

Beyond DERMS: Demonstration of Automated Grid Services, Mode Transition, and Resilience

Energy Systems Division

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Beyond DERMS: Demonstration of Automated Grid Services, Mode Transition, and Resilience

by

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ACRONYMS

ACE	Area Control Error
AGC	Automatic Generation Control
ARPA-E	Advanced Research Projects Agency — Energy
BED	Burlington Electric Department
BTM	behind the meter
DER	distributed energy resource
DERMS	distributed energy resource management systems
DOE	U.S. Department of Energy
EV	electric vehicle
EVSE	electric vehicle supply equipment
FERC	Federal Energy Regulatory Commission
GIS	geographic information systems
HVAC	heat, ventilation and air conditioning
IoT	internet of things
ISO	independent system operator
NODES	Network Optimized Distributed Energy Systems
OE	Office of Electricity
PEM	Packetized Energy Management
QoS	quality of service
R&D	research and development
RTO	regional transmission organization
SoC	state of charge
VB	virtual battery
VEC	Vermont Electric Cooperative
VPP	virtual power plant

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EXECUTIVE SUMMARY

This report describes the results of the Beyond DERMS project aiming to build, deploy, and demonstrate a holistic platform that supports the integrated operation and planning of future power distribution networks with bi-directional power flows, many diverse distributed energy resources (DERs), and inverter-based resources. The results demonstrate how emerging ‘internet of energy’ technologies can be leveraged to simultaneously solve the grid problems of today and prepare for the challenges of tomorrow in a way that goes beyond the capabilities of existing distributed energy resource management systems (DERMS).

The Beyond DERMS platform used in this project was developed from a study of the performance of over 300 smart energy devices, thousands of simulated devices, and data from over 20,000 smart meters connected on the distribution networks of two utility partners, Vermont Electric Cooperative (VEC) and Burlington Electric Department (BED). These devices and data streams were used to test various functions on this single platform. The results clearly showed that the core “Beyond DERMS” concepts are feasible and motivate the need for a large-scale demonstration project to demonstrate how DERMS fits with other key elements of grid modernization that include Advanced Metering Infrastructure, DER and aggregations applying microgrid concepts.

The project was organized in three phases: 1) conceptualization, 2) platform development and 3) advanced use cases. The accomplishments of each phase are summarized below.

Phase 1 (Conceptualization)

1. Development of the core Beyond DERMS concepts and a DERMS platform for integration testing with 300 behind-the-meter (BTM) DERs including water heaters, electric vehicles (EVs), and batteries.
2. Initial system integration tests and simulations of the DERMS platform, in cooperation with utility partner(s).
3. Demonstration of the core Beyond DERMS concepts, such as integrating planning functions within the DERMS, and the capability to deliver grid services for the following:
 - Peak load reduction to mitigate generation and transmission capacity costs.
 - Load shaping (i.e., energy arbitrage) to reduce the cost of wholesale energy purchases needed to supply time-varying loads.
 - Distribution network management services through a software system that can model and manage distribution network constraints in real time.
 - Ancillary services for balancing authorities, independent system operator (ISO), or regional transmission organization (RTO).
 - Resilience for consumers and for the grid as a whole.

Phase 2 (Platform Development)

1. Integration of weather, load, and DER forecasting and integration of economic analysis tools into the Beyond DERMS platform.
2. Demonstration of how the platform can go beyond conventional DERMS to include grid planning functions that allow electric utilities to plan for and manage DERs on a single platform.
3. Demonstration of the capability of a wider range of DERs to provide flexible grid services by integrating weather, load, and DER forecasting and by integrating economic analysis tools that facilitate DER project planning.

Phase 3 (Advanced Use Cases)

Phase 3 demonstrated more advanced use cases including Ancillary Services and Black-sky-day operation and Mode Switching) using the Beyond DERMS platform. Phase 3 tests showed how groups of DERs can provide a range of grid services, such as:

- Peak load management.
- Load shaping for energy price (LMP) arbitrage.
- Distribution network management (in simulation).
- Ancillary services (in simulation).

These tests demonstrated how a Beyond DERMS platform can fuse together AMI, SCADA, and DER data to provide a utility with deep insights into distribution network operations and planning, extending the value of DERMS and BTM DER resources.

These grid services apply to use cases for ancillary services, black-sky-day operations, and Mode Switching. The advanced use cases validate the grid services provided by the Beyond DERMS platform, that integrates DER management with distribution network planning and forecasting functions.

1 INTRODUCTION

Distributed renewable generation, energy storage, and smart energy appliances are increasingly prevalent behind the meter (BTM) in residential and commercial buildings. As the result of years of DOE R&D, microgrid technology for locally managing DERs to provide building-level resilience and to reduce energy costs is well-established. Similarly, the technology for basic demand response (reducing load during peak periods through direct load control or by adjusting thermostat setpoints) is operational in utilities and markets. Demand response programs and time-of-use electric rates continue to drive the adoption of DERs, including home batteries. However, neither basic demand response nor microgrids can address emerging grid impacts, such as managing constraints in distribution networks with bi-directional power flow patterns and providing real-time grid balancing services to balancing authorities. Thus, there is a need for technology that can coordinate millions of DERs to solve problems both within distribution networks and for the bulk power system.

Distributed Energy Resource Management Systems (DERMS) have the potential to address this need but many of the core ideas that underlie the DERMS concept—such as simultaneously providing grid services for the bulk grid and for the distribution network—have not been demonstrated with large numbers of installed diverse devices.

The potential for DERs to contribute to grid balancing services is well-recognized, most notably in Federal Energy Regulatory Commission (FERC) Order No. 2222.¹ The implementation of FERC 2222 has the potential to dramatically change the U.S. electricity industry by opening up new business models that allow distributed energy resources to compete with centralized grid assets in markets.² However, for electric utilities that need to maintain aging transmission and distribution network infrastructure, it is not clear how they can coordinate the actions of thousands of DERs controlled by many different aggregators, each managing overlapping groups of diverse assets that connect on both low- and medium-voltage distribution networks. Operating distribution circuits in this new environment requires innovative modifications for emerging algorithms for DER coordination. These innovative approaches advance earlier research and development (R&D) that focused on microgrids and Distributed Energy Resource Management Systems (DERMS).

The U.S. Department of Energy (DOE) has sponsored a wide range of research, development, and demonstration efforts that have moved many distribution-level smart grid technologies forward. The 2009 American Recovery and Reinvestment Act Smart Grid Investment Grant program accelerated the adoption of advanced metering and other smart grid infrastructure. The DOE's Office of Electricity's (DOE/OE) Grid Modernization Initiative and Microgrid Program have led to significant advances in microgrid controls (energy management systems), DERMS, distribution system modeling software, associated control algorithms, and

¹ FERC Order No. 2222, Participation of Distributed Energy Resource Aggregations in Markets Operated by Regional Transmission Organizations and Independent System Operators (Issued September 17, 2020).

² P. Hines and A. B. Wannop, "FERC Order 2222 should be a watershed moment — Grid operators can help ensure that," Utility Dive. (November 2020).

industry standards.³ The Advanced Research Projects Agency—Energy’s (ARPA-E) Network Optimized Distributed Energy Systems (NODES) program began the development of algorithms required for aggregated DERs to solve a range of real-time grid problems. But what is not yet clear is how best to integrate these various technologies to address the range of problems faced by the electricity industry today and to help them plan for the challenges of tomorrow.

Furthermore, integrated DER management systems have not been effectively demonstrated at scale with thousands of devices and more than 1 MW of aggregated capacity.

³ IEEE 2030.7™ Standard for Specification of Microgrid Controllers and IEEE 2030.11™ Guide for Distributed Energy Management Systems.

2 REVIEW OF BEYOND DERMS PLATFORM ARCHITECTURE AND UTILITY INTEGRATION

This section revisits the architecture and components of Beyond DERMS Platform. A detailed description of these components is available in the Beyond DERMS Phase 1 and 2 report.⁴

2.1 PLATFORM ELEMENTS

The developed Beyond DERMS platform implements three key functions:

1. **Utility Dashboard:** Provide utilities and other grid operators with the ability to manage DERs. The platform described here is specifically designed to provide four types of grid services: peak reduction services to minimize load during event periods; load shaping such that DERs track with a desired daily load shape or with marginal generation costs; ancillary services, such as frequency regulation or spinning reserves; and automated distribution network management functions for both planning and operations.
2. **Customer Interface:** Provide DER owners (e.g., home or business owners) with the ability to connect their DERs and manage how those devices interact with the grid. In this project, we used a custom-designed mobile app to meet this requirement.
3. **Internet of Things (IoT) Interconnections:** Provide the backend IoT technology needed to coordinate the behavior of millions of devices. This project uses Packetized Energy Management (PEM) as the foundation for this IoT system.

Figure 1 illustrates how these three elements come together in the platform. The dashboard provides grid operators with the ability to visualize and manage how DERs operate to provide grid services. The mobile app provides end users with the ability to change how their devices interact with the DERMS. Finally, the backend IoT platform allows devices to interact with the platform in real time, using the core PEM technology.

⁴ <https://www.osti.gov/biblio/1825329-beyond-derms-platform-development-flexibility-prediction-value-measurements>.

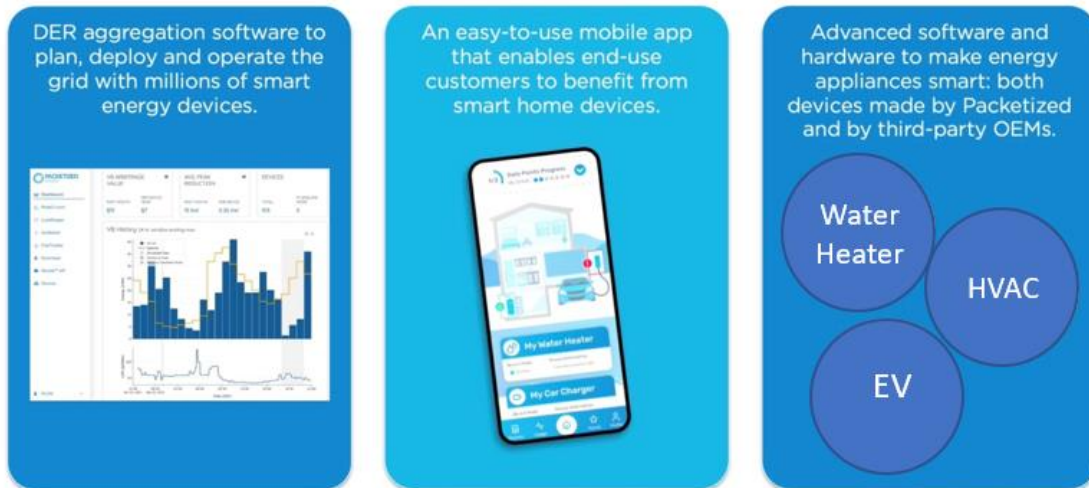


FIGURE 1 The three key elements required for a fully functional DERMS, as implemented in the Beyond DERMS platform, that connects grid operators, DER owners, and their devices.

2.2 GRID SERVICES

The Beyond DERMS platform aims to operate across historical, operations, and planning time scales, while also providing the ability to coordinate DERs for five different grid services:

1. Peak load reduction
2. Load shaping
3. Ancillary services
4. Distribution network management
5. Resilience

2.3 CONNECTING UTILITY SERVICES AND DERS

We connected AMI, SCADA, microPMUs, and engineering network model data into the platform by developing a local “data agent,” which locally communicated with the utility data systems and then securely transferred data to the cloud-based DERMS. This architecture is shown in Figure 2.

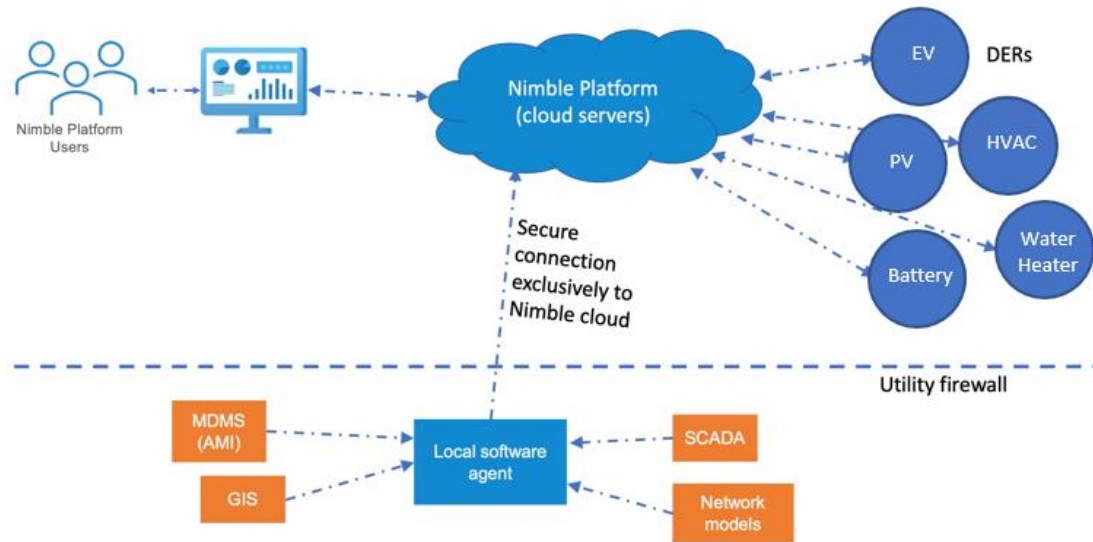


FIGURE 2 Utility interconnection architecture.

The Beyond DERMS platform uses a modern “serverless” cloud software architecture hosted on Amazon Web Services. Figure 3 describes the overall architecture of the software. This serverless architecture allows us to write code that responds to specific events (such as a device requesting a “packet” of energy) without needing to also manage the computer servers that run the code. This asynchronous design aligns well with the asynchronous nature of our core software algorithms, which are designed to be “device driven,” rather than a more conventional top-down optimization approach in which data is collected from devices, centrally optimized, and then centrally dispatched. Instead, our algorithms respond to requests from devices to consume (or produce) “packets” of energy. In the serverless approach, each message from a device (IoT message) triggers a set of code, which subsequently runs the appropriate calculations, records data in the databases, and responds to devices based on grid conditions.

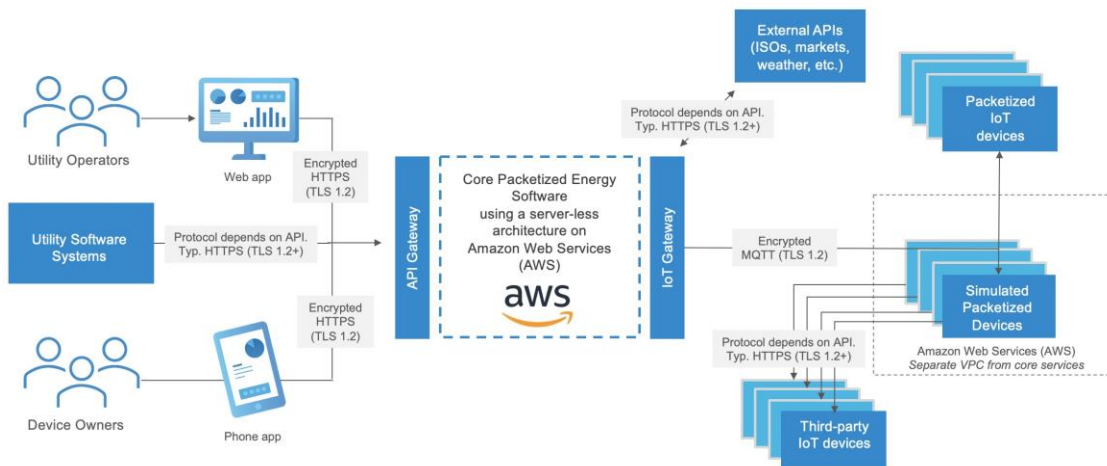


FIGURE 3 Cloud and IoT architecture.

In this project, we were able to successfully implement the software architecture shown in figures 2 and 3, integrating with the partner utility’s (Vermont Electric Cooperative, VEC) meter data management system, geographic information systems (GIS), SCADA, and power flow data. Using this architecture, we built a software module known as GridSolver, which allows the utility to visualize historical data for various assets within their network.

2.4 POWER FLOW MODELING

In order to integrate a power flow model into the platform, we used a Docker container (similar to a virtual machine), which includes the actual GridLab-D simulation engine, following the method developed by Chassin et al at SLAC National Accelerator Laboratory.⁵ We subsequently built a scenario analysis tool into GridSolver, which allows us to run quasi-steady-state power flow simulations within the platform, based on historical utility AMI data, which are fed into the Docker container within our cloud software. We tested this power flow modeling tool using both the IEEE 123 bus test case and a full set of distribution circuits provided by our utility partner VEC.

2.5 TIME SERIES SIMULATION

In order to develop a time-series simulation of the IEEE 123 node test case within GridSolver, we added anonymized time-series data collected from the utility-provided AMI data to each load (or house) in the original network model. This provides us the ability to run the base case, as well as time-series (quasi steady-state time-series, QSTS) simulations.

2.6 DER MODELING

The next subtask was to model DERs within the platform, so that we could simulate the behavior of different types of devices as they were added to the system. In particular, we focused on the development of models of the following device types:

- Level 2 electric vehicle supply equipment (EVSEs).
- Grid interactive water heaters.
- Grid-edge (residential scale) battery systems.
- Rooftop PV systems.
- HVAC systems (particularly with heat pumps).

⁵ D. Chassin, V. Lubeck, and A. Teyber, “Stanford/SLAC development version of GridLAB-D,” from SLAC National Accelerator Laboratory. <https://github.com/slacgismo/gridlabd>.

2.7 DEVICE INTEGRATION

In order to perform integration testing for various DERs and grid services, we connected over 350 DERs in partnership with our two utility partners, VEC and BED. This fleet of DERs includes the following set of devices:

- Electric hot water heaters using the Mello smart thermostat for water heaters (~300 units).
- Level 2 EVSEs, primarily using the Turbo DX from Webasto (~40 units).
- Mini-split heat pumps (~5 units).
- BTM batteries and PV inverters (~10 units).
- Rooftop PV systems.
- Heat, ventilation, and air conditioning (HVAC) systems (particularly with heat pumps).

3 ADVANCED USE CASES: GRID SERVICES FOR DER OPERATIONS AND VALIDATION

In this project, we focused on developing algorithms for each of five different DER use cases.

1. Peak reduction, to mitigate costs associated with generation and capacity (i.e., resource adequacy).
2. Energy arbitrage, to reduce energy costs by shifting load from high-cost periods to low-cost periods.
3. Ancillary services, such as frequency regulation — reducing the need to use conventional resources, like gas turbines — to provide real-time grid balancing.
4. Distribution network constraint management, in which DERs are coordinated to ensure that distribution network voltages and currents remain within limits, thus providing non-wires alternatives to conventional distribution network upgrades.
5. Resilience, in which DERs react to local conditions to help users recover from bulk grid outages (e.g., with the help of solar power and batteries) or to support the resilience of the bulk grid by locally reacting to voltage and frequency deviations.

While some of the use cases have been demonstrated in previous reports, the remainder of this section describes the algorithms used to implement advanced use cases related to mode transition, ancillary services such as frequency regulation, and black-sky-day operations.

The underlying technology used in this project for coordinating distributed energy resources is known as Packetized Energy Management.⁶ In this system, devices make randomized requests for “packets” of energy (an amount of energy consumed over a fixed period of time) to a coordinator who accepts or denies requests based on the real-time energy consumption level, relative to a target. The target (“Optimized power reference” in Figure 4) is chosen via an optimization routine that can consider a wide range of different factors, including the price of energy, carbon emissions levels, renewable generation, or grid constraints. Feedback from the coordinator allows the optimization engine to adjust the optimization formulation and thus the target setpoint for the aggregation of DERs (the virtual battery, or VB). The result is the ability to coordinate a fleet of diverse DERs as if they were a conventional power grid asset, such as a battery or a flexible power plant.

⁶ [ref to IEEE Spectrum Article] <https://spectrum.ieee.org/packetized-power-grid>.

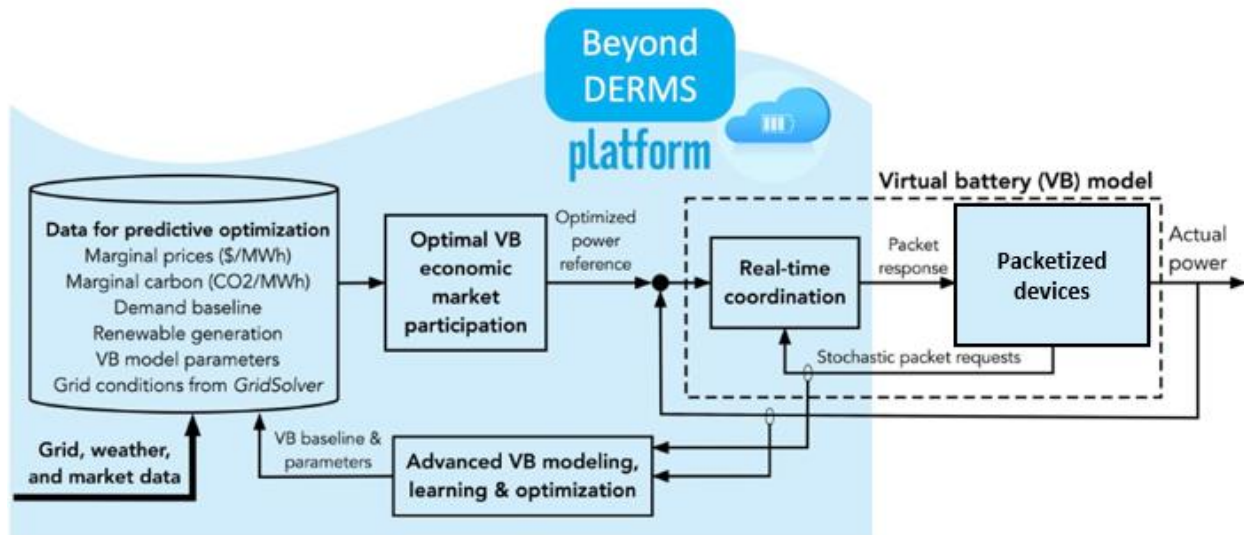


FIGURE 4 An illustration of the overall control architecture for DER coordination within the “Beyond DERMS” platform.

3.1 ANCILLARY SERVICES (FREQUENCY REGULATION)

As variable energy resources such as wind and solar increase, an even greater need arises for real-time balancing resources that can rapidly respond to changes in both supply and demand. In most modern power systems, this real-time balancing comes largely from primary, secondary, and tertiary frequency reserves. When performing primary frequency regulation, a generator adjusts its active power in response to changes in the frequency of the locally measured AC voltage. For secondary frequency regulation (also known as Automatic Generation Control, or AGC), a generator adjusts its power output in response to a signal sent by the regional balancing authority every 2-6 seconds. This signal, known as Area Control Error (ACE), is based on a combination of the deviation between scheduled and actual power exports/inputs and the regionally measured voltage frequency. Finally, for tertiary reserves (also known as contingency reserves), a generator agrees to rapidly increase its output in response to an unexpected loss of some other power generation resource.

FERC Order No. 2222 opens up the potential for aggregated demand-side resources that have an aggregate capacity of at least 100kW to provide ancillary services into wholesale electricity markets. The ruling makes it difficult for utilities to “block” the participation of DERs in ancillary service markets so long as they meet regional telemetry and other requirements.

3.1.1 Frequency Regulation Concept

Motivated by both the increasing need for balancing resources and changes in market rules, this project leveraged the “Beyond DERMS” platform to test the potential for a group of aggregated devices (a virtual power plant, or VPP) to provide secondary frequency regulation services. Specifically, this portion of the project demonstrate that an aggregated group of DERs can provide secondary frequency regulation by rapidly adjusting the aggregated power

consumption in response to an AGC signal. Figure 5 illustrates the overall concept of a VPP bidding into the market with a “frequency regulation bid,” then receiving an AGC signal from the ISO, and then adjusting net power consumption to match this signal.

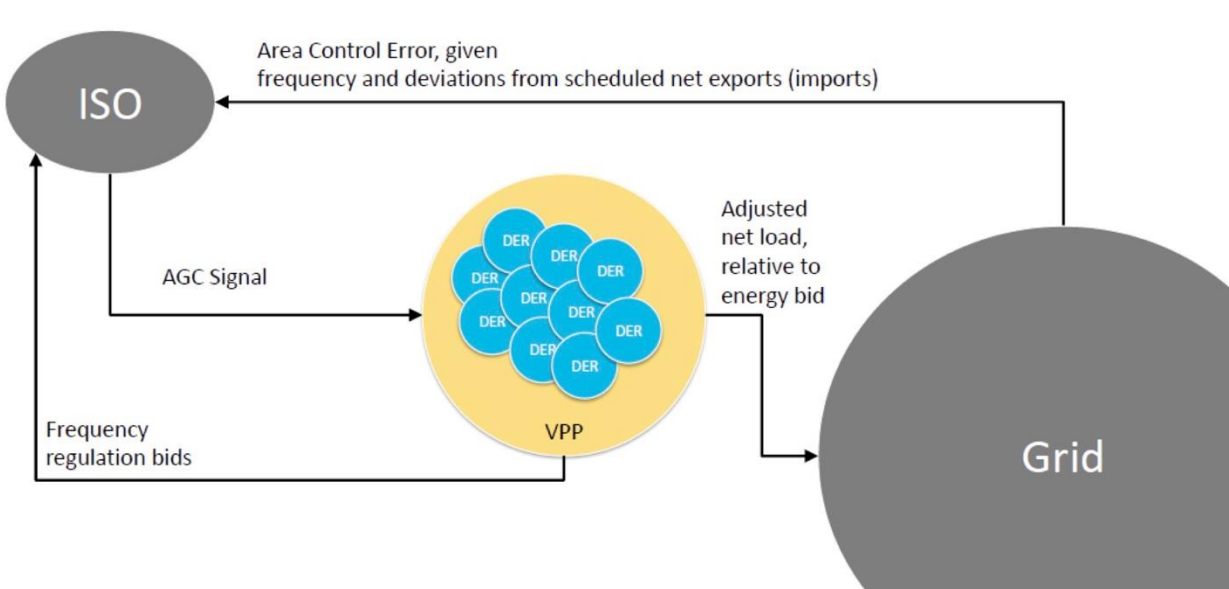


FIGURE 5 An illustration of a virtual power plant (VPP) bidding its frequency regulation capacity into a market, and then adjusting its net power consumption to track with an AGC signal.

3.1.2 Using the Beyond DERMS Platform for Ancillary Services

In order to test the ability of the platform to perform ancillary services, we run several tests in which about 250 distributed energy resources (primarily water heaters) were connected to the platform and used for secondary frequency regulation. Specifically, we tested the ability of the group of devices to track with a “Reg-D” test signal from PJM.⁷ This signal was then scaled to produce a signal that the fleet of devices could track (see experiments in the next section).

3.1.3 Experimental Setup and Results

This section shows the results from several trials in which we tested the ability of the platform to deliver secondary frequency regulation services per the PJM Reg-D test signal. Each trial lasted about 40 minutes and used the same test signal. Trials differed in the time of day, and in location of the tracking signal, relative to the baseline load.

In each trial we measure performance using the three elements of the PJM frequency regulation performance scoring: accuracy, delay, and precision. Accuracy is a measure of correlation between the signals. The Delay score is based on the amount of delay between the

⁷ <https://www.pjm.com/markets-and-operations/ancillary-services>.

target and actual signals, and the Precision score is based on the actual amount of error between the target and actual. Each trial includes 208 online and connected devices.

Trial 1 (Figure 6) was a test trial in which the target power level was set quite high, relative to the actual baseline load. As would be expected, this trial resulted in a low precision score (0.11). The accuracy and delay scores were 0.70 and 0.81, respectively, leading to an overall score of 0.54.

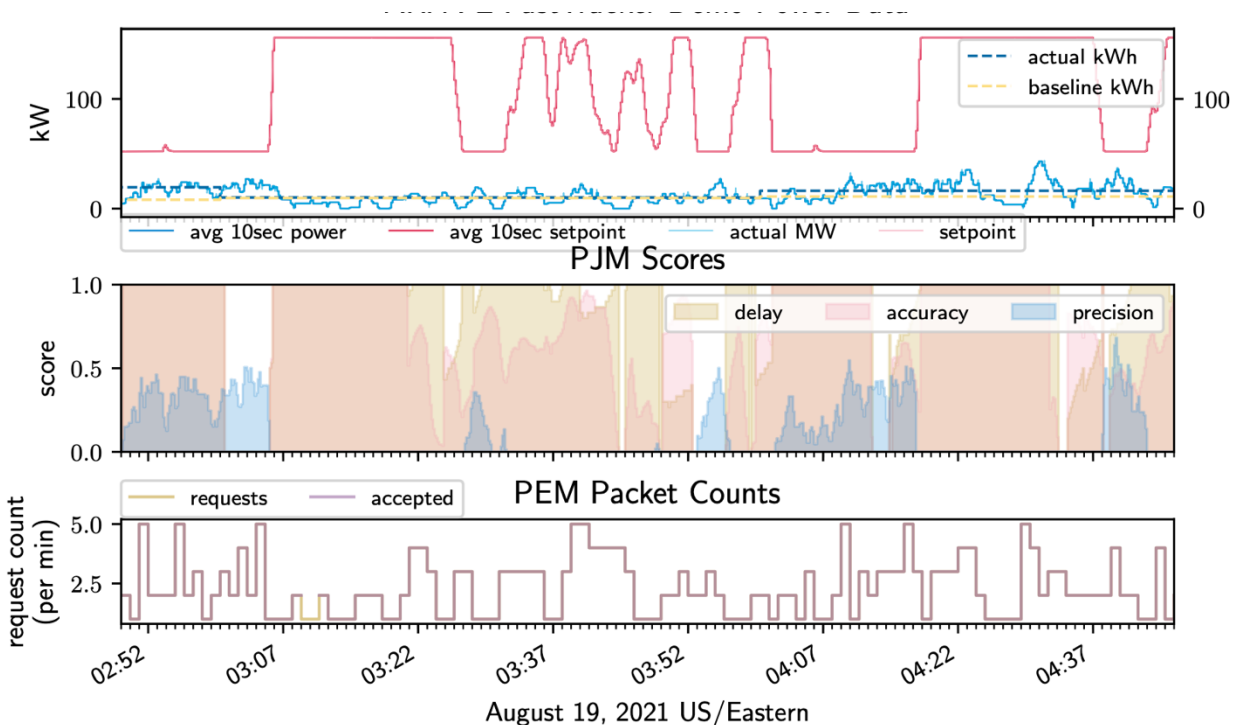


FIGURE 6 Results from Frequency Regulation Trial 1. The upper panel shows the target setpoint and the actual power. The lower two panels show elements of the PJM score and the number of “energy packets” delivered in each time period.

In Trial 2 (Figure 7) we scaled down the relative position of the setpoint, but not far enough to fully allow the load to track with the target signal. In this case, the Accuracy score increased to 0.87, Delay to 0.96, Precision to 0.50, and the overall composite score was 0.78.

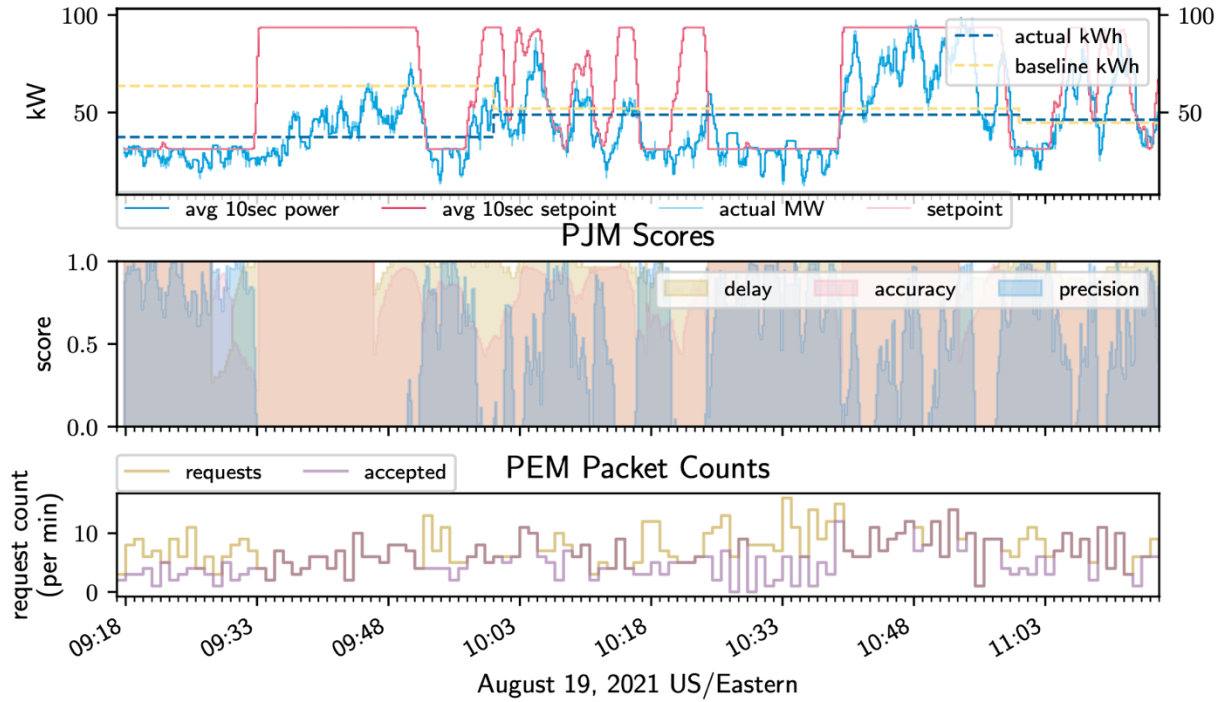


FIGURE 7 Results from Frequency Regulation Trial 2 in which the target setpoint was scaled down to an average of about 60kW, which was still significantly higher than the average water heater load. This trial resulted in a composite PJM performance score of 0.78.

In the final “Trial 3” (Figure 8), we further scaled down the target setpoint to about 50kW, substantially increasing the overall performance scores. This case had an Accuracy score of 0.95, Delay of 0.99, Precision of 0.77, and Composite of 0.90. This score is on par with or exceeds the overall performance scores commonly achieved by natural gas power plants, which suggests that it is indeed possible for aggregated DERs to provide frequency regulation services to the grid.

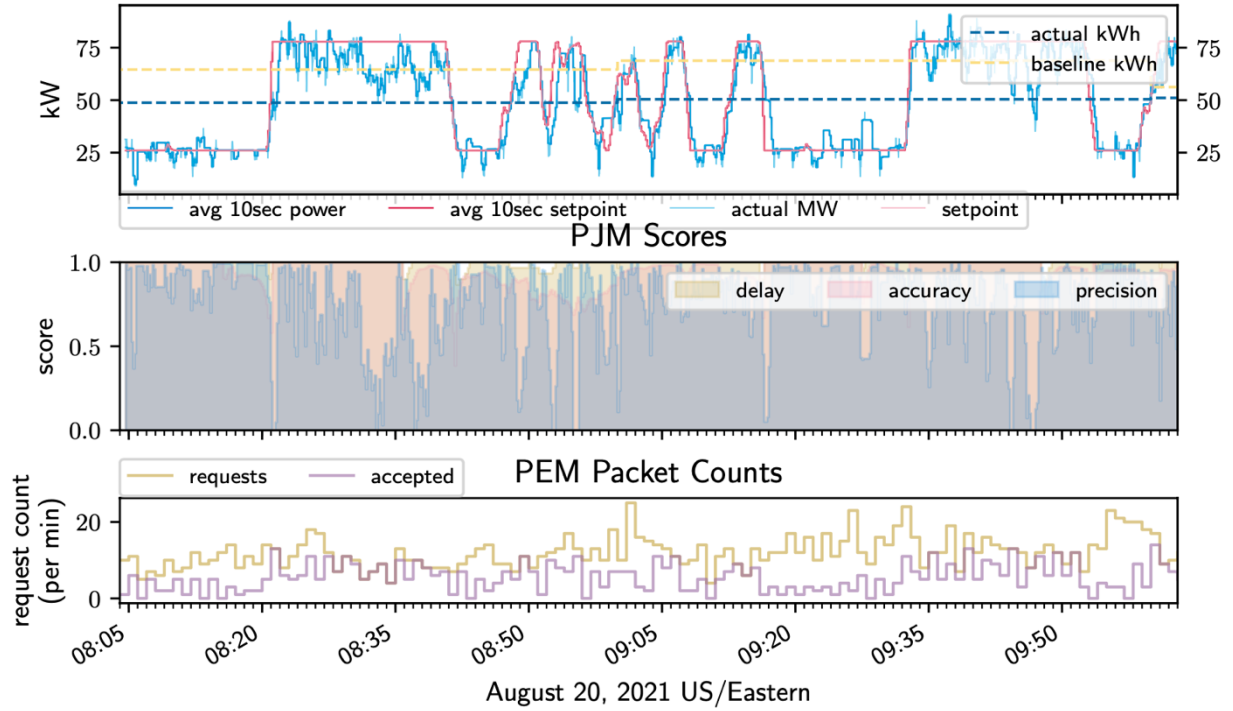


FIGURE 8 Results from Frequency Regulation Trial 3 in which the target setpoint was scaled down to an average of about 50kW. This trial resulted in a composite PJM performance score of 0.90.

3.1.4 Consideration of Stored Energy in DERS for Ancillary Services

Flexible load devices typically have some ability to shift the time at which they pull energy from the grid and “store” energy. Water heaters, refrigeration systems, and buildings store energy in thermal format. EVs and BTM batteries store energy chemically and pool pumps have a daily minimum run time that can be shifted through the day. Understanding how much stored energy exists in a fleet of devices is a useful parameter in DER scheduling in order to provide ancillary services.

In order to understand this stored energy, we used the data from Trial 3 and measured the aggregated amount of stored energy in the fleet but adding up the effective stored energy in each DER (primarily water heaters). For a water heater, devices that are 10 degrees F above their setpoint are considered to be at 100% “state of charge” (SoC), and devices that are 10 degrees below their setpoint are considered to be at 0% SoC.

Figure 9 shows the resulting state of charge for our fleet of devices. Clearly, over the 40 minutes of this trial the total amount of stored energy decreases due to the fact that the target load level is held below the average/baseline for a significant portion of the time. In the final 15 minutes of the trial, stored energy increases again (as the overall load level is higher). This trial shows that it is feasible to monitor stored energy in a fleet of DERs modeled as a virtual battery.

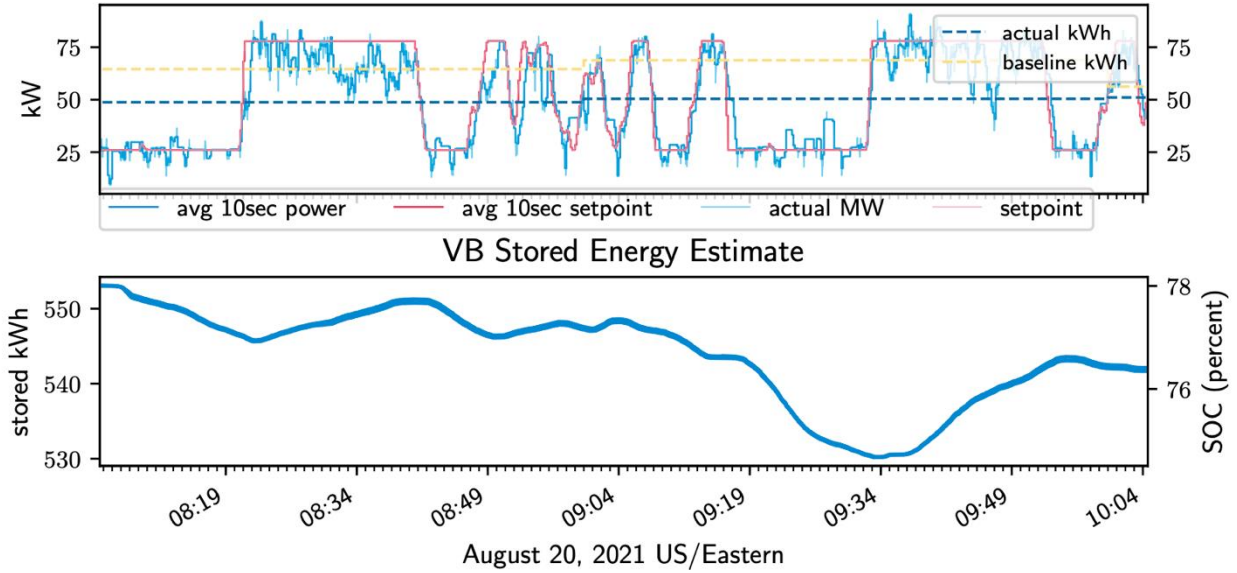


FIGURE 9 Stored energy from Trial 3. The top panel shows the actual and target power timeseries (as in Figure 8). The lower panel shows the total amount of stored energy in the fleet of DERs.

3.2 AUTOMATICALLY TRANSITIONING AMONG OPERATING MODES

This use case demonstrates the ability of Beyond DERMS to automatically switch between operating modes based on grid and market conditions. This use case demonstrates the algorithms for optimally switching in and out of ancillary service markets. In this use case, we optimize DER scheduling among ancillary services, peak reduction, and energy arbitrage. Performing this optimization requires bidding into wholesale ancillary service markets, which are only just now beginning to open up for BTM DER participation.

To enable VBs so that they automatically detect the right time to transition from one operating mode to another, we used relatively simple rules. Under this system, DERs are scheduled to perform energy arbitrage when no peak events have been scheduled and when no network constraints are binding. When a distribution network constraint is binding, the DERs “behind” that constraint automatically switch to a constraint management mode under which they cease to perform services for the bulk grid and focus exclusively on ensuring that voltage and current limits are not violated. Similarly, DERs operate in arbitrage mode until they approach the pre-positioning period for a peak event, at which point they transition into peak management mode. Once the peak event has concluded or the constraint is no longer binding, the DERs return to focusing on their default load shaping grid service.

3.2.1 Motivating Scenarios

Under normal operating conditions when distribution network constraints are not binding, DERs can easily be set to provide services into wholesale electricity markets, such as load shifting for energy arbitrage or ancillary services. However, in the event of a need for peak

reduction or constraint management, DERs must switch operating modes to satisfy system constraints.

In all cases, it is important to manage DERs to honor customer quality of service (QoS) limits. Under normal conditions DERs need to strictly adhere to these constraints.

In the Beyond DERMS platform DERs typically default to an energy arbitrage mode under normal conditions when constraints are not binding. The question is, how can we automatically enable DERs to switch to one of the other modes when it is advantageous or necessary to do so, without requiring unnecessary complexity in the control algorithms.

Here we look specifically at the case of automatically detecting “high-cost windows” and triggering a switch to peak reduction mode when these windows occur. For this use case, we define a “high-cost window” as a period of time when there is a very high probability that this particular hour is the peak hour of the month, which is when utilities in the region are assessed transmission fees based on their contribution to the peak monthly load. During these high-cost windows, it is optimal to transition from the relatively mild load shaping algorithm to an aggressive peak reduction mode.

A key element of the project was enabling customers to stay informed of peak events through the mobile application associated with the platform. We have found that by allowing customers to be informed of events, the impact of peak reduction events has less negative impact on customers’ experienced quality of service. Thus, as an element of enabling automatic mode switching, we developed the ability for the DERMS platform to send peak event notifications to the associated phone application.

3.2.2 Process for Automated Mode Switching

In order to enable mode switching between the energy arbitrage and peak reduction modes we employed the following process:

1. Forecast circuit-level and regional net load over a ~72-hour horizon.
2. Compute the probability of binding network constraints or expensive peak load events.
3. If probability is low:
 - Continue to perform economic grid services within customer QoS limits (ancillary services or load shaping for energy arbitrage).
4. If probability is high:
 - Execute peak load management.
 - a. Notify customers.
 - b. Pre-position.
 - c. Minimize load with (somewhat) relaxed QoS limits.
 - d. Recovery.

The precise methods used for peak load probability estimation were described in a prior report. Figure 10 shows results from the peak load forecasting tool through which the automatic transition into peak reduction mode was enabled.

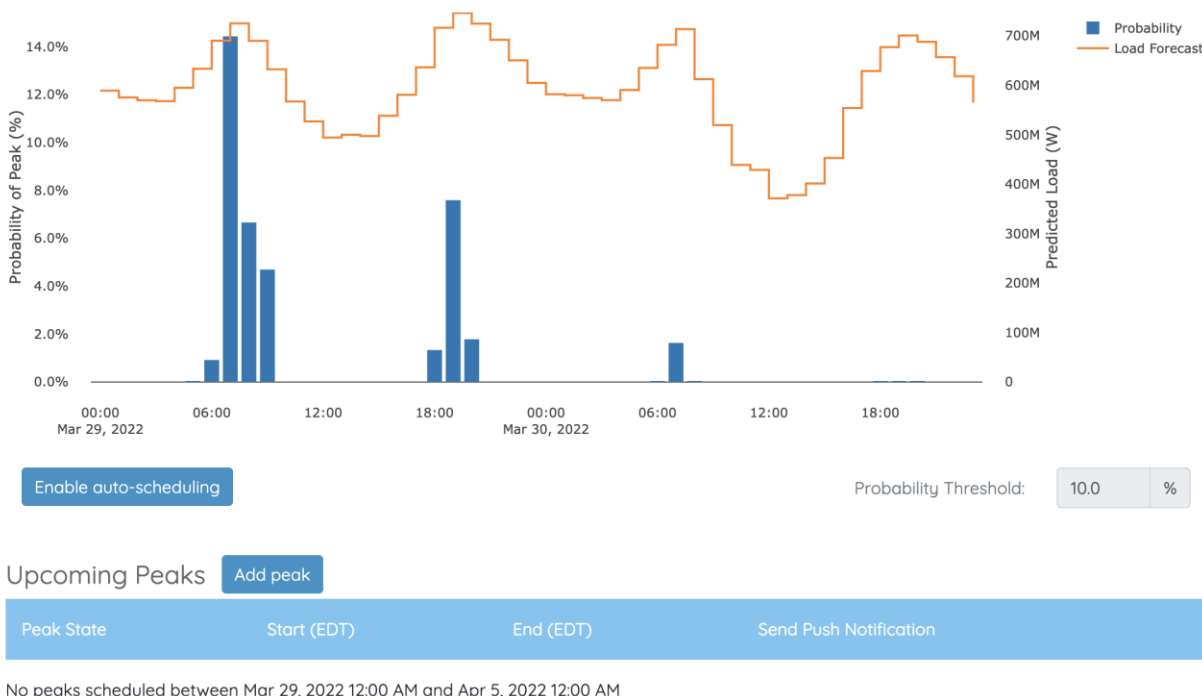


FIGURE 10 A screenshot from the Beyond DERMS platform showing the results of peak load probability forecasting. In the platform these probabilities were used to auto-schedule peak events, thus automatically transitioning from load shaping mode to peak reduction mode.

3.3 BLACK-SKY-DAY OPERATION

Distributed Energy Resources have the potential to generate a wide range of benefits including grid services for utilities and balancing authorities/ISOs and financial savings for consumers. However, many have noted that DERs also have the potential to make both the grid as a whole, and individual customer locations more resilient to bulk grid outages. This section reviews how a DERMS can facilitate both system and local resilience and presents illustrative testing results from a small-scale demonstration with a residential battery system.

Grid-connected batteries are one of the most promising technologies for enabling resilience from DERs. Home battery systems like the Tesla Powerwall are becoming increasingly popular among consumers with rooftop PV systems. And community-scale battery systems, when paired (for example) with community solar, are increasingly being adopted in order to enable community microgrids that can enable limited resilience functionality, such as powering a school or a hospital for a period of time if the bulk grid fails.

In order to deliver resilience to the grid as a whole, a system is needed in which DERs have “good reflexes,” such that they can respond to both local and regional grid problems.

With respect to regional grid problems, the frequency regulation results described in Section 3.1 demonstrate that it is possible for DERs to react quickly (in seconds) to a balancing signal from the bulk grid. With this capability in place, it would be possible for grid operators, for example, to send an emergency ramping signal to a fleet of DERs in order to rapidly reduce load or generation when the risk of a cascading failure is high, thus mitigating blackout risk.

Similarly results previously presented in this project show that it is possible for DERs to sense locally measured voltage and frequency and adjust their power output accordingly.⁸ With this capability, DERs can react to local conditions, enabling behaviors that can increase grid resilience.

Finally, in particular for battery systems combined with solar PV, DERs can provide local resilience by enabling backup power systems that can continue for long periods of time, even if the build grid is unable to provide reliable power.

DERMS platforms have the potential to coordinate these core behaviors, thus enabling both local and regional energy system resilience.

3.3.1 Grid-interactive Battery Demonstration Results

In order to demonstrate that residential-scale batteries can respond quickly to signals from a DERMS when grid-connected, we developed a demonstration using a home battery system connected to a residential-scale inverter, as shown in Figure 11. This system was connected to the Beyond DERMS platform using a small Wi-Fi-enabled microcontroller that communicated with the inverter via the MODBUS protocol.

⁸ <https://www.osti.gov/biblio/1825329-beyond-derms-platform-development-flexibility-prediction-value-measurements>.



FIGURE 11 The residential-scale battery system and inverter used for this “Black Sky” demonstration.

In order to demonstrate that batteries can participate in remotely initiated grid services managed by the DERMS, we performed a simple test in which the DERMS sent a message to the battery controller to initiate a discharge event and then a subsequent charge event. The results in Figure 12 show that this type of remote management is indeed feasible.

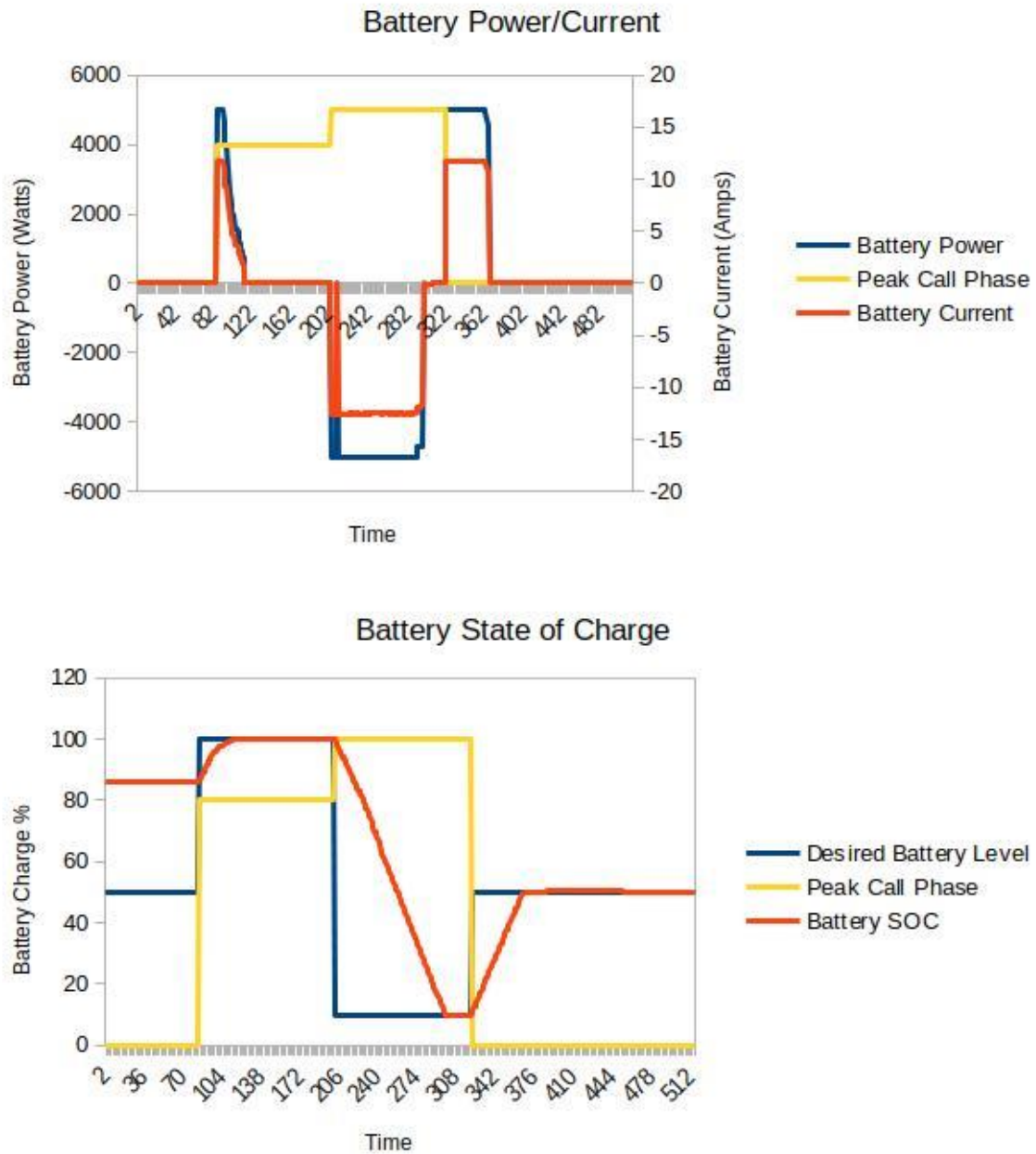


FIGURE 12 The power and current (upper panel) and state of charge (lower panel) for tests initiated by remote commands from the DERMS.

3.3.2 Local Resilience (Off-grid) Mode Battery Demonstration Results

In order to demonstrate the potential for off-grid operations from a residential battery system, we used the DERMS to initially configure the battery so that it would supply local loads in the case of a grid outage. In this grid-forming mode when voltage from the grid is not measured, the inverter sets the battery to discharge current to supply a local load (an EV charging station, in this case).

Figure 13 shows results from a test of this functionality for the battery setup shown in Figure 12. As shown, when the grid is disconnected, the battery switches to supplying current to the local load. After the grid reconnects, the battery charges in order to recover its state of charge to the nominal level.

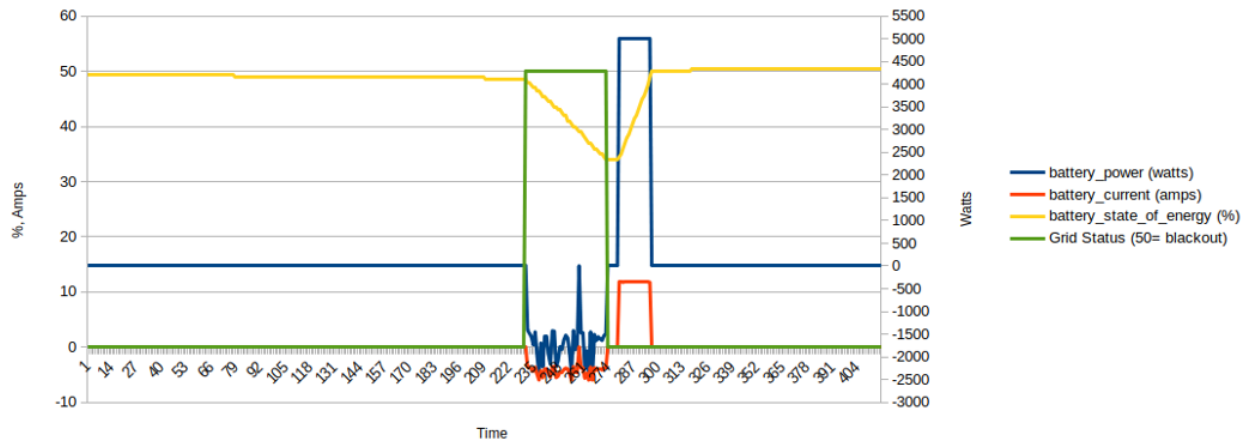


FIGURE 13 Battery behavior during blackout scenario with EV charger.

3.3.3 Other Grid Services

The existing Beyond DERMS platform can be used for other grid services and markets including

- *Resilience & black start*, in which DERs react to local conditions to help users to recover from bulk grid outages (e.g., with the help of solar and batteries) or to support the resilience of the bulk grid by locally reacting to voltage and frequency deviations.
- *Ramping*, in which DERs may be responsible for providing ramping patterns and parameters at regular intervals during the operating day, with Beyond DERMS platform determining a unified optimal ramping capability and ramp rate limits with or without storage.
- *Capacity Services*: Instead of relying only on the nameplate capacity information of the distributed PVs, information about the PV generation under different sun-tracking capabilities can be more useful for accurately estimating the PV capacities. It is important for Beyond DERMS platform to determine the optimal size of combinations of different DERs (e.g., storage + PV, storage + flexible load, etc.) to achieve target MW capacity with a certain guarantee.

4 CONCLUSION AND FUTURE WORK

4.1 CONCLUSIONS

This report on the Beyond DERMS Phase 3 project demonstrates how the Beyond DERMS platform developed in phases 1 and 2 can be leveraged to support a portfolio of grid services based on findings from a small-scale demonstration. In particular, the report describes use cases for enhanced peak management, load shaping, and energy arbitrage along with automated provision of ancillary services to the ISO/RTO (i.e., frequency regulation) using PJM price signals.

The report describes the resilient operation of the Beyond DERMS platform under abnormal grid conditions by dispatching existing storage assets to supply power to the local loads. This demonstrated the automatic mode switching capability of the platform in response to grid conditions (i.e., black-sky-day operation) and market conditions. In the transition mode scenario, DERs can transition from providing grid services to the bulk grid to a resilience mode to support local customer reliability and resilience.

The performance of each grid service is measured in terms of flexible capacity offered per device and for the portfolio as a whole. This report identifies the extent to which different device types can provide different types of grid services; specifically, how much flexible capacity can be delivered for an average device, and for how long. This characterization allows us to build an equivalent “virtual battery” model for a fleet of devices in each category, or for a combination of devices. The model characterizes how flexible capacity changes with season, temperature, and customer quality of service limits.

4.2 GAPS AND FUTURE WORK

4.2.1 Distribution Network Simulator

Distribution network simulation and optimization models are key elements of advanced DERMS software. Open-source software systems (such as GridLab-D, which was used in this project) can be valuable elements of a DERMS. However, we found a number of limitations in GridLab-D that we think could be addressed by migrating to a more advanced power flow tool such as the “PowerModelsDistribution” tool developed by Los Alamos National Laboratory.⁹ Furthermore, new approaches to distribution network simulation and modeling are needed. We hope this need will be addressed in a future large-scale demonstration project.

⁹ The tool incorporates modern methods of optimization-based response and controls to reduce the scalability and convergence challenges that are often faced by simulation, in particular those seen when combining distribution and transmission level modeling.

4.2.2 Large-Scale Deployment

It is important to evaluate the ability of DER management platforms to perform grid services at the MW scale. While the results described in this report are promising, they represent a fairly limited scale and such tests are often viewed cautiously within the U.S. electricity industry. Larger-scale tests often reveal new challenges and opportunities for innovation. Further, results from large-scale demonstrations are often necessary to support tech-to-market transitions. The work completed in this project provides a solid foundation for a larger MW scale demonstration of the ability to orchestrate DERs to provide advanced grid services that go beyond conventional demand response. This DOE/OE from had led to the technology being demonstrated by Packetized Energy on a large-scale project funded by the California Energy Commission BRIDGE Program.¹⁰

4.2.3 Network Constraint and Congestion Management

One of the key challenges in aggregation platforms is managing the network constraints while ensuring grid services. Aggregators have limited visibility of network operating conditions, particularly such constraint violations as reverse power flow, equipment overloading, voltage limit violations, and line congestions due to lack of network model and topology. These constraints are generally managed by DMS or utility DERMS. The interaction of the Beyond DERMS platform with DMS/Utility DERMS can play a significant role in ensuring that the network constraints are respected through network management functions. This concept has been demonstrated by Argonne National Laboratory in collaboration with PECO, Schneider Electric, and Schweitzer Engineering Lab on a DOE-funded project where microgrid is integrated with utility DMS in order to provide support services to distribution grids, particularly the voltage support, load relief, and monitoring of DERs and system operating states.

The Beyond DERMS platform communicates mainly with behind-the-meter units and uses them in an aggregated fashion to coordinate DERs to ensure that system voltages and currents remain within limits, providing a non-wires alternative to conventional transmission and distribution network upgrades, whereas DMS/Utility DERMS uses this platform—among other resources, such as DER aggregators, utility owned and operated DERs, virtual power plants (VPPs), microgrids, and traditional resources such as switches, capacitors, network configurations etc.—to provide DSOs with complete awareness, effortless real-time and look-ahead constraint management, optimal coordination and management of DERs and aggregators, and other system-wide operations. Therefore, if properly integrated, DER aggregators and DMS perfectly complement one another, and can provide a full spectrum of DER services regarding both customer- and grid-related operations regardless of the DERs' sizes and locations. In this configuration, when a distribution or transmission limit violation is identified, either in real-time or forecasted, the DERMS may be in a position to provide service(s) that can help manage that

¹⁰ <https://www.globenewswire.com/news-release/2021/02/03/2169132/0/en/Packetized-Energy-Awarded-2-Million-Contract-to-Make-Energy-Demand-Flexible-and-Help-Solve-California-Grid-Challenges.html>.

violation by re-dispatching its DERs to alleviate overloads or mitigate voltage or power quality problems [IEEE P2030.11].

While network constraint management is an important aspect of future research, it is important to implement and demonstrate the functionality of DERMS functions specified in IEEE 2033.11 in many forms of DER aggregation, in microgrids, virtual power plants, and resource mixes created for specific market applications.

4.2.4 Cybersecurity

At the utility and system operator level, contributions made toward DER cybersecurity do not pay sufficient attention to inter- and intra-domain interactions and smart-inverter connectivity interfaces, and lack effective scrutiny of third-party vulnerabilities and external threats. While the advent of new technologies (such as DERMS and aggregators amid utilities and DERs) looks promising from an operational flexibility and resiliency standpoint, the cybersecurity implications of enabling communication infrastructure remains largely under-researched. Under California's Rule 21, DERs are required to support protocol-based security solutions, which are insufficient. DERs span multiple security administrative domains, meaning that the utility may only be able to monitor the security posture of devices up to the smart meter while DER owners and aggregators control and manage their devices themselves. The various networks used to control the DER are likely to be interconnected with the utility control center, aggregators, manufacturer cloud networks, and other IT networks, thereby increasing the attack surface.

While development of technical and security functionalities for DER communication and control networks is still underway, the adoption of smart-inverter-enabled DERs is taking place at a breakneck speed for utility- and customer-owned DERs. Utility-owned DERs traditionally suffer from security vulnerabilities stemming from the use of legacy systems (e.g., programmable logic controller, primitive gateway) and communication protocols (e.g., DNP3, Modbus) with insufficient security features. Customer-owned DERs use unsecure communication means (e.g., internet) and service platforms (e.g., cloud) to communicate with the control center directly or indirectly via DER aggregators and vendors (non-utility entities) with no propriety advantage.

The autonomy and privileges of these vendors and aggregators over DER devices, if misused, can pose a cybersecurity concern.¹¹ In particular, the security requirements for the interaction between customer-owned DERs and aggregators and between aggregators and utilities are still being discovered when it is highly expected that these aggregators will pervade the local DER administration space in a bid to provide the best experience to customers and optimal grid services to utilities. Several cyber-vulnerabilities also exist at DER devices with remote-control and two-way communication capabilities (IEEE 1547TM 2018 compliant), which,

¹¹ J. Pack. "Cybersecurity for distributed energy resources and SCADA systems." (September 19, 2019). <https://www.tdworld.com/smart-utility/grid-security/article/20973136/cybersecurity-for-distributed-energy-resources-and-scada-systems>

if exploited, could potentially cause a local supply-demand imbalance and power cuts in worst-case scenarios.

A comprehensive framework composed of layered cyber-physical solutions is required to prevent, detect, and mitigate cyberattacks through DER devices and associated communication systems. More research is currently required on (1) the involvement of aggregators in the large-scale DER infrastructure, (2) the cyberthreats and operational risks introduced as a large number of devices and access points integrated into utility systems, and (3) the security of parameters governing the provision of aggregator services. Therefore, there is a need for (1) a secure network architecture for end-to-end solutions for grid services while acknowledging the possibility of attack initiation and propagation from external agents, (2) the realization of cross-domain cybersecurity interoperability, and (3) attack-resilient grid service participation strategy among DMS, DERMS, DER aggregators, utility-scale PV plants, and customer-owned DERs needed to deliver reliable grid services.



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