/standard/1547.3-2007.html.

4.11 IEEE Std 1815 (DNP3)

IEEE Std 1815-2010, *IEEE Standard for Electric Power Systems Communications—Distributed Network Protocol DNP3*, was initially developed in the early 1990s and has since been implemented by U.S. electric utilities (IEEE 2012). It was developed to meet the need for a protocol that provided electric utilities with a standardized option for interoperability among substation computers, remote terminal units, intelligent electronic devices, and master stations. In addition to the electric utility industry, IEEE Std 1815 has been adopted by entities in related industries, such as water/wastewater, transportation, and oil and gas (DNP Users Group 2019). Since 1993, updates to the protocol have been made by the DNP Users Group. In 2010, the protocol was accepted as an IEEE standard and codified as IEEE Std 1815. The latest IEEE revision was in 2012 (IEEE Std 1815-2012). In January 2019, a collaborative team published an application note that contains an information model for enabling new DER functions as required in California Rule 21 and specified in IEEE Std 1547-2018. The application note also includes functional definitions and mapping with IEC-61850-7-420 (Electric Power Research Institute et al. 2019).

- **More information:**
  - https://www.dnp.org/Pages/AboutDefault.aspx
  - http://sunspec.org/wp-content/uploads/2015/06/DNP3-AN2013-001-DNP3-Advanced-Photovoltaic-Profile.pdf
  - https://standards.ieee.org/standard/1815-2012.html.

4.12 Standards Gaps for Photovoltaic Generation

1. Updates to IEEE Std 1547 should consider additional communications-enabled/and or adjusted advanced DER functions, multi-inverter interactions, communications-based anti-islanding, and charging/discharging of energy storage.
2. IEEE Std 1547 does not consider responsive loads as DERs. These topics are important for the future use of grid service capabilities from these DERs. Updates to the standard should consider their inclusion.
3. Additional clarity is needed on the interoperability and response requirements of DERs that lose communications (for those that use the remote communications capabilities). For example:
   a. How often must the DERs communicate to the utility or other external entity to constitute a “good” communications link?
   b. If communications are determined lost, what does the DER do? Must it disconnect? If so, how fast?
4. In IEC 61850-7-420, there is no low-frequency/high-frequency ride-through data model. This should be considered for inclusion in an update.

5.0 Electric Energy Storage and Related Standards

The declining costs of both PV and battery storage backed by favorable state mandates and incentives have sparked interest in the deployment of ESS. As shown in Figure 13, energy storage deployment is the greatest in California, followed by Texas and Hawaii. According to SEPA, the overall growth rate of residential energy storage deployment in terms of installed capacity was more than 200% in 2017. Utilities across the country are trying to leverage the advanced capabilities of PV plus storage that could address transmission and distribution infrastructure upgrades issues, intermittency, and peak load shaving and increase solar dispatchability.

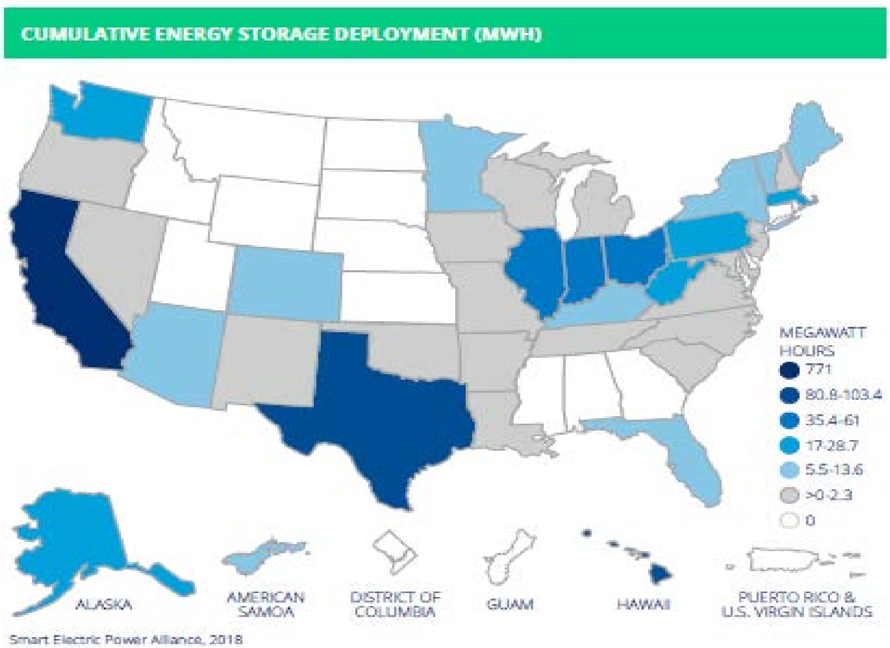

Figure 13. Cumulative energy storage deployment in the United States

Image source: Smart Electric Power Alliance 2018b. Used with permission

Energy storage systems are unique in that they can act as both load and generator. In addition, storage can provide grid services, such as voltage regulation, demand response, and reactive power support. Products tailored to perform these functions are commercially available. One such solution provided by SunRun is Brightbox. SunRun is also collaborating with utilities to provide demand response functionalities for annual peak reduction in Massachusetts. Figure 14 and Figure 15 demonstrate how PV plus storage can manage the problem of a duck curve during the day.

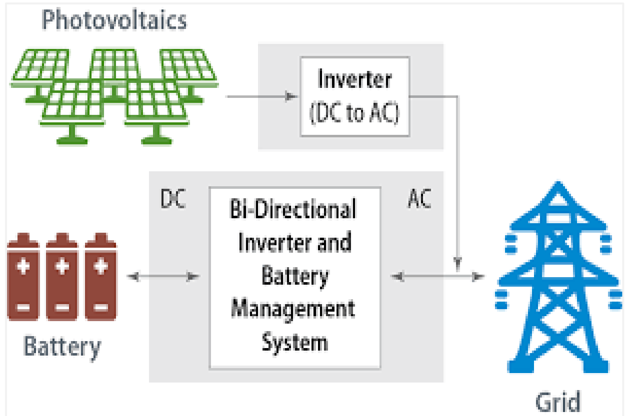

Figure 14. Simplified diagram of solar plus storage

Figure from (Denholm, Margolis, and Eichman 2017)

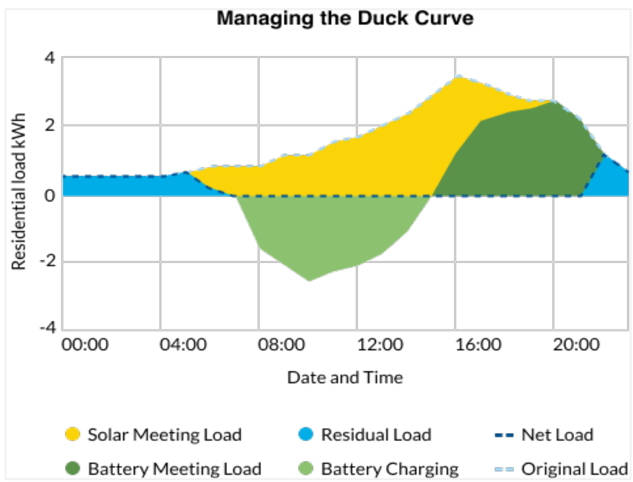

Figure 15. Example of solar plus storage grid service

Image source: SunRun 2019. Used with permission

Another example of battery storage that is commercially available and capable of providing grid services is the Tesla Powerwall. In May 2018, Tesla released a customer application for Powerwall 2 that enables energy-related grid services by charging when rates are low and discharging when rates are high (SEPA 2018a). Tesla is partnering with utilities in California to provide dynamic grid services (on demand and autonomous), control, and monitoring capabilities. Additionally, Tesla Powerpack is designed for utility-scale storage and can provide grid services such as dynamic capacity, flexible ramping, frequency regulation, and volt/VAR support.

Electric ESS interconnection and interoperability codes and standards are similar to inverter-based distributed generation requirements. The requirements for an inverter-based ESS are the same as those for inverter-based distributed generation.[10] The gaps are closely aligned, although

[10] See Section 2.1 for the status of IEEE Std 1547, IEEE Std 1547.1, IEEE Std 1547.3, UL 1741, IEC 61850-7-420, and IEEE Std 2030.5.

no specific electric energy storage functions (e.g., bidirectional frequency-watt functions) are included in some communications standards (IEEE Std 2030.5 and IEEE Std 1815).

With respect to energy storage DERs, there is a need to harmonize the function types, function parameters, monitoring points, commands, function prioritization, and timing parameters in IEC 61850, IEEE Std 2030.5, SunSpec, IEEE Std 1815, OpenADR, and other information models. This is necessary so that data can be translated along utility-aggregator-DER communications paths because currently there are significant differences in these information models. More information on energy storage is available at the Energy Storage Integration Council (led by the Electric Power Research Institute) website: https://www.epri.com/#/pages/sa/epri_energy_storage_integration_council_(esic).

Some ongoing research will lead to a better understanding of ESS interoperability. The integration of batteries, supercapacitors, and flywheels has been investigated to enhance the operational flexibility of run-of-the-river hydropower plants (Luo et al. 2018). In addition, Idaho National Laboratory is leading a field demonstration project to show the application of supercapacitors in providing black-start service. The preliminary findings of the hardware-in-the-loop test were presented at HydroVision International 2019 (Alam et al. 2019). In addition to integration with hydropower, the application of electrolyzers in providing frequency and voltage regulation services according to IEEE Std 1547-2018 is being investigated in a DOE Fuel Cell Technologies Office-funded project (DOE EERE 2020).

5.1 MESA-ESS/SunSpec Energy Storage Specification

The *Modular Energy Storage Architecture-Energy Storage System* (MESA-ESS) defines requirements for DNP3 communications between utility-scale ESS and the utility's grid control, such as a supervisory control and data acquisition or a distribution management system. The specification contains a data model for mapping the DNP3 protocol to specific DER functional performance requirements contained in the latest interconnection standards.

The advanced DER functions in MESA-ESS are defined in IEEE Std 1547-2018, California Rule 21, and the European Network of Transmission System Operators for Electricity DER interconnection requirements . Advanced DER functions are specified in a profile using IEEE Std 1815 (DNP3) based on the IEC 61850-7-420 information model for advanced DER functions. MESA-ESS references the DNP3 Application Note AN2018-001, which contains a direct data object mapping for DER functions between IEC 61850 and DNP3 (MESA 2018; 2014b).

MESA has a broad industry membership that includes utilities, technology manufacturers, and the Pacific Northwest National Laboratory. A strategic partner is SunSpec Alliance.

MESA and SunSpec Alliance released the first draft of the ESS specification (MESA-Device, referred to as the "Energy Storage Model Specification") for adoption in October 2014. MESA then launched a technical working group in March 2015 to develop the MESA-Storage/SunSpec ESS specifications. The ESS models include the following drafts: Battery Base Model, Lithium-Ion Battery Bank Model, Lithium-Ion String Model, Lithium-Ion Module Model, Flow Battery Model, Flow Battery String Model, Flow Battery Module Model, and Flow Battery Stack Model.

The Energy Storage Workgroup—run by SunSpec Alliance with contributions from MESA members—released the latest draft of MESA-ESS in December 2018 (Draft 4).

The latest draft of the *Modular Energy Storage Architecture Standards Alliance-Power Conversion Systems* (MESA-PCS) specification was released in March 2017.

The latest draft of the MESA-Power Meter specification was released by SunSpec in April 2015.

- **More information:**
  - http://mesastandards.org/
  - http://sunspec.org/energy-storage-models-available/.

5.2 IEEE Std 2030.2

Sponsored by the IEEE Standards Coordinating Committee 21 on Fuel Cells, Photovoltaics, Dispersed Generation, and Energy Storage, IEEE Std 2030.2, *IEEE Guide for the Interoperability of Energy Storage Systems Integrated with the Electric Power Infrastructure*, is part of the IEEE 2030 series, which addresses the interoperability of ESS with electric power infrastructure. The standard helps ensure that any given ESS can connect to and be interoperable with the electric power system. IEEE Std 2030.2 provides guidance on terminology, functional performance, evaluation criteria, operations, testing, and the application of engineering principles for ESS integrated with the electric power infrastructure. The latest version was released in 2015.

- **More information:**
  - https://standards.ieee.org/findstds/standard/2030.2-2015.html.

5.3 IEEE Std P1547.9

IEEE P1547.9, *Guide to Using IEEE Standard 1547 for Interconnection of Energy Storage Distributed Energy Resources with Electric Power Systems*, is a new effort intended to provide information about and examples of how to apply IEEE Std 1547 to energy storage.

The primary scope of the effort is to provide guidance on the interconnection of DER storage to power systems. In addition, the guide could address other related topics, such as interconnection considerations for bidirectional electric vehicle supply equipment (EVSE), expanded guidance for nonexporting energy storage, and guidance on charging/generation constraints to minimize negative impacts on the distribution system.

The project was launched in March 2018.

- **More information:**
  - https://standards.ieee.org/project/1547_9.html.

5.4 Standards Gaps for Electric Energy Storage

1. Applicability of IEEE Std 1547 to energy storage DERs when in recharge mode
2. Special consideration/limitations when storage medium is near or at capacity limits (low or high)

3. Constraints or exceptions needed to ensure battery safety
4. Constraints or exceptions needed to ensure battery reliability.

6.0 Electric Vehicles and Related Standards

At the end of 2018, there were roughly 1,298,000 EVs[11] operating in the United States (EIA 2019a). This accounted for slightly more than 2% of total vehicles (Irle 2019). Forecasts suggest that by 2030 the total number of EVs will be between 15 million and 18 million, roughly 7% of the total 259 million vehicles operating in the United States (Cooper and Schefter 2018). Figure 16 shows the historic and forecasted number of EVs in the United States according to the U.S. Energy Information Administration (EIA).

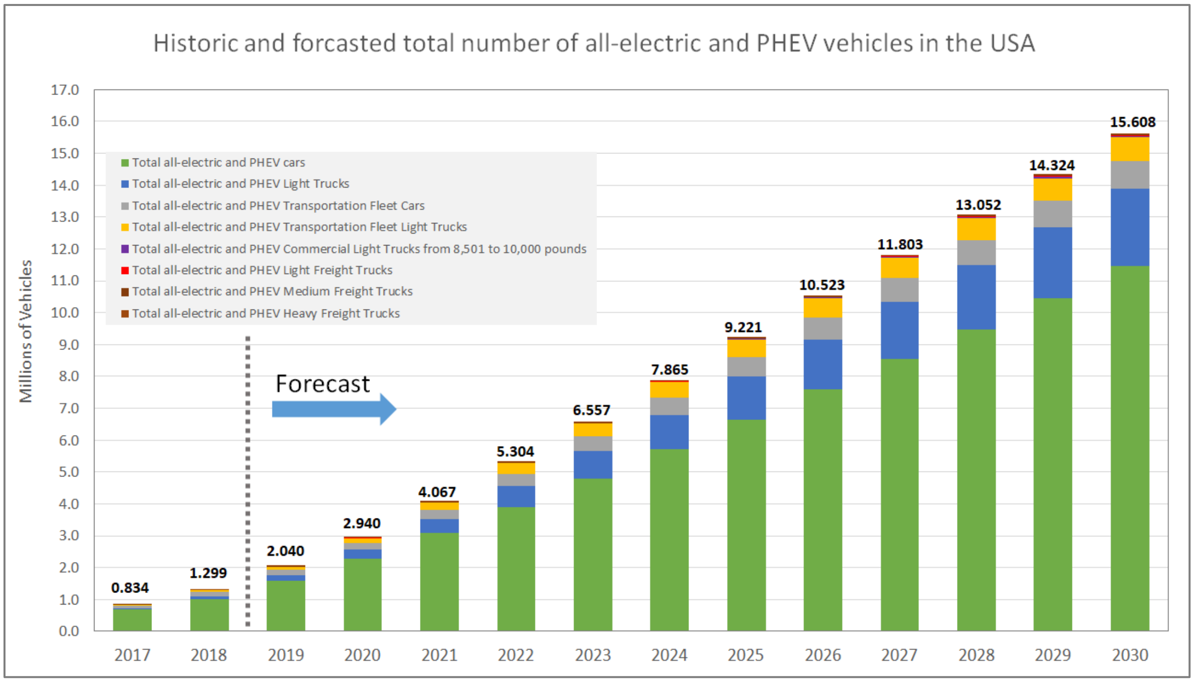

Figure 16. Total all-electric EVs and PEVs in the United States
Image source: U.S. Energy Information Administration (Jan. 2020)

Figure 17 shows states with the highest concentration of EVs as of 2016.

[11] For this report, EVs include all-electric and plug-in hybrid EVs.

PEV registrations per 1,000 people by state (2016 data)

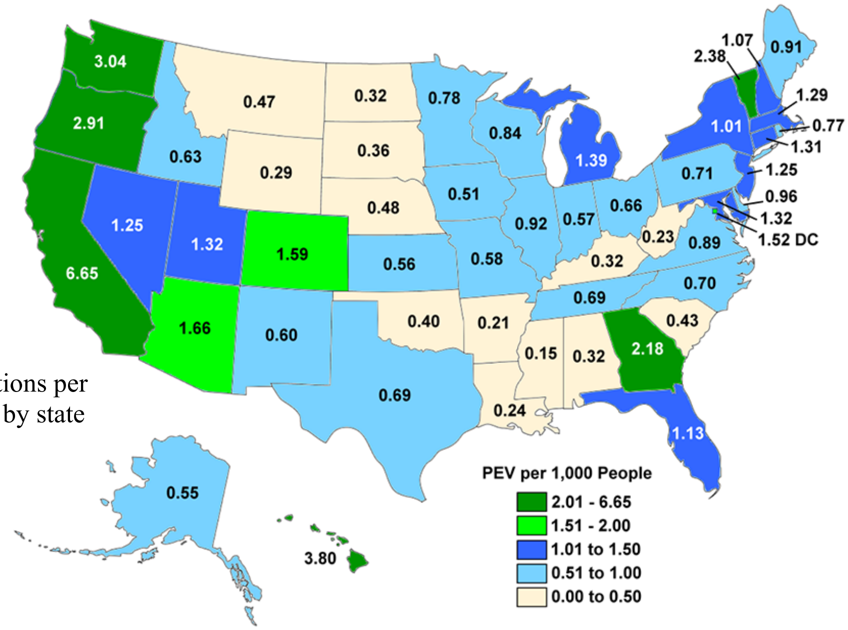

Figure 17. Concentration of PEVs in the United States by state

Image from (DOE 2017b)

The technology for an EV to be an active participant in the electric grid (vehicle-to-grid, or V2G) is still emerging. To date, only one manufacturer offers a commercial product to enable bidirectional energy flow; however, considerable research is ongoing across the public and private sectors. The hope that EVs can become a DER stems from the design of the EV, which includes an energy storage device. Figure 18 and Figure 19 show the major components of EVs.

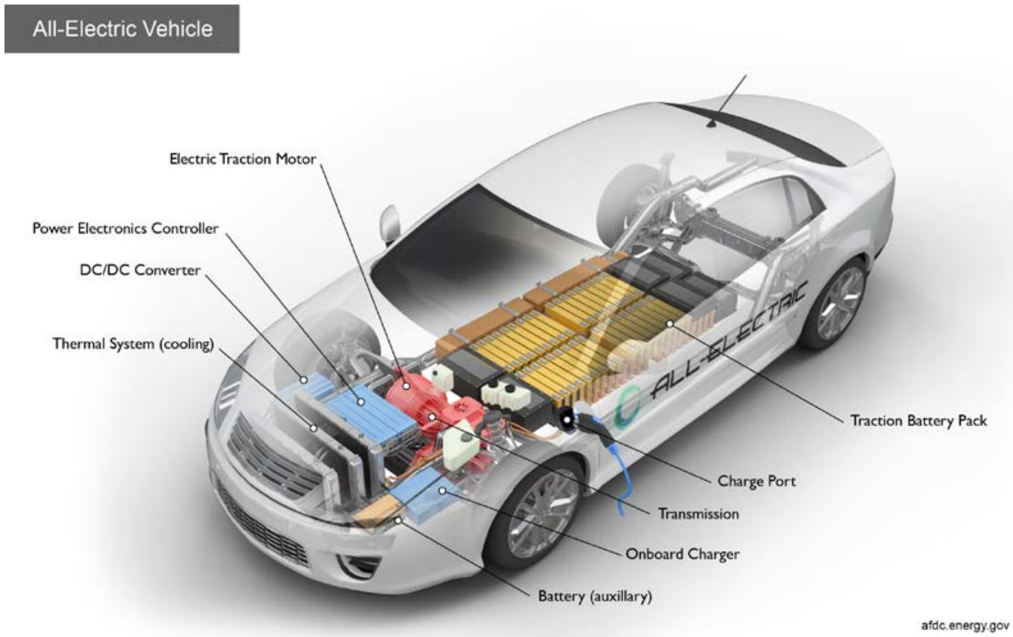

Figure 18. Major components of an all-electric vehicle
Image from (U.S. Department of Energy, Vehicle Technologies Office n.d.)

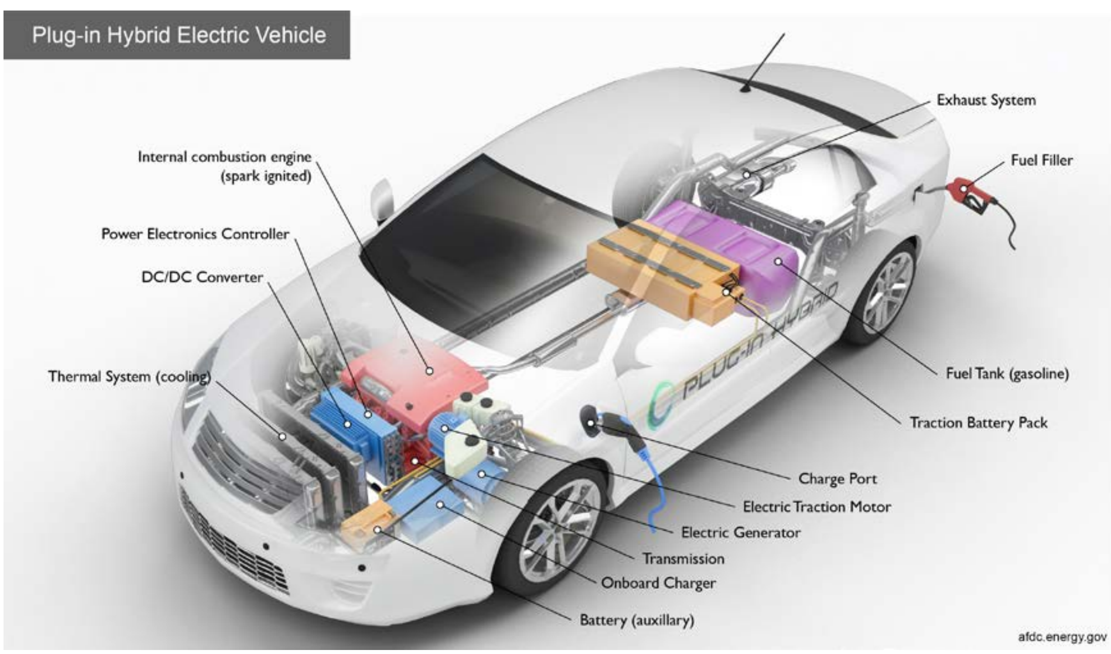

Figure 19. Major components of a plug-in hybrid electric vehicle
Image from (U.S. Department of Energy, Vehicle Technologies Office n.d.)

Figure 20 shows a simplified drawing of an EV and EVSE. The EV allows for bidirectional energy flow, which could potentially act as a DER and provide additional benefits to the consumer and provide services to the electric grid. EVs acting as a source to the grid are referred to as V2G.

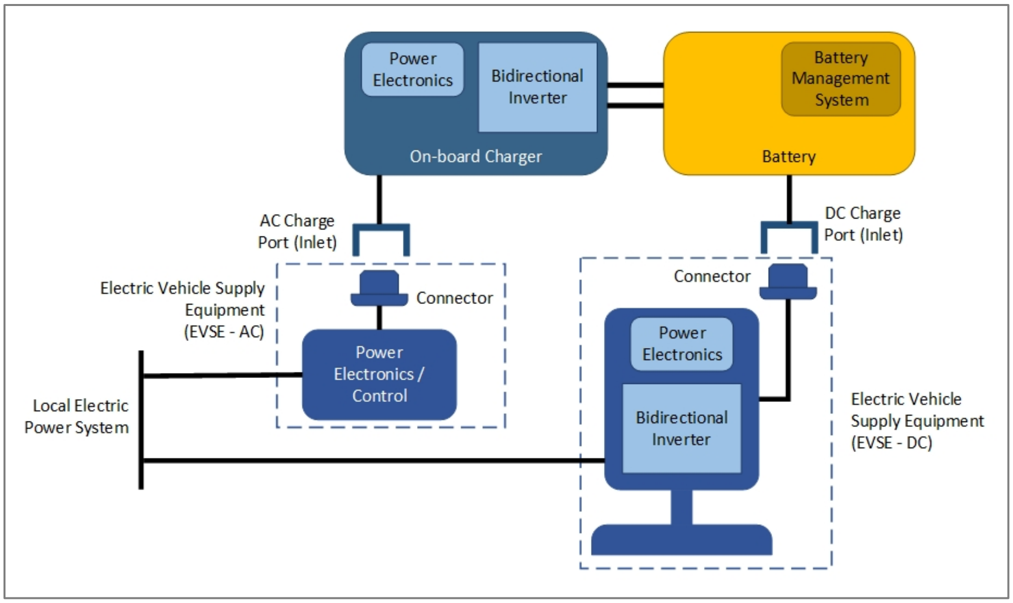

Figure 20. Simplified block diagram; major components of an EV and EVSE

Figure by the National Renewable Energy Laboratory

The first commercial use of EVs to provide grid services to the customer was introduced by Nissan Motor Corporation. Nissan envisions that its LEAF plug-in electric vehicle (PEV), with the addition of a power control system, can be used by customers to shift load to off-peak periods and can also be used for emergency backup power (Nissan Motor Corporation 2019). Figure 21 presents a broader concept of using EVs for grid services.

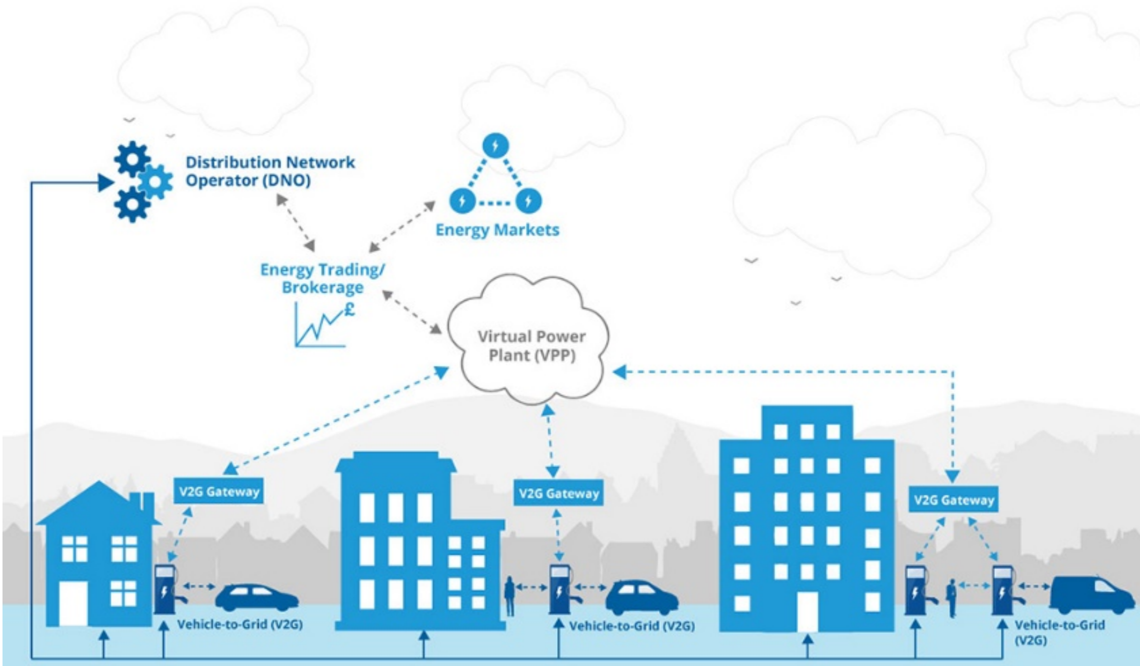

Figure 21. Example representation of V2G

Figure from CENEX 2019. Used with permission

V2G energy exchanges require a complex network of EVSE (equipped with a DC-to-AC inverter). Currently, vehicles/EVSE equipped with this technology are not widely available; however, standards that provide the technical requirements to enable these capabilities are required for the early demonstrations, pilots, and commercial products already emerging.

SAE develops most standards in this area, and some are harmonized to the IEEE interconnection standards. The challenge in these standards is that each industry related to electrical distribution, charging equipment, and vehicles covers only its own portion of the charging process. Often, the motivation of the vehicle manufacturer to ensure that the vehicle is always charged when needed is different from the motivation of the energy service provider/utility that wants to manage loads and sell or distribute electricity under optimal conditions. The final connection of the electrical source to the EV can be accomplished via AC, DC, and wireless charging delivery means. The electrical coupling standards are an evolving process with few gaps, but there is a constant need for updates to remain harmonized to other global EV-charging standards that have evolved.

Communications standards for the interaction of EVSE and EVs are defined. The process can also be accomplished via a simplified pilot signal for AC charging, but regulating the power delivered to the vehicle requires secure digital communications between the EVs and EVSE for DC and wireless. The present state of communications standards covers the electric service providers-to-EVSE via IEEE Std P2030.5 communications of the utility-oriented electricity market price, energy delivered to the vehicle, and other messages that can be used to adjust the rate of delivery of electricity to the PEV.

EV interconnection and interoperability standards encompass a segmented coverage of the dispatch of EV charging loads and at times act as a source of power to the grid (i.e., V2G). Most standards in this area are developed by SAE with some harmonization to IEEE interconnection standards.

The following sections describe key standards.

6.1 SAE J3072

SAE J3072, *Interconnection Requirements for Onboard, Utility-Interactive Inverter Systems*, was released in May 2015, and it establishes interconnection requirements for a utility-interactive inverter system, which is integrated into a PEV and connects in parallel with an electric power system by way of conductively coupled EVSE. SAE J3072 requirements are intended to be used in conjunction with IEEE Std 1547 and IEEE Std 1547.1.

The standard addresses the challenge that an EV is a mobile generation source (a roaming DER) that must follow the connection regulations for the location/jurisdiction at which the PEV is attempting to interconnect and participate in ancillary services or other energy markets. The standard enables PEV manufacturers to certify conformance to IEEE Std 1547.1.

Input is being collected to suggest changes to the second version of SAE J3072. SAE J3072; SAE J2836/3, *Use Cases for Plug-In Vehicle Communication as a Distributed Energy Resource*; and SAE J2847/3, *Communication for Plug-in Vehicles as a Distributed Energy Resource*, are all needed to a define AC bidirectional charging.

- **More information:**
    - http://standards.sae.org/j3072_201505/.

6.2 SAE J2836/0

- SAE J2836/0, *Instructions for Using Plug-In Electric Vehicle (PEV) Communications, Interoperability and Security Documents*, was created in 2017 and published as a technical information reference document in 2018.
- The purpose of J2836 is to document the general information that is supported by the SAE J2836, J2847, J2931, and J2953 series and J3072 for PEVs. It is a road map and reference guide to topics covered in each series of standards and containing links to other subject areas not covered by SAE standards, including areas such as the California Public Utilities Commission's V2G integration communications requirements,[12] National Institute of Standards and Technology (NIST) HB44 commercial metering for EV charging, and power quality requirements.
- **More information:**
    - https://www.sae.org/standards/content/j2836/.

6.3 SAE J2836/3

SAE J2836/3, *Use Cases for Plug-In Vehicle Communication as a Distributed Energy Resource*, is an SAE information report that defines use cases for a PEV communicating with an energy management system as a DER.

[12] See https://www.cpuc.ca.gov/vgi/.

The 2013 initial release of this document defined two system architectures, one with the inverter onboard the PEV and the other architecture with the inverter at the EVSE. This document also provides guidance for updates to SAE J2847/2 to allow an inverter in an EVSE to use the PEV battery when operating together as a DER.

SAE J2836/3 overlaps with SAE J3072 and SAE J2847/3, which address communications for PEVs as DERs.

A new draft was introduced in 2016.

- **More information:**
    - https://saemobilus.sae.org/content/J2836_201807/#scope.

6.4 SAE J2847/2

SAE J2847/2, *Communication Between Plug-In Vehicles and Off-Board DC Charges*, focuses on communications between PEVs and off-board DC chargers, specifically on the application of the off-board DC charger for conductive charging, which supplies DC to the rechargeable ESS of the EV through an SAE J1772 coupler. Communications will be on the SAE J1772 pilot line for power-line carrier communications. The details of power-line carrier communications are found in SAE J2931/4. J2847/2 is a work in progress. An update is currently underway. Version 4 was restarted in June 2015 for harmonization with ISO 15118/DIN 70121.

The current production of EVs with DC charging capability uses the SAE 2847/2 communications standard that is harmonized with the DIN70121 communications standard, which is a placeholder for Edition 2 of ISO15118.

- **More information:**
    - http://standards.sae.org/wip/j2847/2/.

6.5 SAE J2847/3

SAE J2847/3, *Communication for Plug-in Vehicles as a Distributed Energy Resource*, was published as a work in progress to enable users to evaluate and attempt to meet requirements of the standard. SAE J2847/3 overlaps with SAE J3072 and SAE J2836/3, which address use cases for reverse power flow charging/discharging of EVs. This standard focuses on communications for a PEV as a DER. This applies to PEVs equipped with an onboard inverter and that communicate using IEEE Std 2030.5. The initial draft is available for public review and comments and provides the basis for additional testing. J2847/3 Version 1 was published in December 2013. Version 2 is a work in progress.

- **More information:**
    - https://saemobilus.sae.org/content/j2847/3_201312.

6.6 SAE J2894/1/2

SAE J2894-1, *Power Quality Requirements for Plug-In Electric Vehicle Charges*, addresses recommended practices for PEV chargers (onboard or off-board) to assess and ensure appropriate power quality levels while operating. SAE J2894-2 revises the earlier version to create a set of parameters that can be used to create a common platform for information exchange among original equipment manufacturers, suppliers, and utilities with regard to EV charging. (J2894/1/2 Version 1 was published in December 2011; Version 2 was published in March 2015.)

- **More information:**
  - http://standards.sae.org/j2894/2_201503/.

6.7 SAE J2953 PEV-EVSE

SAE J2953, *Plug-In Electric Vehicle Interoperability with Electric Vehicle Supply Equipment*, is an EV-EVSE interoperability requirement and test procedure standard that presently covers only AC charging. It is a work in progress that must close the gap between DC and wireless charging as well as for bidirectional power flow.

Gaps and other areas for future work include updating the SAE J2953 PEV-EVSE interoperability standard to include colocated stationary battery storage functions. These batteries primarily are used to manage grid demand as well as to mitigate demand charges.

- **More information:**
  - https://www.sae.org/standards/content/j2953/1_201310/.

6.8 Open Charge Point Protocol

The Open Charge Point Protocol 2.0, developed by the Open Charge Alliance (Open Charge Alliance 2019), is being adopted by the Organization for the Advancement of Structured Information Standards (OASIS) as a service data object, making this open-charge station protocol interchangeable by using JavaScript Object Notation (JSON 2019), a lightweight high-level description language, for more flexible implementation.

- **More information:**
  - https://www.openchargealliance.org/protocols/.

6.9 IEC 63110

IEC 63110, *Protocol for Management of Electric Vehicles Charging and Discharging Infrastructure*, is part of a series of IEC standards for charging and discharging station infrastructure and interactions with higher level systems (i.e., not the vehicles, which are covered in the IEC 15118 standards). Although it still in early development, it is a very intense international effort.

- **More information:**
  - https://www.iec.ch/dyn/www/f?p=103:38:10925266255447::::FSP_ORG_ID,FSP_APEX_PAGE,FSP_PROJECT_ID:1255,23,100390
  - https://www.iec.ch/dyn/www/f?p=103:38:10925266255447::::FSP_ORG_ID,FSP_APEX_PAGE,FSP_PROJECT_ID:1255,23,100391

- https://www.iec.ch/dyn/www/f?p=103:38:10925266255447::::FSP_ORG_ID,FSP_APEX_PAGE,FSP_PROJECT_ID:1255,23,100392.

6.10 Standards Gaps for Electric Vehicles

1. Bidirectional EV charging—which at times act as a DER—has a large gap in market development that will incentivize the EV interactive owner to spend extra money on this vehicle option. This market-development gap applies to a gradient of "grid interactive" capabilities in the EVSE and EVs such that today very few grid "smart" EVSE are sold because the extra communications functionality has few additional benefits for the vehicle owner.
2. The aggregation and contracting of regulations services or other methods of compensating the vehicle owner is another gap, and it is related to standards development facilitating transparent and open control of EVSE.
3. Additional work is needed to research and resolve potential conflicts between vehicular functions/needs and electric power system needs.
4. Additional effort is needed among metering and measurement standards task groups to coordinate standardized data formats for energy/power measurement information that is used for measurement and verification of EV availability as a DER or load reduction/responsive load changes. Specifically, the National Electrical Manufacturers Association, ANSI, NIST, Project Haystack, Green Button Alliance, Orange Button, SunSpec Alliance, and EMerge Alliance groups are working on meter data format standards.

7.0 Responsive Loads and Related Standards

According to the EIA, 74.9% of electric energy is used by loads in commercial and residential buildings (EIA 2012).

In the future, a substantial portion of these loads could become responsive, thus enabling them to be used not only for their primary usage by the customer but also for the provision of some or all of the grid services considered in this report.

Currently, grid interactions with responsive loads have been largely limited to traditional ("event-based") demand response, which is used to reduce loads on the grid to alleviate capacity constraints; however, recent years have seen dramatic growth in demand response in the form of time-varying rates.

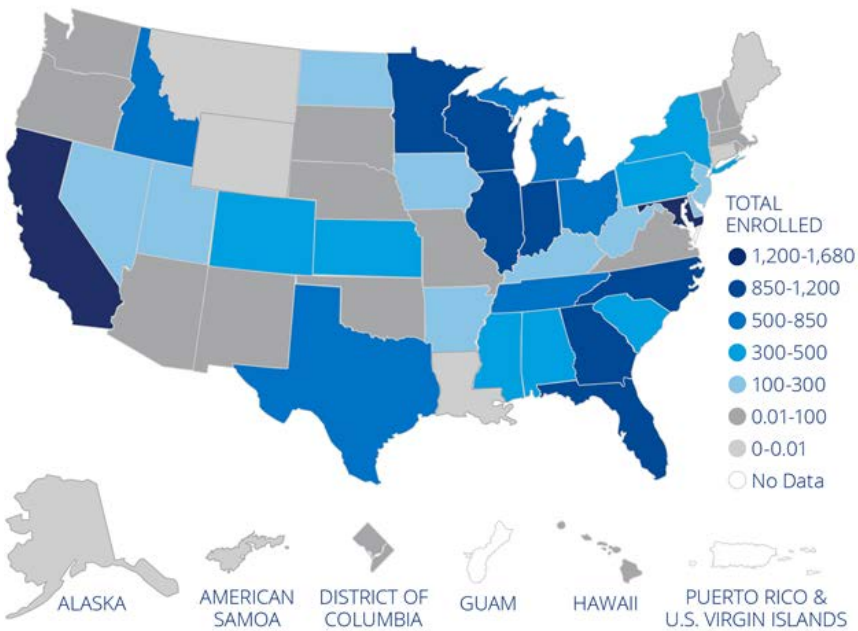

Figure 22. MW Capacity of demand response enrollment across the United States and territories
Image source: Smart Electric Power Alliance 2018a.[13] Used with permission

Figure 22 represents the total enrolled event-based demand response capacity in the United States by state according to the Annual Utility Survey conducted by SEPA. According to the survey, California contributed 8% of the total demand response capacity through AC switch, thermostat, behavioral, and commercial and industrial programs. Price-based demand response operates differently, with large numbers of customers having the opportunity to shed or shift load, but with significant effort needed to create and deploy the necessary technology infrastructure to harness the real potential.

[13] The result was based on responses from 155 utilities that participated in the SEPA Annual Utility Survey for calendar year 2017.

There is a broad range of potential responsive loads, and several solutions are used to connect them. The solution sets are rapidly expanding as nontraditional Internet of Things technology companies are entering the building space through connected devices, networking, and controls. Advancing from the traditional methods of demand response programs, some utilities are exploring grid-interactive water heater capabilities in residential buildings.

Larger commercial and industrial buildings typically have loads such as HVAC, lighting, and other energy-using systems, which can be (and often are) controlled via a building automation system that integrates operations to meet the building and its occupants' needs. In the future, building automation systems might be expected to have the capability to monitor and control loads at the individual appliance level and also connect to various supervisory control and data acquisition systems in use by electric system operators or to third-party aggregators.

Energy management systems are less common in small commercial or residential buildings. For the near term, connections for these facilities will likely be done at the appliance level, which will require an appropriate level of interoperability and response at those appliances to implement grid service functionality.

Today, most residential and small commercial responsive loads do not have this level of interoperability and capability. Traditionally, only larger appliances—such as air conditioners, electric dryers, and water heaters—have been used for demand response using direct utility load control switches. Certain newer communications-enabled devices, however—such as air conditioner thermostats, smart light bulbs, water heaters, plug-in switches, and refrigerators—are now becoming commercially available, which could increase their use in demand response programs in the future.

Common standards used in the buildings interoperability landscape are noted as follows.

7.1 IEC 62746-10-1 (OpenADR 2.0)

OpenADR (Open Automated Demand Response) was initially developed at Lawrence Berkeley National Laboratory (2019) in an effort to standardize automated two-way information exchange between electric utilities and customer-sited resources. In 2010, the OpenADR Alliance[14] was formed to support the continued development and commercialization of OpenADR (Lawrence Berkeley National Laboratory 2019). In November 2018, OpenADR 2.0 was published as an IEC standard, IEC 62746-10-1, *Systems Interface Between Customer Energy Management System And The Power Management System - Part 10-1: Open Automated Demand Response* (IEC 2018)

The scope of the standard is the definition of a communications data model and services for demand response, pricing, and DERs (including load, generation, and storage). The standard provides specifications for basic transport and security mechanisms, the definition of communications to coordinate price and reliability data for wholesale or retail markets, and the definition of communications to provide continuous dynamic price signals.[15] The initial application, as suggested by the name, was demand response programs; however, the global

[14] See https://www.openadr.org/overview.

[15] See IEC 62746-10-1.

increase in DER deployment has prompted broadening the scope of the standard to include information exchange with DERs (OpenADR 2019b).

Based on standard IP communications, OpenADR 2.0 messages can be transmitted using industry-standard information and communications technology equipment. OpenADR facilitates sending and receiving automated demand response signals between a grid entity and electric customers whose loads can respond to the signals. Examples of grid entities include electric utilities, distribution system operators (DSOs), ISOs, or RTOs. If needed, third-party aggregators can also receive and transmit OpenADR signals to provide coordination of end-use loads on behalf of these grid entities.

OpenADR can also work with on-site OpenADR client-embedded gateways. OpenADR interacts directly with building and industrial control systems that are preprogrammed to act based on a demand response signal, enabling fully automated demand response.

OpenADR signals can be received and acted upon by facility end-use loads, such as HVAC, lighting control systems, and EV chargers or via appropriate interfaces to industrial processes. An OpenADR message can be simple (e.g., shed now) or complex (e.g., shed 200 kW for 3 hours starting on a particular date and time). OpenADR currently has two versions, 2.0a and 2.0b, with 2.0b providing additional capabilities beyond those of 2.0a (i.e., 2.0a is a subset of 2.0b). An implementation guide was released in 2016 (OpenADR 2016a), and a more recent revision is in draft (OpenADR 2016b).

OpenADR 2.0 is a profile in the national standard OASIS Energy Interoperation 1.0 (OpenADR references the OASIS Emix and Energy Interoperation standards).

An OpenADR-compliant product can be tested via a certified OpenADR testing facility and certified through a process defined by the OpenADR Alliance (QualityLogic 2019).

- **More information:**
    - https://webstore.iec.ch/publication/26267
    - https://www.openadr.org/.

7.2 ANSI/ASHRAE 135 (BACnet)

ANSI/ASHRAE Standard 135-216*, BACnet: A Data Communication Protocol for Building Automation and Control Networks* has been in active development since June 1987. It was first published as a standard in 1995, became ISO 16484-5 in 2003, and is currently widely used in commercial building control systems.

The standard defines data communications services and protocols and is an abstract, object-oriented representation of information communicated between specific devices and building control systems.

BACnet is based on a four-layer "collapsed architecture" of the Open Systems Interconnection (OSI) model. The layers implemented in BACnet correspond to the physical, data link, network, and applications layers in the OSI model. BACnet defines the application layer and a simple network layer. The data link and physical layers are implemented by reference to other existing standards: Ethernet (ISO 8802-3), ARCNET (ATA 878.1), MS/TP, PTP, LonTalk (ISO/IEC 14908.1), BACnet/IP, BACnet/IPv6, and ZigBee.

The latest version of this standard was published in 2016 (ASHRAE 2016).

A related standard is ANSI/ASHRAE Standard 135.1, *Method of Test for Conformance to BACnet*. A revision was published in August 2019.

- **More information:**
    - http://www.bacnet.org/
    - http://www.bacnet.org/Bibliography/BACnet-Today-09/Bushby_2009.pdf.

7.3 IEEE Std 2030.5

IEEE Std 2030.5,[16] *IEEE Standard for Smart Energy Profile Application Protocol* (IEEE Standards Association 2018), is designed for communicating with DER devices, including responsive loads. IEEE Std 2030.5 is an IP-based standard in that it presumes the information is delivered on an IP communications stack. Because of this, it makes use of today's mainstream communications features and has modern cybersecurity support as part of the standard. IEEE Std 2030.5 is in use on DER integration projects throughout the world, though arguably its most mature deployments appear to be occurring in California based on the state's Rule 21 policy for integrating PV smart inverters and other variable generation. IEEE Std 2030.5 is structured to support different function sets that are tailored for technologies such as smart inverters in PV systems, batteries, EV charging, and demand response. The standard also supports electricity price distribution.

IEEE Std 2030.5 contains function sets for providing demand response but presently is not widely used for this function. IEEE Std 2030.5 is listed within IEEE Std 1547 and has increasing adoption for connection to smart inverters. It has a robust certification program through the SunSpec Alliance.

- **More information:**
    - https://ieeexplore.ieee.org/document/8608044.

7.4 ANSI/ASHRAE/NEMA Standard 201 (Facility Smart Grid Information Model)

ASHRAE/National Electrical Manufacturers Association (NEMA) Standard 201, *Facility Smart Grid Information Model (FSGIM)*, defines an information model to enable interoperability among facilities[17] and electric service providers. The information model includes provisions to communicate information about and to manage electrical loads and generators within the facility.

The standard was developed by ASHRAE and was also published as ISO 17800:2017 (ISO 2019) in December 2017.

[16] Previously known as SEP2.

[17] Facilities could mean homes, commercial and industrial buildings, and industrial facilities (ISO 2019).

In practice, the FSGIM information model is used in conjunction with (mapped to) a communications protocol. Within the larger commercial buildings' or industrial facilities' automation systems, the interaction with grid signals is typically via open standards, including BACnet (ANSI/ASHRAE 135) and LonTalk (IEC 1498).

- **More information:**
  - https://webstore.ansi.org/standards/ashrae/ansiashraenemastandard2012016-2402743
  - https://www.iso.org/obp/ui/#iso:std:iso:17800:ed-1:v1:en.

7.5 LonMark and LonTalk (ISO/IEC 14908-1)

LonMark aims to coordinate interoperable parts of the smart grid through consistent labeling (LonMark 2019). "LonMark profiles" have been created for vertical markets, such as building automation, lighting, security, homes, and transportation. The associated LonTalk (ISO/IEC 14908-1) is an open, international, local area control, networking protocol standard published on November 1, 2011. The LonTalk protocol has been installed in 50 million devices around the world. It is used in buildings, industrial, transportation, and utility/smart meter applications.

- **More information:**
  - https://www.lonmark.org/
  - https://www.iso.org/standard/60203.html.

7.6 ANSI/CEA-2045

ANSI/CEA 2045, Modular Communications Interface for Energy Management, emanated from work done in the Consumer Technology Association's (CTA) Modular Communications Interface for Energy Management subcommittee. The sponsors were CTA R7.8, USNAP Alliance, and the Electric Power Research Institute.

The collaboration resulted in the development of a standardized physical communications interface socket that can be installed in any end-use device, including loads and generation. The socket and a plug-in adapter, called a "universal communications module," work together to connect the end-use device to any communications interface. The standard defines the physical, electrical, and logical properties of the socket and the plug-in adapter.

ANSI/CEA-2045 defines two physical sockets on appliances: there is one socket for use in line voltage appliances (such as water heaters) that uses RS-485 and AC power and a second for use in DC devices (such as thermostats) that uses serial peripheral interface and DC power. The sockets are intended to support plug-in adapters to be provided by the utility or a third party. These adapters would have the necessary physical connections as well as the required communications protocol support for the demand response or other smart grid service. The overall concept is to reduce the total cost of connecting an appliance by placing a small cost into the socket, then providing an easily installed module to enable communications.

The standard supports a limited number of demand response commands, such as "shed," "end shed," and "grid emergency." Feedback from the device—such as consumption—is also supported but might not be available from all appliances. In theory, external interface adapters could use any protocol for demand response (e.g., Smart Energy Profile, OpenADR) as well as any connection media or method.

ANSI/CEA-2045 was approved as an ANSI standard in 2013. Since then, there have been several demonstration projects, primarily focused on large-scale pilot tests. Support in commercial building products is sparse, and only a few products are available for the residential sector, including a thermostat from Emerson (which could also be used in a commercial building without a building automation system, and a heat pump water heater from A. O. Smith. Ongoing work is being done on updating the standard based on feedback from the pilots.

Table 4 summarizes results from a collaborative laboratory demonstration between NREL and the Electric Power Research Institute. In the demonstration, the ANSI/CEA-2045 communications interface was used to control end-use devices, including a Siemens EVSE, Emerson thermostat, Pentair pool pump, A. O. Smith resistive water heater, A. O. Smith heat pump water heater, and a PowerHub battery energy storage system. Various device monitoring and control was demonstrated, including the provision of grid services.

Table 4. Results from Laboratory Demonstration of CTA 2045 Communications

Function	EVSE	Thermostat	Pool Pump	Resistive Water Heater	Heat Pump Water Heater	Solar Inverter	Battery Storage System
Monitoring Operating State	✓	✓	✓	✓	✓	✓	✓
Monitoring Real Power	✓ m	✓ s	✓ m	✓ e	✓ e	✓ m	✓ m
Monitoring Reactive Power						✓	✓
Monitoring Frequency						✓	✓
Monitoring Voltage						✓	✓
Monitoring Energy-Take Capability			✓	✓	✓		✓
Shed (Moderate Real Power Curtailment)	✓	✓	✓	✓	✓		
Critical Peak (Aggressive Real Power Curtailment)	✓	✓	✓	✓	✓		
Load-Up (Real Power Increase)	✓	✓	✓	✓	✓		
Variable Real Power Control	✓		✓			✓	✓
Power Factor Function						✓	✓
Volt-Var Function						✓	✓
Volt-Watt Function						✓	✓
Watt-Frequency Function						✓	✓
Scheduled Operation	✓	✓	✓				✓

m = measured via internal metering, e = device estimate, s = statistical estimate

Source: (Hudgins et al. 2018)

Pilot demonstrations such as this have been valuable in proving the concept; however, the adoption of this standard has not gained critical mass to date.

- **More information:**
  - https://www.nrel.gov/docs/fy18osti/70274.pdf
  - http://eprijournal.com/can-we-talk/
  - https://www.cooperative.com/programs-services/bts/documents/reports/standardized-communications-for-demand-response-report-june-2018.pdf
  - https://smartgrid.epri.com/doc/ICT%20Informational%20Webcast%20CEA-2045%2009APR2015.pdf
  - https://webstore.ansi.org/Standards/CEA/CEA20452013ANSI.

7.7 Standards Gaps for Responsive Loads

1. Despite increases in communications and the Internet of Things in buildings, very few appliances (especially in residential and small commercial loads) can be controlled remotely at all, and even fewer can be controlled through one of the open communications standards described. Few consumers are asking for grid interactivity, and currently there are few financial incentives for them to have it. Until external control of large building loads is more common, using loads as DERs is likely to remain limited.
2. There is a lack of standardization for the use of responsive loads to furnish grid services. Currently, there are multiple, usually proprietary, and potentially unique ways of programming control down to the device level.
3. There are no interconnection standards for specific loads that map back to the grid services directly.
4. There is no standardized method for the use of frequency responsive loads. Currently, end-use devices are not typically programmed to respond to a frequency event. In fact, many end-use devices should not be cycled on and off at the rate needed to respond to frequency response. The end uses that are best suited to frequency response are devices that run off variable-frequency drives, but those are not very common in residential and small commercial buildings. The Pacific Northwest National Laboratory notes that some frequency controllers have been developed, but they have not been mass-marketed (Pacific Northwest National Laboratory 2019).
5. There is no standard method for controlling both active and reactive power in responsive loads.
6. Power quality attributes of responsive loads such as electrolyzers and commercial HVAC systems need to be studied in detail when used to maintain electric grid balance. GMLC 1.4.02, "Definitions, Standards, and Test Procedures for Grid Services,"[18] is investigating the response of loads to different grid service requests. The findings from this research will help identify further gaps in current standards.
7. Reporting of demand response behavior within a given facility is not well defined or commonly standardized. Buildings and industrial facilities do not have a standard for a consistently defined interface (e.g., application programming interface) that describes the power and energy that can be provided to the grid during various time frames. Currently, there are no standards or defined best practices to characterize or predict the electric load response of various end-use systems and technologies, such as HVAC, lighting, electric storage, EVs, or plug loads. The predictability of load responses could facilitate more widespread use of these DERs by better characterizing the environment in which they operate. Research and some proprietary commercial deployments perform these types of dynamic load forecasting calculations for DERs by using off-site cloud computers, on-site computers, or a combination of both.
8. Substantial gaps exist in defining standards for responsive loads and in transitioning the market to include these functions in new products. Gaps include the need for more guidance and definition on how to deliver grid services beyond demand response and

[18] See https://gridmod.labworks.org/projects/1.4.02.

how to provide the necessary transactive negotiations, including estimating deliverable services and providing measurement and verification. Efforts are underway to further develop the concept of an energy services interface that could help manage aggregated appliances in the future.

9. OpenADR currently conveys requests for load reductions consistent with the needs of energy-related grid services. Presently, there are no standards for explicitly requesting reactive power from loads, although testing has confirmed that OpenADR signals can convey sufficiently detailed messages within the time needed to elicit a frequency or voltage correction at the grid level. Formalizing the addition of this functionality to existing standards such as OpenADR should be a priority.

10. Additional standardization is required for responsive load types such as electrolyzers and commercial HVAC systems that require ride-through capability (for voltages and frequency) to stay connected in an islanded electric power system situation. Although HVAC systems are relevant to residential and commercial buildings, the electrolyzer is the key component in a grid-connected hydrogen vehicle refueling station and can serve as a responsive load. This aspect is currently being investigated in a DOE Fuel Cell Technologies Office-funded project, "Dynamic Modeling and Validation of Electrolyzers in Real Time Grid Simulation"[19]; however, other studies are needed.

[19] See https://www.energy.gov/eere/fuelcells/dynamic-modeling-and-validation-electrolyzers-real-time-grid-simulation.

8.0 Grid-Connected Microgrids and Related Standards

According to a study by Navigant and Advanced Energy Economy, intuitions such as hospitals, universities, and military campuses in the United States are deploying microgrids to increase their resilience to power disruptions (Advanced Energy Economy 2019). Islands such as Puerto Rico also plan to deploy microgrids to leverage the microgrid capabilities to operate in both grid-connected and islanded modes, thus improving resilience against natural disasters (Utility Dive 2019).

Figure 23 indicates microgrid deployment in the U.S. mainland in 2017. Increased deployment can be observed in the states of New York, New Jersey, Florida, and parts of California. GTM Research predicted that the microgrid capacity in the United States by 2022 could more than double that of 2017 (3.2 GW). In addition, it is relatively easy to provide energy-related and regulation-related grid services because some functionalities are already built into it, such as islanding and reconnecting.

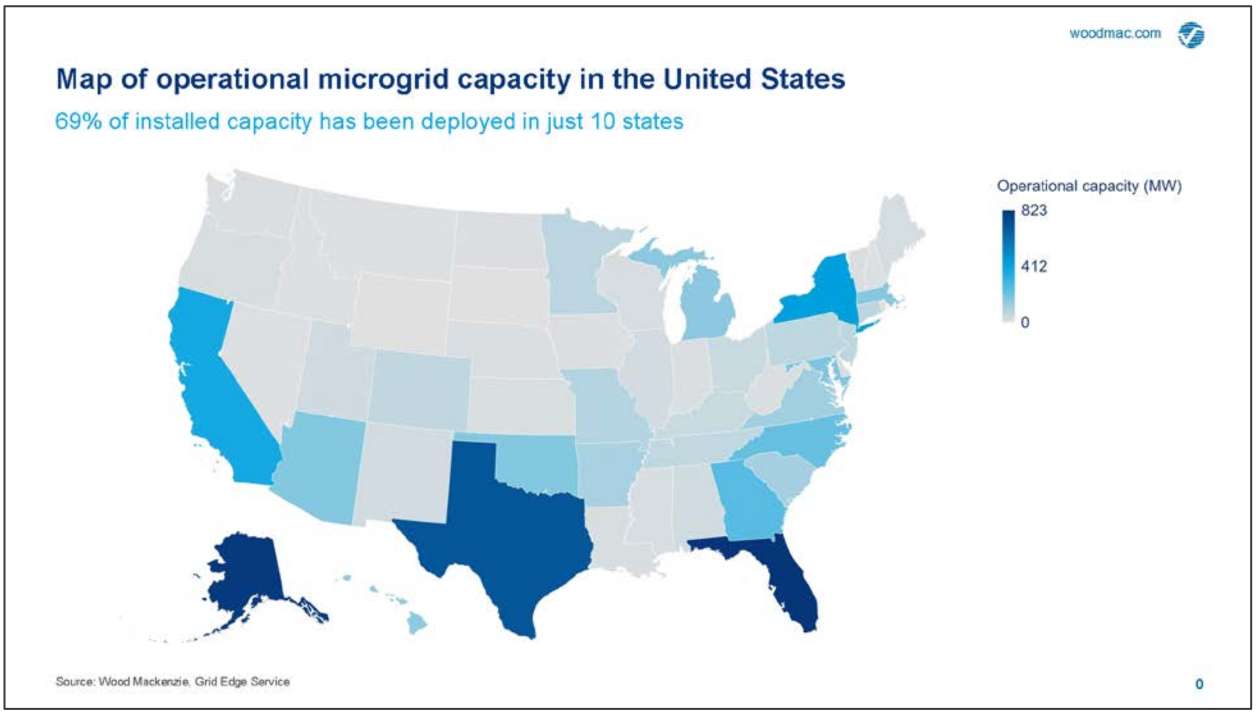

Figure 23. Map of microgrid deployments in the United States

Image source: Wood Mackenzie Power & Renewables, Grid Edge Service. Used with permission

Microgrids are an evolving technology and have gained important roles in improving customer reliability and grid resilience. The DOE Microgrid Exchange Group defines the microgrid as "a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island-mode." This definition is increasingly being adopted as a reference to study, develop, design, and deploy microgrids. Figure 24 shows a typical layout of a microgrid. The black lines represent electrical connections. The dotted blue lines represent communication and control from the microgrid controller to devices. One unique attribute of microgrids that is yet to be harnessed on a substantial scale is the provision of essential grid services to distribution networks.

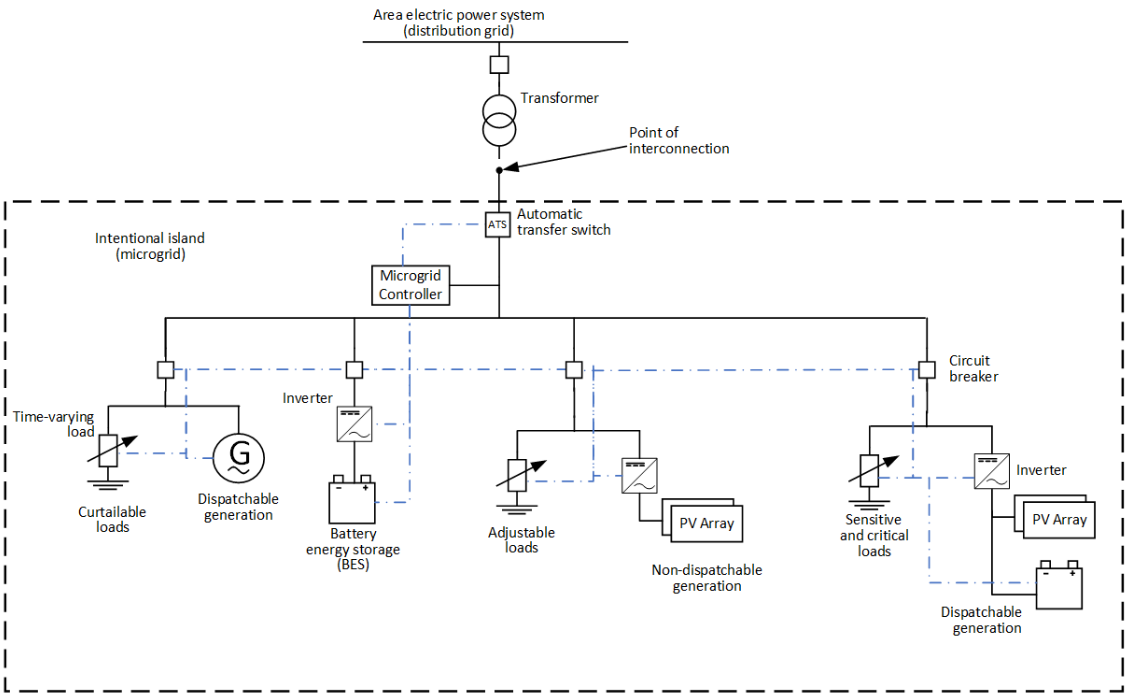

Figure 24. A generic microgrid architecture representation

Image based on IEEE Std 2030.7-2017, Appendix A

A microgrid has two modes of operation: grid-connected and islanded. The transition between modes might be triggered by several items, including loss of the grid, microgrid design objectives, or contractual arrangements.

Microgrids operating in a grid-connected configuration—which could be the most frequent case for many installations—have different challenges with regard to the provision of grid services. Dispatch management and protection system coordination with the upstream distribution networks is necessary. Guidance and test standards with specific criteria for testing the microgrid controllers and the design of the microgrid are required. As mentioned, microgrids can be considered flexible assets that can assist DSOs during both normal and emergency situations. When coordinated, microgrids defined as a single controllable entity can provide real and reactive power, on demand, in a predictable manner. This crucial controllability enhances the overall distribution and even transmission network management with better quality of service to end users/customers. Several design and standard attributes must be addressed prior to the realization of microgrids providing services back to the grids. When the microgrid is connected to the grid, the microgrid control system can remain involved with negotiating services or act as a proxy for the downstream DERs. In this model, the connection between the DSO and microgrid controller is much like that between the RTO and the DSO. Alternatively, the microgrid controller could stop providing grid services when grid-connected and allow the DSO to negotiate directly with the downstream resources.

When the microgrid is islanded (not connected to the grid), the microgrid energy management and control system must be able to provide similar grid services, including managing capacity, voltage, and frequency for the customers within the microgrid. There are also a series of special services that are unique to a microgrid control system, such as the ability to black start and to provide the needed coordination to connect to and disconnect from the grid in a safe and secure manner. This means that the microgrid control system must provide similar services to those provided by the DSO, RTO, or ISO and that the DERs located on the system must be able to respond properly. Additionally, protection system coordination is an important consideration within and outside microgrids, especially with events upstream leading to islanded microgrid operation. In many cases, maintenance and outage management is required in area power systems with microgrids. The provision of black-start services and unintentional energization of faults, which might or might not be detected accurately, are further technical intricacies requiring understanding and eventually standardization. Also, low-fault currents that are difficult to detect in distribution networks could complicate operations, especially when associated with DERs installed in microgrids. Currently, no standards address these attributes for testing and validating the operation of microgrid control systems, although IEEE P2030.7 and P2030.8 plan to address several relevant areas.

The microgrid controller is responsible for detecting the grid conditions and initiating the transition between grid-connected mode and islanded mode, which includes anti-islanding detection and reconnect check.

Microgrids can be designed for varying degrees of scales, ratings, objectives, and geographic expanse. The categorization of microgrids can be done using these variations as well (e.g., residential, large building complexes, university campuses, remote, urban, and even entire utility distribution networks). The objectives for microgrids vary from improved reliability to resilience, quality of service, and reduced carbon emissions. Based on the inherent components and their types, the structure of microgrids can be AC, DC, and hybrid.

Another concept, similar to an energy services interface, is a distributed energy resource management system (DERMS). DERMS are being formulated to interact and control multiple DERs, EVs, combined heat and power plants, and microgrids that are connected to distribution grids. In this context, there can be interactions between individual DERs within a microgrid or with only the microgrid controller.

During grid-connected operation, the microgrid controller must technically understand the expectation of DERMS from the DERs that are included under the microgrid. Grid-connected microgrids must be treated as a single, controllable entity for DERMS operation. Hence, the provision of services from DERs associated with a microgrid has an additional layer of controls in the form of a microgrid controller.

Interoperability and interconnection between DERMS and microgrid controllers to ensure proper command and response for managing the DERs within the microgrid during grid-connected operation to provide grid services is not yet clearly defined. As DERMS evolve, the communications protocols associated with them will also change/evolve.

The IEEE standards relevant to the microgrid controller must have relevant functions to understand/interpret requests from DERMS, especially related to providing grid services. The interpretation must result in the redispatch of DERs within the microgrid to result in the provision of requested grid services. Microgrid controllers, however, require well-defined functions and capabilities to provide grid services, regardless of DERMS. DERMS do not seem to have a defined capability and function like a microgrid controller.

Future systems could have many levels of command and control; it is unclear how DERMS will ensure the provision of higher level requests from DERs controlled by DERMS. There also is no clarity regarding whether DERMS communicate to the energy management system or distribution management system.

Facility DERMS systems are similar to a microgrid but might not operate in islanded mode (though they easily could with the right equipment). California Rule 21 distinguishes this type of DER interface.

Standards related to the microgrid landscape are discussed as follows.

8.1 IEEE Std 1547 and IEEE Std 1547.1

The latest revisions of IEEE Std 1547 and IEEE Std 1547.1 contain requirements for intentional islands. See Chapter 4.0 of this document for more information on these standards.

8.2 IEEE Std 1547.4

IEEE Std 1547.4, *Guide for Design, Operation, and Integration of Distributed Resource Island Systems with Electric Power Systems*, published in 2011, provides useful background and considerations for the use of intentional islands in electric power systems. The term *distributed island system*, also referred to as a microgrid, is used to refer to intentional islands. The standard provides definitions, a system overview, planning, engineering, and operational aspects of islanded systems.

- **More information:**
    - https://ieeexplore.ieee.org/document/5960751
    - http://grouper.ieee.org/groups/scc21/1547.4/1547.4_index.html.

8.3 IEEE Std 2030.7-2017

The scope of IEEE Std 2030.7, *IEEE Standard for the Specification of Microgrid Controllers*, is to address the technical issues and challenges associated with the proper operation of the microgrid energy management system that are common to all microgrids and to present the control approaches required from the DSO and the microgrid operator.

More information:

- https://standards.ieee.org/develop/project/2030.7.html.

8.4 IEEE Std 2030.8-2018

The scope of IEEE Std 2030.8, *Standard for the Testing of Microgrid Controllers*, is to develop testing procedures of microgrid controller functions and requirements defined in IEEE Std 2030.7.

More information:

- https://standards.ieee.org/develop/project/2030.8.html.

8.5 IEEE Std P2030.9

IEEE Std P2030.9, *IEEE Draft Recommended Practice for the Planning and Design of the Microgrid*, provides an overview of the planning and design process and provides some guidance on key topics, including system design, protection, monitoring, and control.

- **More information:**
  - https://standards.ieee.org/develop/project/2030.9.html.

8.6 Standards Gaps for Grid-Connected Microgrids

1. Interconnection requirements for microgrids providing grid services and the expected performances/capabilities must be clearly articulated. This is necessary because microgrids might be expected to provide services to the area electric power system when simultaneous grid disturbances occur. In such cases, microgrid energy management systems typically tend to intentionally island the microgrid from the area electric power system and operate in islanded mode. This intentional islanding operation is the desired mode of operation if the microgrid is not providing any services. Guidelines and requirements for the microgrid energy management system and the microgrid must be established for such cases.
2. Guidelines on testing and commissioning a microgrid system providing these grid service requirements and performance should be specified to harmonize the design and deployment of microgrids and the associated microgrid energy management system with grid services functionality. Having a process to certify a microgrid controller or microgrid energy management system product and to commission a microgrid system requires a consistent and sufficient set of test procedures as well as a self- or industry certification process. To use microgrid controller products at scale, manufacturing certifications are also needed.
3. Interoperability requirements using standard communications protocols for connected or networked microgrids and microgrids to higher level grid management systems must be established. These requirements are essential for providing grid services by individual or multiple microgrids to the area electric power system. Grid services could be provided under an autonomous or supervisory manner by microgrids, and the supporting functionality should be specified. A future standard should consider networked microgrids and a microgrid with multiple points of interconnection, especially for large-scale microgrids that could provide grid services.

4. Cybersecurity requirements and compliance are required for the secure operation of microgrids. Currently, NERC has developed cybersecurity reliability standards, *Critical Infrastructure Protection Version 5*, only for bulk power systems.
5. There is no common definition for a DERMs. The term *DERMS* has been formulated by multiple entities (e.g., NIST, Electric Power Research Institute) and for-profit organizations.
6. Standards on protection schemes deployed within the microgrid—including protection functions of individual components and assets and protection coordination with distribution grid protection schemes—must be developed. Currently, no standards prescribe protection schemes deployed within the microgrid. The fault current contributions from inverter-based DERs are relatively small—typically two to three times the rated inverter current—which makes it hard for traditional protective devices to detect and react.
7. Interconnection and interoperability requirements for DERMS must be translated and specified in future standards to ensure specificity and consistency of performance—for example, a DERMS request for voltage support from microgrids in the form of reactive power generation and its quantification.
8. Management of nonstationary assets such as EVs within a microgrid versus being connected outside but within DERMS must be assessed.
9. Communications among multiple microgrids along with DERMS management signals need to be well-understood for successful grid services from microgrids. Standards must also consider providing information on the prioritization of microgrid goals, such as resilience and reliability enhancements for local loads.
10. Typically, microgrid controllers deal with set point determination during a large time window (i.e., minutes), which needs to be matched with the time interval requested of the grid service.
11. There is insufficient interoperability and interconnection guidance/standards for optimization and dispatch algorithms for existing microgrid controllers to provide energy-related grid services.
12. Microgrid controllers can implement profiles of power import/export that could potentially correspond to the provision of regulation-type services, however, there are currently insufficient standards for the measurement and control for microgrids to provide these type of grid services. For example, set points are typically determined on a 5-minute time resolution; however, for voltage support, this must be more dynamic. A related gap is that it is challenging to distinguish between the provision of voltage support within the microgrid versus the area electric power system.
13. New methods for the computation and quantification of inertial response by microgrids is needed because this is currently difficult. As a result, there is a lack of functionality for microgrid controllers to provide synthetic inertia.
14. Compensation mechanism for microgrids providing grid services lack maturity.
15. The current IEEE Std 1547.4-2011 provides only an introduction and overview of microgrid systems. Detailed interconnection and interoperability requirements are not

sufficiently defined. Islanded interconnection device (the modern equivalent of a smart transfer switch) definitions and usage relative to meeting/harmonizing with IEEE Std 1547.4 are needed. A revision is recommended to define specific grid services requirements for microgrids operating in grid-connected mode. The new revision should serve as a high-level requirement guide for microgrid interconnection and interoperability to provide appropriate grid services, including energy-related, regulations, ramping, voltage management, and virtual inertia, as identified in GMLC project 1.4.2. Revisions to IEEE Std 1547.4 must be consistent with IEEE Std 2030.7 and IEEE Std 2030.8.

16. Current IEEE Std P2030.7 does not address issues related to the power exchanges between the microgrid and the distribution network at the point of interconnection while the microgrid is in grid-connected mode. It is recommended that specifications of microgrid higher level grid service functions while connected to the grid are added to IEEE Std 2030.7 and that their testing procedures to IEEE Std 2030.8 in the next revision cycle.
17. Microgrid energy management system capabilities are addressed, but microgrid operations and communications should also be specified to be universal or transparent under IEEE Std P2030.7.
18. Future work in microgrid standards should extend the functionalities to distributed microgrid inverter control architecture to define architecture-independent general functional requirements.
19. In IEEE Std P2030.7, there is a lack of higher level functional requirements and interoperability between the microgrid management system and distribution management system. The current draft addresses only microgrid energy management system core-level operational functions.
20. Lower level device control functions, interconnection, and interoperability are not addressed in the current draft of IEEE Std P2030.7.
21. Device response time and communications requirements are not addressed in IEEE Std 2030.7.
22. Grid service energy or power requirements must be added in the microgrid controller middle-level (normally realized by a tertiary controller) dispatch function. Currently, the microgrid controller dispatch functionality in IEEE Std P2030.7 is used only to provide the need of local loads and maintain desired reserves, depending on the mode of microgrid operation.
23. Black-start services to the area electric power system need specific interoperability and interconnection requirements to be followed by the microgrid energy management system. These need to be specified in the revisions of IEEE Std 2030.7 and IEEE Std 2030.8.
24. Lower level inverter control functions at the device level when the microgrid is operating in stand-alone mode have not been standardized. The common communications protocols and requirements for distributed or cooperative control schemes need to be harmonized for the interoperability of devices within a microgrid.

25. The seamless transition capability of an inverter and/or accompanying interconnect device from grid-connected/grid-following mode to grid-forming/islanded mode has not been standardized. This is particularly important for battery ESS that integrate to a small-scale microgrids (Cheli 2017).

9.0 Crosscutting Gaps

Standardized Interface for Distributed Energy Resources

Grid operators and utilities throughout the United States do not have a standardized interface (e.g., application program interface) that consistently describes the service interactions needed from the DERs listed in this report. One option could be to use the best practices currently used to characterize and dispatch traditional generators as a starting point to profile and control DERs. Although the profiles of DERs will be different than those of traditional centralized generators, many of the same performance metrics are used, including latency, ramp rate, duration, and time of day. Lack of characterization of all types of DERs in energy terms that are meaningful to grid operators is a key system-wide gap. A potential means of addressing this gap could be the energy services interface.

End-to-End Interoperability Standards and Certification

There currently is no standardized certification process performed by a nationally recognized testing laboratory for end-to-end interoperability of DERs connected to the electric grid.

Standards for Distributed Energy Resource Cyber-Physical Security

Standards for the cyber-physical security of DER systems are still emerging, and they are insufficiently socialized among industry. The offsetting of traditional centralized generation with DERs requires increased automation of operational control and communications among DER providers. This implementation poses the potential for compromising the security of the required information between the assets and the utilities or aggregators. Efforts are underway by many stakeholders to address these gaps, including the following:

- In 2010, NIST and the Smart Grid Interoperability Panel (now merged with SEPA) developed interagency report 7628 (NISTIR 7628) presenting a high-level smart grid architecture and logical reference model. Upon this foundation, NISTIR 7628 provides a set of high-level technical requirements (controls) for cyber-physical security. These requirements are generalized within three families of controls: governance, risk, and compliance (i.e., policy); common technical security requirements (apply to all smart grid interfaces); and unique technical security requirements. Note that NISTIR 7628 is not a communications protocol or language (i.e., IEEE Std 1815/DNP3) or a mandatory standard. Instead, NISTIR 7628 is best described as a process or guide for evaluating cyber risks in a smart grid system when the DERs are contained. Work remains to review the NISTIR 7628 smart grid architecture and logical models relative to today's DER functionality (e.g., coordination with the bulk energy system operator for ride-through); then to review and update the relevant interfaces (communications pathways) for DERs; and to update the unique security requirements/controls as needed to secure additional "smart inverter" functionality.
- SunSpec Alliance together with Sandia National Laboratories launched a DER security working group in August 2017. The aim of the group is to bring together DER interoperability and cybersecurity experts to discuss security for DER devices, utilities, aggregators, and the entire U.S. power system. Five subgroups in this working group have a

focus on the following: DER cybersecurity certification procedure, data-in-flight requirements, patching requirements, secure network architecture, access control, and utility/aggregator auditing procedure. For more information, see https://sunspec.org/cybersecurity-work-group/.

- Lawrence Livermore National Laboratory, Hawaiian Electric Company, and others are currently developing tools to assess the cybersecurity risks of various DER interconnection architectures. The project will also identify remediation and best practice guidelines for DER cybersecurity (DOE 2017a).

References

Advanced Energy Economy. 2019. *Advanced Energy Now: 2019 Market Report: Global and U.S. Markets by Revenue 2011-18 and Key Trends in Advanced Energy Growth*. San Francisco. https://info.aee.net/hubfs/Market%20Report%202019/AEN%202019%20Market%20Report.pdf.

ASHRAE. 2016. *Standard 135-2016 -- BACnet-A Data Communication Protocol for Building Automation and Control Networks*. https://www.techstreet.com/ashrae/standards/ashrae-135-2016?product_id=1918140.

California Energy Commission. 2018. “Tracking Progress.” https://www.energy.ca.gov/data-reports/tracking-progress

Cheli, Maia. 2017. “Blue Lake Rancheria Microgrid: Project Update.” Schatz Energy Research Center. Accessed September 30, 2019. http://www.schatzlab.org/news/2017/10/blue-lake-rancheria-microgrid-project-update/.

Cooper, Adam, and Kellen Schefter. 2018. *Electric Vehicle Sales Forecast and the Charging Infrastructure Required Through 2030*. Washington, D.C.: The Edison Foundation and the Edison Electric Institute. http://www.ehcar.net/library/rapport/rapport233.pdf.

Denholm, Paul, Robert Margolis, and Joshua Eichman. 2017. “Evaluating the Technical and Economic Performance of PV Plus Storage Power Plants.” *Renewable Energy* 36.

Denholm, Paul, Yinong Sun, and Trieu Mai. 2019. *An Introduction to Grid Services: Concepts, Technical Requirements, and Provision from Wind* (NREL/TP-6A20-72578). Golden, CO: National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy19osti/72578.pdf.

DNP. 2019. “Overview of DNP3 Protocol.” https://www.dnp.org/About/Overview-of-DNP3-Protocol.

Electric Power Research Institute, DNP, Modular Energy Storage Architecture, and SunSpec Alliance. 2019. “New Standard Communication Model Enables Grid Operators to Enhance Performance, Value of Distributed Energy Resources.” January 14, 2019. https://www.dnp.org/Portals/0/Public%20Documents/PR%201112%20App%20Note%20Press%20Release_2019-01-14_FINAL.pdf.

Federal Energy Regulatory Commission (FERC). 1996. *FERC Order No. 888*. https://www.ferc.gov/legal/maj-ord-reg/land-docs/rm95-8-00w.txt.

———. 2015. “Regional Transmission Organizations.” https://www.ferc.gov/sites/default/files/2020-05/elec-ovr-rto-map.pdf.

Gevorgian, Vahan, Przemyslaw J. Koralewicz, Hugo Nestor Villegas Pico, Shahil D. Shah, Robert B. Wallen, David A. Corbus, Jonathan A. Keller, R. Hovsapian, M. Mohanpurkar, R. Kadavi, M. Pnawar, J. Leonard, M. Richwine, N. Miller, D. Gao, W. Yan, and W. Gao. 2019. *WGRID-49 GMLC Project Report: Understanding the Role of Short-Term Energy Storage and Large Motor Loads for Active Power Controls by Wind Power* (NREL/TP-5D00-72888). Golden, CO: National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy19osti/72888.pdf.

Gheorghiu, Lulia. 2019. "As 100% Renewables Mandate Nears, Puerto Rico Sees New Microgrid Initiative, Resilience Focus." *Utility Dive*, March 22, 2019. Accessed October 29, 2020. https://www.utilitydive.com/news/as-100-renewables-mandate-nears-puerto-rico-sees-new-microgrid-initiative/551114/.

Greenfield, Lawrence R. 2018. "An Overview of the Federal Energy Regulatory Commission and Federal Regulation of Public Utilities." June 31, 2018. https://www.ferc.gov/sites/default/files/2020-07/ferc101.pdf.

Grid Modernization Laboratory Consortium (GMLC). 2017. "GMLC Grid Services Master List." Accessed September 29, 2019. https://gmlc.doe.gov/resources/gmlc-grid-services-master-list.

———. 2019. "Definitions, Standards, and Test Procedures for Grid Services." Accessed September 27, 2019. https://gmlc.doe.gov/projects/1.4.02.

GridWise. 2019. "Smart Grid Interoperability Maturity Model Summary." Accessed April 24, 2018. http://www.gridwiseac.org/about/imm.aspx.

Hudgins, Andrew P., Bethany F. Sparn, Xin Jin, and Brian Seal. 2018. *NREL Topic 1 Final Report: Cohesive Application of Standards-Based Connected Devices to Enable Clean Energy Technologies* (NREL/TP-5B00-70274). Golden, CO: National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy18osti/70274.pdf.

Institute of Electrical and Electronics Engineers (IEEE) Standards Association. 2018. *IEEE 1547 2018 – IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces*. Piscataway, New York. https://standards.ieee.org/standard/1547-2018.html.

———. 2012. *IEEE 1815-2012 – IEEE Standard for Electric Power Systems Communications-Distributed Network Protocol*. https://standards.ieee.org/standard/1815-2012.html.

International Electrotechnical Commission (IEC). 2018. *IEC 62746-10-1, Systems Interface Between Customer Energy Management System And The Power Management System - Part 10-1: Open Automated Demand Response.* Geneva, Switzerland

Irle, Roland. 2019. "USA Plug-in Sales for the First Half of 2019." Accessed August 13, 2019. http://www.ev-volumes.com/country/usa/.

ISO. 2019. *ISO 17800:2017 Facility Smart Grid Information Model*. Geneva, Switzerland. Accessed April 24, 2018. https://www.iso.org/standard/71547.html.

JSON. 2019. "Introducing JSON." Accessed September 27, 2019. https://www.json.org/.

Lawrence Berkeley National Laboratory. 2020. "About Us." Demand Response Research Center. Accessed December 16, 2019. https://drrc.lbl.gov/about-us.

Lee, Eun-Kyu, Rajit Gadh, and Mario Gerla. 2013. "Energy Service Interface: Accessing to Customer Energy Resources for Smart Grid Interoperation." *IEEE Journal on Selected Areas in Communications* 31 (7): 1195–204. https://doi.org/10.1109/JSAC.2013.130704.

LonMark. 2019. "LonMark." Accessed April 24, 2018. http://www.lonmark.org/.

Luo, Yusheng, Manish Mohanpurkar, Rob Hovsapian, Vahan Gevorgian, Eduard Muljadi, and Vladimir Koritarov. 2018. *Enhancing the flexibility of generation of Run-Of-the-River Hydro Power Plant*. (INL/CON-18-45285-Revision-0). Idaho Falls, Idaho. Idaho National Laboratory https://inldigitallibrary.inl.gov/sites/sti/sti/Sort_5256.pdf.

Modular Energy Storage Architecture (MESA). 2014a. "MESA Standards." Accessed April 24, 2018. http://mesastandards.org/.

———. 2014b. "MESA-ESS." Accessed August 8, 2019. http://mesastandards.org/mesa-ess/.

———. 2018. *MESA-ESS Specification DRAFT*. http://mesastandards.org/wp-content/uploads/2019/01/MESA-ESS-Specification-December-2018-update-v1.pdf.

National Institute of Standards and Technology (NIST). 2014. *NIST Framework and Roadmap for Smart Grid Interoperability Standards, Release 4.0* (NIST Special Publication 1108r4). Gaithersburg, MD. Accessed March 8, 2021. https://nvlpubs.nist.gov/nistpubs/SpecialPublications/NIST.SP.1108r4.pdf.

National Institute of Standards and Technology (NIST). 2021. *NIST Framework and Roadmap for Smart Grid Interoperability Standards, Release 3.0* (NIST Special Publication 1108r3). Gaithersburg, MD. Accessed April 24, 2018. http://dx.doi.org/10.6028/NIST.SP.1108r3.

Nissan Motor Corporation. 2019. "'Vehicle to Home' Electricity Supply System." Accessed August 13, 2019. https://www.nissan-global.com/EN/TECHNOLOGY/OVERVIEW/vehicle_to_home.html.

North American Electric Reliability Corporation (NERC). 2011. *Balancing and Frequency Control*. Atlanta, GA. https://www.nerc.com/docs/oc/rs/NERC%20Balancing%20and%20Frequency%20Control%20040520111.pdf.

———. 2015. "Reliability Guideline: Primary Frequency Control." Atlanta, GA. https://www.nerc.com/comm/OC/Reliability%20Guideline%20DL/Primary_Frequency_Control_final.pdf.

———. 2016. *Essential Reliability Services: Whitepaper on Sufficiency Guidelines*. Atlanta, GA. https://www.nerc.com/comm/Other/essntlrlbltysrvcstskfrcDL/ERSWG_Sufficiency_Guideline_Report.pdf.

———. 2019a. "NERC Regions Map." https://www.nerc.com/AboutNERC/keyplayers/PublishingImages/Regions%2001JUL19.jpg.

———. 2019b. "NERC Balancing Authority Areas." https://www.nerc.com/AboutNERC/keyplayers/PublishingImages/BA%20Bubble%20Map%2020191106.tif.

Open Charge Alliance. 2019. "Open Charge Alliance: Global Platform for Open Protocols." Accessed April 24, 2019. http://www.openchargealliance.org/.

OpenADR. "Overview." 2020. Accessed December 16, 2019. https://www.openadr.org/overview.

———. 2016a. *OpenADR 2.0 Demand Response Program Implementation Guide: Revision Number: 1.0*. The Netherlands. https://www.openadr.org/assets/openadr_drprogramguide1.0.pdf.

———. 2016b. *OpenADR 2.0 Demand Response Program Implementation Guide." Revision Number: 1.1. Draft*. The Netherlands. https://www.openadr.org/assets/openadr_drprogramguide_1_1.pdf.

———. 2019a. "Connecting Smart Energy to the Grid." Accessed April 24, 2018. http://www.openadr.org/.

———. 2019b. "Helping the Industry Manage Energy Resources." Accessed September 5, 2019. https://www.openadr.org/openadr-and-der.

Pacific Northwest National Laboratory. 2019. "Grid Friendly Appliance™ Controller." Accessed April 24, 2019. http://availabletechnologies.pnnl.gov/technology.asp?id=61.

Payne, Greg. 2019. *Understanding the True Value of V2G: An Analysis of the Customers and Value Streams for V2G in the UK*. Leicestershire, UK: Cenex. Accessed September 27, 2019. https://www.cenex.co.uk/app/uploads/2019/10/True-Value-of-V2G-Report.pdf.

PJM. 2017. "PJM - Price Responsive Demand." PJM. https://learn.pjm.com/-/media/about-pjm/newsroom/fact-sheets/price-responsive-demand.ashx.

———. 2020a. "PJM Learning Center - Capacity Market (RPM)." https://learn.pjm.com/three-priorities/buying-and-selling-energy/capacity-markets.aspx.

———. 2020b. "PJM Learning Center - Regulation Market." Accessed January 14, 2020. https://learn.pjm.com/three-priorities/buying-and-selling-energy/ancillary-services-market/regulation-market.aspx.

———. 2020c. "PJM Learning Center - Energy Markets." Accessed January 14, 2020. https://learn.pjm.com/three-priorities/buying-and-selling-energy/energy-markets.aspx.

QualityLogic. 2019. "OpenADR Test Tools and QA Services." Accessed September 27, 2019. https://www.qualitylogic.com/what-we-test/smart-energy-standards/openadr-2-test-tools-and-qa-services/.

Smart Electric Power Alliance (SEPA). 2018a. *2018 Utility Demand Response Market Snapshot*. Washington, D.C. Accessed September 9, 2019. https://sepapower.org/resource/2018-demand-response-market-snapshot/.

———. 2018b. *Utility Energy Storage Market Snapshot*. Washington, D.C. Accessed September 9, 2019. https://sepapower.org/resource/2018-utility-energy-storage-market-snapshot/.

St. John, Jeff. 2018. "Distributed Energy Poised for 'Explosive Growth' on the US Grid." *Greentech Media*, June 21, 2018. https://www.greentechmedia.com/articles/read/distributed-energy-poised-for-explosive-growth-on-the-us-grid.

SunRun. 2019. "Planning for a Changing Energy Landscape." Accessed February 13, 2019. https://www.sunrun.com/grid-services.

Tech-FAQ. 2020. "The OSI Model – What It Is; Why It Matters; Why It Doesn't Matter." Accessed September 27, 2019. http://www.tech-faq.com/osi-model.html.

U.S. Department of Energy (DOE). 2017a. "Cybersecure Interconnection of Distributed Energy Resources." Washington, D.C.: Office of Electricity Delivery and Energy Reliability. https://www.energy.gov/sites/prod/files/2017/09/f36/LLNL_CyberInterconnection_FactSheet.pdf.

———. 2017b. "FOTW #1004, November 20, 2017: California Had the Highest Concentration of Plug-in Vehicles Relative to Population in 2016." November 20, 2017. Vehicle Technologies Office. Accessed August 13, 2019. https://www.energy.gov/eere/vehicles/articles/fotw-1004-november-20-2017-california-had-highest-concentration-plug-vehicles.

U.S. Energy Information Administration (EIA). 2012. "Commercial Buildings Energy Consumption Survey." https://www.eia.gov/consumption/commercial/data/2012/guide.php.

———. 2019a. *Annual Energy Outlook 2019*. Washington, D.C. Accessed August 13, 2019. https://www.eia.gov/outlooks/aeo/.

———. 2019b. "Electric Power Monthly." Electricity. Accessed August 13, 2019. https://www.eia.gov/electricity/monthly/.

Wood, Elisa. 2017. "New GTM Report Forecasts $12.5B Microgrid Investment within US by 2022." *Microgrid Knowledge* (blog), November 30, 2017. https://microgridknowledge.com/microgrid-investment-gtm/.

Widergren, S. E., M. R. Knight, R. B. Melton, D. Narang, M. Martin, B. Nordman, A. Khandekar, and K. Hardy. 2017. *Interoperability Strategic Vision: Enabling an Interactive Grid*. Washington, D.C.: U.S. Department of Energy Grid Modernization Laboratory Consortium, April 2017 Draft. https://gmlc.doe.gov/sites/default/files/resources/InteropStrategicVision2017-04-11.pdf.

Appendix A
Example of Communications Options for Distributed Energy Resource Grid Services

To demonstrate the range of standards used, this section describes one example of a distributed energy resource (DER) providing a grid service. Figure A-1 uses the interoperability framework described in IEEE Std 2030-2011, *IEEE Guide for Smart Grid Interoperability of Energy Technology and Information Technology Operation with the Electric Power System (EPS), End-Use Applications, and Loads*, and shows one option for communications pathways that would enable a DER to provide a grid service. The end points are the utility operations and the DER. The communications pathways are shaded red. Option 1 uses a utility backhaul and neighborhood area network to collect information and communicate with the DER.

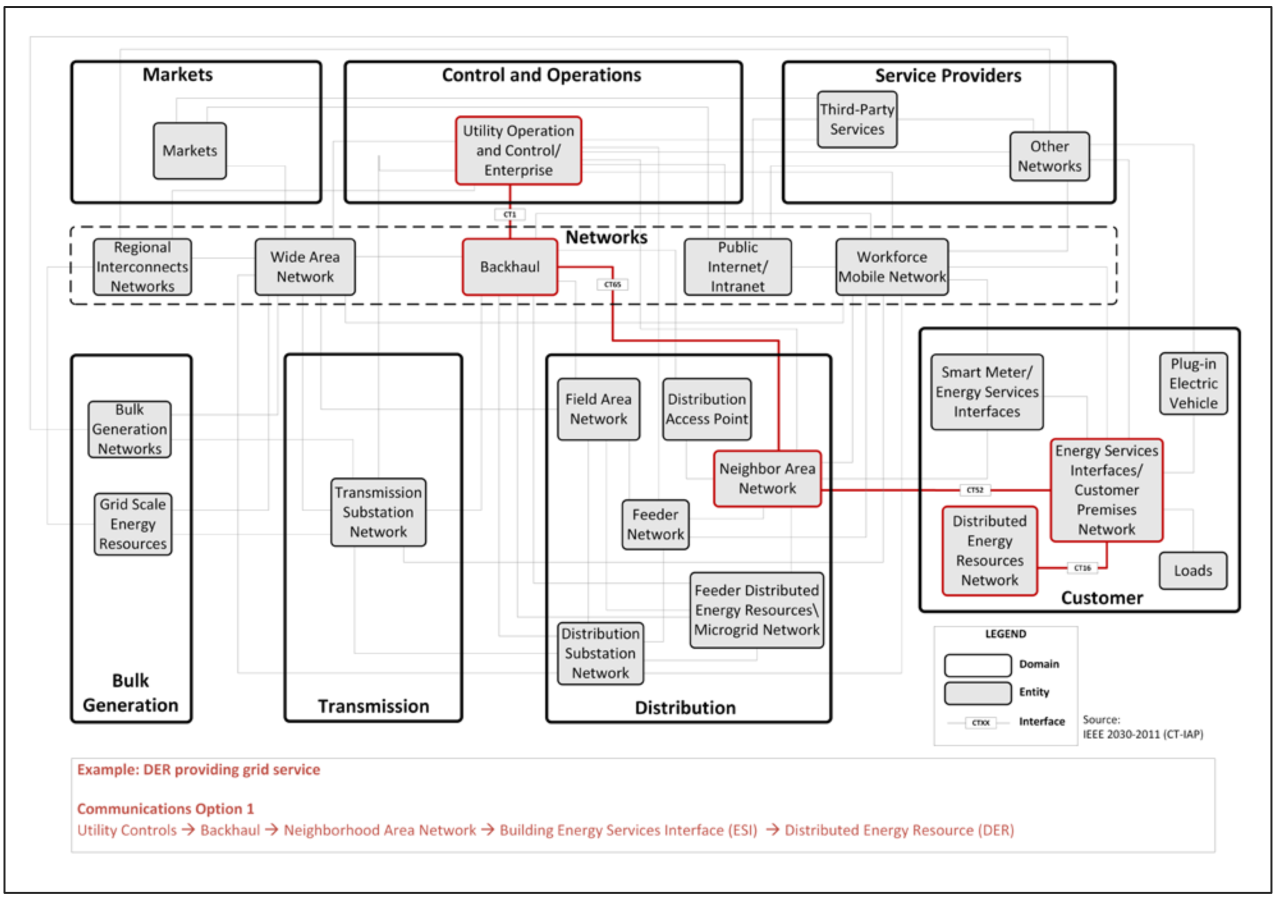

Figure A-1. Example (Option 1) of utility operations requesting grid services from a customer-sited DER

Figure A-2 gives another example (Option 2) for possible communications pathways (interfaces) between the utility operations and the DER. The red lines in this figure show the four communications pathways for Option 2. This path uses a third-party grid service provider and the Internet to achieve communications and information exchange between the utility and DER.

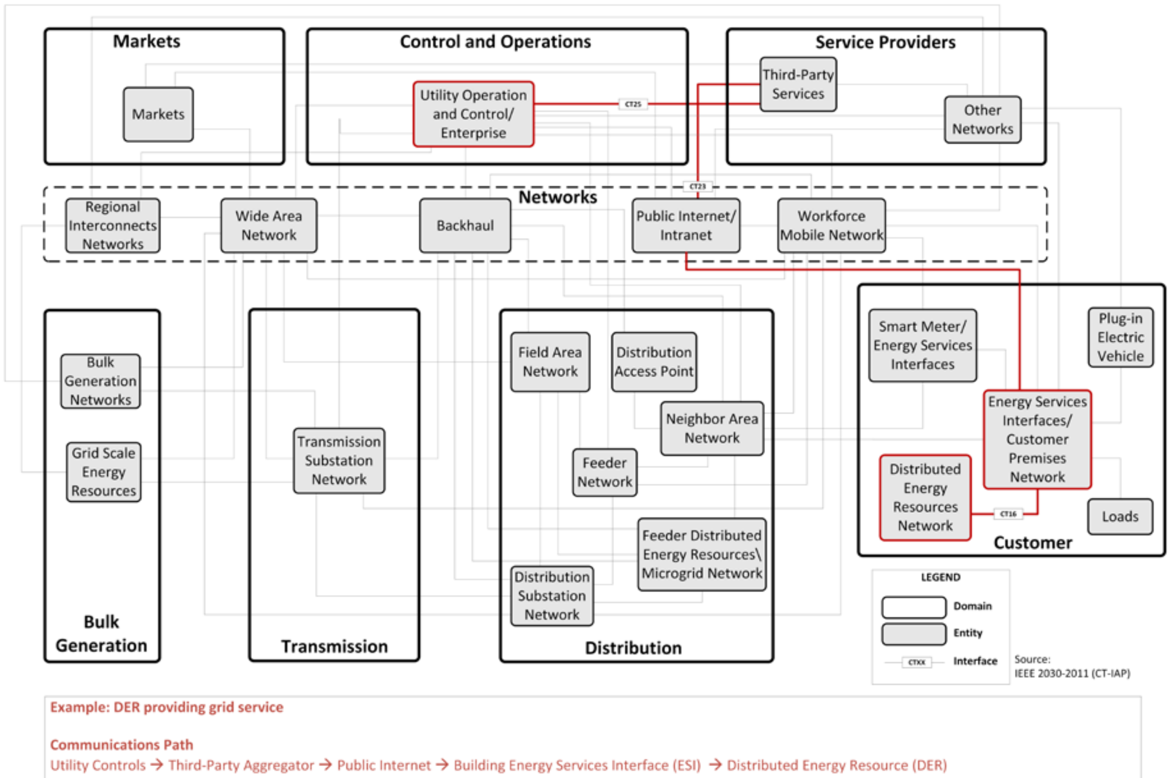

Figure A-2. **Example (Option 2) of utility operations requesting grid service from a customer-sited DER**

Figure based on IEEE Std 2030-2011. Reprinted with permission from IEEE. Copyright IEEE Year 2011. All rights reserved.

Table A-1 shows the GridWise Architecture Council (GWAC) Stack (each row) for each communications pathway (each column) for both options. Note several items: one is that the DER to the local energy management system is the same in each option, and another is that multiple basic connectivity technologies can be applied across the various communications pathways. Basic connectivity can take many approaches, including wireless (e.g., Wi-Fi, WiMAX, cellular), wired (e.g., Ethernet, power line carrier), and fiber-optic connections. At the Network Layer, most communications pathways are migrating toward Transmission Control Protocol/Internet Protocol. At the Syntactic Interoperability Layer and Semantic Understanding Layer, the applications that serve as information translators exist. These applications convert the needed services into commands that the DER or other devices can understand. The upper layers of the GWAC Stack give more business and regulatory connection for the desired function.

As shown by this example, communications among all parts of the smart grid can be quite complex, with a variety of communications technologies and standards existing across the spectrum of devices and systems.

Table A-1. Example of Option 1 for Communications Between Utility and DER

GWAC Stack Layer	Layer Description	(Utility) Controls and Operations to Backhaul	Backhaul to NAN[a] (Message Routing)	NAN to ESI[b] (Message Routing)	ESI to DER network (Message Routing)
Layer 8	Economic/ Regulatory Policy	Policy and economic objectives, rates	N/A	N/A	N/A
Layer 7	Business Objectives	Regulate frequency at a specified level	N/A	N/A	N/A
Layer 6	Business Procedures	Monitor frequency, send commands to DER	N/A	N/A	Respond to command and change frequency
Layer 5	Business Context	Data model for frequency regulation (e.g., IEC 61850-7-420)	N/A	N/A	Data model for frequency regulation (e.g., IEC 61850-7-420)
Layer 4	Semantic Understanding	Various protocols (e.g., SunSpec for ModBus, IEEE Std 2030.5, IEEE Std 1815)	N/A	N/A	Various protocols (e.g., SunSpec for ModBus, IEEE Std 2030.5, IEEE 1815)
Layer 3	Syntactic Interoperability	Various protocols (e.g., SunSpec for ModBus, IEEE Std 2030.5, IEEE Std 1815)	N/A	N/A	Various protocols (e.g., SunSpec for Modbus, IEEE Std 2030.5, IEEE 1815, proprietary)
Layer 2	Network Interoperability	TCP/IP	TCP/IP	TCP/IP	TCP/IP
Layer 1	Basic Connectivity	Various methods (e.g., IEEE Std 802.11, Fiber, IEEE Std 1675)	Various methods (e.g., cellular, IEEE Std 802.16, fiber)	Various methods (e.g., cellular, IEEE Std 802.16, fiber)	Various methods (e.g., cellular, IEEE 802.16 [WiMAX], IEEE Std 802.11 [Wi-Fi], IEEE Std 1675 [PLC], proprietary)
	Interconnection	N/A	N/A	N/A	Interconnection standards (e.g., IEEE std 1547, IEEE Std 1547.1)

[a] NAN: neighborhood area network
[b] ESI: energy services interface

Note: Arrows indicate the communications pathway.

Table A-2. Example of Option 2 for Communications Between Utility and DER

GWAC Stack Layer	Layer Description	Utility to Third-Party	Third-Party to Public Internet (Message Routing)	Public Internet to ESI[a] (Message Routing)	ESI to DER Network (Message Routing)
Layer 8	Economic/ Regulatory Policy	Policy and economic objectives, rates	Policy, programs, customer agreements	N/A	N/A
Layer 7	Business Objectives	Regulate frequency at a specified level	Profit	N/A	N/A
Layer 6	Business Procedures	Monitor frequency, send request to third-party services/aggregator	Send commands to DER	N/A	Respond to command and change frequency
Layer 5	Business Context	Data model for frequency regulation (e.g., IEC 61850-7-420)	Data model for frequency regulation (e.g., IEC 61850-7-420)	N/A	Data model for frequency regulation (e.g., IEC 61850-7-420)
Layer 4	Semantic Understanding	Various protocols (e.g., SunSpec for Modbus, IEEE Std 2030.5, IEEE Std 1815)	Various protocols (e.g., SunSpec for Modbus, IEEE Std 2030.5, IEEE Std 1815)	N/A	Various protocols (e.g., SunSpec for Modbus, IEEE Std 2030.5, IEEE Std 1815)
Layer 3	Syntactic Interoperability	Various protocols (e.g., SunSpec for Modbus, IEEE Std 2030.5, IEEE Std 1815)	Various protocols (e.g., SunSpec for Modbus, IEEE Std 2030.5, IEEE Std 1815)	N/A	Various protocols (e.g., SunSpec for Modbus, IEEE Std 2030.5, IEEE Std 1815, proprietary)
Layer 2	Network Interoperability	TCP/IP	TCP/IP	TCP/IP	TCP/IP
Layer 1	Basic Connectivity	Various methods (e.g., IEEE Std 802.11, fiber, IEEE Std 1675)	Various methods (e.g., cellular, IEEE Std 802.16, fiber)	Various methods (e.g., cellular, IEEE Std 802.16, fiber)	Various methods (e.g., cellular, IEEE Std 802.16 [WiMAX], IEEE Std 802.11 [Wi-Fi], IEEE Std 1675 [PLC], proprietary)
	Interconnection	N/A	N/A	N/A	Interconnection standards (e.g., IEEE Std 1547, IEEE Std 1547.1)

[a] ESI: energy services interface

Note: Arrows indicate the communications pathway.

Table A-2 shows another option communications between a utility and DER.

Table A-3 illustrates which GWAC layers are referenced by various standards for different DER technology domains.

Table A-3. Example of Interoperability and Interconnection Mapping Across Technology Domains

<table>
<tr><th>GWAC Stack Layer</th><th>Layer Description</th><th>Inverter-Based Generation and Storage</th><th>Electric Vehicles</th><th>Responsive Loads</th><th>Grid-Connected Microgrids</th></tr>
<tr><td>Layer 8</td><td>Economic/ Regulatory Policy</td><td colspan="4" rowspan="3">● Grid service defined by policy or economic market
● Grid service enabled as a business objective
● Entity provides signal requesting grid service
● Inverter-based systems/vehicles/responsive loads/microgrid respond to request for grid service
● Device controls are defined for provision of grid service</td></tr>
<tr><td>Layer 7</td><td>Business Objectives</td></tr>
<tr><td>Layer 6</td><td>Business Procedures</td></tr>
<tr><td>Layer 5</td><td>Business Context</td><td colspan="4">● Data modeling relevant for providing a specific grid service</td></tr>
<tr><td>Layer 4</td><td>Semantic Understanding</td><td>● SunSpec PV models
● SunSpec/MESA device models
● OpenFMB</td><td>● Vehicle data models</td><td>● OpenADR 2.0
● ASHRAE 201 (FSGIM)
● OBIX
● OASIS EMIX</td><td>● IEEE Std P2030.7
● IEEE Std P20308</td></tr>
<tr><td>Layer 3</td><td>Syntactic Interoperability</td><td>● IEEE Std 2030.5
● IEC 61850-7-420
● IEEE Std 1815
● IEEE Std 2030.2
● IEEE Std 1547.3
● Modbus</td><td>● SAE J2847/3[a]
● SAE J2847/2</td><td>● OpenADR 2.0
● ASHRAE 135 (BACnet-WS)
● IEC 14908 (Lon Mark)
● IEEE Std 2030.5
● Modbus</td><td>● Modbus
● IEEE Std 1815</td></tr>
<tr><td>Layer 2</td><td>Network Interoperability</td><td>● TCP/IP
● ZigBee
● IEEE Std 1815
● CAN bus</td><td>● TCP/IP
● UDP
● FTP
● HTTP</td><td>● TCP/IP
● DALI
● ZigBee</td><td>● TCP/IP
● IEEE Std 1815
● CAN bus</td></tr>
<tr><td>Layer 1</td><td>Basic Connectivity</td><td>● Twisted Pair
● CTA-2045
● IEEE Std 802.11 (Wi-Fi)
● IEEE Std 802.15.4 (Thread)</td><td>● Twisted pair
● CTA-2045
● IEEE Std 802.11
● SAE J1772 (PLC)
● SAE J2931/4 (PLC)</td><td>● IEEE Std 802.11
● IEEE Std 802.15.4</td><td>● Twisted pair
● RJ-45
● CTA-2045
● IEEE Std 802.11
● IEEE Std 802.15.4</td></tr>
<tr><td></td><td>Interconnection Performance (Not on GWAC Stack)</td><td>● IEEE Std 1547
● IEE Std E 1547.1
● UL1741
● IEEE Std 2030.2</td><td>● SAE J3072[b]
● SAE J2894-1 (PQ)</td><td>● N/A</td><td>● IEEE Std 1547.1
● IEEE Std 2030.7
● IEEE Std 2030.8
● IEEE Std 1547.4</td></tr>
</table>

[a] SAE J2847/3 supports IEEE Std 2030.5.
[b] SAE J3072 enables conformance to IEEE Std 1547.1

Appendix B
Review of Communications Protocols and Concepts

Traditionally, the electric grid has been designed and managed by the electric industry, which includes investor-owned and municipal utilities, independent system operators (ISOs), merchant generators, and transmission and distribution system operators (DSOs). The system has been largely managed from the top down, with system operators who forecasted and analyzed loads and appropriately dispatched generation to ensure reliable and economic system operation. These dispatchers were able to view some high-level system disruptions and—to a limited extent—make changes to keep the system operating. Historically, the electric power system has been dominated by large, central-station supply and dispatch. Because of the emergence of variable renewables and distributed energy resources (DERs)—including photovoltaic, wind, demand response, combined heat and power, electric and thermal storage, and new loads such as electric vehicles—the old model of grid dispatch and control must be revised to allow for the control and dispatch of these additional assets. Innovations introduced from information and communications technology can enable the electric grid to be more flexible in operation, connect resources, and provide a series of new services.

Much work has been done to develop interconnection and interoperability standards to define how to connect devices to form a "smart" or "modern" grid. A major challenge with these standards is that they are typically developed within each domain area, without a complete vision for how the parts need to interconnect. Individually, the standards might be technically robust and meet the needs within that domain, but they might not support the emerging grid services to enable these services to be cost-effective and reliable. To achieve increased levels of interconnection and interoperability, there must be consistency in data models, communications, connectivity, and security that reaches from one end of the grid to the other.

DER Communications and Control

Another important consideration when examining the interconnection and interoperability of DERs is how the DERs communicate and operate with the surrounding electric grid. A variety of higher level grid operators can interface with DERs. This section describes three options: DSO, third-party aggregators, and microgrids.

Distribution System Operators

Traditionally, grid services have been coordinated through an ISO or regional transmission operator that was responsible for the operation of the transmission network. These services were typically delivered by dispatching generation resources and, if needed, by curtailing large industrial users. This level of function will still be required as the grid is modernized. As more DERs are integrated into the grid, it is anticipated that this function will be coordinated and shared with operators who are more focused on the distribution network.

The role of the DSO is to manage the distribution grid. Many of these functions are related to reliability and can include monitoring capacity and rerouting power to avoid outages. Other DSO tasks include the management of DERs, including those located on the distribution network and those that are behind the customer's meter. As is the case for an ISO, it is anticipated that a DSO would have a process to take bids for various services; issue commands to trigger services; and have a process to measure, verify, and make financial payments. An example of such a transaction might include a DSO seeing that a specific circuit lacks the capability to meet the current load. To alleviate this issue, a DSO sends a signal to discover what power generation on that circuit could be started and what loads could be shed or shifted. Based on the response received from either a generator or customer stating price and quantity (the "bid" in $/MW or $/MWh), the operator sends out a signal for the most cost-efficient solution. Generators could start, batteries could discharge, and loads could decrease until the circuit has the needed capacity.

The Open Systems Interconnection Model

To understand interoperability across the grid, it is helpful to examine how communications standards are used in the power system and to review some basics of operation. Historically, communications were proprietary in nature and did not allow for interoperability between devices. To help characterize and standardize some of the basic communications and network functions, the Open Systems Interconnection (OSI) model was developed in the 1980s.

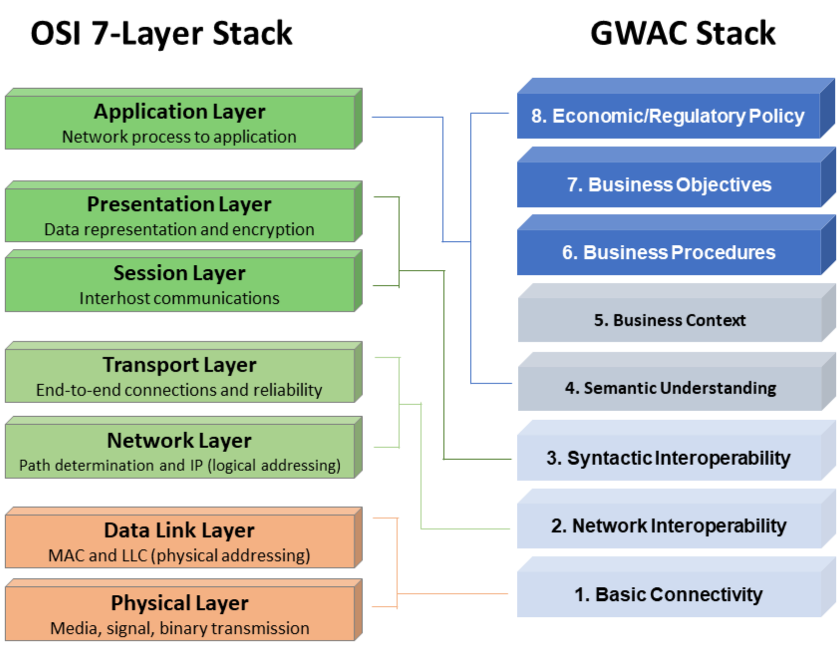

Figure B-1. OSI model mapped to GWAC Stack

Image source: Pacific Northwest National Laboratory. Used with permission

The OSI model defines seven layers (Figure B-1, left) of functionality that together allow for an understanding of interoperability in communications and networks. The seven layers can be used to describe any communications pathway in a network. Although this model is still valid, the development and broad acceptance of information technology-based standards such as the Internet Protocol (IP) make most layers largely irrelevant for communications protocols. With few exceptions, there is no need for a communications protocol to define the physical, media, or network connection. Instead, most protocols are built on the IP and are part of the Application Layer, which is at the top of the OSI stack. Below that layer, standard information technology solutions—such as Transmission Control Protocol (TCP)/IP, User Datagram Protocol, Ethernet, and Wi-Fi—can be readily used, thus providing a variety of options for routing and network transport.

Interoperability, however, requires more than the ability for two systems to be able to share bits and bytes with each other. Ideally, a truly interoperable solution provides a series of services so that communications can include the following:

- Cyber-secure and trusted connection
- Metadata that provides context or semantics about the connected devices
- Shared devices or functions.

One model of an extended communications protocol stack is defined by the GridWise Architecture Council (GWAC) (GridWise 2019) and is used by both the Smart Grid Interoperability Panel and the National Institute of Standards and Technology (NIST).

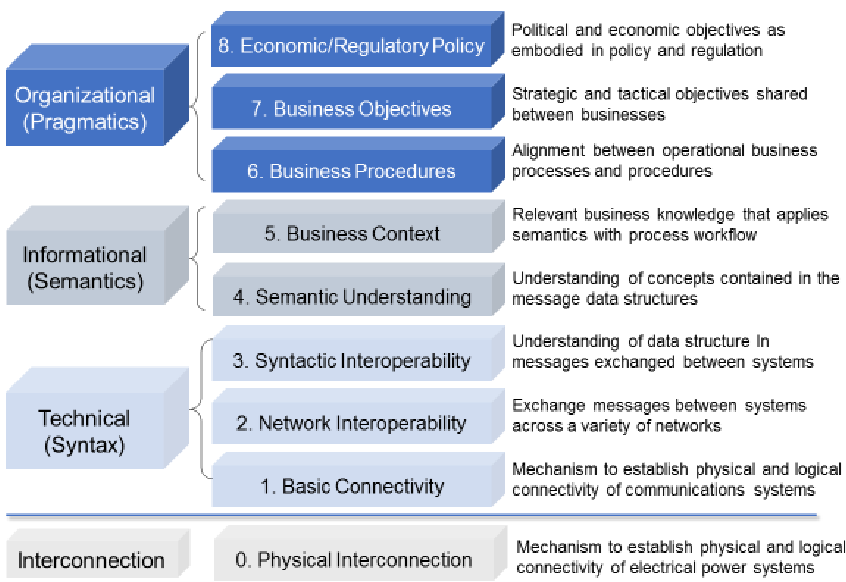

Figure B-2. Description of GWAC Stack and physical interconnection

This image is based on Figure S.2 in The GridWise® Interoperability Context-Setting Framework: https://www.gridwiseac.org/pdfs/interopframework_v1_1.pdf. This material was created by the GridWise® Architecture Council and is available for public use and distribution. The GridWise® Interoperability Context-Setting Framework is a work of the GridWise Architecture Council.

Figure B-2 shows the "GWAC Stack." The GWAC Stack consists of layers 1 through 8. These define the communications and interoperability between devices. A "Layer 0: Physical Interconnection" has been added to represent the physical interconnection to an electric power system. The GWAC Stack basically uses the six lower layers of the OSI model at its lowest level for technical communications, then expands the application layer to define organizational (or pragmatic) agreements and informational (or semantic) agreements. Not all standards cover these upper layers; however, agreements (whether formally stated, ad hoc, or implicit) must be in place for connected devices and systems to interoperate. In fact, few smart grid standards address the top or organizational level. A set of recognized standards that covers the lowest levels, however, does exist and functions generally by adopting existing information technology standards (such as TCP/IP).

Figure B-1 provides an example of how a grid service would map to the GWAC Stack. In the example, the organizational interoperability is the "function" known as frequency response and business process interactions to carry out this function. The informational interoperability then supports this function with the specific data models related to the controls that a smart inverter requires to perform the function. The technical interoperability layers then convert that information into the bits that are communicated to and interpreted by the smart inverter. Finally, Layer 0 describes the requirements for how the smart inverter physically connects to the electric grid. Figure B-3 illustrates the GWAC Stack (left) to example functions and communications (right). An additional layer has been added on the bottom to indicate physical interconnection of devices.

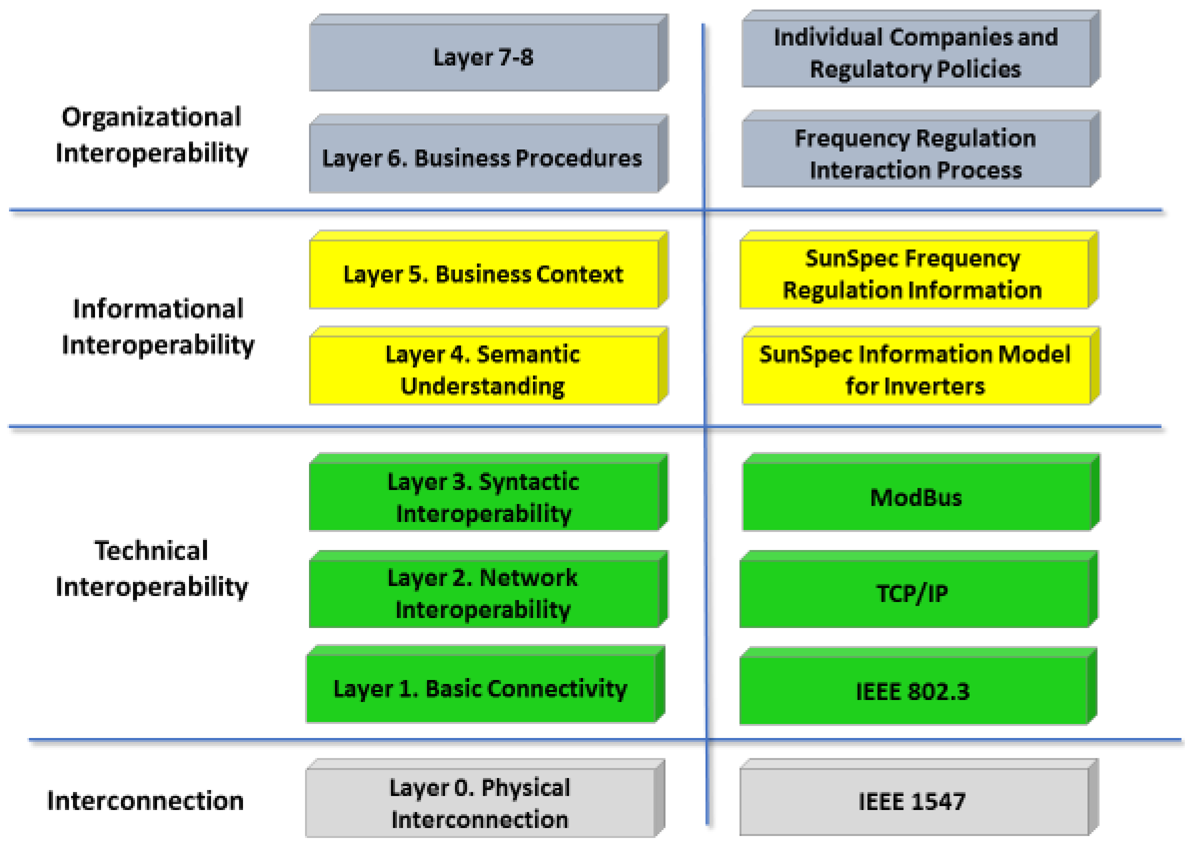

Figure B-3. Mapping of GWAC Stack (left) to example functions and communications (right)

Image source: Pacific Northwest National Laboratory. Used with permission

National Institute of Standards and Technology Smart Grid Conceptual Models

NIST was tasked under the Energy Independence and Security Act of 2007 to work to develop a framework that includes protocols and model standards for information management, ultimately to achieve interoperability of smart grid devices and systems. Building on work previously performed in the private and public sectors, NIST created a framework using a systems approach that was designed to be flexible, uniform, and technology-neutral. In the first release, a high-level conceptual reference model for the smart grid was developed and published as *NIST Framework and Roadmap for Smart Grid Interoperability Standards, Release 3.0* (NIST 2014).

The NIST Conceptual Reference Model is descriptive and can serve as a tool for identifying actors, devices, and possible communications paths in the smart grid (NIST 2014). Figure B-4 provides a high-level grouping of what NIST has deemed the smart grid domain, including: the customers, markets, service providers, operations, bulk generation, transmission, and distribution.

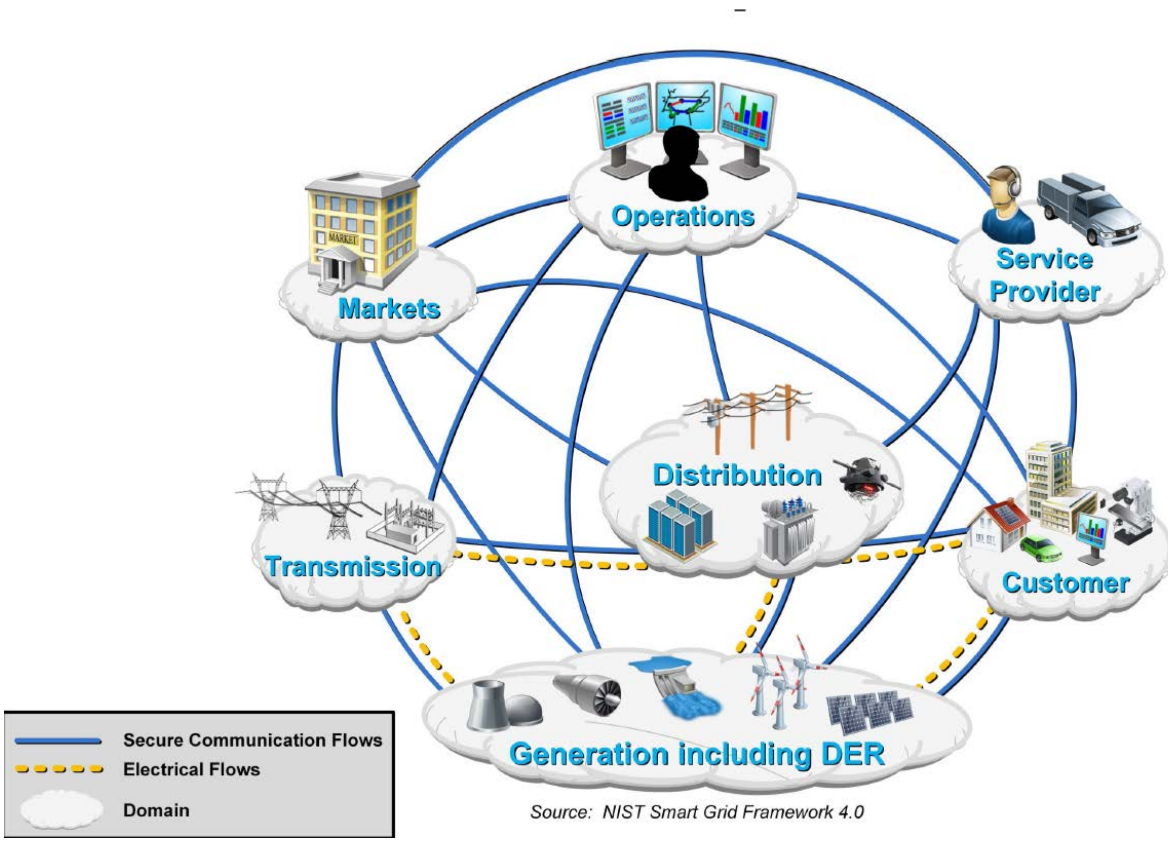

Figure B-4. NIST smart grid conceptual model
Image source: (NIST 2021). Used with permission

Appendix C
The Energy Services Interface

The following gaps in an energy services interface (ESI) were identified by the Smart Grid Interoperability Panel (now SEPA).

"Layers" of interconnectivity should be identified. The lower technical layers of communications networking and protocol, such as standard Internet Protocols (IPs), should be clearly separated from the higher layer specifications, such as the information modeling and business processing layers, which could run on different protocols yet still provide system-wide interconnection and interoperability with proper design. Subsystem interoperability, security, network management, and use of IPv4 versus IPv6 should all be considered.

Use cases and associated actors and devices should be considered. The interaction of wholesale markets, utilities, and ratepayers with behind-the-meter assets such as batteries, photovoltaics, and load control should be considered. To ensure end-to-end security and breach mitigation, various types of bad actors (i.e., hackers) also should be considered.

To enable a cost-effective and easy-to-use architecture that eliminates the technical impediments of the standards, Figure C-1 is suggested by Lawrence Berkley National Laboratory. Figure C-2 illustrates one example of this type of architecture. Through an ESI in a building management system, the grid operators' "needs" are communicated to the controls and appliances in the building. In addition to providing network communications among facility subsystem silos, the management system can perform the important function of orchestrating and optimizing subsystem device behavior to provide the greatest benefits from the financial, service level (e.g., comfort), and environmental perspectives.

This architecture provides grid communications to multiple legacy site protocols and provides grid communications based on market and functional requirements. Behind-the-meter subsystem networks and protocol silos are abstracted and harmonized via the ESI. Separate physical networks are connected to each subsystem. The ESI also decouples grid communications signals and behind-the-meter communications.

In other words, the ESI function enables system architectures wherein its actual presence can exist either outside the building (e.g., direct load control from the utility to a smart water heater), within the building (i.e., in a gateway, which receives grid signals and then communicates to the building automation system), or within a building's subsystem (i.e., in an advanced, networked lighting control system that can receive signals directly from the grid).

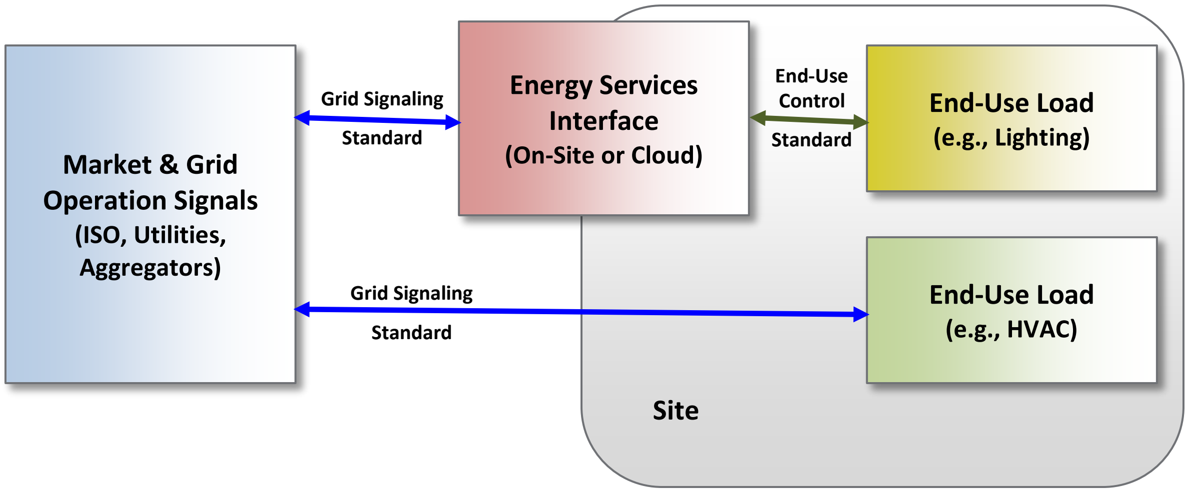

Figure C-1. Building communications architecture

Figure by Lawrence Berkeley National Laboratory. Used with permission

An alternate approach conveys the grid request to an intermediate management system, where internally established thresholds are compared against the request from the grid to determine what loads, if any, will be reduced.

Appendix D
Grid Modernization Laboratory Consortium Team Gap Analysis and Prioritization (August 2017)

This appendix contains an overview of the Grid Modernization Laboratory Consortium (GMLC) project 1.4.1 team's methodology for determining a prioritization strategy for engaging in various standards efforts at the beginning of the project. *Note that this analysis was completed by the GMLC 1.4.1 team in August 2017 and is therefore intended to be a historical reference rather than a description of the state of the art.*

Prioritization Methodology

There is a broad range of distributed energy resource (DER) technologies and an even broader set of potential grid services that could be provided. To limit the scope within the time, funding, and resources, the GMLC 1.4.1 team developed a method to prioritize activities. The methodology presented here reflects the team's consensus assessment in the initial stages of the project (2017) and should therefore be considered a static snapshot. During the project, the team adjusted activity and priority based on emerging information and developments.

Certain DER technologies are expected to provide a large portion of the grid services mentioned in the previous section. These include electric energy storage, photovoltaics (PV), electric vehicles (EVs), responsive loads, and generation controlled by building energy management systems. These DER technologies were considered the priority focus areas when this analysis was undertaken.

To prioritize the identified gaps in each DER technology areas, the team established a score based on four areas. This methodology was used because there are potentially many gaps, and recommendations were needed about which gaps should be addressed first to improve the harmonization of interoperability and interconnection among devices. Prioritization was established based on the following four scoring fields; the fields have different impacts on the overall score, and this relative weight is shown in parentheses:

- Opportunity for impact (prioritization weight: 25)
- Time to fill gap (prioritization weight: 30)
- Locational urgency and resource relevance (prioritization weight: 20)
- Technical difficulty (prioritization weight: 25).

Opportunity for Impact

The opportunity for impact refers to the market potential: how many installations (realistically) are available to provide the respective grid services in the near term (3–5 years). A zero or low score means that there is a small market for the resource (it cannot affect the standard within a meaningful period), and the highest score (25) indicates that significant market potential exists.

Because PV DERs presently have more than 35 GW of installed capability and because projections indicate aggressive growth, the opportunity for impact has significant relevance, and the scoring allocated to this area is appropriate. With the projected aggressive growth of this DER, the time frame for implementing communications-based DERs is important, and the scoring is justifiable. The high penetration level of DERs can make the urgency for communications-based DERs relevant, and the low score in this area indicates the need for growth. Implementing communications-based electric power system support functionality is challenging, but a path forward is being developed to meet the needs of electric power systems and end users.

Time to Fill Gap

The time to fill gap refers to the intervention period required to fill a gap. This measure attempts to capture the estimated time it would take for the technology domain community to address the gap through revisions made to standards. This includes the time and process for consensus-building and convening appropriate organizations and schedules. For example: Is it within the 3-year period typical of standards development? Or is the intervention out of cycle with the standards-setting process and requires a mid- or long-term period to fill the gap? The scoring relates to whether work conducted in the next 2 years would be meaningful based on standard cycle and project duration. A low score means that the project's work effort cannot affect the standard within the near-term time frame. The highest score (30) means that this project has great potential for addressing the gap within these time frames.

Local Urgency and Resource Relevance

Local urgency and resource relevance refer to high-impact areas with colocated DERs that are appropriate to provide the relevant grid services. This attempts to capture the notion that there are pockets of activity where certain technology domains have become concentrated, and therefore if the grid service were enabled in those locations, the change would have an appreciable significance. At the same time, this measure attempts to address the notion of whether the concentration of technology at the particular location could successfully provide the required grid service.

Locational urgency refers to high-impact areas of the country at the state and/or regional level where capacity issues or grid stress is serious. Examples include Hawaii and Southern California.

Resource relevance refers to appropriate resources available to provide the grid service (i.e., batteries are available to serve a midday peak load versus attempting to meet the grid service with heating, ventilating, and air-conditioning systems when experiencing high temperatures and increased cooling requirements).

A low score means that not many areas are experiencing a need or not enough "appropriate" resources can be deployed at scale to provide impact. The highest score (20) means that this work could be very useful (immediately or within 5 years) in certain locales.

Technical Difficulty

Technical difficulty refers to the attempts to capture the estimated difficulty in developing appropriate technical solutions and consensus to overcome the stated gaps. A low score means that technically developing and deploying grid-enabling resources is challenging. The highest score (25) means that appropriate technical means to address the gap are readily available.

To provide easy comparison across the technology domains and across the scoring fields, the scores in each category were divided by the total weight in that category to normalize them (e.g., Opportunity for Impact score of 18/25 = 0.72). To normalize the final prioritization score across all domains, the scores in all categories were summed and divided by four. This gap priority score is meant to show the higher relative short-term priorities. Scoring ranges from 0 to 1, and a higher score indicates that a priority gap should be addressed first. A score of 1 indicates:

- The opportunity for impact is significant within 3–5 years.
- The time to fill the gap is very short (3–5 years).
- The locational urgency is great, and the resource is highly relevant to providing the required grid services.
- There are no technical barriers to overcoming the identified gaps.

Electric Vehicle Scoring Considerations

The EV gap analysis scoring section depends on the EV and electric vehicle supply equipment (EVSE) market development trajectory. More specifically, the number of features that customers are willing to pay for today impacts the development and closing of other standards gaps. Stated another way, best-case/worst-case market trends of features for which consumers will pay extra affect the rate at which the standards gaps are closed.

Prioritization scoring criteria is oriented to the ability of EVs to adjust their rate/direction to serve the grid-related functions. Presently, EV standards are focused on the positive customer charging experience (ease of connection/process initiation and reliably completing the charging session). Standards exist for regulation-related grid services tied to EV charging, but they are implemented only in demonstration-level deployment because of the lack of a compensation mechanism to the owner/operator of the vehicle or charging station.

The other limitation is that on-board charger electronics aim for the lowest production cost (i.e., lowest feature set) for a vehicle that must compete in price with lower cost internal combustion vehicles. As such, current regulation and external communications response time are not cost-effective features to add in today's EV market. Similarly, off-board DC charging can combine local DC buffer battery energy storage that could both serve to charge an EV at full rate (up to 350 kW in the latest generation of EVs-EVSEs), even during a demand response event or demand charge limit at a facility.

Likewise, the same buffer battery could be used to serve regulation-related grid services while not actively charging a vehicle (standby mode). Similarly, the draft version of ISO/IEC 15118 (EV-EVSE communication) includes bidirectional energy flow for wireless charging. Considering large battery electric commercial buses produced today (500 kW-hr+), an off-duty bus fleet with wireless charging could enable a large spinning reserve for grid regulation.

EV charging gap priority scoring for regulation-related grid services reflects the future-looking market in which EV charging loads can be aggregated and have the ability to adjust active power charging rates and ramp rates in exchange for compensation to the customer for deferred charging. IEEE Std P2030.5, *Standard for Smart Energy Profile Protocol*, could pass regulation services via aggregation parameters to the EVSE, which then adjusts the charge rate accordingly and reports the action taken to adjust active power charging rates.

Gap Prioritization Results

Table D-1 summarizes the prioritization of all grid services and technology domains. Using the prioritization method, the highest ranked grid services by technology domain were as follows:

1. **Inverter-based DERs**: voltage management, energy services, regulating services, and inertial response
2. **Responsive loads**: energy services, regulating services, voltage management, and inertial response
3. **Electric vehicles**: energy services, regulating services, voltage management, and inertial response
4. **Grid-connected microgrids**: Energy services, regulating services, voltage management, and inertial response.

Table D-1. Summary of Gap Prioritization Results and Opportunities

Grid Services	Prioritization Weight	Inverter-Based Systems (Electric Energy Storage, PV Systems)				Electric Vehicles (EV, EVSE)				Responsive Loads				Grid-Connected Microgrids			
		Energy	Regulation, Reserve, Ramping	Distribution voltage mgmt.	Artificial Inertia	Energy	Regulation, Reserve, Ramping	Distribution voltage mgmt.	Artificial Inertia	Energy	Regulation, Reserve, Ramping	Distribution voltage mgmt.	Artificial Inertia	Energy	Regulation, Reserve, Ramping	Distribution voltage mgmt.	Artificial Inertia
Opportunity for impact	25	18	18	25	5	10	8	5	0	19	19	19	7	15	15	5	5
Time to fill gap	30	25	25	25	5	15	10	6	1	7	5	5	5	25	25	15	5
Locational urgency & resource relevance	20	10	10	10	10	8	8	5	0	15	15	15	10	8	8	5	5
Technical difficulty	25	20	20	20	20	10	8	6	10	20	10	10	3	20	20	13	15
Overall Gap Priority Score (Weighted)	100	73	73	80	40	43	34	22	11	61	49	49	25	68	68	38	30

low opportunity		high opportunity

GRID
MODERNIZATION
LABORATORY
CONSORTIUM
U.S. Department of Energy

http://gridmodernization.labworks.org/