Distributed Energy Resource Aggregation using Customer-Owned Equipment: A Review of Literature and Standards

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Review article

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ABSTRACT

Large-scale deployment of renewable energy resources, both utility-scale and distributed, create reliability concerns for electrical power system operators. The weather-dependent, non-dispatchable nature of renewable resources decreases the ability of operators to match supply with demand. Concurrently, distributed energy resources, defined as small-scale loads, generation sources, and storage systems, are becoming ubiquitous within modern electrical systems. This literature review presents the grid services that utilities use to alleviate power systems reliability concerns, particularly those caused by renewable resources, and how aggregations of residential-scale distributed energy resources can be used to provide these services.

By aggregating distributed energy resources *en masse* to provide grid services, grid operators can concurrently improve reliability while ensuring high penetration levels of renewable resources. Academic researchers have developed the theoretical methods for achieving these objectives. Standards bodies have created open communication frameworks for linking these resources with grid operators. And, large-scale utility programs have demonstrated the potential for providing grid services using aggregations of these resources. This manuscript presents a review of the literature, methods, and standards that have created the foundation for distributed energy resources to help decarbonize electrical power systems.

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1. Introduction

Due to the growing impacts of climate change, electricity customers and societies are demanding that their electricity be sourced from greener alternatives. In response, governments have established legal mechanisms, such as Renewable Portfolio Standards (RPS) and carbon trading markets, that motivate electric utility companies to add RER to their generation portfolios. However, RER like Photovoltaics (PV) and wind present several challenges. Specifically, the energy resource is, by nature, stochastic and largely non-dispatchable; weather probabilistically dictates availability, and these resource cannot be called upon reliably. This decrease in dispatchability lessens a utility's capacity to satisfy demand and maintain system reliability.

Utilities can, however, gain an additional degree of freedom through dispatch of residential-scale loads and resources. While not a novel idea, customer-owned equipment can be provisioned to provide grid support services that help match generation with load (Stitt, 1985). Early forms of such systems provided easily-dispatched grid services like Demand Response (DR) and load shifting during peak periods.

Generally referred to herein as DER, these residential-scale equipment include appliances such as water heaters and HVAC systems; generators, like PV; and energy storage systems, including Battery Energy Storage System (BESS) and Plug-in Electric Vehicle (PEV). Table 1 summarizes several DER and notes their characteristics that could be useful for providing grid services. Hundreds of thousands of DER may be aggregated by a single authority, such as a utility, system operator or third-party aggregator. Such aggregation systems, herein called DERMS, collect energy state and energy usage data from thousands of DER and then provision grid services based on the cumulative power and energy capacity available from those DER.

New and updated communication protocols like OpenADR, SunSpec Modbus, CTA-2045, and IEEE 2030.5, have established methods for interacting with customer-owned equipment to provide a wide range of grid services. A growing number of residential-scale equipment that have communications capability and a control module are now being manufactured. These devices can receive dispatch commands from a grid operator or aggregation service to provide frequency response, regulation, ramp-rate control, and volt/VAr support, among others.

This manuscript addresses questions regarding how utilities can address the challenges imposed by RER using residential-scale DER assets, how those assets may be aggregated, how aggregations of such assets can be used to address grid issues through dispatch as ancillary services, and how communication and control may be realized using open protocols. The review begins by presenting the problems that large-scale RER adoption is causing within the utility industry. This is followed by a presentation of the services that utilities use to address these problems, known as ancillary grid services. The article then presents a review of DER aggregation solutions that can be used to provide these grid services, specifically dispatchable standby generation, demand side management, and asset aggregation. Recognizing that standardized communication and control protocols are imperative for dispatching DER to provide grid services, the paper presents a review of open standards that have been developed to promote DER aggregation. The DER technologies, ancillary service, aggregation programs, and communications standards presented in this review will help address the challenges imposed by large-scale RER adoption, which in turn will lead to higher penetration levels for these fossil-free energy resources.

2. General nature of the problem

The proliferation of RER, specifically PV solar and wind power, has presented economic, operational, and systematic challenges to electric utilities, energy balancing authorities, market dispatchers, and the aging electric grid at large. RER are becoming less expensive and widely adopted (Zhang and Dincer, 2016), and they are helping to minimize dependence on fossil fuels. However, for all the benefits afforded the electric utility industry by RER, they create unintended and adverse effects on the electric grid. RER provide *energy* to meet day-to-day energy demand, but they are not well-suited for providing the *grid services* that are critical for maintaining power system reliability.

2.1. Stochastic nature of RER

Because RER are weather-dependent, they often produce rapid changes in power output, resulting in unscheduled ramping events. These ramping events present scheduling challenges for utilities operating within hourly or sub-hourly electricity trading markets (Ela and Edelson, 2012; Bitar et al., 2012; Rastler, 2010). For instance, uncertainty regarding the forecast of wind ramping events, specifically the timing and ramp rates, affects energy dispatchers' options for maintaining balance between electricity supply and consumer demand, which is measured using the Area Control Error (ACE). Utilities that allow their ACE to deviate outside of defined limits may face fines from regulating authorities. Consequently, the unpredictable nature of RER directly impacts most electricity marketers' ability to readily and easily satisfy their energy supply and delivery contracts (Liu and Tomsovic, 2012; Ummels et al., 2007).

2.2. Impacts on grid reliability

Presently, the current growth rate of traditional RER is unsustainable. If left unchecked, RER can cause bus voltages to rise above limits (Carvalho et al., 2008), and hinder frequency response by decreasing system inertial mass (Zarina et al., 2012; Hossain and Ali, 2013). If growth trends continue without accommodating these system impacts, grid reliability will be put at risk. Installations and inter-connections need to be properly planned and strategically deployed, and distributed RER need to become responsible participants within electric power systems.

Voltage variations and the stochastic nature of RER make power system planning challenging, as it is difficult to predict solar and wind resources. Coupled with the fact that energy cannot be stored economically at a large scale, grid reliability engineers have to take what they are dealt by these RER and allocate Traditional Generating Resource (TGR) around the availability RER.

Table 1

A summary of select residential DER, and their electrical characteristics, that would be suitable for providing grid services. Characteristics are provided as qualities and estimates, rather than precise quantities, since there are wide ranges of products in each of these categories. Response time qualities relate to providing grid services, summarized in Table 4, specifically the ability to respond to PJM RegA and RegD area control error regulation signals (Anon, 2017c).

DER	Response time & availability	Energy Capacity	Power direction & capacity
PV Inverters	Fast, intermittent	None	Source, 10's kVA
BESS	Fast, dependent on state of charge	10's kWh	bi-directional, 10's kVA
EVSE	Fast, intermittent	10's kWh	Load (presently), 10's kW
Resistance water heaters	Fast, often	100's Wh	Load, ~4 kW
Heat pump water heaters	Slow, often	100's Wh	Load, <1 kW

Traditionally, system planning is engineered based on reliability factors like customer load, voltage drop concerns, and frequency regulation. As penetration levels of RER increase, grid reliability becomes a concern when new RER installations conflict with utility planning. For instance, in the Hawai'ian islands, the nameplate capacity of installed PV was 586 MW in 2016, or around 45% of the state's peak load. That year, the Hawai'ian Electric Company (HECO) halted thousands of application requests to connect customer-owned PV within its balancing area. The high penetration levels were causing voltage swings within distribution feeders as the solar resource ebbed and flowed (Hoke et al., 2018). Further, with no fault ride-through requirements, PV inverters were required to disconnect from the grid upon sensing an event. Utilities in Arizona and California, and in countries such as Japan and Germany, have expressed similar concerns.[1,2]

Several standards have been developed in response to these challenges. IEEE 1547 was recently updated, recognizing that wide-spread disconnect of PV inverters in response to a grid event can further exasperate problems by removing generation when it is most needed. The standard now specifies grid-tied inverters have fault ride-through capabilities to avoid tripping over a wide range of disturbance types. Inverters must also be capable of providing reactive power support to aid with voltage regulation (Anon, 2018a). And, the UL 1741 standard establishes inverter testing requirements for manufacturers to ensure inverters have these ride-through and grid support capabilities (Anon, 2010). UL 1741 compliance is now part of the interconnection requirements in both Hawai'i and California.

2.3. Transmission congestion

Often, electricity generation and consumption are geographically separate. This is particularly true of large-scale wind farms and PV facilities, which tend to be located in rural areas far away from load centers. Linking generation and load are transmission lines, which must be properly sized to accommodate peak demand and anticipated load growth. Transmission congestion occurs when these lines cannot accommodate a marginal increase in power without jeopardize the safety and reliability of the transmission network (Akhil et al., 2016).

Most of the United States' electrical transmission infrastructure was built in the 1950's and 1960's. Occurrences of transmission congestion increase when transmission capacity fails to track growth in peak electric load. And as these transmission lines age, their thermal limits and maximum allowable ampacities decrease. Further, peak ampacity limits are not constant; they change with loading, ambient temperature, wind speed, and other factors.

Utility-scale RER cause transmission congestion due to their weather-dependent nature and market preferences. RER are often the least-expensive energy option within energy markets, and in some jurisdictions, they are given dispatch priority over TGR. When RER generation increases, RER power displaces output from TGR, and being rurally located, must be transferred to load centers via transmission lines. Sudden RER ramping events can cause these lines to exceed their thermal limits, which in extreme cases could result in line tripping and loss of generation. As such, optimal planning for and operation of transmission lines is challenging due to stochastic production from RER. Adjusting transmission tariffs to dissuade wheeling of RER power through congested lines is one means for addressing this issue, but tariffs do not change as quickly as ramping events.

2.4. Excessive curtailments

Until recently, RER have not been required to provide frequency regulation support services. Wide fluctuations in power produced by PV and wind can cause severe frequency stability problem to the electrical grid, an issue multiple researchers have examined. Liang et al. present a control method for BESS to provide frequency regulation to an adjacent wind farm (Liang et al., 2012). Wu et al. examine a similar arrangement by applying a two-stage control strategy (Wu et al., 2015). Díaz-González et al. provide a review of control methods and utility codes applicable to wind farms that participate in system frequency control (Díaz-González et al., 2014). Changes in power production affect the speed of rotating machines, to which electrical frequency is directly proportional. Because RER are not large, mechanically-synchronized rotating masses, they lack the mechanical inertia that helps maintain frequency stability in the event of system disturbances. As such, an increase in the penetration of RER can cause frequency stability problems because they do not have means for rapidly injecting or absorbing real power in the event of a sudden frequency deviation. When this happens, TGR are quickly brought online to help stabilize frequency, putting stress on these TGR. Such reactionary dispatches increase operation and maintenance costs, and decrease expected lifetimes of TGR. Hence during periods of high power production, RER, especially wind, may be curtailed as a balancing area approaches its stability margin.

3. Solutions for addressing RER challenges

A number of solutions to these problem already exists, and the benefits have been demonstrated in both literature and practice by researchers and electric utility companies. Within this section, we first discuss ancillary grid services, which are used by utilities to alleviate frequency and voltage issues. We then present three solutions that use aggregations of distributed resources to provide ancillary grid services, specifically Dispatchable Standby Generation (DSG), Demand-side Management (DSM), and DER aggregation.

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[1] Reuters, "Clouds over Hawaii's Rooftop Solar Growth Hint at U.S. Battle", December 18, 2013

[2] Scientific American, "Three Reasons Hawaii Put the Brakes on Solar-and Why the Same Won't Happen in Your State", December 15, 2015

3.1. Ancillary grid services

Currently, utilities address frequency and voltage issues using a suite of tools referred to as *ancillary grid services*, sometimes simply called *grid services* or *ancillary services*. Traditionally, these services are provided by TGR that are set in reserve to react in cases when they are needed. With increased penetration of RER, frequency and voltage stability issues have become exacerbated. Utilities continue to use TGR to provide ancillary services in order to accommodate the stochastic nature of RER, but doing so places further strain on these resources and limits their energy production. Aggregations of DER may provide a reasonable solution for providing the ancillary services that alleviate the burdens currently being imposed on TGR.

The framework in which the problems caused by RER exist cannot be fully comprehended without a proper understanding of what ancillary services are, and why they are important to electricity supply and demand. In an effort to avoid confusion, in 1995, the Federal Energy Regulatory Commission issued a definition of ancillary services as those *"necessary to support the transmission of electric power from seller to purchaser given the obligations of control areas and transmitting utilities within those control areas to maintain reliable operations of the interconnected transmission system".*[3] Simply put, ancillary services are necessary for continuous uninterrupted operation of grids. For this paper, we focus on a subset of services. These include, but are not limited to the following services, considering definitions from both North American Electric Reliability Corporation (NERC) (Anon, 2012) and the California Independent System Operator (CAISO) (Colbert, 2016).

3.1.1. Frequency response

Frequency response is a balancing area's ability to stabilize frequency immediately following the sudden loss of generation or load. Frequency response assets activate quickly, such as when the frequency slew rate exceeds a set value (Hz/s), in order to avoid tripping last-resort protection systems. Frequency response is often referred to as Primary Frequency Control, as these resources are the first to respond to sudden changes in system frequency. Frequency response services are critical for providing grid reliability during sudden and unexpected disturbances.

3.1.2. Frequency regulation

Frequency regulation, or *Secondary* Frequency Control, consists of resources that act to continuously correct changes in frequency. These dispatch automatically through automatic generator control by monitoring the balancing area ACE. Frequency regulation helps ensure a steady frequency by reacting to events that are not drastic, in contrast to those that trigger Primary Frequency Control. Though, Secondary Frequency Control may be called upon to subsequently support a Primary Frequency Control event response.

3.1.3. Ramp rate control

Ramp rate is defined as the change in power output of a generator as it is ramping up or down. Ramp rate control is maintained through the dispatch of *spinning* and *non-spinning* reserves. Dispatch is initiated by system operators. Also known as *Tertiary* Frequency Control, these reserve resources must be able to reach their full capacity within 10 min of a dispatch request. For example, such reserves are dispatched as a wind farm experiences a steady decrease in wind resource; TGR come online

as the RER resource diminishes. Ramp rate is important for grid stability, helping to ensure generation matches load at all times.

Spinning reserves are generators that are grid-synchronized, ready to produce power upon dispatch. Non-spinning reserves are on standby, but are not synchronized to the grid. Both of these forms of reserve can be called online within a short period of time, but must be fully online within 10 min.

3.1.4. Voltage/VAr compensation

Inductive loads, such as motors that drive compressors in air conditioners and refrigerators, consume reactive power. Also called *VAr* (volt-amps reactive), reactive power is the resonant energy exchange between capacitive and inductive elements within a power system. VAr occupy ampacity within transmission and distribution lines, since this resonant energy is exchanged through current. As such, reactive power contributes to voltage drop. Volt/VAr compensation is provided by capacitor banks and over-excited generators, which produce VAr to compensate for VAr consumption by inductive loads. When properly placed, these VAr sources boost voltage back up to acceptable levels.

Volt/VAr compensation can also be used as a means for peak shaving, a service commonly known as conservation voltage regulation. Power is proportional to the square of voltage, so small adjustments downward in voltage at the point of load connection will decrease power delivered to that load. As such, Volt/VAr compensation can be used to reduce stress on the grid by decreasing load and distribution losses during periods of peak demand.

The ancillary services summarized in Table 2 help ensure the continuous, reliable operation of electric grids because they help prevent potential fault-induced disruptions, thereby ensuring grid reliability. Some types of TGR are well-suited for providing one or more of these ancillary services. With the increased penetration of RER in recent years, new TGR power plants are being built specifically to provide ancillary services, rather than to provide base load generation. For example, because some varieties of natural gas plants can be quickly ramped up and synchronized to the grid in a mater of minutes, they are suitable for providing fast-response ancillary services, which are often needed during peak hours when demand is high and the solar resources is beginning to decline (Arroyo and Conejo, 2004).

As the penetration of renewables increases, RER displace conventional bulk power production from TGR. Increasingly, TGR are dispatch to provide ancillary services, which results in short dispatch durations and frequent cycling (Guisández et al., 2013). These factors lead to higher TGR operation & maintenance costs. Consequently, some utilities have assigned specific power plants for some ancillary services, as long as the plants can meet the minimum requirements for participation in that particular ancillary services market. Building new TGR is an expensive undertaking that can take many years to complete. Furthermore, many approvals and revisions are required from public utilities commissions, public agencies, and regulatory authorities (Ghazzani et al., 2017).

3.2. Dispatchable standby generation

DSG systems are aggregations of large commercial and industrial customers that permit utility companies to upgrade, maintain, service, and dispatch customers' on-site generators when the need arises. DSG often provide non-spinning reserve service, though they can provide support during outages, brownouts, and cascading blackouts. Vaimen et al. provide a risk assessment of cascading outages (Vaiman et al., 2012). As well, the IEEE Cascading Failures Task force, under the PES Computer Analytical Methods Subcommittee, presented several methods and practical applications for reducing and preventing cascading outages by

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[3] Federal Energy Regulatory Commission, "Guide to Market Oversight Glossary", March 15, 2016

Table 2
A summary of select ancillary services that could be provided through aggregation of DER, and including their principle grid service actions.

Service	Alternate name	Action
Frequency response	Primary frequency control	Stabilize frequency against major loss of load or generation.
Frequency regulation	Secondary frequency control	Continuous correction of frequency deviations.
Ramp rate control	Tertiary frequency control	Accommodate changes in RER generation.
Volt/VAr	Reactive power compensation	Ensure voltage stability and/or provide reactive power to loads.

using DSG (Vaiman et al., 2013; Papic et al., 2011). And, Al-Salim et al. present how outages may be prevented and mitigated using DSG (Al-Salim et al., 2015), as do Koenig et al. though specifically within the context of the New York City utility Con Edison (Koenig et al., 2010).

DSG programs depend on contracts between the utility and the DSG-owning customer. These contracts significantly limit the number of annual run hours, which may be as little as eight hours annually due to air quality regulations (Osborn, 2004). As a result, utility companies implementing DSG usually have a large pool of many participants, though dispatch frequency and duration are low. The value of these systems for utilities is that they contribute towards the utility's non-spinning reserve requirements at a cost that is significantly less than that of dedicated TGR.

3.3. Demand side management

DSM is defined as any means or technology by which a utility can modify its customers' energy consumption pattern in order to suit the utility's need. There are many ways in which participating customers' energy profile and usage can be customized by a utility company. Some of these include, but are not limited to, time-of-use tariffs, DR programs, load shedding, and load balancing. Often this is done by simply turning on or off customer-owned equipment.

DER are used for achieving DSM. DER include customer-owned assets like air conditioning units, water heaters, commercial pumps, commercial refrigerators, and heat pumps, that can be switched on or off for the purposes of absorbing or shedding power. DER also include small storage assets like batteries with inverters, and Electric Vehicle Service Equipment (EVSE), which can be used to both discharge power to the grid or absorb power from the grid. With proper planning and forecasting, DSM can be used to relieve TGR during peak hours when traditional fossil fuel peaker plants are run for just a few hours to cover forecasting shortfalls caused by the stochastic nature of RER.

3.4. Asset aggregation

Asset aggregation allows for the grouping of DER to provide grid services. DER asset aggregation platforms enable real-time, two-way secure communications and interoperability between the aggregated assets and utility systems (Ardani et al., 2018).

Depending on the context, the term *'asset aggregation'* can be used to mean two different things. In the first definition, asset aggregation is defined as the use of an application platform to control a large number of loads. This definition is similar to the one used by Mahmoudi et al. (2017), where aggregation is defined as a customer-based approach to DR. In short, aggregation is a program or platform that can actively participate in the energy market by controlling customer-owned assets.

In the second definition, aggregation is a service offered by third-party entities for the purpose of providing energy or grid services. An aggregator serves as an intermediator between consumers, who provide DER, and power system participants, such as utilities, who deploy grid services (Carreiro et al., 2017). In other words, aggregation is the grouping of DER owned by electricity

customers for the purpose of acting as a single entity on the customers' behalf (Burger et al., 2017).

Aggregation is expected to continue to change the current operating model of electric utility companies (Shimomura et al., 2014). Due to changes in government oversight and regulations, consumers in some U.S. states may now choose their electricity supplier, thereby opening retail competition for electricity suppliers and aggregators. The delivery, transmission, and distribution of power remains the responsibility of the regulated power company. Consumers in deregulated states have the ability to choose or supply their own power back into the grid (Chapman et al., 2016).

As these systems continue to develop, future asset aggregation programs can be expected to be comprised of hundreds of thousands of diverse kinds of DER, have computational intelligence with decision making capability, aggregate multiple different kinds of DER, and dispatch these DER to provide a wide range of services, such as DSM, economic arbitrage, and ancillary services.

4. Literature and standards reviews

A survey of existing literature was conducted on the topics of Demand Side Management and Asset Aggregation in order to present a comprehensive understanding of how DER are being aggregated and dispatched to relieve the problems created by RER by providing grid services. There exists a large body of research on DSM, though many of the reviewed papers focus on peak load shifting. DSM literature is presented in Section 4.1. Fewer publications were found that pertain to Asset Aggregation (AA). A review summary for AA is examined in Section 4.2.

An ecosystem of grid operators, aggregators, and consumers will need efficient means for communicating with and dispatching hundreds of thousands of DER. Adopting common standards will help foster this ecosystem by providing protocols that facilitate transactions between these disparate groups. Standards facilitate innovation by providing a platform for development of interoperable products and services. Appliance manufacturers, aggregation platform developers, and utilities that adopt open standards will contribute to a broad Energy Grid of Things (EGoT) marketplace. Significant effort has gone in to developing such standards. A review of several of these standards is presented in Section 4.3.

4.1. Literature review of demand side management

Applications of DSM in literature are examined in this section. Contributions cover theoretical research projects as well as large-scale utility deployments, which are presented below, starting with the latter. As a note of caution to the reader, the term DSM was found to be interchangeable with DR in literature, although DR is one of the many ways of achieving DSM.

DSM has been demonstrated as a way to encourage utility customers to shift their electricity usage patterns (Strbac, 2008). Beginning in 1979, Florida Power Corporation developed a large-scale Direct Load Control (DLC) program for DER customer-owned equipment, which grew to include 50,000 water heaters, 45,000 central air-conditioners, 42,000 central heating systems, 8000

pool pumps and 35 MW of commercial space-conditioning equipment (Stitt, 1985). These units were cycled throughout the day based on permission levels determined by customers. The results obtained are ground breaking. The underlying goal was to help with load shifting through DSM. The authors concluded that there are three extremely important factors that can help with the integration of DLC programs to the operations of utility bulk power supply, namely: customer acceptance, the reliability of the hardware used, and aggregate load-shaping performance.

Detroit Edison Electric summarized the effects of field operating conditions on large-scale electric water heaters in applications for load management systems (Hastings, 1980). Often, load control is considered a peak shaving strategy or merely as DSM when in fact it can be used by operators to optimize the system. Findings from this study helped Detroit Edison conclude that load management strategies can be very useful for the refinement of economic dispatch of generation units.

Gustafson et al. presented a novel method to evaluate the effectiveness of a water heater DLC program for DSM (Gustafson et al., 1993). Engineering insights into the energy use of residential hot water systems were used by the authors for estimation. The DLC programs were implemented by three different utility companies in the Western United States. The findings include methods to apply average customer electricity usage and instantaneous demand to evaluate the potential effectiveness of a direct hot water heater load control program in a given region. Their method resulted in an algorithm for evaluating the potential for load control. A procedure was developed that allows the dispatch system planner to determine if such a program will be cost-effective and successful compared to a program developed through a more traditional pilot or demonstration approach. The authors also outlined how the same method can be used to determine a procedure for the dispatchers to properly initiate and terminate a load control program without hot water recovery problems.

Omaha Public Power District and the U.S. Department of Energy conducted several experiments on the application of demand-limiting equipment in all-electric homes (McIntyre et al., 1985). Dual control of demand limiters allowed customers to select the desired peak demand level, which was maintained by the logic of the demand controller. The utility could then reduce the level proportionally by transmission of control signals. Here, no aggregation was applied and it was again a DSM approach. Analysis of the results showed that both modes of operation, the local mode and the direct utility control modes, were effective in reducing peak demand.

Wisconsin Electric used a bi-directional power line carrier that enabled its system operator to manually control around 92,500 domestic water heater load control receivers (Bischke and Sella, 1985). This was done manually by the system operators, as needed. However, customers were allowed to choose an 8 h window during which their water heaters could not be turned off. The load control receivers sent a command to turn on the water heater circuit in fifteen minutes intervals. The water heaters were then kept off for several hours by sending a turn-off command every 12 min. This work concluded that DLC strategies using hot water heaters can be used to minimize operating costs by shifting energy usage to eliminate the expense of start-up and excessive cycling of TGR that happens earlier in the day.

Carolina Power and Light Company developed general modeling techniques to provide other electric utility companies with tools for analyzing load test data (Lee and Wilkins, 1983). The authors demonstrate that benefits from load management may be assessed in different ways depending upon the goals to be achieved. Direct control resulted in peak load reductions of up to 3%. The models defined by the authors were applied to predefined groups of water heaters but not to individual units.

Considering academic research, the energy pattern of about 700,000 water heaters of small residential users were studied by Rautenbach and Lane (1996). The energy curve was then grouped based on the switching times of their appliances, water heater size, and house hold size. A multi-objective controller was used to provide a new method of controlling like-kind residential domestic hot water loads. The objectives included reducing peak system demand, minimizing discomfort to the end-user, and reducing customer electricity bills. The controller responded to time-differentiated tariffs. Results show that the system peak load was reduced per customer. The authors noted that their control models may not be applicable to commercial, industrial, or other large scale electricity customers.

Ninagawa et al. used Fast Automated Demand Response (FASTADR) to control office building air-conditioning facilities. They experimented with 120 different models, each with different stochastic disturbances (Ninagawa et al., 2015). Then a neural network model was built using actual buildings facilities' time-series data. The authors noted that with FASTADR, some responses received from the controllers tend to oscillate, depending on the communications timing, the signal sampling time, or other stochastic disturbances on the network.

Mai and Chung developed a model to control HVAC systems in commercial buildings by using preset time-varying electricity prices to minimize electricity costs (Mai and Chung, 2016). The authors asserted that their research significantly reduced peak demand and increased energy savings and efficiency, without disrupting occupants' comfort level. This work demonstrated that large HVAC loads can be modeled and operated in a tightly controlled manner in an effort to reduce system peaks without compromising equipment efficiency. Modeling of such systems can be complicated, making it harder to replicate the load control schemes in buildings with similar HVAC systems (Bastida et al., 2019).

Of all the DSM literature presented above, none considered the use of DSM for participation in ancillary services markets. Few scholarly publications describe systems that provide ancillary services via DR. Research using DR for ancillary services was published by Motalleb et al. and Dehghanpour et al. Motalleb et al. discussed using DR for only frequency regulation Motalleb et al. (2016a). Dehghanpour et al. presented a technical review of literature on how to use demand side management of customer loads for the purposes of providing ancillary services like frequency regulation Dehghanpour and Afsharnia (2015). Rahimi and Ipakchi considered important elements for reliable and economic operation of the transmission system and the wholesale markets (Rahimi and Ipakchi, 2010), reporting that under a smart grid paradigm, DR response can be used as a market resource.

Other DER research has focused largely on DR market strategies including game theory in electricity markets (Nekouei et al., 2015), optimized DR in wholesale markets (Parvania et al., 2013), DR scheduling within deregulated markets (Nguyen et al., 2013), and, a two-stage hierarchical market framework for residential-based DR (Ali et al., 2015). As previously noted, DR is a subset of DSM and is the only subset of DSM that was found to use DER as a market resource. Very little literature exists in this space compared to the rest of DSM, suggesting that the use of DSM applications for energy transactions in this way is still in its early stages.

4.2. Literature review of asset aggregation

An MIT study on AA from 2013 (Burger and Luke, 2017) analyzed utility business models for deployment of DER including DR, Energy Management System (EMS), energy storage, and solar PV. This work focused on the business and policy implications

of AA alone. The MIT study used business operation data from 144 regionally-diverse utilities whose business operations are associated with one or more DER. The technical details of the composition of aggregated DER were outside the scope of this study. Instead, discussions of the revenue streams, customer segments, and electricity services were presented. Because the utility business models were diverse (144 regions), policy dependent, and heavily regulated, the research concluded that regulation and policy changes need to be considered when developing business models for AA type applications.

Similarly, Zhang (2016) and Funkhouser et al. (2015) both explored the economic benefits of deploying AA applications. Neither addressed the technicalities or architecture involved. Instead, they studied and analyzed data gathered from utility companies and profiled the type of services, based on the business model and customer outreach programs of the respective companies.

Koliou et al. used DR to aggregate customer loads for DSM (Koliou et al., 2014). They investigated how DSM of aggregated loads can be used as a resource for balancing the grid. Small customer loads were bundled and aggregated for transactions in the energy market. The authors illustrated how aggregation companies can bundle small customer loads and use this as a market participation resource. The authors noted however that as a viable market resource, aggregation of DR loads for DSM is still in its early stages. Pruggler came to similar conclusions, demonstrating the economic potentials of DSM, especially for spot market-oriented loads at household levels (Pruggler, 2013).

Calvillo et al. noted that the market share of aggregators in the energy market globally was between 1% to 2% and that proper planning and efficient operational strategies, along with friendly government regulations, will likely help grow the role of aggregators (Calvillo et al., 2016).

DER that provide DR were referred to as flexibility service providers by Eid et al. (2016). The authors argued that many barriers still exist that limit aggregators from participating in balancing markets and that policy makers and regulatory commissions should assist to lower those barriers and develop better compensation mechanisms between aggregators, utility companies, and generation suppliers. They state that such flexibility services are necessary for the reliability and sustainability of the grid.

A review of literature discussing AA and select pilot-projects was presented by Niesten and Alkemade (2016). In their analysis, they reviewed data from 434 European and US smart grid projects. They noted that the aggregator is critical in making any market participation of customer DER in the energy market economically viable. The authors further demonstrated that aggregation of DER (PEV batteries in this case) and the role of aggregators is necessary to further the business case for the wide adoption of a variety of other smart grid services for market participation.

Motalleb et al. demonstrated how distributed DR scheduling can be used to provide frequency regulation during contingency periods (Motalleb et al., 2016b). DER, including battery banks and electric water heaters, were used in aggregate as sources of ancillary services. The researchers implemented a control system model and specialized algorithms that optimized these DER for DR. Two points worth noting are that this paper focused on DR alone and secondly, the algorithms presented were limited to only when contingency events occurred on the grid.

Roos et al. developed an optimization framework for a load aggregator participating in wholesale power and capacity regulation markets. They used actual data from a set of Norwegian electricity consumers to test the model and estimate the value of aggregation to the market (Roos et al., 2014). This report concluded that the aggregator value largely depends on factors such

as daily price variations, the definition of market on-peak and off-peak periods, and the price of storage. The aggregator's objective was to minimize the total energy costs to the consumers. Select customers for this study included shopping centers and food production sites with loads such as heating, air conditioning, and lighting. The technology to do this was developed by Enfo Consulting AS, a European smart grid solutions company that enables communications and control for residential loads.

The CAISO conducted a pilot study in collaboration with Lawrence Berkeley National Lab in 2009 that determined the feasibility of allowing commercial and industrial DR-enabled DER to participate in grid service markets (Kiliccote et al., 2011). The objective was to assess the technical and financial feasibility of using retail loads to participate in the day-ahead wholesale non-spinning reserve ancillary service market. Three facilities, a retail store, a local government office building, and a bakery were used as DER resources and linked together using OpenADR (see Section 4.3.5). The researchers found that DR strategies for HVAC and lighting can provide responses suitable for participation in the non-spinning reserve market. This research focused on optimizing the communication and telemetry infrastructure needs, understanding the capabilities in commercial and industrial facilities to automatically deliver load within the limitations of the non-spinning reserve product, and testing the feedback controls to maintain the commitment of loads.

An aggregator was proposed for time-of-use applications by Rahnama et al. (2014). A supermarket refrigeration system and a chiller with ice storage were used in a case study. Results obtained from the study were verified against actual supermarket energy use to determine potential profitability. A centralized controller, whose responsibility is to aggregate load flexibility in an optimal way based on preset market time-of-use prices, was used for large commercial customers.

A DLC algorithm was developed for aggregated control of domestic electric water heaters by Diduch et al. (2012). Some of the challenges encountered in this DLC experiment were due to uncertainties in estimating water heater temperature fluctuations, hot water consumption, and reserve load. The authors recommended using load modeling and machine learning as a means of improving the accuracy of the algorithms developed.

Ruiz et al. created a Virtual Power Plant (VPP) by aggregating several DER loads, specifically air conditioning units, water heaters, and electric space heaters (Ruiz et al., 2009). This was accomplished by aggregating the capacity of the DER in order to make them more accessible and manageable in the day-to-day energy markets. An algorithm was developed to manage the VPP and a large number of customers with thermostatically controlled appliances. The algorithm, similar to Diduch et al. and based on DLC, determines the optimal control schedules that an aggregator should apply to the controllable devices in order to optimize load reduction over a predetermined duration (Diduch et al., 2012). The results define the load reduction bid that the aggregator can present in the electricity market, but the models used for the bids are not flexible, nor are they divisible. They are constrained by the parameters of the models, which need to be reset every time a new customer is added.

The possibility of providing regulation services with small loads, such as water heaters, electric heaters, or air conditioners was considered by Kondoh et al. (2011). Specifically, DLC models were developed for aggregating water heater loads for the energy market. The models also estimate the minimum amount of water heaters needed, the duration of regulation, as well as the amount of regulation (MWh) needed. The researchers concluded that the aggregated regulation service provided by water heater loads can become a major source of revenue for load-serving entities. To guarantee customer comfort and provide regulation service

however, the water heater thermostat control circuit was modified. Because every thermostat control circuit must be modified, scaling is a challenge. One limitation of this work is that from 00:00 to 06:00, regulation is not available due to low power consumption of water heaters during those hours.

A method was developed by Keep et al. that uses aggregated electric loads to balance forecast shortfalls on the ACE on the grid, thereby providing a frequency regulation service (Keep et al., 2011). The strategy is quite unique compared to others in that it relies only on load switches as the source of local control actuation, yet it is capable of both decreasing and increasing the total aggregate load while causing little to no disruption to the end users. Load switches were used for controlling refrigerators. However, the application of aggregation to household refrigerators alone limits the scope of this work. The authors presented a mathematical model for the control algorithm. The authors appropriately noted that other appliances like space heaters and water heaters should be expected to provide similar results.

4.3. Review of communications standards for DER aggregation

Large-scale aggregation of DER, and their dispatch for providing grid services, will require the adoption of standards that define the means of communication and methods of control between DER and DERMS (Anon, 2019a). A marketplace of grid operators, aggregators, and DER owners will need efficient means for establishing communication, facilitating automated transactions, and ensuring device interoperability if a robust, large-scale ecosystem is to evolve.

This review focuses on the open (non-proprietary) communications standards that address network connections between DER and the DERMS that are used by aggregators and grid operators to aggregate and dispatch large numbers of DER. These standards describe the interface layers of a network. The Open Systems Interconnection (OSI) Model defines seven such layers: the physical, data link, network, transport, session, presentation and application layers (Day and Zimmermann, 1983). Standards typically address only a subset of these layers. The latter is the most pertinent to this context, defining the communicating participants, the available data properties, and the methods for control.

Other standards exist that define the interface between a DER and the electric power system at the point of common coupling. These include UL 1741, which defines the product testing requirements for inverter manufacturers, addressing issues such as low-voltage ride through, anti-islanding, and voltage regulation testing requirements, among others (Anon, 2010); and IEEE 1547-2018, which provides extensive technical requirements for operation, performance, and safety of grid-interactive inverters (Anon, 2018a). These are critical standards for ensuring reliable grid operation when PV penetration is high, as demonstrated by their adoption in California Rule 21 and HECO Rule 14H. However, these standards are outside of the scope of this review.

4.3.1. ANSI/CTA-2045
The ANSI/CTA-2045 standard defines the means by which a dispatchable customer-owned appliance can interface with a grid operator or aggregation service (Anon, 2013a). The Consumer Technology Association (CTA) established the standard with the objective of promoting grid connectivity between residential appliances and a DERMS, which in turn can provide grid services; CTA-2045 enables consumer appliances to actively support a reliable electric grid.

CTA-2045 provides specifications at the physical, data link, network, and application layers. At the physical layer, CTA-2045 defines form factors and electrical interfaces for two Universal Communications Modules (UCM). These UCM provide the physical and communications interfaces between an appliance and a DERMS application layer standard, such as IEEE 2030.5 and OpenADR. At the data link layer, the standard defines link handling, error codes, and power negotiation, among others. The standard identifies two sets of application layer messages, *Basic* and *Intermediate*, which define the properties that describe a DER and the methods that are available for its control. CTA-2045 also allows pass-through of messages from other application layer standards including IEEE 2030.5, OpenADR, and general IP. The 2045 messages and pass-through capabilities are the means by which DERMS may aggregate consumer appliances to provide grid services.

Manufacturers are producing consumer products that feature CTA-2045 UCM ports, including water heaters, pool pumps, EVSE, thermostats, and PV inverters. The Electric Power Research Institute and the National Renewable Energy Laboratory have conducted performance tests on several of these products, including water heaters (Thomas and Seal, 2017a), PV inverters (Thomas and Seal, 2017b), and EVSE (Thomas and Seal, 2017c). The Bonneville Power Administration conducted a large-scale demonstration project using CTA-2045 water heaters (Anon, 2019a), and in 2018, the U.S. state of Washington passed legislation requiring water heaters sold in the state to include the CTA-2045 capabilities (Anon, 2018b).

4.3.2. SunSpec Modbus
The SunSpec Modbus standard applies specifically to grid-enabled PV inverters and inverter-based energy storage systems (Anon, 2015a). The standard promotes interoperability between these devices and a DERMS by establishing a common communications protocol based on Modbus. Modbus is a serial communications protocol, developed in the 1970's, for industrial automation. At its most basic, Modbus is used to connect Remote Terminal Units (RTU) with supervisory control and data acquisition systems. RTU contain data stored in registers; Modbus commands instruct an RTU to report its register values, change register values, and read or write to I/O ports. As such, Modbus addresses the physical, data link and application OSI layers. Variations of Modbus address the network and transport layers too, such as Modbus TCP/IP and Modbus UDP.

SunSpec Modbus was created by the SunSpec Alliance to provide protocols that define which Modbus register blocks contain what types of information pertinent to inverter communication and control, thereby creating a more specific application layer. As such, SunSpec Modbus is an application layer standard that promotes interoperability between DERMS and inverters. SunSpec Modbus defines several information models, which are blocks of registers with identified addresses that are reserved for specific inverter-related properties. These include a Common Model, Aggregator Model, Network Configuration Model, Inverter Model, and Storage Model, among others.

SunSpec Modbus configuration requirements and information models have been adopted by other organizations to standardize communication and control for grid-tied inverters and battery storage systems. These include both UL 1741 and CA Rule 21, which specify the SunSpec Modbus information models required for communication (Anon, 2010, 2017a).

4.3.3. SAE J3072
SAE J3072 defines interconnection requirements for the on-board, utility-interactive inverter systems within PEV. The physical interconnection between the on-board inverter and the electric power system occurs at the EVSE. J3072 defines the information exchange required for an on-board inverter to be properly configured and authorized by the EVSE prior to energy exchange, particularly for PEV-to-grid discharge (Anon, 2015b). As such, the standard provides specifications at the presentation layer.

The Society of Automotive Engineers (SAE) developed J3072 in order to allow utilities to approve interconnection of EVSE, rather than PEV. Since PEV are mobile, a utility interconnection agreement can only consider the electrical specifications of EVSE. J3072 provides means for EVSE to authorize J3072-certified PEV inverters, and to configure those inverters to conform to the terms of the EVSE interconnection agreement.

For testing criteria, the standard references IEEE 1547.1 and UL 1741. Though SAE J3072 references these standards, it does not require testing and implementation of smart inverter functions such as voltage and frequency ride through requirements. The standard places responsibility on the EVSE manufacturer, rather than a nationally recognized testing laboratory, to perform EVSE conformance testing and to issue a certificate of conformance.

While SAE J3072 defines the required interconnection standards for EVSE, SAE J2847-1 discusses the communication requirements and functions of IEEE 2030.5 that could be used to permit an EMS to dispatch PEV as a DER (Anon, 2019b). Use cases for dispatching PEV as DER are presented in SAE J2836/3, which considers how PEV could be used by an EMS to support grid operations while concurrently prioritizing the PEV energy capacity for its primary purpose, transportation (Anon, 2017b).

4.3.4. IEEE 2030.5-2018

IEEE 2030.5-2018 is the IEEE (IEEE) standard for implementation of the Smart Energy Profile (SEP) application protocol (Anon, 2018c). IEEE 2030.5 was originally developed by the Zigbee Alliance and the HomePlug Power Alliance, who released the SEP 2.0 protocol in 2012 (Anon, 2013b). Considering the OSI network model, IEEE 2030.5 establishes specifications for the application layer. It specifies security protocols at the presentation layer, TCP for the transport layer, and IP for the network layer.

The standard may be viewed as a comprehensive EGoT platform, providing mechanisms for device discovery and defining multiple security attributes in addition to its extensive library of resources, support services, and function sets. IEEE 2030.5 is intended to enable information exchange between many types of energy-service devices including consumer appliances, EMS, metering devices, storage systems, and DR. It is expansive in its scope, ensuring interoperability between DERMS and consumer-owned DER.

IEEE 2030.5 defines sets of Support Resources and Common Resources, which include basic function sets, subscription processes, acceptable responses, device status updates, configuration, logging, and network status. The standard also has an extensive library of Smart Energy Resources, which specify function sets for DR & Load Control, Metering, Pricing, Billing, Energy Flow Reservation, and DER, among others. Security attributes include certificate requirements, device identifier specifications, and access control lists. Also included with the specification are example cases, including code, for many of the function sets.

IEEE 2030.5 has been mandated within the Common Smart Inverter Profile (CSIP), which calls for an IEEE 2030.5 interface that meets the Phase 2 requirements for CA Rule 21 (Anon, 2018d). It is also specified as one of only three allowable communication protocols by IEEE 1547-2018, alongside SunSpec Modbus and DNP3 (IEEE 1815), for grid-interactive inverters (Anon, 2018a).

4.3.5. OpenADR

Open Automated DR Communications Specification, or OpenADR, is a comprehensive EGoT application specification designed to facilitate DR and DER. OpenADR was developed by LBNL, with funding from the California Energy Commission, beginning in 2002 (Koch and Piette, 2008). One of the development objectives was to build a platform that would support dynamic pricing

Table 3
Summary of presented standards. The first three are product interface standards for DER while the latter two are DERMS communications standards for aggregators and utilities.

Standard	OSI layers	Product segment
ANSI/CTA 2045	Application, network, data link, physical	Customer-owned appliances
SunSpec Modbus	Application	Grid-enabled inverters (PV, BES)
SAE J3072	Presentation	EVSE
		DERMS capabilities
IEEE 2030.5–2018	Application, presentation, transport, network	DR, DER & load control, pricing, billing, etc.
OpenADR	Application, presentation	DR, DER & load control, dynamic pricing, etc.

in order to increase reliability and improve energy economics through DR (Piette et al., 0000; Bienert, 2011). The platform allows electricity providers to communicate directly with facility control systems using pricing and DR event signals using two-way internet protocol. The facility control systems then automatically respond to a grid event based on these signals (Motegi et al., 2007).

Energy pricing and reliability signals can be readily exchanged between customers, utilities, independent power operators, and system operators using real-time hourly day-ahead and day-of pricing. Facilities that are automated to respond to these signals can therefore be aggregated to provide grid services (Samad et al., 2016). OpenADR facilitates communication between building systems (e.g. BACnet, Modbus) and external services, such as a DERMS.

OpenADR provides specifications at the OSI presentation and application layers. OpenADR defines two types of nodes. Virtual top nodes, such as a utility DERMS, publish grid condition and event information. Virtual end nodes, such as DER and building control systems, respond to that information. The top nodes may be considered servers, with the bottom nodes as clients. The communication is a two-way stream, as end nodes may convey information up to top nodes. Exchanged between these nodes are energy interoperation services. These services handle discovery, registration, reporting, availability, and event information. Security is addressed by multiple means, including through the use of certificates, requirements for use of TLS1.2, ECC, and RSA cipher suits, a system registration process for top nodes and end nodes, and XML digital signature cryptography (Anon, 2015c).

In addition to DR, OpenADR 2.0 defines profiles for DER control. DER controlled using OpenADR can be dispatched to provide grid services. For instance, OpenADR is used by the VOLTTRON platform, which is an agent-execution platform that connects grid service requests to available agents (Katipamula et al., 2016). Developed by the Pacific Northwest National Laboratory, VOLTTRON aggregates DER such as water heaters, PEV, and building services to provide grid services using the OpenADR energy interoperation services (Haack et al., 2013, 2016).

This suite of open standards, summarized in Table 3, provides some of the necessary criteria that will promote the growth of an EGoT ecosystem, specifically by ensuring interoperability between DER and DERMS. SunSpec Modbus, SAE J3072, and CTA-2045 define standardized product interfaces for manufactures, which could make products more competitive by creating value for consumers. Just as an Energy Star energy efficiency rating has become a hallmark of a desirable residential appliance, so too could "grid-ready" connectivity; utilities and aggregators could entice customers to participate in aggregation programs by providing credit towards customer electricity bills, for example. IEEE 2030.5 and OpenADR provide utilities and aggregators

Table 4

Associations between residential DER and the grid services they could provide when aggregated, relating Tables 1 and 2, and in reference to analysis of inverter-based systems (Slay, 2018) and water heaters (Clarke et al., 2020; Marnell et al., 2020).

DER	Appropriate grid services
PV Inverters	Frequency response, regulation, ramp-rate control, volt/VAr support
BESS	Frequency response, regulation, ramp-rate control, volt/VAr support
EVSE	Frequency response, regulation, ramp-rate control
Resistance water heaters	Frequency response, regulation, ramp-rate control
Heat pump water heaters	Ramp-rate control

with standardized functions, properties, and security protocols for building DERMS and aggregating DER, thereby allowing these companies to capture value through DER dispatch as ancillary services. California's adoption of IEEE 2030.5 for the CSIP mandate and Washington's CTA-2045 bill are early market drivers that are compelling manufacturers to adopt open communications standards. An EGoT ecosystem of products and services is now developing, with companies producing clients & servers, interoperability testing services, and DERMS, all based on exploiting these open standards.

5. Conclusion

This manuscript addresses questions regarding how utilities can address the challenges imposed by Renewable Energy Resources using residential-scale Distributed Energy Resource assets, how those assets may be aggregated, how aggregations of such assets can be used to address grid issues through dispatch as ancillary services, and how communication and control may be realized using open protocols. The review begins by presenting the problems that large-scale RER adoption is causing within the utility industry. This is followed by a presentation of the services that utilities use to address these problems, known as ancillary grid services. The article then presents a review of DER aggregation solutions that can be used to provide these grid services, specifically dispatchable standby generation, demand side management, and asset aggregation. Recognizing that standardized communication and control protocols are imperative for dispatching DER to provide grid services, the paper presents a review of open standards that have been developed to promote DER aggregation. The DER technologies, ancillary service, aggregation programs, and communications standards presented in this review will help address the challenges imposed by large-scale RER adoption, which in turn will lead to higher penetration levels for these fossil-free energy resources.

This literature review introduced the system reliability challenges that arise due to the stochastic nature of renewable energy resources, particularly wind power and PV solar. The negative impacts that excessive RER generation have on power system reliability can limit the decarbonizing benefits that RER provide. Unsupported overgeneration from RER can lead to overvoltages, severe frequency deviations, and transmission congestion, which in turn may force excessive curtailment. These reliability issues then become a self-limiting factor to the wide-scale deployment of RER.

The review presented several means by which utilities can address these challenges using aggregations of residential-scale DER assets. Also presented are the ancillary grid services used by utilities to alleviate frequency and voltage problems, and how aggregations of assets can be dispatched to provide these services through the use of open communications protocols.

Residential-scale loads, generation sources, and storage systems have the potential to contribute to the evolution and reliability of electric power systems. If networked together, these devices become distributed energy resources capable of contributing value to an electric power system. Aggregations of large numbers of DER can be dispatched to provide utility services that address reliability while concurrently enabling high penetration levels of RER.

This review examined the work of researchers who have developed the theoretical framework for achieving these objectives, the products of standards bodies that have created open communication frameworks for linking DER with grid operators, and the utility programs that have demonstrated potential for providing grid services using aggregations of DER. The efforts of these parties has established a foundation for an Energy Grid of Things ecosystem that will help decarbonize electrical power systems and ensure power system reliability.

Utility programs that address these challenges include Dispatchable Standby Generation, Demand Side Management, and Asset Aggregation. AA programs that use direct load control of customer-owned equipment were found to be very good solutions for addressing reliability issues, such as through demand response. Improved network communications would allow for the aggregation of very large numbers of DER, while an enhanced suite of control functions would increase the ability of AA to provide a wide range of grid services.

Aggregation of multiple behind-the-meter loads, storage systems, and customer-owned generation resources will be enabled via protocols like CTA-2045, Sunspec Modbus, SAE J307, IEEE 2030.5, and OpenADR. Aggregations of DER will be dispatched in concert to provide ancillary services in order to ensure reliability and support stochastic renewable energy resource generation. When aggregated to provide these ancillary services, DER help reduce dependence on traditional generation resources that contribute to climate change while concurrently ensuring power system reliability. Open standards will enable large aggregations of DER to seamlessly enter and reliably participate in energy service markets, and a new industry will arise to provide the equipment, software, products, and enterprise systems to enable the transition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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