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Characterization of Residential Distributed Energy Resource Potential to Provide Ancillary Services

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Characterization of Residential Distributed Energy Resource Potential to Provide Ancillary Services

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Abstract
This report reviews a set of electric grid ancillary services and analyzes the technical potential for residential devices to provide those services. A set of common residential devices are evaluated against six indicators of capability: flexibility, availability, fast response, reserves, reactive power, and power level. Based on these indicators of capability, three scores are developed to express the potential of a device to provide frequency response, reserves and reactive power services. These scores are additionally used to estimate how many of each device might be required, in aggregation, to provide a meaningful level of each of these three ancillary services to the grid. This report also provides a review of some existing programs and pilot efforts where residential devices are being used to provide ancillary services. Lastly, the report provides insights on a continued path to increased integration of residential devices for ancillary services provision.

Keywords
ancillary services; electric grid; frequency control; frequency response; reactive power; regulation; reserves; residential devices; voltage control

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1. Introduction

Historically, the electrical power system was designed for a one-way flow of energy. Large generation plants produced electrical power that was transported to industrial, commercial, and residential customers via high-voltage transmission lines and lower-voltage radial distribution lines. The generation plants were scheduled and dispatched for expected loads, while transmission operators were responsible for maintaining grid stability and reserve power for contingencies. The provision of reserves and moment-to-moment balance of generation and load, for grid stability, are together included in ancillary services.

There is no "one" defined set of ancillary services, but a basic set is generally provided in the context of the transmission grid. The Federal Energy Regulatory Commission (FERC) defines this set of services that a regional transmission operator (RTO) must provide [1]:

(1) Scheduling, System Control and Dispatch Service;
(2) Reactive Supply and Voltage Control from Generation Sources Service;
(3) Regulation and Frequency Response Service;
(4) Energy Imbalance Service;
(5) Operating Reserve - Spinning Reserve Service; and,
(6) Operating Reserve - Supplemental Reserve Service.

These six services are not uniformly relevant to the distribution system. Scheduling, System Control and Dispatch are provided by a coordinator and are related to interchange between transmission control areas. Some degree of control and dispatch may be required on the distribution grid for residential devices. However, residential devices do not act as grid controllers. Reactive Supply and Voltage Control matters for the distribution grid and is something that residential devices (particularly inverters) may provide; this topic will be discussed in depth in this report. Regulation and Frequency Response are key ancillary services that residential devices can provide, and are further discussed in this report. The Energy Imbalance Service is an hourly makeup service for balancing the accounting of energy exchange between areas. This service is not relevant to residential devices for providing ancillary services. Finally, Operating Reserves are within scope for residential devices providing ancillary services and are demonstrated in today's demand response programs.

What is changing today in the electrical grid that requires rethinking the role of customer devices for grid operation? The energy generation portfolio is moving away from large fossil fuel generators toward smaller distributed renewable resources. These renewable resources are intermittent, driven not by load on the grid, but instead by wind and sun. Additionally, the greater number of smaller generators presents scalability and communication challenges. However, there are forces working to mitigate the challenges presented by intermittent and distributed generation. Intelligent customer devices, including batteries and electric vehicles (EVs), provide flexibility for shifting load peaks and providing stability. Smart meters have been installed on many homes, permitting effective tracking of customer energy use at sub-hourly time intervals. And regulations are steadily evolving to enable participation of smaller devices to provide grid services.

There are a few important implications of these trends on grid operations. First, as generators become smaller and more distributed, frequency control services must change to accommodate these resources. Second, with intermittent generators on the distribution system, voltage control becomes more challenging and distribution resources must be marshalled for effective control. The premise of this report is that residential distributed energy resources (DER) have a role to play in ancillary service provision in the changing grid. In general, customer facilities can provide these services to stabilize not only the distribution system, but also the bulk grid. They can do this through the provision and consumption of real and reactive power in response to different stimuli and with different response times. For the purposes of this paper, residential DER is defined as any controllable electricity consuming or producing device in the home, including EVs.

There are many published reports presenting simulation results for various devices providing frequency regulation or other ancillary services, e.g., [2]–[5]. To that end, a 2008 report [6] stated that there are no insurmountable barriers to loads providing any of the main ancillary services. A 2011 report by the Department of Energy [7] provides an overview of some of the challenges to residential device provision of ancillary services. It specifically identifies the need for research to characterize the ability of individual devices to meet requirements of specific grid services. A 2016 report [8] provides an analysis of the capability of some residential devices to provide ancillary services according to criteria that can be mapped to the ones used in this report. However, they examine a smaller list of devices and do not include reactive power provision. The present study analyzes ancillary services to identify those services that are most suitable for residential devices, and the potential of these devices to provide each of these services. In addition, this work breaks down the services into fundamental parameters that are used to determine scores that reflect the capability of these devices to participate in each service.

2. Review of Ancillary Services

2.1. Overview

As noted in the introduction, FERC defines six ancillary service classes [1] that are important for the health of the grid and applicable at the transmission system level. Of these, the following categories are relevant to customer DER:

(1) Regulation and Frequency Response;
(2) Operating Reserves; and,
(3) Reactive Supply and Voltage Control.

Organization and implementation of these services, including rules for which resources may participate and how, are not consistent across transmission control areas. For example, the PJM Interconnection (PJM), managing the transmission grid and wholesale markets in the Pennsylvania, New Jersey, Maryland, and surrounding areas, breaks frequency regulation into two parts: Reg A for slower traditional generator regulation and Reg D for faster response resources such as electrical storage and demand response. Reserves are broken into four separate products: primary, synchronized, quick start, and supplemental. In addition, PJM operates both real-time five-minute and day-ahead energy markets[1]. Loads of 100 kW and above can participate in any of these services and markets. PJM requires transmission level generators to supply reactive power. The California Independent System Operator (CAISO) also requires generators to provide reactive power and operates ancillary service markets for regulation and reserves. These regulation and reserves are broken into regulation up, regulation down[2], spinning, and non-spinning reserves. CAISO also operates real-time and day-ahead markets. However, Duke (a vertically integrated system operator in the Carolinas and Florida) requires the transmission provider to offer a set of ancillary services aligned with the FERC set of six services, plus additional specific services, and the transmission customers are required to purchase these services with rates set in a published Open Access Transmission Tariff [9]. There are no wholesale markets as for PJM and CAISO.

As the above examples show, how ancillary services are implemented is not consistent across the U.S. The following section will introduce the ancillary services identified above, leading to an analysis of the capabilities of devices to provide the fundamental services, without focusing on how these might be implemented with today's market products. The section begins with a discussion of how these services fit together to manage grid stability.

2.2. The Grand Scheme of Grid Balancing

The electric power system today is operated within a regulatory framework and according to specific technical performance boundaries such that electric power of sufficient power quality is available in all locations for a reasonable price. Transmission system operators work to arrange generation assets to meet customer loads. Generators are scheduled via energy markets in regions with independent system operators, and dispatched to provide power as needed. Loads may participate in some markets as aggregated demand response resources. Scheduling and dispatching of energy resources occurs continuously. Thus, energy markets provide the foundation for a balanced power system. Voltage and frequency control are layered on top to maintain a reliable grid that delivers sufficient power quality.

Voltage control occurs alongside this marshaling of energy generation. Transmission and distribution operators monitor and manage real and reactive voltages at different locations, both for stability as well as to deliver power at expected voltages. Voltage control is not traditionally a fast time response activity. Although the voltage on the grid can become unstable quickly, fast action by automated switches or solid-state equipment can mitigate this problem.

The frequency control service, making use of 4-second regulation dispatch (and even faster primary automatic response), is how second-to-second grid balancing is managed. Frequency control also includes dispatch of operating reserves to backup lost generation resources and manage other contingencies. Transmission operators monitor and manage frequency to keep it within a tight band around 60 Hz (in the U.S.).

[1] Energy markets serve to identify (and later dispatch) the lowest-priced generation resources to supply day-to-day energy needs based on expected (day-ahead) and observed (real-time) loads.

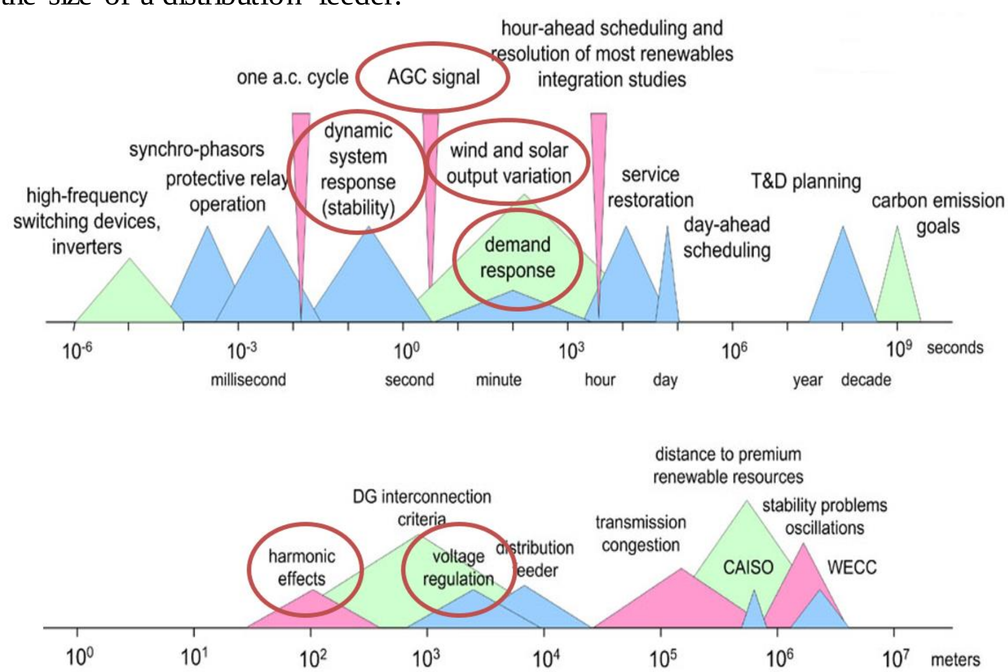
[2] Regulation up and down indicate increase or decrease of power generation.

In summary, the next day procurement and scheduling of generators for energy to meet load forecasts sets the grid up for a balanced operation. When the system is balanced, power flows from generators to loads and the voltage throughout the system is monitored and managed. The frequency control service is used to support these activities and fine-tune the second-to-second balance of the supply and demand and ensures reserves to backup unforeseen contingencies.

2.3. Context of Time Scales and Demand Response

Ancillary services' time scales generally fall in the range of seconds to hours, overlapping those of energy markets which extend from minutes to days and automated protective devices for grid stability that operate at the sub-second time scales. Demand response is a related concept that falls in the same range of seconds to hours. This section discusses time scales and the relationship of ancillary services to demand response.

The time and length scales of ancillary services can be seen in Fig. 1, where the issues relevant to this report are circled in red. In the top sub-figure, which presents time scales, frequency response covers all red circles including demand response. Primary frequency control is indicated by the sub-second "dynamic system response (stability)". The automatic generation control "AGC signal" is important to secondary frequency control, discussed below in more detail. Voltage regulation, in the bottom sub-figure, is more defined by length scales than time scales, due to changes in voltage along electric wires. The length scales for voltage regulation are on the order of kilometers, and thus roughly the size of a distribution feeder.



Note: "T&D" = transmission and distribution, "DG" = distributed generation, "WECC" = Western Electricity Coordinating Council

Figure 1. Time and length scales relevant to ancillary services (highlighted with red circles), adapted from [10].

The relationship of demand response (DR), seen in Fig. 1, to ancillary services deserves some discussion. DR is generally *not* defined in terms of the services that it can provide, but rather as a general term indicating that loads are providing some response to grid needs. It has traditionally been associated with event-based load shifting for peak reduction [11]. FERC defines DR [11] as:

> *Changes in electric usage by demand-side resources from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized.*

Residential device participation has generally been limited to air conditioning and water heater cycling implemented by utilities or aggregators through DR programs [11], [12]. However, DR has been used to meet energy needs in different grid service categories including forward and real-time markets as well as frequency response services including regulation and reserves [13]. A number of researchers have performed simulations and implemented tests of load resources used for faster frequency response [14], [15] with response times of one minute or less. Aggregators then bid the load reductions into wholesale markets. The scope of DR has stretched to include price-based response, increased or decreased consumption, and response rates from real-time to slower reserves. Thus, DR overlaps with ancillary services. However, ancillary services include voltage control and primary frequency response, two services that are not typically discussed in the DR context.

2.4. Defining the Services

The purpose of this section is to examine ancillary services at a deeper level, since these services are fundamental to maintaining stability of the grid and customer power quality. After this review, the potential of residential devices to provide these services is also examined. A simple summary is that ancillary services are broken into frequency response (with different stages of response according to time elapsed since a frequency deviation occurred), reserves, and voltage control. Many residential devices can quickly reduce or modulate energy consumption to participate in these ancillary services. In addition to reducing or modulating energy consumption, residential inverters can also provide reactive power.

2.4.1. Frequency Response

In the U.S., grid frequency is maintained at 60 Hz, and any deviation above or below indicates an imbalance of supply and demand. Stability of the system depends on actively managing the balance, supplying additional power or reducing power on a second-by-second basis. Frequency response (also commonly referred to as frequency control) is the collection of generator responses to observed frequency deviations, at different response time scales, that together work to restore frequency back to 60 Hz. Frequency response to a deviation from 60 Hz is typically broken into three phases in time: primary, secondary, and tertiary. These phases are shown in Fig. 2. Each of these phases is defined as follows (adapted from [16], [17]).

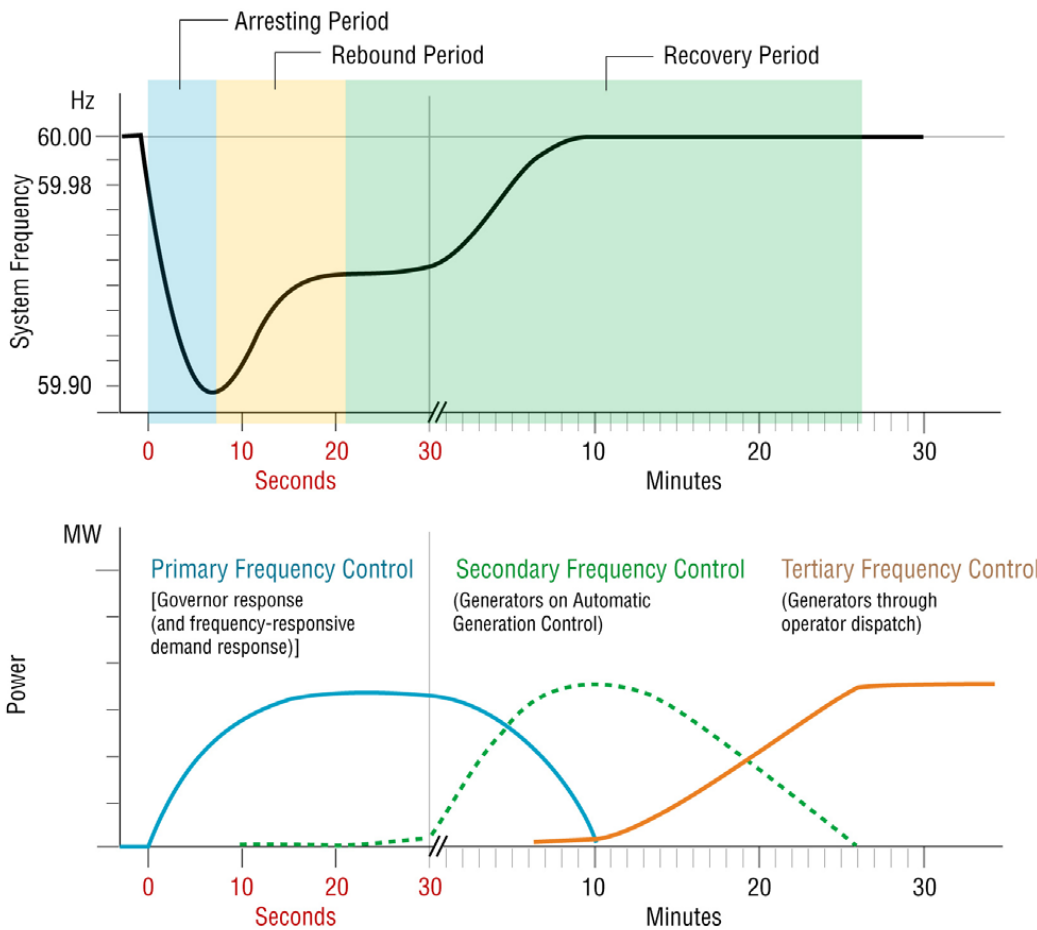


Figure 2. The sequential actions of primary, secondary and tertiary frequency controls following sudden loss of generation and their impacts on system frequency, adopted from [16].

Primary frequency control is the first stage of frequency control and is the inherent response of resources and loads to arrest local changes in frequency. Primary frequency control is automatic and begins within seconds after the frequency changes. Inertia of rotating machinery (generators and motor loads) slows the drop in frequency. Synchronous generator governor response (also known as speed regulation) and other devices providing automatic response serve to arrest the frequency drop and enable a rebound of the frequency.

Secondary frequency control is the action taken by a balancing authority in the first 1 min to 10 min following a disturbance to correct the resource-to-load imbalance that created the original frequency deviation. This action restores the system to the scheduled frequency and restores primary frequency response capability. Secondary frequency control uses the centralized automatic generation control system to deploy regulation (see description of regulation below) and may also include dispatch of synchronized reserves if required.

Tertiary frequency control is the action taken by a balancing authority to replace the secondary control resources by reconfiguring reserves. Reserves are dispatched in the 10 min to 60 min following a disturbance and coordinated to minimize inter-region power flows. Tertiary control action includes use of economic dispatch (that is, markets).

2.4.1.1. Frequency Regulation

The FERC ancillary service name "Regulation and Frequency Response" calls out regulation separately from frequency response, and yet regulation is an important component of secondary frequency control. Frequency regulation corrects for short-term changes in electricity use and loss of generation that might affect the stability of the power system. The main goal of regulation is to keep the system's area control error (ACE) within acceptable bounds. ACE accounts for differences between scheduled and actual electrical generation based on power flows measured at control area inter-ties. It also accounts for variations in the system's frequency. A calculation is made based on ACE, and this result is used to compute required adjustments to generator outputs. The calculation and a resulting dispatch signal to each generator is made on a 4 s cycle. This system and the signal are known as automatic generator control. Participating in regulation generally is limited to large generators due to the significant cost for telemetry, although smaller devices may participate through an aggregator presenting those devices as a virtual generator.

2.4.1.2. Reserves

The transmission operator must make allowances for contingencies, including generators or power lines tripping offline, transformers and voltage regulators failing, sudden unforeseen wind resource changes, etc. Each of these events requires having a pool of reserve power generation ready to step in. As noted earlier, different transmission operators define and use these reserves in different ways to meet system needs. Generally, they are associated with frequency control. As seen in the FERC list of ancillary services, reserves are customarily broken into spinning reserves (or synchronized reserves), indicating online and unloaded generators, and non-spinning or supplemental reserves. As an example, PJM has primary reserves that can respond within 10 min and subdivides this category into spinning reserves and "quick-start" non-spinning reserves. They also have supplemental reserves that can be called to respond in 10 min to 30 min.

2.4.1.3. Markets

It is important to note the role of markets in relation to ancillary services. Independent system operators (ISOs), which include PJM and CAISO as well as seven others in North America, operate energy markets and may operate forward capacity markets (reserving generation resources for years ahead) and ancillary services markets. Energy markets (e.g., day-ahead and real-time) serve to balance supply and demand on a day-ahead forecasting basis and a real-time basis. However, energy markets cannot meet the second-to-second balancing requirements of the grid, nor are they expected to provide firm reserves. Therefore, regulation and reserves are necessary for management of grid frequency in addition to energy markets. Regulation and reserves may be procured in a market where the resulting contract is a call option; that is, committed resources are waiting to be called in the event of a contingency. In the case of an energy market, committed resources expect to be dispatched based on a published schedule. In the end, different markets, with different purposes, work together for the proper operation of the grid.

2.4.2. Voltage control and reactive supply

2.4.2.1. Reactive power and why it matters

Many alternating current (AC) inductive loads such as motors and transformers rely on magnetic and electric fields to accomplish their design function. Motors use electrical energy to create a magnetic field in the air-gap between the stator and the rotor to then turn the rotor and perform work. The magnetic field absorbs and returns energy on each power cycle, and this power does no “real” work, although it is necessary. The portion of the total power contained in the oscillating magnetic or electric fields of the transmission and distribution lines and required by some devices is called reactive power (Q). The unit for Q is Volt-Amp reactive (VAR) to distinguish it from real power (P) in watts (W), which does perform real work. If a load absorbs both P and Q, then a generator must supply the required power. The power supplied to the loads that meets this requirement is known as apparent power (S), with the relationship between real, reactive, and apparent power as shown in Fig. 3. Apparent power is expressed in Volt-Amps (VA).

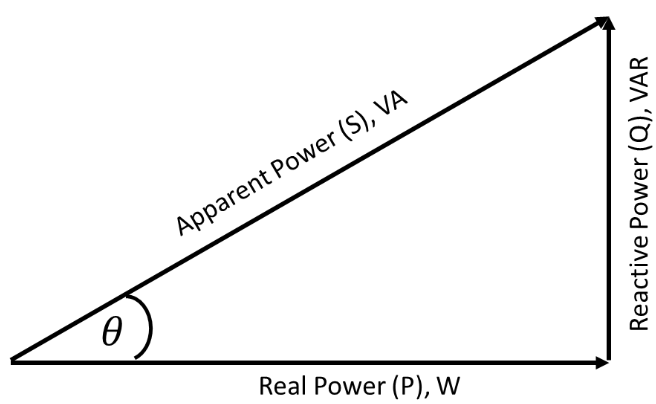


Figure 3. Power triangle showing the relationship between real, reactive and apparent power component of an AC supply.

Reactive power can be understood as a result of the current waveform leading or lagging the voltage waveform. The current lags the voltage in inductive loads and leads in capacitive loads. If the current lags or leads the voltage by 90°, then the power is said to be purely reactive. The phase angle (θ) between the current and voltage waveforms ties directly to power factor. Power factor is defined as the ratio of P divided by S, indicating what fraction of apparent power is real. Since P can never exceed S, the power factor cannot be greater than one. When power factor equals unity, the reactive power Q equals zero.

Practically, operating the grid at a low power factor (with significant presence of Q) results in increased current flows for no additional real work. However, Q cannot be eliminated since induction motors, transformers, and some lighting ballasts (for example) are inductive and operate at a reduced power factor. Power lines themselves are inductive under loading and consume Q in a non-linear relationship with load. Since generation sources and loads vary with time, the presence of Q at different locations on the grid is dynamic. However, the ability of power lines to efficiently deliver power is negatively impacted by the presence of Q; therefore, grid operators seek to manage it.

2.4.2.2. Voltage control and reactive supply services

Voltage control is the act of monitoring and managing the real and reactive voltage levels at generators, substations, and equipment (e.g., voltage transformers) along the power lines to provide real power to customers at regulated voltage levels [18]. Transmission and distribution operators have a number of tools at their disposal to use for voltage control [19], including dispatch of generation (for real and reactive power), adjustment of voltage transformers, and switching of reactive power compensators, some of which may occur automatically.

A generator is typically able to provide some reactive power without impacting ability to supply real power. Photovoltaic power (PV) system inverters (or any inverter) may also be designed to provide reactive power independent of real power generation. Large generators are required to provide reactive power as needed. Utilities typically require larger PV installations to provide some reactive power [20]. Additionally, distribution utilities as well as industrial and commercial customers typically install capacitor banks near large inductive loads to improve power quality locally and remove the need to transmit reactive power over the transmission lines. On this point, it is important to note that reactive power is ideally supplied where it is needed rather than transmitting across miles of transmission lines, where it may then increase heating of the lines and reduce transmission capability. It is also important to note that real voltage levels can be adjusted up and down through the injection or absorption of reactive power. The increasing presence of DER on the distribution system is challenging traditional voltage control strategies, but distributed generators also offer the potential to provide reactive power for voltage control management.

2.5. Impact of Responsive Customer DER on Distribution System Ancillary Services

While frequency control is a transmission level service requiring transmission-level coordination and control, it nonetheless relies on generators (and DR) to provide frequency response. As more and more of the generation fleet moves to the distribution grid, and as more loads become responsive to grid conditions, the distribution system generators and loads will become increasingly important to bulk grid frequency control. The questions surrounding this transformation include, (1) to what degree customer DER can provide frequency response, (2) how customer DER will be integrated into (or provide services to) the grid and (3) how fast this transformation will proceed. The first question is answered, at least in part, in the following sections.

Voltage control remains a shared responsibility between transmission and distribution grid operators, but the growth of customer DER is changing the distribution grid. Whereas previously the distribution utility may only have needed to supply capacitor banks to provide reasonable reactive power compensation, and voltage transformers for real voltage correction, now PV generation along the distribution feeders as well as batteries and EVs are changing the dynamics.

There are several changes that PV, batteries, and EVs bring to the distribution system. PV systems generate power that can raise and lower the voltage on the distribution grid. These voltage fluctuations can be concentrated to one part of the feeder if the PV generation is concentrated in that location, and the outputs of PV systems are intermittent and highly influenced by cloud cover. Likewise, as PV generation can cause a voltage rise, a concentration of EVs at one location can cause a voltage dip. Nonetheless, given the capability of inverters to provide reactive power, an inverter might provide reactive power to dynamically compensate for fluctuations in its own real power production (or consumption) and thus help maintain local voltages.

Besides the presence of inverters, the growth of smart loads may be useful for voltage control in addition to providing frequency response. Specifically, if loads near a PV generator can be incentivized to increase consumption when the sun is shining and decrease when the clouds pass, this behavior can also help stabilize local voltage fluctuations. The challenge here is developing a mechanism for incentivizing loads to respond to a very localized voltage measurement.

The ability of smart loads on the distribution system to both help with managing PV-induced voltage swings and bulk grid frequency response raises the issue of coordination between transmission and distribution grid operators. One concern is that the same load could bid its consumption flexibility to a wholesale aggregator for frequency response services while simultaneously selling that flexibility to a distribution utility for voltage control service, thus getting double payment. When considering potential future retail markets, this concern has led to the proposal of a local distribution system operator as market maker that coordinates wholesale and retail markets to mitigate such gaming concerns. A completely different concern is the potential for a load to provide services for one or the other purpose (frequency response vs. distribution voltage management) when the two are at cross-purposes. For example, one might imagine that the bulk grid is stressed and is calling for demand response even while the sun is shining and voltage levels are near violation limits at a PV hot spot. Should a load near the hot spot reduce consumption? Probably not.

While this section has provided an overview of ancillary services, the following section looks at the technical potential for various residential devices to provide these services.

3. Analysis of Capability of Residential Devices for Provision of Ancillary Services

3.1. Residential Device Classification

There are many devices in a home and potential ways to select and classify those devices for the purposes of this analysis. Devices range in size, variety of components, and complexity of control. There are many occupant-controlled devices (e.g., oven, toaster, stove, lights) that are typically labeled "uncontrolled." Some devices can generate power like PV systems, while some can consume or generate electrical power like batteries and

EVs, all of which in a typical grid-tied application have inverters for AC/DC power conversion. There are also smaller loads such as mobile phone chargers and persistent loads such as security systems that are connected to the grid. Can these various devices be grouped such that the resulting classes can be more easily analyzed for their ability to provide ancillary services?

One lens used to analyze devices is that of component technologies, whether there is a compressor (with its power characteristic), electric resistance heater, or inverter. Another view looks from a controls perspective, whether a device may be used to shift or shed load, store energy, generate power, or is uncontrollable [21]. The analysis presented in [22] looks at device classification from the perspective of capability to store energy in thermal mass (ice, the building structure, hot water), in processes (shiftable and sheddable loads, and in production line), fuel (generators) and batteries, and examines how commercial and industrial systems could provide different ancillary services, including frequency regulation, spinning reserve, and reactive power.

While the above lenses are useful for understanding device capabilities, the analysis performed in this paper evaluates common residential devices according to a set of key capability indicators defined below.

3.2. Key Indicators of Capability

Device analysis requires understanding key indicators of ability to provide different ancillary services. For example, frequency response provision requires fast time response capability, as well as some measure of power and energy capacity. Voltage control provision requires the capability of devices to supply reactive power, or alternatively to reduce or increase load based on local voltage levels. Additionally, one must consider whether a device is available at any given time to provide some service.

Each device has been analyzed according to the following six factors (with abbreviated names used in Table 1 provided in parentheses):

1. Flexibility (Flex)—A device can be used multiple times consecutively, powering on and off, with operation at different power levels. Flexibility also captures the ability to shift a device's cycle to later times. The "Flexibility" of different devices is analyzed and assigned one of three levels (High, Med, Low) in Table 1 based on analysis presented below the table;
2. Fast response (Fast Resp)—ability to respond in seconds up to 5 min. This response encompasses primary and secondary frequency response[3]. "Fast Response" of difference devices is analyzed and assigned one of three levels (High, Med, Low) in Table 1 based on analysis presented below the table;
3. Reserves (Reserves)— indicates ability to provide energy in the 5 min to 1 h time range. The value used here is the amount of available storage capacity (e.g., thermal storage capacity of water heater). This reserve can be applied to serve tertiary frequency response and other ramping and reserve market products;

[3] Initial analysis showed that any device capable of "fast response" (under 5 min) is equally able to provide both primary (automatic) and secondary (dispatched) capability.

4. Reactive power (Q)—amount of reactive power that may be produced by a typical device.
5. Availability (Avail)—defined as the Equivalent Availability Factor (EAF) [23], which is the fraction of time that a resource is fully available to provide some grid service. Availability has been broken into three categories in the analysis below due to the inherent differences in the ability of devices to provide one service versus another. These are "FR Avail" for fast response, "Res Avail" for reserves, and "Q Avail" for reactive power;
6. Power level (P)—typical real power level (amount consumed or produced).

These criteria align closely with the factors presented in a PJM analysis of generator reliability attributes [24] where the authors examine how integration of renewables will impact grid stability, with key results summarized in Fig. 4. The PJM report shows the impact of a generation portfolio that is increasingly composed of variable generation resources where flexibility is seen to increase while fuel assurance is seen to decrease significantly. This loss of fuel-on-hand is in fact one of the strong drivers for considering and incentivizing customer load and storage to participate in the operation of the grid.

The "Availability" factor above maps to the "Fuel Assurance Capability" in Fig. 4, while the "Fast Response" factor maps to the "Frequency Response Capability," "Reserves" maps to the "Ramping Capability," and "Reactive power" to "Reactive Capability." The "Power Level" described above is an additional factor that acknowledges that most residential devices have common power consumption levels, corresponding to their ability to provide grid services, which factors into aggregation analysis described later.

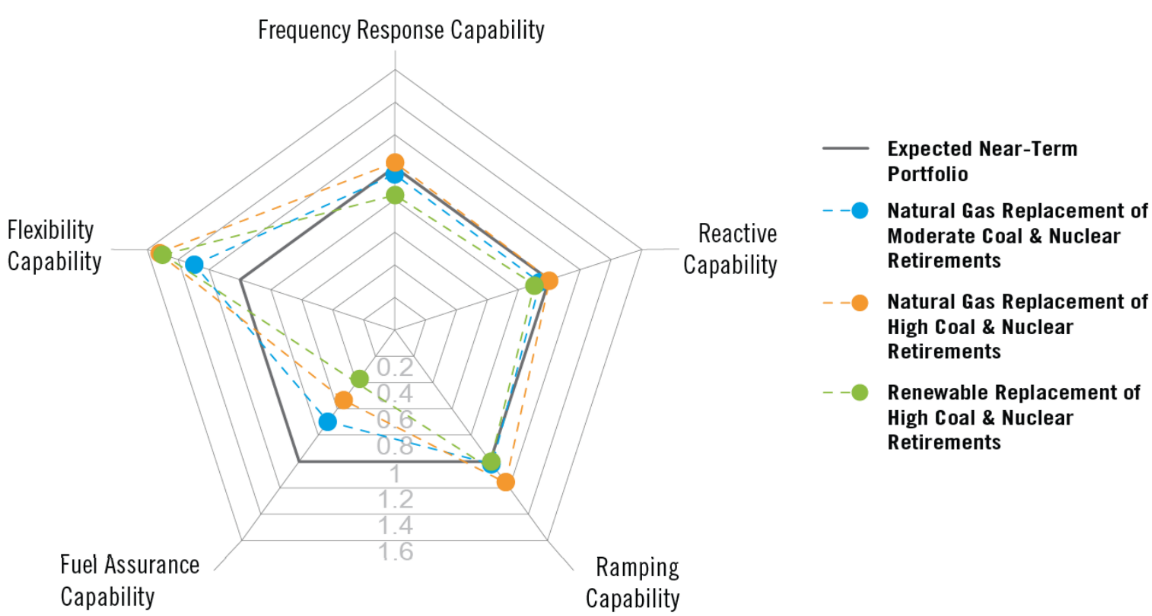


Figure 4. PJM Analysis of impact of shifting generation portfolio, adopted from [24].

The context of the PJM analysis in Fig. 4 provides helpful input on key indicators, but also shows that residential devices are being asked to provide services that have heretofore been provided by generators at the transmission level.

3.3. Residential Device Rating Against Key Capability Indicators

Eleven residential devices have been evaluated against the above six factors (P, Res, Q, Flex, Fast Resp, and Avail), and the results are shown in Table 1, along with three scores discussed below. For the purposes of calculating these scores, [High, Med, Low] are assigned the values of [1.0, 0.6, 0.2]. The rationale for assigning values to each device in each column of Table 1 is presented in 3.3.1 to 3.3.11.

Table 1. Analysis of Residential Devices Against Six Factors and Three Scores

Device	P (kW)	Res (kWh)	Q (kVAR)	Flex	Fast Resp	FR Avail	Res Avail	Q Avail	*FR Score*	*Res Score*	*Q Score*
Air conditioning (summer only) Heat pump (summer & winter)	2.4	2.4	0	High	Med	0.20	0.20	0	***0.29***	***0.48***	***0***
Electric resistance heat (winter only)	10	10	0	High	High	0.26	0.26	0	***2.6***	***2.6***	***0***
Electric water heater	4.5	2.5	0	High	High	0.12	0.12	0	***0.54***	***0.3***	***0***
Refrigerator	0.23	0.14	0	High	Med	0.6	0.6	0	***0.083***	***0.084***	***0***
Electric clothes dryer	2.8	2.8	0	High	High	0.03	0.03	0	***0.084***	***0.084***	***0***
Clothes washer	0.26	0.26	0	Low	Low	0.04	0.04	0	***0.0004***	***0.002***	***0***
Dishwasher	0.33	0.33	0	Med	Low	0.03	0.03	0	***0.0012***	***0.006***	***0***
Pool pump	1.0	8	0	Med	High	0.33	0.33	0	***0.20***	***1.6***	***0***
PV inverter	6	0*	2.6	Med	Med	0.31	0.31	1	***0.67***	***0***	***2.6***
Battery	5	5	2.2	High	High	1	1	1	***5***	***5***	***2.2***
Electric vehicle (EV)	6.2	28	2.7	High	High	0.97	0.97	0.97	***6.0***	***27***	***2.6***

* A PV system will not be able to provide reserve power unless it continuously operates below full power.

Many assumptions were made that lead to the ratings in Table 1. These assumptions and reasons for their ratings are provided below. Three scores are provided in Table 1 that serve as indicators for comparing the relative capability of a given device to provide fast frequency response (FR), reserves (Res), or reactive power (Q).

The FR score is given by

$$FR\ Score = Flex * FR\ Avail * Fast\ Resp * P\,. \qquad (1)$$

The FR Score represents the capability of a device to provide fast frequency response, with dependency on the flexibility of a load (Flex), availability for frequency response (FR Avail), fast response (Fast Resp) capability, and real power level (P). Considering a typical air conditioning system as an example (from Table 1), the air conditioner draws 2.4 kW (P = 2.4), has a high flexibility (Flex = High), medium fast response capability (Fast Resp = Med), and 20 % availability (FR Avail = 0.20), resulting in FR Score = 0.29 kW. This score represents the amount of power (averaged over time) that a single typical air conditioning unit can provide to a larger aggregation of these devices, given practical flexibility, availability, response capabilities, and typical power level of the resource. Please see discussion below for the determination of the values in Table 1.

The Res Score is computed by

$$Res\ Score = Flex * Res\ Avail * Reserves\,. \qquad (2)$$

The Res Score represents the capability of a device to provide operating reserves and depends on the flexibility of a load or generator (Flex), its reserves availability (Res Avail), and the reserves storage capacity (Reserves) that can be shifted in time. Taking the electric water heater as an example (from Table 1), the typical water heater has a Reserves storage capacity of 2.5 kWh, high flexibility (Flex = High), and 12 % availability (Res Avail = 0.12), resulting in Res Score = 0.3 kWh. This represents the amount of storage capacity (averaged over time) that a single electric water heater can provide to a larger aggregation of these devices, given practical flexibility, availability, and typical reserves storage capacity of the resource.

Lastly, the Q score is calculated by

$$Q\ Score = Q\ Avail * Q\ . \qquad (3)$$

The Q Score represents the capability of a device to provide reactive power and depends on the reactive power availability and the amount of reactive power that a given device can produce.

3.3.1. Air conditioning and heat pumps

- Power Level: The average residential air conditioning (AC) energy requirement for a 2 ton (24 000 Btu/h) unit is 2000 kWh per year [25] at an estimated power level of 2.4 kW and run time of 800 h/y[4]. This estimated value can be much less or more depending on climate, home size, unit efficiency, insulation levels, etc.
- Reserves: An estimate of one hour of storage in the thermal mass of the house equates to 2.4 kWh of stored energy for the 2.4 kW AC running for one hour. This value would be higher or lower depending on the insulation levels of a home as well as other factors. This storage capacity allows an air conditioning system to be modulated off and on to distribute the needed run time over more hours. Note: a heat pump system can reverse heat flow and provide heating in the winter, extending availability into the winter, but otherwise has approximately the same properties as an air conditioning system.
- Flexibility: An AC system can turn off and on (depending on need for cooling) multiple times and may be able to run at multiple fan and compressor speeds. It thus provides a needed increase or decrease in power usage. However, while fans can be turned off and on frequently, a compressor can be turned off but not immediately turned back on. This lockout is typically 5 min to 15 min.
- Fast Response: Compressors are fast to shut off[5], slow to come back on (due to compressor lockout). Therefore, when the AC is running, it can be shut off to provide primary frequency response, and regulation up service. Aggregation may mitigate the lockout issue and allow provision of regulation down service.

[4] While [25] provides average AC yearly power consumption, it does not provide size and efficiency which are required to determine typical power level and availability. These have been roughly estimated based on a variety of sources. The analysis here assumes an average energy efficiency ratio (EER) of 10, considering housing stock age, and sizes from multi-family apartments to single-family homes.

[5] Fast shut-off would require direct control, versus a typical DR command to adjust a setpoint which may not result in immediate compressor power off.

- FR Availability: The average AC system in the US runs 800 h per year (as noted above), corresponding to the cooling season and generally in the afternoons and evenings of summer days. This time equates to roughly 20 % of the hours in a six-month cooling season.
- Res Availability: Reserves availability might be viewed through two lenses. The first lens is that of the typical demand response peak capacity reduction use case where reserves are called to meet summer AC-induced load peaks. In this case, reserves availability would be 100 % since AC units can be shed to reduce AC load. A second lens is the more generic situation of an aggregator providing reserves for any reserves use case, whether summer peaking, wind ramps, loss of generator, or other. In this case, a value of 20 % is appropriate (same as the FR Availability). The value in Table 1 was chosen to reflect the generic case.
- Q Availability: Common alternating-current-driven air conditioner (and heat pump) compressors and fan motors are naturally inductive loads, and there is no active Q production capability. Thus, the Table 1 value is set to zero. However, variable speed drive direct current (VSD DC) compressors operate with a power inverter to modulate the DC compressor speed. These devices already dominate the residential air conditioning markets in some countries and may someday also have a significant presence in the U.S. This kind of inverter-driven air conditioning system would be able to provide reactive power.
- Reactive Power: None (for alternating-current-driven units).

3.3.2. Electric resistance heat

- Power Level: Baseboard heating is typically sized at approximately 110 W/m^2 (10 W/ft^2), which equates to 10 kW load for a typical 93 m^2 (1000 ft^2) home [26].
- Reserves: An estimate of one hour of storage in the thermal mass of the house equates to 10 kWh.
- Flexibility: A pure resistive space heating system (baseboard heaters and space heaters) can turn off and on (depending on need for heating) multiple times and may be able to run at multiple levels, and thus provide a needed increase or decrease in power usage.
- Fast Response: For pure resistive baseboard heating there is no limit on how often it can be switched on/off, enabling effective frequency response during heating season.
- FR Availability: A typical home heated by space heaters consumes 11 300 kWh of electrical energy per year [25], which for a 10 kW system would equate to 1130 h of operation, or an availability of 26 % of hours in a six-month heating season. Availability might be increased with partial load heating.
- Res Availability: Similar to the discussion above for AC reserves, the electric heater will have high availability to provide reserves to reduce winter early morning heating peaks. However, the value used in Table 1 corresponds to availability to meet any call for reserves, and has been set equal to FR Availability.
- Q Availability: Purely resistive loads have no availability for Q production.
- Reactive Power: Electric heaters are purely resistive and produce no reactive power.

3.3.3. Electric resistance water heater

- Power Level: Typical power requirement of electric resistance water heater is 4.5 kW [27] .
- Reserves: The energy storage capacity of a 190 L (50 gal) water heater might be equated with the energy required to raise the water temperature from a minimum 49 °C (120 °F) up to a maximum 60 °C (140 °F), which is 2.5 kWh. This range could theoretically be extended significantly for a water heater designed with a temperature mixing valve to prevent scalding temperatures at the faucet.
- Flexibility: A pure resistive heater element can turn off and on (depending on need for heating) multiple times to provide a needed increase or decrease in power usage.
- Fast Response: For pure resistive water heating, there is effectively no limit on how often it can be switched on/off, enabling fast frequency response.
- FR Availability: Water heating is required daily, more in winter than summer. Actual hours of heating depend on occupant requirements. Average yearly consumption is 4700 kWh [25], which for an average 4.5 kW electric water heater equates to 1040 hours of heating, or 12 % of hours in a year. The heating might be modulated off and on to distribute the needed run-time over more hours.
- Res Availability: Water heating could be delayed providing reserve capacity. However, water heating is likely to be scheduled when electricity prices are low, which equates to times when reserves would not be called. Therefore, availability will typically be low.
- Reactive Power and Q Availability: Resistive loads have no capability for Q production.

3.3.4. Refrigerator

- Power Level: Typical refrigeration load is 225 W [27].
- Reserves: Residential refrigeration has an average yearly consumption of 1260 W [25] , and thus an average load of 140 W, with the compressor running 62 % of the time. If one estimates that a typical refrigerator could delay cooling for one hour (with a sensor to ensure temperature limits are maintained), then this operation equates to 140 Wh of thermal storage. Actual value will depend on amount of food in the refrigerator, door openings, etc.
- Flexibility: Compressor may be shut off and cooling delayed. Defrost cycle can be moved to any time of day or night.
- Fast Response: Similar to other compressor categories, the compressor may be shut off or modulated for regulation service (with limits on restart).
- FR Availability: The 62 % run-time corresponds to a regular on/off cycle and high availability.
- Res Availability: Same as for FR Availability.
- Reactive Power and Q Availability: Refrigerator compressor, fans and defrost heaters have no active Q production capability.

3.3.5. Electric clothes dryer

- Power Level: Average clothes dryer power is 2790 W [27].
- Reserves: A typical dryer load might be one hour, which equates to 2.8 kWh.

- Flexibility: Electric resistive heating element(s) can be turned on/off during a drying cycle. A drying cycle may be extended when a dryer is operated at a lower power setting to provide power modulation.
- Fast Response: Similar to water heater.
- FR Availability: The average U.S. household runs five loads per week [28], which equates to only 3 % of hours in a week for one-hour dryer run times. When the dryer is running, it may be possible to modulate the power.
- Res Availability: The timing of a dryer load might be shifted with owner's approval (clothes must be in the dryer and the operator willing to wait after that point). Availability is still low, set equal to FR Availability.
- Reactive Power and Q Availability: Resistive loads have no capability for Q production.

3.3.6. Clothes washer

- Power Level: An average-size clothes washer consumes 255 W [27].
- Reserves: If a wash cycle duration is taken as one hour at 255 W, then the energy of that load is 255 Wh.
- Flexibility: The clothes washer follows a complex operation cycle which may not be easily adjusted or paused. The cycle may be shifted to a later time if a homeowner approves.
- Fast Response: Fast shut off and restart may be possible; however, heating of water and presence of bleach and soap may not allow stopping the cycle without a rinse and restart.
- FR Availability: The average U.S. household runs six loads per week [28]. The washer is only operated 4 % of hours in a week.
- Res Availability: Same as for FR Avail. The wash cycle could be delayed, if the owner is willing to delay cycle start, for example, in response to a "high price" warning.
- Reactive Power and Q Availability: Clothes washers have no capability for Q production.

3.3.7. Dishwasher

- Power Level: An average-size dishwasher consumes 330 W [27].
- Reserves: If a dishwasher cycle is taken as one hour, then a typical cycle would consume 330 Wh of electrical energy.
- Flexibility: The dishwasher has a complex operation cycle which may not allow adjusting power levels, but the dishwasher cycle is easy to delay to later with little impact.
- Fast Response: If the power is shut off during operation, then the cycle may require restart.
- FR and Res Availability: The average U.S. household runs five loads per week [28] for one hour. This equates to an availability of 3 % of hours per week.
- Reactive Power and Q Availability: Dishwashers have no capability for Q production.

3.3.8. Pool pump

- Power Level: An average pool pump consumes 1000 W [27].

- Reserves: Pool pumps need to run continuously for some duration to filter the pool water. A typical run-time is 8 h per day [29] to effectively and sufficiently filter the pool water, which equates to 8 kWh of reserve capacity.
- Flexibility: Can start/stop multiple times for short times off and on, but should not be shut off for extended time during a cleaning cycle. May be variable speed.
- Fast Response: Can provide fast response on/off.
- FR Availability: If the pool pump run time is 8 h, then the availability is one third of the daily hours.
- Res Availability: Set equal to FR Availability.
- Reactive Power and Q Availability: Pool pumps have no capability for Q production.

3.3.9. PV inverter

- Power Level: 6 kW peak power production for the average residential system [30].
- Reserves: Cannot shift production; there is no storage. Curtailing real power may be useful for frequency response, but not for reserve capacity (generation). The only way to enable potential for providing reserves, as well as up and down regulation, is to operate at reduced capacity, with the accompanying cost of curtailed power.
- Flexibility: Can only reduce power (and lose generation revenues by doing so). Cannot control when it is producing power.
- Fast Response: Can provide fast response with power curtailment.
- FR and Res Availability: PV system availability is captured in a variable called Capacity Factor (CF), which is defined as the actual annual electrical energy output divided by the maximum possible electrical energy output (which equals nameplate peak power multiplied by hours in a year). CF varies from around 0.10 in a cloudy region for smaller rooftop systems up to 0.30 for large utility-scale systems located in the southwest U.S. CF is influenced by installation latitude, cloud cover, panel orientation, shading, and temperature. Typical residential PV systems average around CF = 0.16 [31]. But the number of hours that a PV system is actually producing some power is a larger number, dependent on latitude and cloud cover. A typical value for average annual hours of sun for some populous states around the U.S. is 2730 h [32]. If that value is taken as the hours when real power is available, then this number equates to 31 % of the hours in a year.
- Q Availability: Full availability, assuming that the inverter is designed to enable reactive power production independent of real power production.
- Reactive Power: Can dynamically vary Q production. The IEEE 1547 standard default Volt-VAR function [33] specifies that a PV inverter be able to produce reactive power up to a level of 44 % of the real power rating at peak power production. Thus, the magnitude of reactive power (Q) is set to 0.44 * P in Table 1. A greater amount of reactive power may be produced at lower real power levels. Inverters may be designed to produce reactive power even when real power generation is zero [34].

3.3.10. Battery inverters

- Power Level: Typical available residential battery installations (currently available [35]) have sustained power transfer rates of 5 kW with typical storage capacity around 10 kWh.
- Reserves: Not all storage capacity will be available to be used as reserves due to state of charge limits as well as operational concerns. A value of half of the total 10 kWh has been assumed, but this will vary considerably depending on whether the stored energy will be required soon for other purposes.
- Flexibility: A battery can charge or discharge at any time (with extended charge/discharge limited by state of charge), at different rates, and at varying power levels.
- Fast Response: Can provide fast response charging or discharging.
- FR and Res Availability: The battery may have other owner facility uses such as back-up power that limit the range of discharge, but generally is highly available.
- Q Availability: Full availability.
- Reactive Power: Can dynamically vary Q production. Q is set to 0.44 * P.

3.3.11. Electric vehicle

- Power Level: 1.4 kW (Level 1, 120 V), 6.2 kW (Level 2, 240 V), or greater than 20 kW (Level 3), based on current values [36], [37]. A Level 3 power rating is not standard with different vendors developing much higher power connections. This report uses the common Level 2 charging rate of 6.2 kW.
- Flexibility: Same as for battery above.
- Reserves: EV battery capacity averages 55.6 kWh based on January 2018 market survey data [38]. However, not all of this energy will be available for reserves, considering that a battery charging agent will need to provide a charged battery at the time when a driver is ready to depart. A value of half is used, as was assumed for the residential battery system.
- Fast Response: Can provide fast response charging or discharging.
- FR, Res and Q Availability: The EV may provide grid services any time that it is connected to the grid. The average American driver spends 293 h driving each year [39]. That equates to 48 minutes per day when the car is not connected to a charging station and 97 % of daily hours when the car could be connected to the grid. This value might be appropriate for a commuter car that is always plugged in at home and work. Note however, the ability to provide grid services may be limited by (1) manufacturer constraints on the capability of the battery to put power on to the grid and (2) location of the car at work vs. home.
- Reactive Power: Can dynamically vary Q production. Q is set to 0.44 * P.

3.4. Discussion of Capability Results

The appliances in Table 1 show significant variability in their flexibility, availabilities, typical power levels, and resulting ability to serve different ancillary services. Some appliances have such low power requirements or low availability that they have a low total score and hardly seem worth considering using for ancillary service provision (apart from the potential of aggregation). On the other hand, some devices (battery, EV, water heater, and electric resistance heater) score much higher and seem to have the most potential for ancillary services provision. The devices that are most used now for demand response (primarily serving the Reserves use case) fall in the middle, like air-conditioning and pool pumps, but high-scoring electric water heaters are also commonly used today for DR.

Table 1 shows that some devices may serve very well to provide one grid service, but not another. As noted for PV systems, the PV inverter can produce reactive power, but is not well-suited for frequency response. Electric heaters are the inverse, performing well for frequency response, but not able to generate reactive power. Devices with compressors can provide slower frequency response; after shutting off power, the compressor must remain in that state for some time, so active high-frequency on/off behavior is not possible, although this limitation can be overcome in aggregation [40]. There are also seasonal limitations on availability of air-conditioning and space heating. Batteries, including EVs, when connected to the grid, can provide all services well, but their ability to do that will be constrained by the need to provide services to the owner ahead of some grid services. Note that EV manufacturers may not enable any flow of power from the car to the grid in order to protect the battery for its intended purpose.

Note that the devices in Table 1 rely on storage for shifting energy use. Batteries use chemical storage, home heating and cooling relies on house thermal storage, water heaters rely on water thermal storage, and the pool pump relies on storage of cleaned water. A PV system, as a generator relying on sunshine, has no locally stored energy, and cannot shift production.

Furthermore, Table 1 focuses on capability, not practical implementation. The table relies on averaged data, which does not account for regional variation where a certain resource may be prevalent and available for ancillary services provision in one utility territory when it does not exist in another's territory. For example, air-conditioning is more prevalent in the southern states and it is also the main load responsible for the system peak on hot days. Likewise, the cost to enable one device to provide services may be significantly more or less than for another device depending on complexity of appliance controls, provision of standard communication ports, size of the resource (relative cost of device to value of service provided), etc.

3.5. Aggregation for Service Provision

Aggregation has been a key enabler for demand response and, more recently, for newly-emerging ancillary service provision. Aggregation has opened the door for smaller distribution-level assets to participate in wholesale-level markets including peak-shaving (classic DR programs), frequency response, ramping, and reserves.

The power of aggregation is that while a single residential device has limited power, flexibility, and availability, an aggregation of the same device from multiple homes can produce a flexible resource to provide ancillary services to the electric grid via a retail or wholesale market. In addition, combining different device types with different characteristics can provide the equivalent of a flexible resource able to absorb or provide electrical energy to serve most ancillary service needs. The data presented in Table 1 indicates the capability of any single residential device to provide some ancillary service.

Accessing that capability requires a practical and affordable method to control the device based on a signal from the grid (e.g., demand response), as well as metering of the result. Aggregation of devices provides one approach to combine the resources of individual devices to reach a total power capability to achieve a significant impact on the grid. The FR, Res, and Q Scores in Table 1 indicate how much real power, storage capacity, and reactive power, respectively, that a single typical device can provide to an aggregated resource.

How many devices of one type are required to be aggregated to have a “sufficient” response to a grid service need? Today’s wholesale markets have varying requirements for minimum power level requirements for participation. PJM and the Texas ISO (Electric Reliability Council of Texas) have the lowest bar to market participation set at 100 kW for FR and Reserves. This threshold provides one measure of “significant impact” for aggregation.

Using the FR and Res Scores in Table 1 along with the 100 kW minimum wholesale market participation level, one can estimate the numbers of aggregated devices required to provide significant frequency response and reserves services to the grid by simply dividing the aggregated power level (P_{agg} = 100 kW) by the relevant score. The number of devices required in aggregation to provide frequency response services, N_{FR}, can thus be found from this equation:

$$N_{FR} = P_{agg} / (FR\ Score), \qquad (4)$$

where FR Score is taken from Table 1 and the resulting N_{FR} is provided in Table 2 for each device type.

Likewise, the number of aggregated devices of a single type required to provide reserve power, N_{res}, can be estimated by:

$$N_{res} = P_{agg} / (Res\ Score), \qquad (5)$$

where Res Score is taken from Table 1, and the resulting N_{res} is given in Table 2. N_{res} has the units of 1/h, which may be interpreted as the number of aggregated devices that can provide P_{agg} power for one hour.

The number of devices required to provide some significant level of reactive power service, N_Q, depends on the end-use application for the reactive power. There is no wholesale market for reactive power, but rather RTOs require large generators to provide it as part of the open access transmission tariff. The obvious application for distribution-level device reactive power provision is on the distribution system in response to localized reactive power needs. In a recent simulation study [41], PNNL showed that a single house PV inverter, by injecting 3 kVAR of reactive power, could move the voltage at the meter by 0.4 %. In this case, ten PV inverters (total peak power rating of 70 kW) could move the local secondary voltage from a 125 V violation limit back to 120 V by consuming 30 kVAR of reactive power. This result may or may not be typical or practical; nevertheless, the simulation was based on an existing residential feeder and the Institute of Electrical and Electronics Engineers (IEEE) 8500 reference grid [42], and provides a tangible reference value.

If one takes 30 kVAR as an estimate for a significant aggregated amount of reactive power on the distribution grid, Q_{agg}, then one can derive the number of inverters required to provide aggregated reactive power, N_Q, for use by a distribution utility.

$$N_Q = Q_{agg} / (Q\ Score), \qquad (6)$$

where Q Score is taken from Table 1. The result is shown in Table 2.

Table 2. Estimated number of devices required in aggregation to provide frequency response (N_{FR}), reserves (N_{res}) and reactive power (N_Q) services.

Device	N_{FR}	N_{res}	N_Q
Air conditioning (summer only) Heat pump (summer and winter)	347	208	--
Electric resistance heat (winter only)	38	38	--
Electric resistance water heater	185	333	--
Refrigerator	1200	1200	--
Electric clothes dryer	1200	1200	--
Clothes washer	240 000	48 000	--
Dishwasher	84 000	16 800	--
Pool pump	505	63	--
PV inverter	149	--	12
Battery	20	20	14
Electric vehicle (EV)	17	4	11

Note that the values in Table 2 are based on many assumptions and estimates as laid out in the sections preceding Table 2. Actual numbers may vary considerably.

Considering the importance of aggregation for residential device service provision to the grid (refer to following section on current applications), one can see that Table 2 summarizes which devices are likely to best serve future grid needs. The clothes washer and dishwasher are clearly not significant players for the grid, and refrigerators and clothes dryers are also of limited use, apart from a large aggregation network. And while air conditioning, heat pumps, water heaters, and electric resistance heaters are very valuable, the most useful home devices for grid service provision going forward will likely be the PV inverter, home battery inverter, and EVs. These devices not only perform strongly for providing frequency response and reserves (excluding the PV system), but they will also likely be key providers of reactive power on the distribution grid.

4. Current Residential Device Provision of Ancillary Services

Residential devices are being used today to provide ancillary services. All currently available paths to enable residential devices to provide ancillary services involve aggregation. There also appears to be rapid development of local energy markets and potential for these devices to serve local grid service needs.

There are currently no retail markets or residential tariffs for ancillary services. There are also practical challenges around how to measure the performance of individual small devices and then reward that response [6], [7], summarized as:

- Costs of enabling technologies for communications and control that are currently required for primary and secondary frequency control;
- Reliability rules, grid protocols, and service definitions developed for large generators that hinder load participation;
- Lack of standard communication protocols for secure communications;
- Capability to forecast demand; and
- Complex regulatory environment.

Available rates, programs, and markets vary considerably across the U.S. Each of the examples below demonstrates the role of aggregation, since no individual residential devices can participate directly in the wholesale markets.

Aggregation is used today in two primary ways to provide services to the grid. First is via DR programs implemented by curtailment service providers (CSP). The CSP is an aggregator that bids the load reduction, as if it were generation, into a wholesale DR program [43], or else the CSP is the distribution utility itself using DR to reduce load at peak times. Alternatively, aggregators may bid device response into various wholesale energy and ancillary services markets (e.g., PJM allows demand to bid into any market).

Aggregators use different methods to control end-use devices. One approach is to use an existing standard communication protocol (e.g., IEC 62746-10-1 OpenADR [44], IEEE 2030.5 SEP 2.0 [45]) to connect the CSP to an energy management gateway in a home or building. Alternatively, an aggregator may use a proprietary network to aggregate device response. This approach is common for interactions with electric vehicles and water heaters and may be a possible approach for integration of home appliances, with appliance manufacturers serving as aggregators.

Examples below show provision of either regulation or reserves, including for peak shaving and backup for renewable resources ("wind-firming"). Additionally, some examples of currently developing transactive market platforms and projects are presented, since these efforts will likely enable residential DER provision of grid services. The examples given below are current projects or programs representative of many more that are being added regularly.

4.1. Examples of devices providing frequency regulation and primary frequency response

The following list provides example aggregations of residential devices for providing frequency regulation and primary frequency response.

- EVs providing regulation to CAISO [46].
- Water heaters providing regulation and wind-firming in Oahu, HI [47] [48].
- Network of water heaters used for regulation in the PJM Reg-D fast regulation market [49].

- Utility supplying water heaters to homeowners in Quebec and using them for regulation and for peak-shifting [50].
- Home energy managers used to enable residential devices to provide regulation, voltage control, and peak-shifting to Australian grid [51].
- EV fleet management system using aggregated vehicles to provide primary frequency response by shutting off charging [52]. This demonstrates capability for primary frequency response that might be implemented for residential EVs.

4.2. Examples of devices providing energy reserves and peak-shaving

The following list provides example aggregations of residential devices for providing energy reserves and peak shaving.

- Ice storage systems used for shifting summer cooling load off-peak [53].
- Brick thermal mass equipment used for winter heat storage [54].
- Water heaters and smart thermostats used for peak shifting [55].
- Battery storage systems used with TOU rates to manage energy [56], and for aggregation into utility DR programs and CAISO Proxy Demand Resource market [57].
- EVs used for peak-shaving in NYC [58] and in San Diego (via TOU rates) [59].

4.3. Transactive energy via retail markets

Transactive energy (TE) enables the use of market mechanisms to engage smaller devices on the distribution system via retail markets, typically real-time [60]. In essence, the aggregator uses market mechanisms to manage load response, rather than direct control or other signals. These markets can potentially be used to engage residential devices to provide frequency response, reserves, and voltage control. The following list describes ongoing projects and implementations of retail markets that are helping to develop this approach to residential grid service provision.

- A pilot project in CA is using the OASIS Energy Interoperation standard and TeMix profile [61] with tenders to pre-purchase energy sent to individual homes to incentivize devices to manage energy [62]. The price is specific to each meter. The TeMix platform enables devices to have certainty on future energy prices and to buy or sell in order to optimize energy cost.
- PowerMatcher cities of Hoogkerk, Grongingen, and Heerhugowaard [63] [64]. PowerMatcher technology [64] uses an auction market approach to find an equilibrium price for real-time energy. These prices are used in different projects to encourage consumer management of consumption, energy source switching, charging and discharging of storage, and other end uses.
- Isle Au Haut microgrid [65]—A transactive platform has been developed for this island microgrid. A central system monitors supply and demand to form a real-time price signal. This price is adjusted based on supply and demand at distribution nodes so as to best incentivize loads and generators to provide or consume more or less power. Intelligent edge devices use historical data to formulate energy use plans.
- A transactive blockchain technology platform is used to manage energy exchanges (including forward hedges) between neighbors in Brooklyn, NY and

elsewhere. Used within a local energy market, the transactive platform enables blockchain-based energy trading to enable residential devices to participate in local grid management [66]. An independent blockchain-based transactive platform is being piloted in the Chicago, IL area [67].

- A distribution system platform technology is being implemented in upstate NY that can deliver granular prices to individual homes, and which also has the potential to better incentivize residential devices to provide grid services [68].

5. Summary and Looking Forward

In this report, the capability of residential DER to provide grid ancillary services has been analyzed based on six indicators. The evaluation methodology and the values presented in Tables 1 and 2 are key results of this report. The evaluation focuses on the technical capabilities of devices, not on the challenges of actual implementation. Existing programs have been identified that demonstrate how residential devices can currently provide ancillary services. Yet the grid continues to evolve, driven by the increasing use of renewable energy sources and customer-owned DER. Utilities and regulators will continue to rework how the U.S. electric grid operates, leading to new pathways for small DER to provide grid services. What can be said about the likely path forward for each of the key ancillary services?

As shown in Table 1, most devices can provide fast response needed for primary frequency response. Any device could be equipped with sensors and intelligence to monitor grid frequency and to drop load in the event of a frequency drop [3], [69]. This approach for engaging small DER for primary frequency response may become more important as DER replace large generators which are currently relied on for primary frequency response.

Regulation service is currently implemented via automatic generation control signals to large generators and aggregators. Given the cost for telemetry and metering, it is likely that this service will continue to rely on aggregators and only be implemented for larger residential devices. Aggregators must demonstrate delivery of power that follows the regulation signal, and currently, each device must have a utility-grade meter. Having a trusted meter at every device may be cost prohibitive; therefore, research is needed on methods that can satisfy requirements for response verification at lower cost.

DR programs and markets will continue to operate in their current forms because they deliver proven resources, even though they rely on virtual baselines [70], that is, paying a consumer for what they *don't* use based on an estimate of what they would have used if they had not responded. Device manufacturers and other aggregators may find new ways to exercise residential device flexibility (load shifting and storage) and sell that flexibility in wholesale energy markets. Providing real-time and forward price signals to customer energy management systems and device agents will slowly move the country toward paying for energy based on when it is used (and the value of energy at that time) and reduce the importance of traditional event-based DR.

Voltage control is primarily a distribution system challenge, made much more difficult by the growth of customer-owned renewable generation. It is possible that PV systems and batteries will be required to provide voltage support services as a condition for interconnection, as is being pursued in California [71]. Voltage control may also be provided via markets, if retail real and reactive power markets prove economical. Development of distribution system operators (DSO) and transactive platforms will help explore these options.

The current approaches for managing frequency and voltage may not be sufficient for the future energy grid. One possible development for grid management may be a DSO managing real and reactive power by a variety of methods including distribution-scale retail markets. The DSO could use a single real energy price in a retail market to incentivize device response to a variety of grid needs, such as voltage support, or aggregating responses to sell into an available wholesale market (e.g., regulation, reserves, or ramping products)[6]. Automatic primary frequency response provision and inverter reactive power provision would not be metered. This combined approach for residential device provision of ancillary services requires only a single house meter and may provide a simple path to support the shift from large generators to distributed generation while continuing to provide needed ancillary services.

In conclusion, ongoing development of energy tariffs, market products, retail markets, home energy technology, and utility programs provide evidence of how smaller distribution-level DER will participate in providing grid services. Air conditioning, heat pumps, electric resistance heaters, and water heaters will continue to see strong use for DR and ancillary services. With rapid expansion of distributed PV systems, battery storage and EVs, we may expect that these systems will increasingly be relied upon to handle energy balancing on the grid as well as local voltage control.

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