2021 IEEE Conference on Technologies for Sustainability (SusTech)

An Energy Service Interface for Distributed Energy Resources

Tylor Slay, Robert B. Bass
Department of Electrical & Computer Engineering
Portland State University
Portland, OR, USA
tslay@pdx.edu, robert.bass@pdx.edu

2021 IEEE Conference on Technologies for Sustainability (SusTech) | 978-1-6654-1927-7/20/$31.00 ©2021 IEEE | DOI: 10.1109/SusTech51236.2021.9467416

Abstract—**Renewable energy resources, particularly wind and solar photovoltaic, are becoming significant contributors to electric power generation. These resources will contribute towards achieving sustainable electric power systems. However, renewable resources will dramatically increase the demand for flexible power system operations. This paper proposes an energy service interface that will allow aggregated distributed energy resources, such as residential loads and inverter-based systems, to participate in NERC-defined smart energy reliability services. Such cyber-physical systems will increase system flexibility by ensuring match between energy supply and energy demand.**

Aggregation and coordinated dispatch of millions of distributed energy resources will require development of large-scale computing networks. Several smart grid interface-enabling technologies, including IEEE 2030.5, Common Smart Inverter Profile, SunSpec Modbus, and CTA 2045, are discussed. Residential loads are categorized by their static and dynamic energy characteristics to identify services in which they can participate. The business model for the energy services interface as well as probabilistic modeling for resource estimation are highlighted as future considerations.

Index Terms—**Essential Reliability Services, Distributed Energy Resources, Distributed Energy Resource Management System, Energy Services Interface, Smart Grid, Ancillary Services, Reliability Services**

I. Introduction

The primary objectives of an Independent System Operator (ISO) or Regional Transmission Organization (RTO) are the coordination, control, and monitoring of energy transfer between generating facilities and load centers. These objectives are achieved through ensuring sufficient generating capacity to meet the constant baseload of the system and the peak load under critical conditions. Figure 1 demonstrates a baseload of nearly 18,000 MW with a peak load of 32,000 MW. Note in this case that the Operating Authority must be able to ramp its generation nearly 13,000 MW within three hours to maintain balance between system load and generation when solar generation declines in the afternoon. The North American Electric Reliability Corporation (NERC) recommends a comprehensive study on ramping capabilities of interconnected generation to ensure adequate flexibility to guide interconnection of new Variable Energy Resources (VER) in regards to Essential Reliability Services (ERS).

Each Operating Authority achieves stable balance between generation and load through the dispatch of *ancillary services*. Ancillary service definitions vary from one operator to another, but they all have the same objective: to ensure reliable energy transfer. NERC's *Essential Reliability Services Task Force: A Concept Paper on Essential Reliability Services that Characterizes Bulk Power System Reliability* defines ERS, which is their name for ancillary services, to maintain Bulk Power System (BPS) frequency and voltages to ensure reliable energy transfer [1]. Any grid services that respond to unstable conditions or recover from power outages have been deemed outside the scope of this paper.

Typical generating resources reserved for providing ancillary services have large power and energy capacities, thereby allowing Operating Authorities to commit a small number of resources for each service. This paper presents design guidance for designing an Energy Services Interface (ESI) that uses large-scale aggregations of Distributed Energy Resources (DER) to achieve the same reliability using the IEEE 2030.5 IEEE 2030.5 Smart Energy Profile (IEEE 2030.5) 2.0 application protocol standard. The ESI will enable cyber-physical power systems to use renewable energy when it is available while accounting for real-time energy demands, thereby

This work was performed under US DOE agreement DE-OE0000922.

contributing to a more sustainable and efficient bulk electric power system. These ESI design guidelines highlights the need for creative expertise in large-scale network computing, and provides a pointer toward the contributions that computer scientists and engineers could make in helping to develop a more sustainable electric power system.

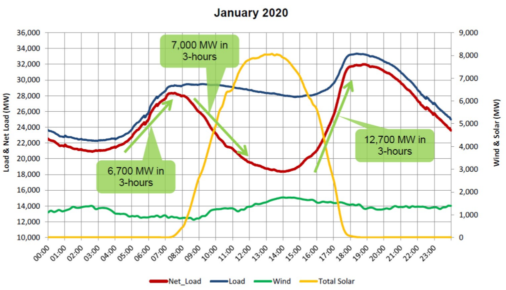

Fig. 1. Wind and solar baseload scenario for ramping in 2020 [1]

II. Essential Reliability Services

The ERSs are classified into frequency and voltage groups. The frequency services are used to balance generation and load at varying response speeds. The BPS's frequency is a global property that can be affected by any resource of sufficient scale. The voltage services are used to maintain system voltage between all service points. Unlike frequency, voltage is a local property, which requires voltage service resources to be distributed throughout the system.

A. Frequency Support

The primary objective of frequency support is to ensure stable and synchronized operation of the BPS. The BPS balances load and generation through load following, regulation, response, and contingency reserve services. Each of these services are defined by NERC as follows [1]:

1) Regulation: "Regulation is the provision of generation and load-response capability, including capacity, energy, and maneuverability that responds to automatic controls issued by the operating authority." Each participating resource allocates a percentage of its capacity to balance small discrepancies in actual load on the system compared to forecast load. These control signals are typically in the sub-minute range.

2) Response: "Response is the provision of capacity from Interconnected Operations Service (IOS) resources that deploy automatically to stabilize frequency following a significant and sustained frequency deviation on the interconnection." Unlike frequency regulation, response assets are reserved for large frequency disturbances. Figure 2 shows the sequential frequency control after a significant disturbance. The three stages of frequency control work sequentially to stabilize the grid as quickly as possible and then gradually shift back to normal generating resources.

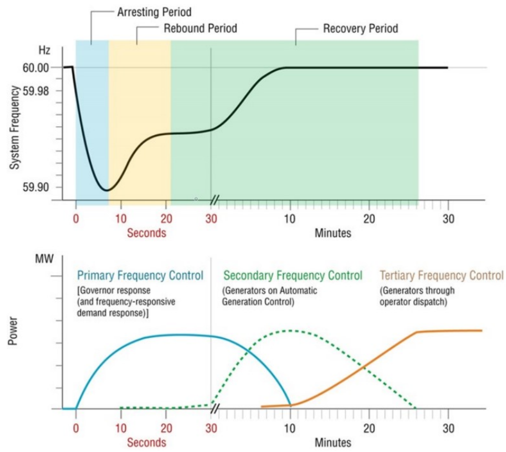

Fig. 2. Sequential actions and impacts on system frequency after a disturbance [2]

3) Load Following: "Load Following is the provision of generation and load-response capability that is dispatched within a scheduling period by the Operating Authority, including capacity, energy, and maneuverability." Load following is similar to regulation, but on a longer time scale. Depending on the operating authority, the control signals can be in the 5-15 minute range.

4) Contingency Reserve: "Contingency Reserve is the provision of capacity deployed by the Operating Authority to reduce the Area Control Error (ACE) to meet the Distributed Control Standard (DCS) and other NERC and Regional Reliability Council contingency requirements." The reserve is a mixture of spinning, non-spinning, and supplemental resources to meet the reliability requirements during a BPS event.

B. Voltage Support

1) Reactive Power Supply: "Reactive Power Supply is the provision of reactive capacity, reactive energy, and responsiveness from IOS resources, available to control voltages and support operation of the Bulk Electric System" [3]. The voltage support resources can be static, but within balancing areas with high penetration levels of inverters, there exist excellent opportunities to leverage the fact-acting four-quadrant capabilities of inverters to provide dynamic reactive power support.

III. Ancillary Services

Ancillary Services are “services 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” [1]. This paper focuses on PJM’s Regulation A/D Ancillary Service to demonstrate the dynamics of frequency regulation.

A. PJM Regulation

PJM Interconnection is an RTO that coordinates the movement of wholesale electricity in all or parts of Delaware, Illinois, Indiana, Kentucky, Maryland, Michigan, New Jersey, North Carolina, Ohio, Pennsylvania, Tennessee, Virginia, West Virginia, and the District of Columbia.[1] PJM uses two control signals, RegA and RegD, to balance load and generation within its operating region.

1) Reg A: Figure 3 shows the RegA control signal, defined as a low pass filter signal suitable for traditional regulating resources [4]. The ramping rates required to follow a RegA control signal are much lower than for RegD.

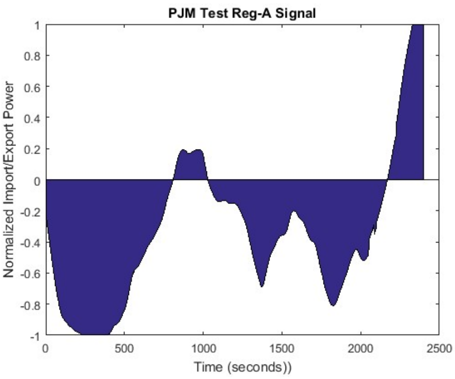

Fig. 3. PJM’s RegA test control signal [4]

2) Reg D: Figure 4 shows the RegD control signal, defined as a high pass filter signal suitable for dynamic regulating resources. The ramp rates are significantly greater than RegA, with more frequency changes between importing and exporting power. RegD is a symmetric signal, unlike RegA, thereby ensuring a regulating resource will import the same amount of energy that it exports over every hour.

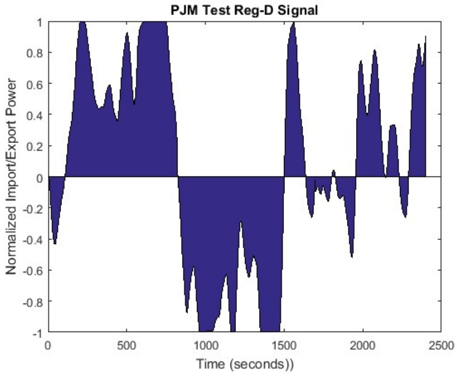

Fig. 4. PJM’s RegD test control signal [4]

PJM’s regulation market obligations state that assigned resources must be capable of responding to either RegA or RegD control signals immediately and meet their capability within five minutes [4]. Resources participating in PJM’s regulation market must also maintain the required performance characteristics. Both RegA and RegD control signals are sent to participating regulating resources every two seconds.

IV. Enabling Standards

This section highlights the standards that define the functions and properties that the ESI will use to manage DER participation in an ERS. The ESI will use IEEE 2030.5 to standardize Wide Area Network (WAN) communication between an Operating Authority’s server and DER clients. Common Smart Inverter Protocol (CSIP) builds on IEEE 2030.5 by defining expected behavior as well as client/server and aggregator interactions. The end device standards, SunSpec Modbus and CTA-2045, provide means for device-level interfacing with DER.

A. IEEE 2030.5-2018

IEEE 2030.5-2018, also known as IEEE 2030.5 2.0, follows the Open Systems Interaction (OSI) four-layer Internet stack network model. The standard defines the mechanisms of exchanging messages between clients and servers, as well as the exact messages exchanged, including errors and security features [5]. IEEE 2030.5 defines several function sets that enable dispatch of ERS using DER. The most notable function sets are:

1) Time: Establishes a means for the client to synchronizing with the IEEE 2030.5 server clock to ensure controls are executed at the correct time.

[1]About PJM: https://www.pjm.com/about-pjm/who-we-are.aspx

2) Demand Response and Load Control: Allows IEEE 2030.5 servers a means of shifting loads or adjusting control set points to reduce energy consumption during peak usage times. This resource is intended to control residential loads, but the following *Flow Reservation* resource provides a more flexible way of scheduling DERs with a small set of parameters.

3) Flow Reservation: Allows the client a means of requesting a specified amount of energy or a specified amount of power for a duration of time from the IEEE 2030.5 server within a future time window. The server responds with the start time for the specified amount of energy or power with the ability to supersede the control any time within the time window.

The flow reservation resource provides an excellent opportunity for machine-learning at the device to predict the optimal time to schedule a device to turn on while minimizing the discomfort to the device owner. heating, ventilation, and air conditioning (HVAC), water heaters, dishwashers, and pool pumps are excellent examples of devices who's energy can be displaced to benefit the bulk power system. To displace these loads, the device should have some understanding of the residential usage to prevent displacement that would cause discomfort. A machine-learning algorithm could be implemented to achieve this and only request flow reservations when it will not affect the device owners comfort.

4) Distributed Energy Resources: Allows the server to control the active/reactive power settings of inverter based systems as well as autonomous Volt-VAr, Volt-Watt, and Frequency-Watt control curves.

5) CSIP-2.0: The CSIP standard builds on the IEEE-2030.5 protocol to provide interoperability between Operating Authorities, Aggregators, and DERs. The behavior between Operating Authorities and DERs is defined in scenario 1, and Operating Authorities and Aggregators in scenario 2 [6]:

Scenario 1: This scenario defines *direct* DER communication with an Operating Authority. The communication architecture may be achieved in the following ways:

1) DER with Smart Inverter Control Unit (SMCU): The SMCU provides the communication component for a single inverter to interact with the Operating Authority.
2) DER with Generation Facility Energy Management System (GFEMS): The GFEMS mediates interaction between one or more DER with the Operating Authority.

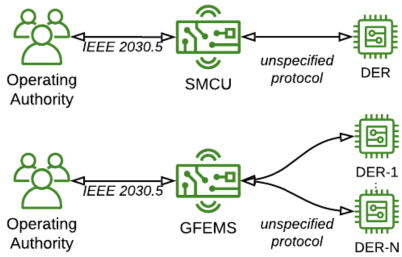

Fig. 5. CSIP Scenario 1: Direct SMCU communication architecture (top), and GFEMS architecture (bottom)

Scenario 2: This scenario defines an *aggregator interface* to manage DER communication with an Operating Authority. The aggregator is assumed to manage a large number of DER across a service territory and is responsible for relaying any operational changes and data requests. Figure 6 shows the aggregator communication architecture and highlights the ability to aggregate any DER, SMCU, or GFEMS.

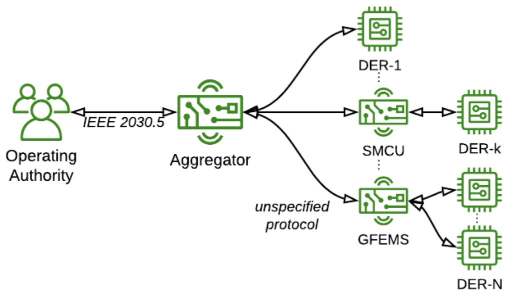

Fig. 6. CSIP Scenario 2: Aggregator communication architecture.

IEEE 2030.5 defines a variety of function sets and controls that can be implemented with a client/server. CSIP establishes acceptable behavior for clients when a control event overlaps or is superseded by another control event. There are three specified behaviors:

1) Overlapping: two control events occupy the same time window. In this situation, the highest primacy value cancels the lower primacy value control.
2) Nested: a new control event is issued that occupies the same time window as an active control event. In this situation, the higher primacy value supersedes the lower primacy value control which is then canceled.
3) Stacked: two control events overlap, but the operations do not interfere. In this situation,

both controls are executed. Figure 7 shows the time relationship of stacked control events.

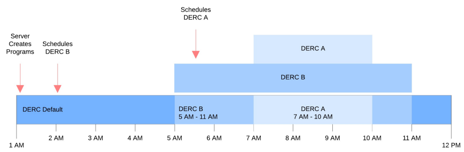

Fig. 7. Time relationship of stacked control events

CSIP provides both Operating Authorities and manufacturers with testing procedures and certification of compliance. The California Energy Commission has mandated CSIP for all grid-tied inverters under CA Rule 21 [7].

B. SunSpec Modbus

SunSpec Modbus was developed by the SunSpec Alliance to establish designated blocks of Modbus registers for standardised information and control [8]. This gives manufacturers an interface to build into grid-tied inverters that allows participation in ERSs. This standard also supports pass-through of other standards, such as IEEE 2030.5. Many inverter manufacturers have implemented the SunSpec Modbus models, but there is a trend of manufacturers bypassing local control and forcing control through their proprietary aggregators.

C. CTA-2045

The CTA defined Consumer Technology Association (CTA)-2045 to provide any product an Modular Communications Interface (MCI) to participate in ERSs. The primary objective of this standard is to give manufacturers a standard energy management interface to build into any product. The MCI protocol supports pass-through of other standards, including IEEE 2030.5.

Bonneville Power Administration recently used CTA-2045 in a large-scale water heater demonstration project [9]. The U.S. state of Washington has passed legislation requiring CTA-2045 or like capability be included on all water heaters sold in the state [10]. This level of adoption makes CTA-2045 a promising standard in enabling the use of DER for ERSs [11].

V. Energy Services Interface

In 2012, the National Institute of Standards defined the ESI as a device or application that serves as a "gateway to the customer premises network," residing between a Grid Service Provider (GSP) and customer devices [12]. The ESI facilitates communication between these devices and the GSP. Lee *et al.* further defined the ESI as an application located at the boundary between the customer domain and the GSP domain, across which energy data are exchanged. They state that the ESI consumes energy services provided by the GSP, provides energy services to the GSP, and applies security measures to secure communication between the GSP and the customer. Lee *et al.* state the ESI provides a logically-defined communication interface in order to allow a variety of implementation architectures [13].

Widergren *et al.* succinctly defined the ESI as a set of concepts, noting it is a "bidirectional, service-oriented, logical interface that supports the secure communication of information between entities inside and outside of a customer boundary." This definition adds "service-oriented" to Hardin's definition of the ESI from 2011 [14]. Widergren *et al.* note the purpose of the ESI is to facilitate interactions between an "external body" and DER within "client facilities," for which they specify generation, storage, and loads [15]. In a 2018 white paper, the Grid Modernization Laboratory Consortium builds upon the ESI concept, noting the ESI compliments the layered decomposition approach to power systems control [16]. In this approach, reductionism is applied to abstract the complexity of system coordination into successive layers, each with its own objectives. The ESI enforces decomposition between management of DER clients and the external domain of grid operations management.

We concur with these concepts and regard the ESI as a set of rules that dictates the information exchange between a GSP, either a utility through *Scenario 1* or an aggregator through *Scenario 2*, and a utility customer that allows the customer to make their DER available to the GSP for dispatch. These exchanges facilitate energy interactions between the customer's DER and the GSP, thereby allowing the GSP to provide ERSs through dispatch of the customer's DER.

Defining the ESI as an open and logical communication interface ensures the ESI promotes a variety of possible implementation scenarios. Information exchange between these parties is bidirectional and service-oriented. A service-oriented architecture delineates the expectations of the service from the means by which the service is provided. It is not important that a GSP know *how* a DER responds to its request for service, but rather that its performance meets the expectations of the service. This approach leaves the execution of the service to the DER or a DER management system, and ensures separation of responsibilities between participants [15].

The ESI defines boundaries between the customer and the GSP, delineates the functions and responsibilities of each party, and establishes the point of demarcation for security and privacy. Information exchange between parties must be both secure and trustworthy. The ESI should obscure the customer's management of its DER from external parties, including the GSP. The ESI should reduce transaction complexity by limiting information exchange between the GSP and the customer's DER, such as by defining a subset of ERS that the GSP can deploy using the customer's DER.

A. Implementation

In order to initiate transactions between a GSP and a utility customer, the GSP provides the customer with a cloud-based assessor. The assessor is governed by the rules of the ESI, which, with permission, assesses the customer's suite of DER. Based on this assessment, the assessor determines the value of the customer's DER, which does not include private information such as the customer's DER profile or behaviour patterns. The GSP then provides the customer with a set of subscription options based on this assessment. The customer selects from these options, thereafter making their DER available for dispatch by the GSP. The GSP adds the customer's DER to its aggregate, with constraints imposed by the selected subscription service and the ESI privacy rules.

IEEE 2030.5 and CSIP were originally developed for inverter-based systems. For our approach, we apply the function sets of IEEE 2030.5 and the methods of CSIP to all DER, either directly or through a Universal Communication Module (UCM), an SMCU, or a GFEMS. The ESI uses IEEE 2030.5 to establish WAN communications between the GSP and each customer's DER, regardless of DER type, as shown in Figure 8. The ESI inherits the behaviors defined in CSIP for all DER to ensure interoperability. The IEEE 2030.5 messages are sent to the DER, either passed through directly as IEEE 2030.5 messages or translated to another protocol, such as SunSpec Modbus, SAE J3072, or CTA-2045, that is comprehensible to the DER.

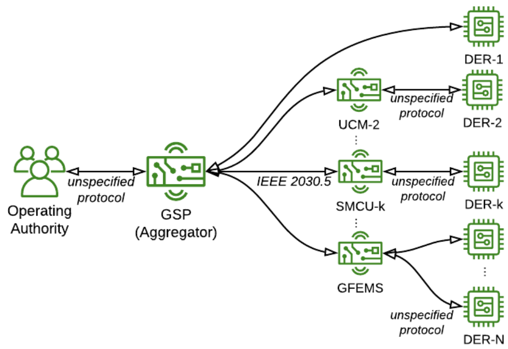

Fig. 8. EGoT Scenario communication architecture. UCM extend IEEE 2030.5 functionality to non-inverter DER.

The ESI does not specify a communication protocol between the Operating Authority and the GSP. The GSP needs to customize the articulation of its services using a protocol preferred by the Operating Authority's operations dispatch system. This may be an open protocol, such as OpenADR, or a proprietary one. Though an open and common protocol would be preferred, the overarching goal is to favor integration into existing operations dispatch systems.

Unlike traditional generating resources, many DERs have dynamic energy characteristics that are dependent on the habits of the residential customer. In aggregate, there will be a baseline resource available for dispatch and some percentage of resource that will only be available during a set time window. This presents the aggregator an opportunity to apply machine learning techniques to accurately estimate resource availability and optimally schedule resource participation in ERSs based on their individual and aggregate characteristics. Based on previously published research on water heater aggregation [17] and water heater peak-shifting and frequency response [18] we characterise individual DERs into three categories:

1) **Inverter**: These DERs are grid-tied inverter-based systems that are able to import/export real power while consuming/injecting reactive power, and include Battery-Inverter Systems (BIS) and PV/inverter systems. The CSIP standard establishes autonomous control settings, making them ideal for frequency response services. They can also participate in voltage support services without interfering with frequency response services.

2) **Static Energy**: These DERs are resources that have a fixed power and energy such as

dish washers and cloth washers/dryers. Using the IEEE 2030.5 *flow reservation* function set, these resources can be used as a reverse load following service. These resources may require more configuration by the customer to participate in ERSs. For example, the customer would need to establish the time window for the flow reservation request to be completed in. This window will vary depending on the customers personal schedule and the type of device. Dishwashers typically could have all night to complete their cycle, but the customer would not start a cloths washer at 9 PM just to let the clothes sit for 8 hours to mildew. By setting the time window, they customer can provide flexibility to their load, while still maintaining a level of comfort.

3) **Dynamic Energy**: These DERs are resources that have a fixed power and dynamic energy such as water heaters and pool pumps. The customer's use of these resources need not be coupled to concurrent electrical supply, either because they have inherent energy storage, or their use can be delayed and interrupted. Using IEEE 2030.5's *flow reservation* function set, these resources shed their loads and request the energy they would have used. This allows these resources to be dispatched as a frequency regulation service when increased load is required.

B. *Essential Reliability Services Mapping*

Each DER uses the IEEE 2030.5 function sets mapped in Table I. While overlapping control events are only defined within the CSIP standard for inverters, if they are adopted by all DERs it will enable reliable participation in all ERS. The Frequency Reserve service could be satisfied by allocating a percentage of each service for emergency use.

TABLE I
DYNAMIC ESSENTIAL RELIABILITY SERVICES MAPPING

ERS	**SEP Function Set**
Frequency Response	DER
Voltage Support	DER
Frequency Regulation	Flow Reservation
Load Following	Flow Reservation

C. *Frequency Regulation Scheduling*

Unlike PJM's RegA and RegD control signals that are broadcast to participating resources, IEEE 2030.5 servers create a resource that clients will poll to determine when they should participate. This process becomes more complicated as the aggregator cycles between resources to ensure it meets the required set points. This process can be achieved by superseding flow reservations controls and rescheduling. The aggregator should utilize the first-in last-out (FILO) accounting method to ensure resources that have received the most energy are rescheduled before resources that were just dispatched.

There are limitations to how fast the clients will be able to poll the server without consuming its bandwidth. The server traffic can be dramatically reduced if the client supports subscription/notification from the server. This way only the resources that need to be updated will recieve new schedules.

VI. CONCLUSION

Following the ESI design guidance proposed in this paper, it will be possible to establish a cyber-physical network to provide ERSs using aggregations of DERs. The ESI will ensure information exchange between GSPs and utility customers' DERs is secure and trustworthy, and that transactions are service-oriented. However, expertise in large-scale distributed network computing will be needed, which presents an opportunity for contributions from the computing and engineering communities to contribute to the development of a sustainable electric power system.

Business models must also be considered. For instance, an aggregator may participate directly with a utility or through an energy services market. A market-based business model will require an aggregator meet minimum bid-sizes, handle transaction costs, and acquire their own customers. This could lead to increase market complexity and slow adoption of DERs for ERSs. EnerNOC, Innovari, Ohmconnect, and Encycle are examples of the implementation of this business model that have shown success [19].

A utility-based business model would have aggregators provision ERSs directly to a utility. This could help with adoption of DERs for ERSs with the added benefit of integrating the aggregator into the utility's power flow studies for optimized dispatch. EnerNOC, Comverge, and EcoFactor operate under this business model.

In either scenario, participation of DERs must be validated. However, validation of participation could be significantly challenging. For instance, DERs providing frequency response services would need to provide high-resolution data to demonstrate adequate response to participation requests. A deterministic approach will not be feasible for many residential loads since they are not able to measure their own energy consumption. An aggregator may need to use a probabilistic model with an understanding of individual device behavior to estimate participation with an acceptable level of confidence.

A probabilistic model could be refined through spot validation and support from manufacturers, but it will still require considerable changes to business models and market regulations. Currently, load and renewable generation forecasts routinely use probabilistic modeling techniques to inform dispatch operations. Such techniques could also be applied to characterize the power and energy capacities of aggregated DER in order to reliably provide ERSs. Considering these challenges, development of commercial, large-scale ESI-based aggregation systems will depend on significant contributions from the computing community, and provide ample opportunity for computing to significantly impact the sustainability of electric power systems.

REFERENCES

[1] North American Electric Reliability Corporation (NERC), "Essential Reliability Services Task Force: A Concept Paper on Essential Reliability Services that Characterizes Bulk Power System Reliability," North American Electric Reliability Corporation (NERC), Tech. Rep., October 2014.

[2] J. H. Eto, J. Undrill, P. Mackin, and J. Ellis, "Frequency Control Requirements for Reliable Interconnection Frequency Response," Tech. Rep., February 2018.

[3] North American Electric Reliability Corporation (NERC), "Essential Reliability Services Task Force," North American Electric Reliability Corporation, Tech. Rep., November 2015.

[4] PJM, "PJM Manual 12: Balancing Operations," PJM, Tech. Rep., November 2017.

[5] IEEE, *IEEE Standard 2030.5-2018 (Revision of IEEE Std 2030.5-2013) Standard for Smart Energy Profile Application Protocol*. IEEE, December 2018.

[6] IEEE Common Smart Inverter Profile Working Group, "Common Smart Inverter Profile: IEEE 2030.5 Implementation Guide for Smart Inverters," Common Smart Inverter Profile Working Group, Tech. Rep., March 2018.

[7] SunSpec Alliance, *SunSpec UL1741 Supplement SA/Rule 21 Implementation Guide: SunSpec Alliance Application Note, Version 0.3*. SunSpec Alliance, May 2017.

[8] ——, *SunSpec Information Model Specification: SunSpec Alliance Interoperability Specification, Version 1.9*. SunSpec Alliance, April 2015.

[9] Bonneville Power Administration (BPA), "CTA-2045 Water Heater Demonstration Report including A Business Case for CTA-2045 Market Transformation," BPA, Technology Innovation Project 336, Tech. Rep., November 2019.

[10] *Concerning appliance efficiency standards*. Washington State Legislature HB 1444 - 2019-20, August 2018.

[11] Consumer Technology Association, "ANSI/CTA-2045-A: Modular Communications Interface for Energy Management," Consumer Technology Association, Tech. Rep., January 2018.

[12] Office of the National Coordinator for Smart Grid Interoperability Engineering Laboratory, "NIST framework and roadmap for smart grid interoperability standards, release 2.0," National Institute of Standards and Technology, Tech. Rep., February 2012.

[13] E. Lee, R. Gadh, and M. Gerla, "Energy service interface: Accessing to customer energy resources for smart grid interoperation," *IEEE Journal on Selected Areas in Communications*, vol. 31, no. 7, pp. 1195–1204, 2013.

[14] D. Hardin, "Customer Energy Services Interface White Paper," Grid-Interop Forum, Tech. Rep., 2011.

[15] S. Widergren, R. Melton, A. Khandekar, B. Nordman, and M. Knight, "The plug-and-play electricity era: Interoperability to integrate anything, anywhere, anytime," *IEEE Power and Energy Magazine*, vol. 17, no. 5, pp. 47–58, 2019.

[16] Grid Modernization Laboratory Consortium, "Interoperability strategic vision, a GMLC white paper," Pacific Northwest National Laboratory, Tech. Rep., March 2018.

[17] K. Marnell, C. Eustis, and R. B. Bass, "Resource study of large-scale electric water heater aggregation," *IEEE Open Access Journal of Power and Energy*, vol. 7, pp. 82–90, 2020.

[18] T. Clarke, T. Slay, C. Eustis, and R. B. Bass, "Aggregation of residential water heaters for peak shifting and frequency response services," *IEEE Open Access Journal of Power and Energy*, vol. 7, pp. 22–30, 2020.

[19] S. P. Burger and M. Luke, "Business models for distributed energy resources: A review and empirical analysis," *Energy Policy*, vol. 109, pp. 230 – 248, 2017.