Final Scientific/Technical Report

University of Vermont
Final Scientific/Technical Report
Packetized energy management:
coordination transmission and distribution
DE-AR0000694

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Public Executive Summary

The project Packetized Energy Management (PEM): Coordinating Transmission and Distribution was part of the ARPA-E NODES program from 2015 to 2023. The high-level goal of the project was to develop and demonstrate novel, scalable, and impactful technologies related to the coordination of networked distributed energy resources (DERs). By demonstrating responsive means by which fleets of DERs could be coordinated to enhance grid operation and reliability, the U.S. could accelerate renewable integration and electrification efforts and meet decarbonization goals.

The PEM technology[1] builds on concepts that underpin the largest device-driven network on the planet: the Internet. The Internet's scale is enabled by key principles around anonymity, packetization of data, and random-access protocols. This project has adapted these key principles to the problem of coordinating networked DERs, which means that PEM technology represents one of the most advanced, scalable, and comprehensive DER technologies on the market today. Specifically, PEM achieves the following major advantages:

- **Distributed intelligence** means that devices compute locally to ensure that end-user *quality of service* (QoS) and device health is maintained.
- **Randomization** of device access requests ensures that devices have *equitable* access to the grid during DER coordination.
- **Packetization of energy** requests ensures that the DER Coordinator can manage diverse and heterogeneous fleets of DERs with a real-time coordination mechanism, which enables a *responsive* fleet capable of delivering grid-services across timescales.
- **Bottom-up framework** enables *plug-and-play* scheme that allows for highly efficient device-grid-coordinator data-driven actions and enables network-aware PEM and decentralized PEM modes to dynamically manage *grid reliability.*

Upon completion of the project, PEM technologies satisfy NODES Category II specifications for synthetic balancing reserves and exceed PJM's Reg-D performance specifications for frequency regulation and can deliver valuable grid services across a myriad of relevant timescales (e.g., capacity markets, whole-sale energy markets, ancillary services, such as frequency regulation, and fast synthetic inertia/damping). Combined, these grid services generate anywhere from \$100-\$1,000 per year per *flexible* kW (depending on location and operating times), which is more than enough (at scale) to deploy and operate fleets of DERs under PEM for a technology payback of less than 2-3 years (again, depending on location). Thus, this project has shown that PEM technology is technically and economically feasible! Beyond the R&D advancements and achievements, the technology resulting from the project completed the entire TRL cycle: concepts, peer-reviewed papers, patents, products, commercialization, and reaching scaling due to the successful outcomes and hard work of the Performance Team and the spin-off company, Packetized Energy, which was acquired within the duration of the project (2015-2023). Thus, this project directly resulted in the creation of 10s of domestic jobs, know-how, and new

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[1] For a basic overview of Packetized Energy Management technology, please see IEEE Spectrum article from Feb, 2022: https://spectrum.ieee.org/packetized-power-grid and a separate YouTube video made by a STEM influencer: https://www.youtube.com/watch?v=NU3woCaFSZs

technology that is now being incorporated into software coordinating over 1 million devices – *it worked and it matters*!

The technical performance of PEM was illustrated through development of a real-time, cyber-enabled DERs+Grid simulator at the University of Vermont in 2018, a Vermont-based field demonstration with 156 packetized devices in Aug., 2019, and another field demonstration with 208 devices in Vermont and South Carolina in Dec., 2021. Specifically, the major technical results of the project are summarized below:

1) **Diverse device applications:** Before the project kicked off, packetized concepts had only been adapted for electric vehicles (EVs) and only considered static power limits on a fleet of EV chargers. Upon completion of the project, PEM concepts have been adapted and applied to map the following distributed energy resource (DER) assets' need for energy (NFE) to the probability of making a packet request. This enabled responsive re-shaping of the fleet of devices and the delivery of grid services. In particular, the PEM technology today has been extended and adapted for the following types of devices:
    - Thermostatically controlled loads (TCLs), including electric water heaters, A/Cs, and heat pumps;
    - Stationary electric batteries;
    - EV chargers;
    - Single-phase PV inverters to coordinate active and reactive power.

2) **Signal Tracking**: PEM concepts have been advanced to dynamically prioritize DERs based on their NFE. This is accomplished by mapping the NFE to the mean time-to-request (MTTR). The incoming requests are then accepted/denied by the DER coordinator to modulate aggregate demand. This capability has been applied to complete NODES Category 2 specification successfully. In the first phase of the project, the PEM-enabled fleet of DERs would provide synthetic ramping services (Fig. 1). In the second phase of the project, this method was extended to consider faster frequency regulations (Fig. 2). This work has supported numerous IP filings and peer-reviewed publications.

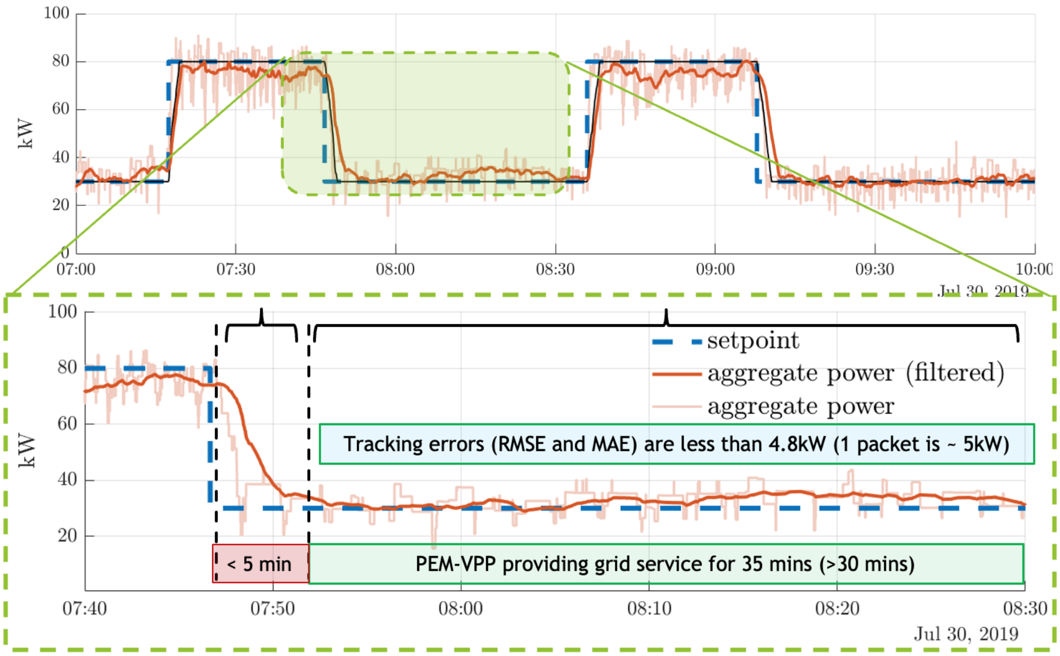

Figure 1: Q12 PEM demonstration results and performance specifications for a VPP with 158 packetized DERs located in Vermont and tracking a square-wave RMT signal on July 30th, 2019.

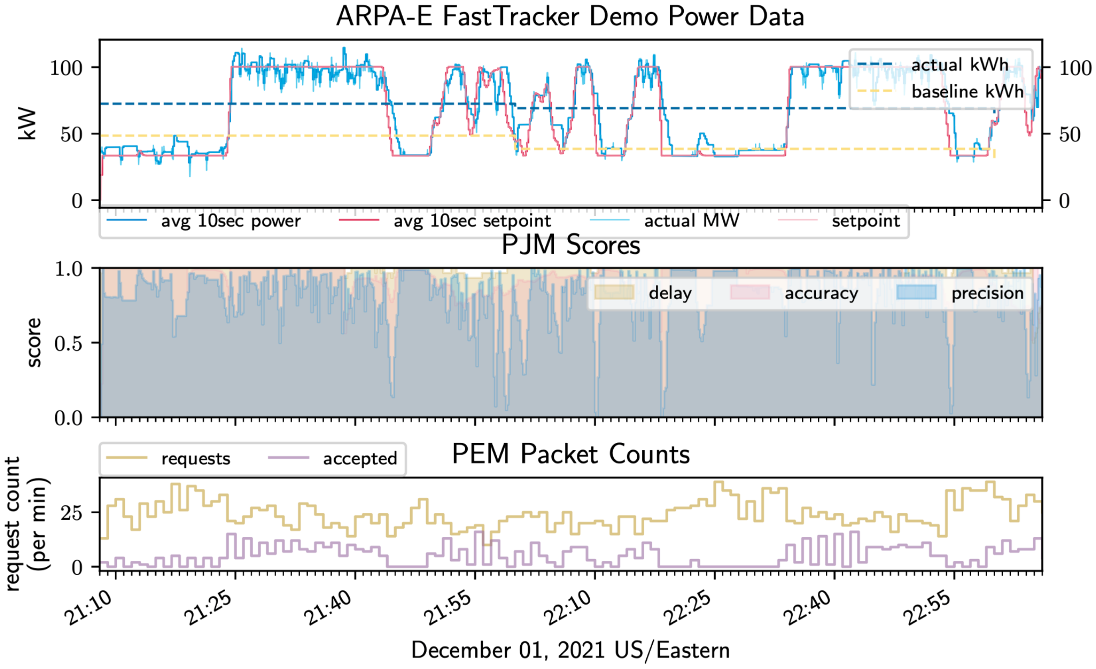

Figure 2: Q22 results from PE demonstrating frequency regulation with PEM with a fleet of 208 packetized devices in Dec, 2021.

3) **Synthetic Inertia and Damping**: A fleet of PEM-enabled DERs can provide various grid services based on *signal tracking* capability. However, new markets for synthetic inertia/damping (e.g., fast frequency response) are evolving and represent an additional

source of revenue for a packetized VB. Technology was specifically developed for accurately estimating and delivering fast frequency response from a fleet of packetized devices. For each accepted packet, the PEM coordinator updates a timer that contains information about each DER's packet completion time. In aggregate, this information is compiled by the Coordinator into the Timer Distribution. Thus, the Timer Distribution represents the proportion of devices that will expire in the next *T* seconds. From this information, we devise a control law that interrupts packets based on the locally measured frequency and their time-to-completion (TTC) – e.g., see Fig. 3. This mapping considers both rate and relative terms of the frequency measurement, which represents a Proportional-Derivative (PD) control law. This work has supported numerous IP filings and peer-reviewed publications.

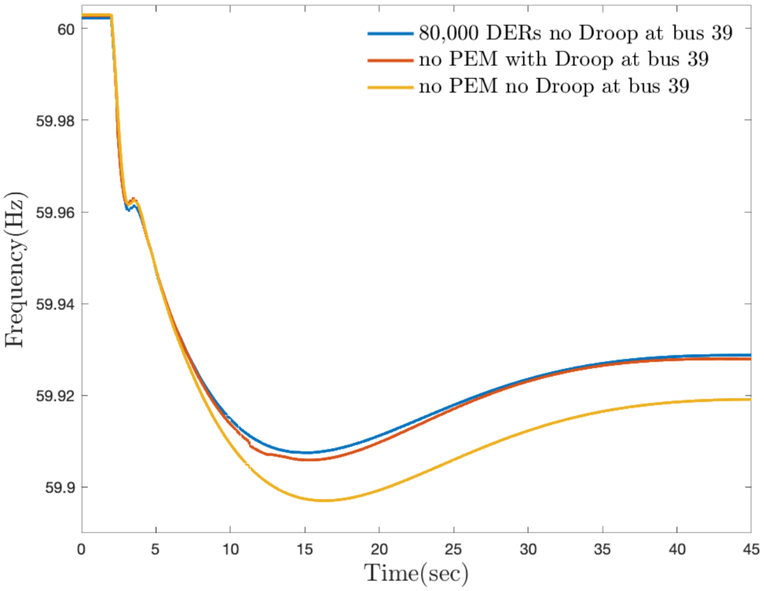

Figure 3: Illustrating M9.3.2 (Q16) and the effect on simulated grid frequency from synthetic damping provided by Decentralized PEM control technology that dynamically interrupts packets based on devices' measured frequency and time-to-completion. Note how 80,000 packetized loads can deliver similar virtual damping (blue) as a generator's droop response (red).

4) **Network-aware PEM**: combining PEM Tracking capability with available grid (status) measurements (e.g., nodal voltage magnitude and/or transformer current or just locations of measured grid violations), we have developed PEM technologies that actively mitigate grid violations caused by DERs as seen in Fig. 4. The approach requires grid data and/or grid models to be shared with PEM coordinator to reject packet requests from nodes (voltage) or feeders (transformer) with active violation. This effort has supported numerous peer-reviewed publications.

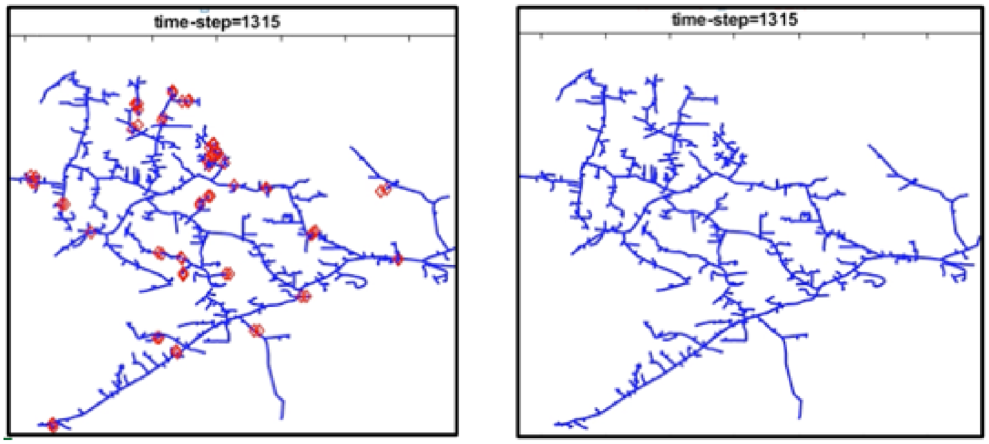

Figure 4: Illustrating grid simulation without (left) and with (right) Grid- or Network-Aware PEM (NAPEM) for a specific time-step. The number of grid violations (red) are entirely eliminated with NAPEM with a negligible loss of (tracking) performance (PJM composite scores drop less than 1.5%).

Accomplishments and Objectives

This award allowed the University of Vermont to demonstrate a number of key objectives. The focus of the project was on developing the technology, Packetized Energy Management (PEM), to advance the state of the art in distributed energy system.

A number of tasks and milestones were laid out in Attachment 3, the Technical Milestones and Deliverables, at the beginning of the project. The actual performance against the stated milestones is summarized in Table 1.

Table 1: Key Milestones and Deliverables

Tasks	**Milestones & Deliverables**

Task 1: Develop realistic distribution and transmission grid models 1.1 Gather and verify data from GMP and VELCO. 1.2 Process data from industrial partners	Q1 (M1.1.1): Deliver report detailing the amount and type of grid models and data gathered from GMP and VELCO and determine Reserve Magnitude Target (RMT) for primary technical targets. **Actual Performance:** (October 31, 2016). 100% complete as we successfully delivered data metrics on: 500-bus (positive sequence) transmission and 500-node (3-phase) distribution circuit data metrics and more than 2000 sub-metered electric water heater data at 15-minute sampling intervals. RMT was estimated at ±10% of total controllable load capacity (i.e., 5kW water heaters yields about ±500W flexibility, on average). Q2 (M1.1.2): Deliver report describing smaller version of a large-scale GMP and VELCO models. **Actual Performance:** (January 30, 2017) 100% complete as report was submitted to ARPA-E and outlined reduced models of a 162-bus transmission system and a reduced 35-node unbalanced distribution feeder. Q2 (M1.2.1): Generated a salient set of separate daily historical load and renewable generation profiles **Actual Performance:** (January 30, 2017): 100% complete as we leverage established methods from statistics and signal processing to first interpolate 10-15-minute real data with a cubic spline after which we add zero-mean high-frequency variability to the spline with an appropriate noise model. Q3 (M1.2.2): Delivered verification of grid data and profiles represent feasible AC solutions on transmission and distribution on 1-minute time-scale for salient data profiles **Actual Performance:** (Completion date) 100% complete. Team provided details and simulation results on the systems: Green Mountain Power and VELCO. The three-year hourly data of total load in Vermont were given to team. The hourly data given by VELCO were interpolated to 1 minute by the team. The team realized that VELCO has some voltage sag in some areas,

	when not enough reactive power is available. This is in agreement with feedback from VELCO. It was also demonstrated using MATLAB and the sweeping power flow method that the 3- phase unbalanced distribution system converges in less than 10 sweeps.

Task 2: Level 1 Transmission Development under PEM 2.1 Assess state- of-the-art SC- OPF formulations and down- select to 2-3 suitable formulations for testing. 2.2 Develop, implement and test SC- OPF algorithms. 2.3 Develop Level 1 Model- Predictive Energy Balancing Controller (MPC). 2.4 Leverage previous work, develop and implement stochastic MPC with stochastic load and renewable forecasts and stochastic VPP	Q1 (M2.1.1): Deliver report describing and comparing assessed SC- OPF formulations **Actual Performance:** (October 31, 2016). 100% complete as we reported on an hourly SC-OPF economical generator set-points on a rolling horizon (to manage uncertainty in forecasts) and computation of a feasible secure economical costs subject to uncertain renewable and load profiles and VPP resources Q2 (M2.2.1): Deliver report comparing the optimal solutions and computational efficiency of the down-selected SC-OPF formulations. **Actual Performance:** (January 30, 2017): 100% complete as report was delivered to PD. Report shows that CC-based SCOPF compares well with traditional (deterministic) DC-based SCOPF (solves times are almost identical (at 1-4 seconds and less than 2% difference in optimal solution). This indicates that uncertainty can be contained within a possible predictive grid optimization scheme to incorporate flexible demand, energy storage, and generator ramp-rate limits. Q3 (M2.3.1): Solved centralized deterministic MPC problem **Actual Performance:** (June 8th, 2017): 100% complete as the MPC was implemented on IEEE RTS96 test case using realistic load and generation patterns. The report included 5 different scenarios of placing and capacity of storage devices over different receding horizons. Solve time was less than 25 seconds on a laptop. **Q4 (M2.3.2 Go/No-Go)**: Solved combined SC-OPF+MPC Level 1 problem **Actual Performance:** (July 30th, 2017): 100% complete as the average SC-OPF run time for each hour is less than one second (~ 0.5 sec) and average run time of MPC (for prediction horizons below 40 steps is less than two seconds (~ 1.5 sec) across different scenarios of length of control horizon and capacity of VPPs.

	Q4 (M2.3.3): Compiled report on Level 1 communication/data requirements for Level 1 SC-OPF and Level 1 MPC coordination. **Actual Performance:** (July 30th, 2017): 100% complete as report was approved by PD and showed that the proposed Level 1 solution represents trivial bandwidth requirements (even at scale 100X network size or more than 10,000 buses) compared to existing data infrastructure in transmission operations. Q7 (M2.4.1): Solved stochastic MPC problem in less than 25 seconds in MATLAB on personal laptop **Actual Performance:** (May 23, 2018): 100% completed. We formulate key components of an uncertain VPP and provide an analytic reformulation of a stochastic MPC problem and complete analysis from simulations of Level 1 MPC with two and ten uncertain VPPs and show we can solve in less than 5 seconds, which satisfies the 25 seconds limit. The term Dynamic Capacity Saturation was coined as well here and led to numerous publications on stochastic virtual power plants.

Task 3: Level 2 Distribution Development s for PEM 3.1 Develop a mixed- integer nonlinear programming (MINLP) formulation of three-phase distribution optimal power flow model in MATLAB. 3.2 Solve MINLP three-phase unbalanced distribution optimal power flow model with parallel computing for scalabilit 3.3 Develop Level-2 VPP Coordinator to reschedule VPPs	Q2 (M3.1.1): Model converges with default solver parameters to a local optimal solution in 30 minutes for the modified small test feeder from GMP. **Actual Performance:** (January 30, 2017): 100% complete as the small 35-node (unbalanced) test-feeder solves a continuous relaxation of the MINLP formulation (i.e., NLP formulation), which works well for smaller networks. The solve time is 25 minutes and meet specs. The formulation includes 3-phase configurations of transformers, lines, and shunts and batteries and uses a look-ahead horizon of 3 hours with 15-minute intervals (i.e., 12 timesteps). Q3 (M3.3.1) Linearized QP model computes optimal solution in 20 seconds for small test feeder. **Actual Performance:** (June 8th, 2017): 100% complete as the QP distribution optimal power flow model has been developed in GAMS and MATLAB and solves in less than 2 seconds. The models were tested with 68-node feeder (based on real GMP feeder) using CPLEX solver. The QP-DOPF model is executed every 30 seconds using CPLEX solve in GAMS with tolerance of 1e-5. Q6 (M3.2.1): Distributed computation of MINLP problem converges to a locally optimal solution **Actual Performance:** (May 23, 2018): 100% completed as distributed MINLP OPF scheme was tested on 534-node (>500 nodes) realistic (radial) feeder in less than 30 minutes. The formulation considered a multiperiod formulation (15-minute resolution, over one hour, so 4 timesteps) and partitioned full centralized problem into 10 subproblems, which were solved iteratively and converged to a final (locally optimal) solution in no more than 4 iterations and no more than 24.4 minutes. State of the art commercial solvers could not solve the full (centralized) problem, even when integers were relaxed.

	Q7 (M3.3.2): Linearized QP model computes optimal solution in 20 seconds for large test feeder. **Actual Performance:** (May 23, 2018): 100% completed as the linearized, multiperiod QP-DOPF formulation solved the large 534-node test feeder with 3 VPPs in 14 seconds, which is less than 20 second requirement. The DOPF formulation allocates the total dispatch across the VPPs to achieve the total demanded net load from feeder.

Task 4: Level 3 Packetizing VPP Developments for PEM 4.1 Design automata for PEM - Identify load types, models, and metrics by which consumer QoS will be measured for various loads 4.2 Design automata for PEM 4.3 Design automata for PEM - Augment automaton structure with dynamic epoch-management capabilities 4.4 Establish the communicati on requirements for the developed automata for various load types, epoch lengths, and implementation scenarios 4.5 Develop inference tools for a VPP under PEM 4.6 Develop Inference tools for a VPP under PEM - Forecasting a 30-minute estimate of VPP flexibility and analyze the uncertainty in the prediction 4.7 Develop metrics that define and describe conditions under which VPP can satisfy primary tech targets	Q1 (M4.1.1): Deliver report on the classes of loads applicable for PEM and detailing the metrics and methods for computing consumer's QoS from devices participating in PEM **Actual Performance:** (October 31, 2016). 100% complete as we reported three load types for this project: electric water heaters, electric vehicles, and batteries. We focused on the following metrics for QoS: average SoC, mean deviation from set-point, total discomfort (total shortfall / area outside of SoC bandwidth) and worst-case comfort (maximum magnitude of violation). Q2 (M4.1.2): From sub-metered GMP water-heater data processed in earlier task and from assessment of literature on water **Actual Performance:** (January 30, 2017): 100% complete as the reporting below covers the sub-metered population of 2329 electric water heaters at 15-minute intervals. The report includes relevant metrics and statistics. Interestingly, the data includes on-going water-heater demand response (DR)program, where all heaters are forced OFF around 3-6PM and then are allowed to turn ON (and all do so at the same time). Q2 (M4.2.1): Model and manage one-directional plug-in electric vehicles (e.g., Tesla Motors), thermostatically controlled loads (e.g., water heaters), and bi-directional distributed energy storage (e.g., Tesla PowerWalls) with a packetizing automata for PEM. **Actual Performance:** (January 30, 2017): 100% complete as we present a general automata framework under which one can packetize the three different loads and simulate 1000 (>100) TCLs, 250 (>100) EVs, and 250 (>100) ESSs under a single VPP. Q2 (M4.2.2): Deliver report on simulations of a VPP coordinating 300 heterogenous packetized loads. **Actual Performance:** (January 30, 2017): 100% complete with 300 heterogeneous packetized devices simulated with a single VPP. We show how the VPP responds to step inputs

	in , we will step up and down 300kW. Stepping up, we will track for over 90 minutes with a (30-minute) root-mean-square tracking error of 1.4%, which is 4.6kW or about a single heater. That is, tracking performance meets Primary Performance metrics for upward step-change of 5% of RMT. Stepping down, we can track with 11kW RMS tracking error for 30 minutes and reasonably well for about 60 minutes. Q2 (M4.5.1): Developed inference tools for a VPP under PEM **Actual Performance:** (January 30, 2017): 100% complete as we identified incoming request rates and the previously accepted packet requests rates (i.e., packet completion rate) as critical to estimate available flexibility. It was also shown how more than 100 devices are necessary for the macro-model to accurately capture the behavior of the fleet. These results, though early in the project, aligned well with most modeling/analysis developed in the entire project. Q3 (M4.3.1): Repeated simulations from Milestone 4.2.2 but with a VPP equipped with variable epoch length capability to track dynamic balancing signals (ramp up/down). **Actual Performance:** (June 8th, 2017): 100% complete as the team compared different pairs of (packet length, MTTR) parameter pairs for tracking step changes in the VPP reference signal and provided simulation results for different scenarios. It was found that a fundamental trade-off exists between tracking performance, MTTR, packet length, and QoS. Minimizing MTTR subject to communication bandwidth constraints and having packet lengths no smaller than MTTR provides excellent performance in general. Q3 (M4.6.1): Deliver report on forecast/prediction accuracy and uncertainty as a function of epoch length. **Actual Performance:** (June 8th, 2017): 100% complete as report was approved by PD. The report showed that the macro-model was able to estimate open-loop performance across a

	range of packet lengths and for a broad class of reference signals. Q4 (M4.4.1): Design automata communication requirements for PEM. **Actual Performance:** (July 30th, 2017): 100% complete as the analysis leveraged AWS IoT cloud infrastructure costs of $17/million pings and a conservative upper bound of no more than 96 pings per hour per device. That yields costs of less than $1.20/month-device. Under practical consideration, this cost could easily be made less than $0.40/device-month (or $5/device-yr in cloud costs), which is less than 20% of total revenue generated by a PEM-enabled DER participating in a fleet. This cost is possible to sustain, if no other API fees are required for device-level access. Q4 (M4.7.1): A report on VPP's ability to estimate and predict flexibility: **Actual Performance:** (October 30th, 2017): 100% complete as we described a) a novel optimization-based mechanism to compute the nominal behavior for a PEM fleet, and b) provided a method to characterize power and energy limits of a PEM fleet, from which "trackability" of a VPP can be derived.

Task 5: Hardware Validation of PEM 5.1 Develop hardware-in- the-loop (HiL) system design specifications 5.2 Preliminary Level 3 hardware validation at UVM. 5.3 Preliminary Level 1 hardware validation in OPAL-RT 5.4 Preliminary Level 2 hardware validation in OPAL-RT 5.5 Integrate Level 1/Level 3 in OPAL-RT for small- case transmission test system. 5.6 Integrate Level 2/Level 3 in OPAL-RT for small- case distribution test system. 5.7 Phase I HiL Validation: couple all three levels for OPAL-RT HIL testing for the small GMP and VELCO systems 5.8 Phase II HiL Validation: large-scale GMP and VELCO coupled system from Task 2 at NIST's Lab with OPAL-RT (up to 12- cores) 5.9 Large-scale realistic PEM simulation in MATLAB with VELCO/GMP systems. 5.10 Phase III HiL Validation: implement hardware PEM demonstratio n with GMP and Spirae/NRG and Rainforest Automation in Rutland, VT.	Q3 (M5.1.1): Deliver report specifying OPAL-RT hardware design and requirements for implementin g and testing Level 1, Level 2, and Level 3, including communicati ons, modeling, and test cases. **Actual Performance:** (June 8th, 2017): 100% complete as report was approved by PD. The OPAL-RT design setup was more or less what was implemented with the major caveat being that AWS cloud infrastructure was not used in the lab setting (but was used in demonstration). Q4 (M5.2.1): Satisfied Category II Primary Tech Targets and consumer QoS **Actual Performance:** (December 4th, 2017): 100% complete as a real-time, cyber-enabled VPP (set up a separate simulator + server) that can ramp up (net) demand within 5 minutes and track a supplied balancing reference signal to within ±5% target value (<2% MAPE), while satisfying QoS. Q4 (M5.3.1): The Level 1 HiL validation **Actual Performance:** (December 4th, 2017): 100% complete as Level 1 transmission system optimization tools interact with OPAL-RT grid simulator, which models the response of a simplified VELCO system. The VELCO system has been augmented with dispatchable VPP that are abstractions of reality (i.e., Level 3) and, thus, illustrate the ability to close the loop between Level 1 tools and Level 1 real-time grid simulator. The specs achieved are solve time less than 25s, comms less than 5s and ability of VPPs to respond within 5 minutes. Q4 (M5.4.1): Level-2 HIL validation **Actual Performance:** (July 30th, 2017): 100% complete as the Level-2 HIL setup is developed for GMP’s 64-node distribution feeder using OP5600 simulator with all required optimization modules built in GAMS/MATLAB and interfaced with the simulator. The feeder had 4 LTCs, 3 cap banks, and was split into 3 VPPs with a total of 100 PEM-enabled electric and illustrated real-time simulation capability for Level 2.

	Q5 (M5.5.1): Level 1 (Transmission) and Level 3 (VPP) validation **Actual Performance:** (December 4th, 2017): 100% complete as the validation results for 1000 PEM-enabled devices in a VPP was shown to be dispatched optimally by MPC and then can track the VPP's balancing signal over 30 minutes with tracking error less than 2%. The metrics defined in the milestone have thus been reached. Q5 (M5.6.1): Level 2 (Distribution) M5.6.1 and Level 3 (VPP) validation. **Actual Performance:** (January 30th, 2018): 100% complete as server can now support up to 10 VPPs and 2 VPPs were coordinated/optimized on 64-node realistic distribution feeder to manage transformer constraint. This was achieved within NODES Category II specs (5sec/5min/30min). Q5 (M5.7.1): Validation of M5.7.1 all three levels coupled **Actual Performance:** (January 30th, 2018): 100% complete as we successfully integrated Level 1 (Transmission) and Level 2 (Distribution) optimization schemes with ePhasorSim in OPAL-RT to enable coupled T&D simulation with packetized loads (PEM in Level 3). These simulations satisfy NODES Category II specs (5sec/5min/30min). Q6 (M5.7.2): Deliver functional specifications for centralized Levels 1 and 2 and Level 3 **Actual Performance:** (February 6th, 2018): is 100% complete as we outlined the function specification to PD. We proposed to use Matlab and ePHASORSIM for Level 1 (T) and Level 2 (D) interactions while HTTPS was proposed between Level 2 (D) and Level 3 (VPP), since VPP resides in cloud environment. The devices in a cloud-based VPP then communicate with physical devices via HTTPS. **Q8 (M5.8.1 – Go/No-go):** Satisfied all primary technical targets in OPAL-RT for step-change and ramping events for test-data developed in Task 2.

	Actual Performance: (Sept 26th, 2018): Is a 100% complete as a combined T&D model has been constructed from VELCO and GMP data, which has allowed us to design three simulation case studies. The case studies show how a VPP performs under step and ramp changes while satisfying NODES primary technical specifications (5s/5m/30m) while meeting local QoS requirement, as required. In addition, we showcase PEM under contingency operation, when a VPP is unexpectedly output-constrained, but is dynamically re-dispatched to consider the updated VPP limits. The contingency is then alleviated via re-dispatch from TSO and/or DSO and the VPPs are able (in aggregate) to recover and achieve the large-scale tracking objective. Q8 (M5.8.2): Deliver finalized functional specifications for fully distributed PEM and provide detailed testing plan for GMP demonstration in follow- up testing phase. **Actual Performance:** (Sept 26th, 2018): Is 100% complete as we proposed a viable path for a successful demonstration project with Packetized Energy (PE), GMP, MTU, and UVM. GMP would recruit customers (up to 150 packetized devices) to be part of the GMP VPP managed by PE. The VPP will react based on Level 2 (D) simulated control signals, which are informed from Level 1 (T) simulation. Q9 (M5.9.1): Performed large-scale MATLAB simulation of PEM **Actual Performance:** (November 29th, 2018). 100% complete as we completed a large-scale Matlab-based simulation that involved 500-bus transmission system (Level 1), a 500-node unbalanced distribution system (Level 2) and 10,000 simulation packetized loads (Level 3). The simulation results served to illustrate that PEM can complete primary and secondary NODES technical specification, including a 10% change in demand (>5% RMT requirement), providing reserves for 35 (>30) minutes, ramps up VPP within 5 minutes, satisfies QoS and graceful recovery requirements, and tracking

	error within 5% for 100 (>95) out of 100 simulated trials. Q10 (M5.9.2): A report on the methodology for evaluating the financial and reliability benefits of PEM **Actual Performance:** (Feb 28th, 2018). 100% completed as the financial benefit for flexible demand (water heaters) were reported as $120-$180 per year per electric water heater for grid services that align with NODES Cat. 1+2+3 (Freq regulation, load shaping, and peak reduction). Load shaping and peak reduction were implemented in the field and delivering value already. Since the grid services in modern markets are interwoven with reliability the benefits are strongly related. Q10 (MQ10-PS): *Deploy 150 PEM-enabled electric water heater controllers (100 from existing GMP contract with PE and another 50 from project strengthening).* **Actual Performance:** (Feb 28th, 2019). Delayed due to slow deployment (installation). Despite 300 customers reaching out within first week of announcing GMP program (Nov, 2018), only 33 devices were installed and deployed on PE's VPP by end of February, 2019 with another 44 devices in queue to be installed. By end of May, 2019, only 74 devices were installed, which is short of 150 devices required. So, a VT-wide VPP aggregation approach was taken to complete M5.10.1, which included 156 water heaters and 2 batteries in VT. By end of Q12, utility partner had deployed just 84 devices. Q11 (M5.10.1): Complete full-scale industry hardware validation satisfying all primary technical targets **Actual Performance:** (July 31, 2019): 100% complete as PE's API and updated cloud software implementation of PEM enabled us a VPP with 158 packetized devices to track a step-down response to within a single energy packet (MAE and RMSE, less than 5% of RMT) and to have the VPP respond more quickly (~1 sec; less than 5s) and hold step responses

	longer than 35 minutes (more than 30 min). Note that as the project evolved the priorities of industry partners (and their vendors) shifted, which made it impossible to execute the entire project in just Rutland, VT (i.e., deploying with tight geographical constraints was not possible). In addition, the inclusion of PE as a commercialization arm of the project required a re-thinking of the initially designed demonstration project, which had previously been designed around a different set of hardware and software vendors. Q12 (M5.10.2): A report detailing the demonstration results and effect of PEM on grid operators and consumers **Actual Performance:** (July 31, 2019): 100% complete as demo data illustrated that consumer temperatures (for water heaters) were within their 20*F* temperature dead-band (±10*F*). At 158 packetized devices spread across VT, there were no grid concern and analysis showed. In addition, the PEM demonstration represented a reduction in load of 0.50kW per device, which will not cause problems either. Analysis showed that hosting capacity of a large utility feeder could support up to 5 PEM devices per node in a 1500-node feeder. Thus, Level 2 corrections were not necessary nor would they have been activated.

Task 6: Technology Transition 6.1 Preliminary T2M plan development 6.2 T2M updates 6.3 Technology Disseminatio n, Demonstration, and Deployment 6.4 Follow-up funding	Q1 (M6.2.1): T2M updates: Qualified T2M contact and Industrial advisory board invited **Actual Performance:** (October 31, 2016). 100% complete as Prof. Paul Hines volunteered to take on T2M position and IAB was put together and convened. 24 companies across energy industry was included. The industrial advisory board (IAB) met in July, 2016, via conference call to introduce themselves and to get the first status update. We have managed to bring ConEdison on- board as the large utility member and have also added PNM from New Mexico along with GMP, BED, and VELCO from Vermont. On October 21-22, 2016, UVM and MTU hosted our first industrial advisory workshop. We had 14 industry attendees from Vermont, Massachusetts, Quebec, and Michigan. The event provided useful feedback from industry (regulators, ISOs, transmission, utilities, effi- ciency utilities) on implementation and customer expectation. Q2 (M6.1.1): Preliminary T2M plan: Present the preliminary T2M plan **Actual Performance:** (January 30, 2017): 100% complete as we presented T2M plan to IAB and UVM OTC during one of two IAB meetings. In addition, we launched a startup company focused on commercializing our prior Packetized IP. OTC has provided this company (Packetized Energy) with an initial grant to pay for a full-time IoT (Internet of Things) engineer to develop hardware and software products associated with this prior IP (and new IP generated from this project). Q2 (M6.2.2): T2M updates: Industrial advisory board established **Actual Performance:** (October 31, 2016). 100% complete as 21 companies across energy industry were included in IAB and met in July, 2016, via conference call to introduce themselves and to get the first status update. On October 21-22, 2016, UVM and MTU hosted our first industrial advisory workshop. We had 14 industry attendees from Vermont, Massachusetts, Quebec, and Michigan. The event provided useful feedback from industry

	(regulators, ISOs, transmission, utilities, efficiency utilities) on implementation and customer expectation. Q3 (M6.2.3): T2M updates: (1) Demonstration of capabilities and applications, (2) IP arrangement **Actual Performance:** (June 8th, 2017): 100% complete as IP arrangement and PEM capabilities were presented and compared against state of the art. Q3 (M6.4.1): Follow-up funding: Establish startup company for existing IP **Actual Performance:** (June 8th, 2017): 100% complete as company has secured follow-on funding from UVM to support spin-off company's technology demonstration platform. Q4 (M6.2.4): T2M updates: (1) Novel Capabilities, (2) Pathways to adoption **Actual Performance:** (July 30th, 2017): 100% complete as the report was approved by the PD. Specifically, the Technology to Market Plan was updated after review and comments from the ARPA-E program's Tech to Market lead, John Tuttle, as well as significant discussions with our Industrial Advisory Board (IAB). It included, for example, descriptions of novel capabilities offered by PEM (simplicity, scalability, etc), use cases (e.g., peak, arbitrage, ancillary services, non-wire alternatives, and fuel switching). Q4 (M6.3.1): Technology Dissemination, Demonstration, and Deployment: Portable Testbed **Actual Performance:** (July 30th, 2017): 100% complete as the team put together 10 tea kettles to represent loads and, via AWS cloud services, coordinated the 10 kettles using PEM technology concepts. This was illustrated at the ARPA-E Summit (booth/DC), TechConnect World Innovation Conference (in DC), and GridWise Alliance (Burlington) in 2017. Q6 (M6.2.5): T2M updates: Competitive analysis

	Actual Performance: (January 30th, 2018): 100% complete as we provided detailed discussion of 25 companies offering products that are related to those being developed by project's commercialization partner, Packetized Energy, including differentiated value proposition relative to batteries, scalability, and competing approaches to DER coordination schemes (multiple timescales: peak reduction, energy price arbitrage, frequency regulation, and grid management). Q6 (M6.4.2): Follow-up funding: Apply for supplementary funding through SBIR/STTR programs **Actual Performance:** (January 30th, 2018): 100% complete as we (team) and commercialization partner have each obstained significant funding to support product development, deployment, and related technologies, including NSF EPSCoR, NSF STTR, DOE Grid Modernization project, private investor capital, and 3 utility-funded pilot projects (in Vermont). Q8 (M6.3.2): Technology Dissemination, Demonstration, and Deployment: Present results from large-scale HIL testing **Actual Performance:** (Sept. 26th, 2018): Is a 100% complete due to numerous demonstrations at technology venues. Through a collaboration between PE and UVM, the deployment of a hardware-in-the loop simulation involving about 150 simulated devices and ~20 hardware elements was presented at DistribuTech 2018 and at the 2018 ARPA-E Summit. Results with more than 100 packetized hardware devices are now deployed through utility projects have been presented to a number of industry audiences. Finally, a VPP with more than 75 in-the-field devices was presented at the MISO Market Symposium in August 2018. Note that due to participation of Packetized Energy (PE) in this project and the availability of ePhasorSim at UVM, there is no need for NIST to support large-scale HIL simulations. Finally, numerous journal and conference papers have been disseminated in

	technical communities (e.g., IEEE PES and CSS). Q8 (M6.4.3): Follow-up funding: Identify larger demonstration project partner **Actual Performance:** (Sept. 26th, 2018): Is 100% complete as PEM technology is already on contract to be demonstrated at a larger scale (300 devices) with Vermont Electric Coop (VEC) and a multi-year contract is in the negotiation stage with Burlington Electric Department (BED) to include EV charger management. In addition, conversations are ongoing with major utilities and major OEMs for demonstration projects at the scale of 1000s. Q10 (M6.2.6): T2M updates: Business model **Actual Performance:** (Feb. 28th, 2019): 100% complete as we sketched out a path to $1M/yr revenue with $30/yr SaaS fee and $150/device fee to install. In addition, an exclusive license agreement was completed between UVM and PE while technology roadmap was updated to consider HVAC, frequency regulation and grid optimization (as part of PlusUp). Q10 (M6.3.3): Technology Dissemination, Demonstration, and Deployment: Trade show demonstration **Actual Performance:** (Feb. 28th, 2019): 100% complete as UVM has working real-time, cyber-enabled PEM simulator and PE has developed a simulator for Peak + LoadShaper. Finally, PE attended DistribuTech 2019 tradeshow. Q12 (M6.2.7): Technology to Market update: Final assessment (A): **Actual Performance:** (July 31, 2019): 100% complete as it was a duplicate of M6.3.5 (below). Q12 (M6.3.4): Technology Dissemination, Demonstration, and Deployment: GMP demonstration results: **Actual Performance:** (July 31, 2019): 100% complete as the GMP demonstration results and future demonstration sites have been

	communicated with numerous technology VCs and potential partners as part of PE’s fundraising and partnership discussions. Q12 (M6.3.5): Technology to Market update: Final assessment (B): **Actual Performance:** (July 31, 2019): 100% complete as the establishment of startup company Packetized Energy, via this NODES project, has accelerated the technology from TRL 3 or 4 to TRL 9 in three years and has the ARPA-E developed technology deployed across the US (in UL-certified products). Q12 (M6.3.6): Technology Dissemination, Demonstration, and Deployment: (1) Community engagement and industry adoption, (2) Industry demonstration update **Actual Performance:** (July 31, 2019): 100% complete as the ARPA-E team continues to engage with utilities through numerous venues. One is through the IAB that was established at the project’s onset. Another is a ”*Future of Energy*” workshop that was held at UVM in late 2018 and involved over 100 representatives from utilities, national labs, and universities to discuss issues related how DERs will impact grid economics, flexibility, and resilience. In addition, UVM co-organized a workshop with NIST in April, 2019, on Smart Grid Test Beds that involved all of Vermont energy industry (GMP, BED, VEC, VELCO, VEIC) and major NY utilities (ConEd, ORU). Q12 (M6.4.4): Follow-up funding: Identify larger demonstration project partner **Actual Performance:** (July 31, 2019): 100% complete as PEM technology had being deployed commercially by the company Packetized Energy through five on-going contracts. Two of these contracts are operating Virtual Batteries (VB) with a number of devices that is reaching the critical mass (~100 devices) to show meaningful results. As an example, the Vermont Electric Coop VB has been operational for over a year. The Company continues to deploy devices with its current demonstration contracts to eventually result in ~500 packetized

	devices being deployed. The Company has been invited to submit to follow on projects that would increase this total by an order of magnitude, in for example, California and New York.
BEGIN PLUS-UP CONTINUATION AWARD (Q13-Q20 with NCE until Q22)	

Task 7: Develop frequency-regulating/responsive PEM 7.1: Develop low- order VB model for PEM 7.2: Develop controller for frequency-regulating PEM 7.2.1: Develop pre-compensator for frequency-regulating PEM 7.2.2: Develop advanced controller for frequency- regulating PEM 7.2.3: Select most appropriate controller for frequency- 7.3: Design decentralized , frequency-responsive PEM 7.4: Develop learning- based parameter adaption	Q14 (M7.1.1): Virtual battery (VB) model validated **Actual Performance:** (March 23, 2020): 100% complete as a low-order VB model with 4 states (state of charge, charging and discharging levels, and opt-out level) was able to sufficiently predict available power and energy bounds across diverse DERs (EWHs and batteries) at populations greater than 5000 devices with RMSE less than 5%. Results of VB were published in different venues (IEEE CDC and IEEE Transactions on Smart Grid). Q14 (M7.3.1): Frequency- responsive testing plan developed **Actual Performance:** (March 23, 2020): 100% complete as plan was presented and approved by PD for gathering data to model how a fleet of packetized loads would respond to a local frequency-responsive load controller. The plan was based on testing of 3 different frequency sensors to understand effects of quantization, sampling rate, and measurement errors between PE's (low-cost) sensor and standard micro-PMU sensors and GridBallast option. PE's sensor had quantization error of 10mHz with RMS error (relative to micro-PMU's measurement) of 5.24 mHz, which makes it suitable for planned tests and technology development. Q15 (M7.2.1): Test pre-compensated VB controller **Actual Performance:** (May 19, 2020): 100% complete as a VB pre-compensator was developed and tested over 100 hours of PJM Reg-D historical AGC data. The tests showed that VB baseline demand, Reg-D statistics, and a predictive MPC-based pre-compensator can be used by pre-compensator to improve precision score. In particular, the pre-compensator performance improvement increases with longer packet lengths. Q16 (M7.2.3): Test advanced VB controller **Actual Performance:** (August 25, 2020): 100% complete as different controllers were tested. In particular, a linear, delay-based, and

	MPC-based pre-compensators were tested. The linear compensator was unable to improve tracking performance, while delay-based compensator leveraged Reg-D performance score metrics to improve precision score by 5%. The MPC-based pre-compensator leverages AGC statistics and ARMA prediction mode to improve precision score of PEM for Reg-D frequency regulation by about 6% (which yields about a 1% improvement in Performance Score). More importantly, the pre-compensator provides uniform (but small) improvement across all test cases. Q18 (M7.4.1): Test learning- based parameter adaptation. **Actual Performance:** (April 30, 2021): 100% complete as two methodologies were proposed for adapting parameters of a PEM virtual battery (VB) model online using available measurements (total power and requests). We deployed (1) a physics-informed Extended Kalman Filter (EKF) approach to adapt baseline end-use consumption parameter (which affects nominal power) and (2) a data-driven methodology for parametrizing a PEM VB (energy and power limits and time constant) as a function of energy levels (SoC) and then updating SoC estimate online. The data-driven (DD) methodology only required offline agent-based simulations for VB parameters and just 48 hours of fleet training data at 2-sec resolution for SoC estimate. When deployed, DD method outperformed EKF-based methods by order of magnitude when estimating SoC. Both methods were successfully tested over multi-hour operations for fleets of packetized batteries (ESSs) and electric water heaters (EWHs).

Task 8: Develop grid- aware packetized virtual battery (VB) 8.1: Develop constraint- aware coordination for PEM	Q16 (M8.1.1): Test constraint- aware PEM on small proof-of- concept, realistic unbalanced distribution system feeder **Actual Performance:** (August 25, 2020): 100% complete as Grid-Aware PEM was tested on two large realistic distribution feeders (534-node actual distribution feeder and 2500-node synthetic feeder). It was shown over 100 1-hour AGC tests that grid reliability can improve with Grid-Aware PEM without sacrificing delivery of grid services. The method requires Grid Operator and PEM Coordinator to share (at least) status of grid voltages and transformer power flows (i.e., red = overloaded and green = not overloaded).

Task 9: Validation and Demonstration 9.1 Validation of low-order VB model for PEM 9.2: VB controller validation 9.3: Validate Frequency- responsive PEM 9.4: Validate Learning- based VB 9.5: Validate grid- aware packetized VB 9.6: Deploy with utility (BusDev) 9.7: Final Demonstration with utility and reporting 9.8: Conduct benefit analysis	Q15 (M9.3.1): Technical feasibility of packetized device in frequency- responsive PEM **Actual Performance:** (May 19, 2020): 100% complete as frequency-responsive PEM was illustrated on a physical device (PE’s Mello) with response time of less than 800ms (ONàOFF, under-frequency event) and 600ms (OFFàON, over-frequency event). This required updating the PEM state-machine to consider low and high frequency conditions and effectively opting out of “Normal” PEM mode. Thus, packetized devices can feasibility deliver frequency-responsive services. Q16 (M9.1.1): Complete validation of low-order VB model for PEM. The VB technology developed in Task 7 will be used online at PE’s VB simulator to estimate VB parameters and the VB’s state of charge. The VB parameters will be used to design a family of power reference signals that explores the available range of flexibility. **Actual Performance:** (August 25, 2020): 100% complete as UVM implemented and validated VB model for PEM on PE’s simulator with 3000 simulated packetized water heaters. The validation was conducted over 3 case studies (periodic signal, ramp signal for power limit prediction, and energy limit prediction). In all 3 cases, the VB model could accurately estimate energy and power levels relative to the agent based simulation. Q16 (M9.1.2): Provide a recipe book for VB flexibility bids into ancillary services markets **Actual Performance:** (August 25, 2020): 100% complete as a methodology was provided that allows for estimation of sufficient number of devices and PEM settings to deliver 1MW capacity in hourly frequency regulation markets for any hour of the day (based on background demand/baseline model). Methodology was based on a representative sampling of historical AGC data (from PJM Reg-D database). Multi-hour bids and mixed DER fleets were also investigated to provide greater flexibility in VPP construction and bidding mechanics.

	Q16 (M9.3.2): Complete validation of Decentralized PEM **Actual Performance:** (August 25, 2020): 100% complete as frequency-responsive PEM was tested on IEEE 39 bus test system across a range of parameter, system, and event scenarios. Leveraging packet timer distribution information at PEM Coordinator and packet interruptions based on frequency and RoCoF, the aggregate demand be made responsive to frequency. Performance of Decentralized PEM was tested across a range of population, actuation delay, and sensor resolution parameters and showed improved in grid response under all realistic scenarios. Furthermore, the ability of the PEM Coordinator to estimate available synthetic damping in real time is valuable to grid operators. A patent application was filed for this method. Q16 (M9.6.1): Sign MOU with utility **Actual Performance:** (August 25, 2020): 100% complete as MOU was signed on 9/8/2020 between PE and a utility in Carolinas for frequency regulation testing as part of this project. Backup was also constructed by allowing VPPs to be aggregated (again) and disaggregated automatically, but, this time, for frequency regulation (faster timescale). Q17 (M9.6.2): Utility partner provides frequency and voltage measurements **Actual Performance (April 30th, 2021)**: 100% complete as grid measurement was gathered and communicated from utility grid connection to PE platform. Specifically, a Python-based library was created to share data from micro-PMU to cloud platform over FTP server with sample rate of 8.333 ms. Note that due to COVID-19, the utility deployment of frequency/voltage sensor (micro-PMU) was delayed. After much discussion with utility and due to lack of personnel during COVID-19 and no clear transformer maintenance windows, the plan to install sensor at a substation was abandoned. Instead, a wall-socket attachment was constructed to attach micro-PMU at utility

	headquarter to allow us to test data pathways between “grid” (outlet) PMU data and PEM cloud platform. Q18 (M9.2.1): Complete validation of VB controller **Actual Performance (July 31st, 2021)**: 100% complete as the MPC-based pre-compensator was selected as VB controller and implemented on PE’s cloud-based platform and coupled with PE’s device emulator to validate frequency regulation control and communication capabilities. This required PE to deliver an enhanced API which provided 6 data points updated every 2 seconds (related to power, requests, and packets). These data points are ingested by VB controller to optimize re-shaping of the Reg-D reference signal. Three (real-time) hourly tests were completed with VB controller and achieving composite performance scores greater than 83% which exceed minimum target score of 40%. In addition, advanced controller was shown to improve PEM performance across all cases’ precision scores. Q18 (M9.5.1): Complete validation of grid aware packetized VB **Actual Performance (March 23, 2021)**: Grid-aware PEM was developed and tested on a modified 2500-node distributed test feeder with 800 packetized devices operating as a virtual battery (VB). The method relies on updated grid measurements being available to VB no more frequently than 30 seconds and requests being compared to local voltage measurements before being accepted by coordinator. A sensitivity-based (*dV/dP*) nodal hosting capacity term was added to constraint logic to robustify against changing background demand and opt-outs. Three separate AGC trials were conducted with grid-aware VB and achieved a Performance Score above 80% while improving feeder voltage profiles relative to grid-agnostic VB. Q18 (M9.6.3): Virtual battery ready for testing **Actual Performance (October 31, 2021)**: 100% complete as 208 packetized devices

	were deployed and active across the aggregated VB on PE’s platform. The aggregated VB considers devices across multiple utility programs in Vermont and South Carolina and is ready for final testing. Q19 (M9.4.1): Complete validation of learning-based VB **Actual Performance (March 14, 2022)**: 100% complete as temporal convolutional network (TCN) was shown to generalize machine learning methods to accurately estimate a heterogeneous VB’s state of charge from just aggregate power and request data. TCN outperformed other learning-based methods, such as NNs and CNNs across all test cases. Training was completed on just 5 days worth of data and SoC estimates had RMSE below 1.5% across a wide range of practical parameter variation (e.g., up to 10% packet request loss, ±40% tank-size variation, ±15% background demand variation, and ±10% VB population change). These results highlight that TCN methodology is practically viable for PEM and generalizes to a series of realistic practical challenges. Note that this deliverable had to be scaled back from cloud-based validation on PE’s simulator to UVM’s MATLAB-based simulator. The reason for that is that PE was acquired, and its cloud-based simulator was shut down. However, this change in simulation platform only affects the quality of data exchanged (MATLAB simulation produces reliable and high quality data) but does not affect the outcomes (since a suitable platform system would have access to high quality historical and streaming data). Q19 (M9.7.1): Perform HIL demonstration with utility partner(s) **Actual Performance (December 9th, 2021)**: 100% complete as more than 208 packetized devices (>200 required) were part of four virtual battery (VB) frequency regulation demonstration events on four different days in December, 2021. Each event was a 2-hour demonstration of the VB tracking a historical PJM’s Reg-D signal fed to VB as a live signal (updated every

	2 seconds). The signal was “energy neutral” by PJM’s design and the VB achieve a Performance Score of no less than 89% (>75% required) with a Precision Score of at least 75% in all four cases, which exceeds . The results were published in the IEEE Spectrum magazine in Feb, 2022. Note that the team developed their own script for calculating PJM’s Performance Score for this event and validated it against PJM’s own calculator. Q20 (M9.8.1): Deliver final report on PEM for ancillary services: **Actual Performance (March 31st, 2023)**: 100% This is the final report. For the financial benefit analysis we presented in Q22 a “FastTracker” revenue estimate highlight strategies for 2500 devices (±0.40kW/device) acting as a VB and delivering ±1MW for frequency regulation. Using ISO-NE and PJM capacity clearing price data from 2019 and PE’s historical device power data, it was shown that targeting just the 1200 most profitable hours (or 14% of year) result in about 50% of the expected total annual revenue. Thus, the key outcome of the benefit report was to recommend focus on developing market-facing tools to predict and bid flexibility into markets to maximize VB profit.

Task 10: Technology transfer and outreach (TT&O) 10.1: Attend industry workshops and tradeshows (TT&O) 10.2: Present technology at ARPA-E Energy Innovation Summit, technical conferences, and industry workshops (TT&O)	Q14 (M10.1.1): Present frequency-regulating PEM at DistribuTech 2020 in San Antonio, TX. **Actual Performance (March 23, 2019)**: 100% complete as PE attended DistribuTech 2020 and shared a booth with OpenADR, who is PE's partner on DR standards for (frequency regulation) grid services at the fleet level. Q18 (M10.1.2): Present FastTracker at DistribuTech in February 2021, in San Diego, CA. **Actual Performance (Dec 8th, 2019)**: 100% complete as PE was invited to present their grid-edge flexibility platform Nimble at utility-facing and popular technical conference PLMA, which will took place online November 9-12, 2020. PE presented Nov. 5-6, 2020 on *Scalable Technology, Scalable Customer Value at* Greentown Lab's inaugural *Climatech Summit* in both their Startup Showcase and a Lightning Round (1 min. pitches). Note that DistribuTech 2021 was canceled due to COVID-19.
BEGIN PLUSUP AWARD (2021-2022: Q20-Q26)	
Task 11: Demonstrate App, Plan, and Materials 11.1 Marketing plan 11.2 Project microsite 11.3 Customer AMI data	Q22 (M11): Submit final marketing plan with overview screenshots of project microsite and mobile app. **Actual Performance (August, 2021)**: 100% complete as the *Get Nimble, Cali!* marketing program was launched in California with a microsite in August, 2021 and enrolled 10 customers with their Emerson thermostats and Emporia Smart Plugs. Note that the assets and personnel of Packetized Energy were acquired by EnergyHub in December of 2021. Thus, from the acquisition, NODES related activities ceased. As a result of the acquisition, the *Get Nimble, Cali!* microsite is no longer active and the *Get Nimble*app is no longer available for download. Therefore, milestones beyond M11 will not be completed, nor charged for.

Task 12: PEM Algorithms for new device types 12.1: PEM for thermostats 12.2: PEM for smart plugs	Q23 (M12): Report on PEM Algorithms **Actual Performance (Incomplete)**: 0% as the assets and personnel of Packetized Energy were acquired by EnergyHub in December of 2021. Thus, from the acquisition, NODES related activities ceased. As a result of the acquisition milestones beyond M11 will not be completed, nor charged for.
Task 13: Deployment at scale 13.1: Deploy 100 devices 13.2: Deploy 1000 devices 13.3: Deploy 2000 devices	Q24 (M13): Report on Deployment Results **Actual Performance (Incomplete)**: 0% as the assets and personnel of Packetized Energy were acquired by EnergyHub in December of 2021. Thus, from the acquisition, NODES related activities ceased. As a result of the acquisition milestones beyond M11 will not be completed, nor charged for.
Task 14: Demonstrations 14.1: Demonstrate Peak Reduction 14.2: Demonstrate Load Shaping 14.3: Analysis of Frequency regulation	Q25 (M14): Report on Demonstration Results **Actual Performance (Incomplete)**: 0% as the assets and personnel of Packetized Energy were acquired by EnergyHub in December of 2021. Thus, from the acquisition, NODES related activities ceased. As a result of the acquisition milestones beyond M11 will not be completed, nor charged for.
Task 15: Financial Models 15.1: Develop Preliminary Financial Model 15.2: Financial Performance Data 15.3: Updated Financial Model	Q26 (M15): Deliver Financial Model **Actual Performance (Incomplete)**: 0% as the assets and personnel of Packetized Energy were acquired by EnergyHub in December of 2021. Thus, from the acquisition, NODES related activities ceased. As a result of the acquisition milestones beyond M11 will not be completed, nor charged for.
Task 16: Submit white-paper 16.1: Draft white-paper 16.2: Present results at PLMA 16.3: Present results at ARPA-E Summit 16.4: Utility outreach	Q26 (M16): Deliver white-paper **Actual Performance (Incomplete)**: 0% as the assets and personnel of Packetized Energy were acquired by EnergyHub in December of 2021. Thus, from the acquisition, NODES related activities ceased. As a result of the acquisition milestones beyond M11 will not be completed, nor charged for.

Project Activities

The project's focus was on developing PEM technology for signal tracking, signal tracking with (grid) constraints, and validation. Signal tracking focused on developing a privacy-aware, equitable, scalable, and plug-and-play device coordination scheme that permits packetized devices to effectively respond to grid variability and enhance reliability. Signal tracking was validated with two separate field demonstrations (in 2019 and 2021) involving over 150 distributed devices and validating PEM's capability to provide NODES Category II synthetic balancing reserves (in 2019) and PJM Reg-D frequency regulation services (in 2021). In addition, large-scale simulations of 80,000 and more packetized devices were conducted in 2020 to augment PEM's signal tracking technology with the additional ability to accurately estimate and deliver fast frequency-responsive services similar to NODES Category I specifications (i.e., synthetic damping/inertia). Signal tracking with constraints focused on extending PEM technology to account for distribution grid constraints by updating a PEM Coordinator's power tracking reference signals based on grid optimization algorithms (in 2018) and integrating live grid measurements with PEM Coordinator's control logic (in 2021). Validation of signal tracking with constraints was successfully carried out with large-scale simulations involving a 500-node realistic distribution feeder (2018) and a 2500-node distribution test feeder (2021).

There were three modifications to the project during the 26 quarters:

1. During the initial phase of the project (Q1-Q12; Tasks 1-6; 2016-2019), a commercialization partner called Packetized Energy Technologies, was added to the project to execute a 156-device field deployment and technology demonstration (MQ10 was added). This was successfully completed on time.
2. During the second phase of the project (Q13-Q20-Q22; Tasks 7-10; 2019-2022), additional milestones were added to enhance PEM's capability at faster timescales and a 208-device field demonstration successfully completed this project. Due to COVID-19 effects, we re-budgeted unused travel funds to support (i) software development of API for PEM's cloud-based simulator for signal tracking validation purposes and (ii) additional commercialization outreach efforts. This phase of the project was successfully completed after two quarterly NCEs from delays in deployment due to COVID-19.
3. In the last phase of the project (Q22-Q26, Tasks 11-16; 2021-2022), the commercialization partner, Packetized Energy, was acquired by EnergyHub, which halted all progress beyond Task 11. That is, only Task 11 was fully completed while Tasks 12-16 remain incomplete, but not charged for. Thus, the final phase of the project was not completed.

Project Outputs

A. Journal Articles

1. S. R. Shukla, S. Paudyal, and M. R. Almassalkhi, "Efficient distribution system optimal power flow with discrete control of load tap changers," IEEE Transactions on Power Systems, vol. 34, no. 4, pp. 2970-2979, 2019.
2. M. Amini and M. R. Almassalkhi, "Optimal Corrective Dispatch of Uncertain Virtual Energy Storage Systems," IEEE Transactions on Smart Grid, vol. 11, no. 5, pp. 4155 - 4166, 2020.
3. A. Khurram, L. A. Duffaut Espinosa, R. Malhame, and M. R. Almassalkhi, "Identification of Hot Water End-use Process of Electric Water Heaters from Energy Measurements," Electric Power Systems Research, vol. 189 (106625), 2020. Presented at 21st Power Systems Computation Conference (PSCC), June 29 - July 3, 2020.
4. L. A. Duffaut Espinosa and M. R. Almassalkhi, "A packetized energy management macromodel with quality of service guarantees for demand-side resources," IEEE Transactions on Power Systems, vol. 35, no. 5, pp. 3660-3670, 2020.
5. L. A. Duffaut Espinosa, A. Khurram, and M. R. Almassalkhi, "Reference-Tracking Control Policies for Packetized Coordination of Heterogeneous DER Populations," IEEE Transactions on Control Systems Technology, vol. 29, no. 6, pp. 2427-2443, Nov. 2021.
6. N. Nazir and M. R. Almassalkhi, "Guaranteeing a physically realizable battery dispatch without charge-discharge complementarity constraints," IEEE Transactions on Smart Grid, 2021 (Early Access).
7. N. Nazir and M. R. Almassalkhi, "Grid-Aware Aggregation and Realtime Disaggregation of Distributed Energy Resources in Radial Networks," in IEEE Transactions on Power Systems, vol. 37, no. 3, pp. 1706-1717, May 2022
8. M. Botkin-Levy, A. Engelmann, T. Mühlpfordt, T. Faulwasser, and M. R. Almassalkhi, "Distributed control of charging for electric vehicle fleets under dynamic transformer ratings," IEEE Transactions on Control Systems Technology, vol. 30, no. 4, pp. 1578-1594, July 2022.
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11. M. Banaei, F. D'Ettorre, R. Ebrahimy, M. R. Almassalkhi, H. Madsen, "Procuring Flexibility in Power Systems with Incentive-based Grid Access Requests," (under review), 2023.
12. H. Mavalizadeh, L. A. Duffaut Espinosa, and M. R. Almassalkhi, “Improving frequency response with synthetic damping available from fleets of distributed energy resources,” (under review), 2023.

13. M. Matar, H. Mavalizadeh, S. Brahma, M. R. Almassalkhi, and S. Wsah, “State-of-Charge Estimation of Heterogeneous Fleets of Distributed Energy Resources using Temporal Residual Networks”, (under review), 2023.

B. Papers

1. M. R. Almassalkhi, J. Frolik, and P. D. H. Hines, "Packetized energy management: asynchronous and anonymous coordination of thermostatically controlled loads," American Control Conference (ACC), May 24-26, 2017.
2. L. A. Duffaut Espinosa and Mads Almassalkhi and Paul Hines and S. Heydari and Jeff Frolik, "Towards a Macromodel for Packetized Energy Management of Resistive Water Heaters," IEEE Conference on Information Sciences and Systems (CISS) , March, 2017.
3. L. Duffaut Espinosa, M. R. Almassalkhi, P. D. H. Hines, and J. Frolik, "Aggregate Modeling and Coordination of Diverse Energy Resources Under Packetized Energy Management," IEEE Conference on Decision and Control (CDC), . December, 2017.
4. M. R. Almassalkhi, L. A. Duffaut Espinosa, P. D. H. Hines, J. Frolik, S. Paudyal, and M. Amini, "Asynchronous Coordination of Distributed Energy Resources with Packetized Energy Management," 20th In: Meyn S., Samad T., Hiskens I., Stoustrup J. (eds) Energy Markets and Responsive Grids. The IMA Volumes in Mathematics and its Applications,, pp 333-361, vol 162. Springer, 2018.
5. M. Amini and M. R. Almassalkhi, "Trading off robustness and performance in receding horizon control with uncertain energy resources," Power Systems Computation Conference (PSCC), 11-15 June 2018.
6. L. Duffaut Espinosa, M. R. Almassalkhi, P. D. H. Hines, and J. Frolik, "System Properties of Packetized Energy Management for Aggregated Diverse Resources," Power Systems Computation Conference (PSCC), 11-15 June 2018.
7. M. Amini, A. Khurram, A. Klem, M. R. Almassalkhi, and P. D. H. Hines, "A Model-Predictive Control Method for Coordinating Virtual Power Plants and Packetized Resources, with Hardware-in-the-Loop Validation," IEEE PES General Meeting (PESGM), 4-8 Aug., 2019.
8. L. A. Duffaut Espinosa and J. Frolik, A localized and packetized approach to distributed power inverter management, IEEE Power and Energy Society General Meeting, Atlanta GA, August 4-8, 2019.
9. K. Desrochers, V. Hines, F. Wallace, J. Slinkman, A. Giroux, A. Khurram, M. Amini, M. R. Almassalkhi, and P.D.H. Hines, "Real-world, full-scale validation of power balancing services from packetized virtual batteries," EEE PES Conference on Innovative Smart Grid Technologies (ISGT), 18-21 Feb, 2019.
10. H. Mavalizadeh, L. A. Duffaut Espinosa, and M. R. Almassalkhi, "Decentralized Frequency Control using Packet-based Energy Coordination," IEEE International Conference on Communications, Control, and Computing Technologies for Smart Grids (SmartGridComm), December, 2020.
11. L. A. Duffaut Espinosa, A. Khurram, and M. R. Almassalkhi, "A Virtual Battery Model for Packetized Energy Management," IEEE Conference on Decision and Control, 14-18 Dec., 2020.

12. A. Khurram, L. A. Duffaut Espinosa, and M. R. Almassalkhi, "A Methodology for Quantifying Flexibility in a fleet of Diverse DERs," IEEE PES PowerTech , June 28 - July 2, 2021.
13. M. R. Almassalkhi, J. Frolik, P. D. H. Hines, “How to prevent blackouts by packetizing the power grid,” IEEE Spectrum, 29 July 2022.
14. A. Khan, S. Paudyal, and M. R. Almassalkhi, "Performance Evaluation of Network-Admissible Demand Dispatch in Multi-Phase Distribution Grids,". IREP Bulk Power System Dynamics and Control Symposium, 2022.
15. S. Brahma, H. Ossareh, and M. R. Almassalkhi, "Statistical Modeling and Forecasting of Automatic Generation Control Signals,". IREP Bulk Power System Dynamics and Control Symposium, 2022.

C. Status Reports

There were 26 quarterly status reports submitted to ARPA-E as part of this project. In addition, two PhD students and one MS student were trained at UVM on this project with a research scientist and four postdoctoral associates contributing to the project.

Student Ph.D. Dissertations and M.S. Theses

Considering graduate degrees as a form of status reports, below are the seven students, who have graduated from this project and moved to academia and/or industry:

1. Mahraz Amini (2019), Optimal dispatch of uncertain energy resources, Ph.D. Dissertation, University of Vermont, Burlington, Vermont, https://scholarworks.uvm.edu/graddis/1046/.
2. Adil Khurram (2021), Modeling and Control for Packetized Energy Management, Ph.D. Dissertation, University of Vermont, Burlington, VT, https://scholarworks.uvm.edu/graddis/1480/.
3. Mohammad Asif I. Khan (2022), Transmission and Distribution Co-Simulation and Applications, Ph.D. Dissertation, Florida International University, Miami, FL.
4. Jingyuan Wang (2019), Active and Reactive Power Control of Flexible Loads for Distribution-Level Grid Services, Ph.D. Dissertation, Michigan Technological University, Houghton, MI. https://digitalcommons.mtu.edu/etdr/757/
5. Guna R. Bharati (2017), "Hierarchical Optimization Framework for Vehicle-To-Grid (V2G) and Building-To-Grid (B2G) Integration," Ph.D. Dissertation, Michigan Technological University, Houghton, MI, https://digitalcommons.mtu.edu/etdr/489/
6. Sharabh R. Shukla (2018), Mixed Integer Conic Programming Formulation of Distribution Optimal Power Flow and Unit Commitment Problems, M.S. Thesis, Michigan Technological University, Houghton, MI, https://digitalcommons.mtu.edu/etdr/624/
7. Micah Botkin-Levy (2019), Distributed Control of Electric Vehicle Charging: Privacy, Performance, and Processing Tradeoffs, M.S. Thesis, University of Vermont, Burlington, VT, https://scholarworks.uvm.edu/graddis/1049/

D. Media Reports

- Herman K. Trabish, ‘The future grid’: How one DOE program is pushing the boundaries of aggregated DERs, UtilityDive, Feb 4, 2016
- Jeffrey Wakefield, “UVM Spinoff’s Small Packets Are a Big Deal for Energy Industry”, UVM Media, March 17, 2018.
- Jeff St. John, “Meet the Top Companies Changing the Face of the Electric Grid in 2018”, GreenTechMedia, April 26, 2018.
- Alexandra Mongomery, "Vermonters being asked to sign up for water-heater technology," WCAX, 28 May 2018.
- Joyce Marcel, "Packetized Energy Technologies: Microenterprise of the Year," Vermont Business Magazine, 2 Aug 2020.
- Jeff St. John, “EnergyHub buys Packetized Energy to get millions of thermostats and EVs to help balance the grid,” Canary Media, 3 March 2022.
- “EnergyHub acquires Packetized Energy,” Vermont Business Magazine, Mar 2, 2022
- Joan Koka, “Breakthrough software platform supports grid services, empowers utilities and consumers,” Argonne National Labs, 20 Sept 2022.

E. Invention Disclosures

None.

F. Patent Applications/Issued Patents

1. Systems and methods for random access charge management using charge packetization, University of Vermont, US Patent 10,256,631 (Issued: April 9, 2019) and US Patent 11,171,484 (Issued: November 9, 2021).
2. Packetized energy management control systems and methods of using the same, University of Vermont, US Patent 11,150,618 (Issued: October 19, 2021).
3. Systems and methods for randomized, packet-based power management of conditionally-controlled loads and bi-directional distributed energy storage systems, University of Vermont, US Patent 11,210,747 (Issued: December 28, 2021), US Continuation: 17/454,563 (Filed: November 11, 2021), and Australian Patent 2017330374 (Acceptance: April 7, 2022).
4. Decentralized Frequency Control with Packet-Based Energy Management , University of Vermont, US Patent Application: 17/305,491 (Filed: July 8, 2021). Pending.

G. Licensed Technologies

1. Packetized Energy Management, University of Vermont (Cases C499 and C653), license to Packetized Energy Technologies, Inc., signed April 15th, 2018.
2. Packetized Energy Management, University of Vermont (Cases C499, C653, and C738), perpetual license to EnergyHub, effective December 15, 2021.

H. Networks/Collaborations Fostered

Numerous networks and collaborations were fostered as part of this project. This was largely led by the PI (Dr. Mads Almassalkhi) and T2M lead (Dr. Paul Hines) at UVM and via spin-out commercialization partner, *Packetized Energy*. These collaborations resulted in academic collaborations, proof-of-concept hardware experiments, and commercial pilot projects. Some specific partners during the project's evolution as listed below:

1. Enphase Energy (battery software integration)
2. Emerson (thermostat software integration)
3. Emporia (smart plugs software integration)
4. National Institute of Standards and Technology, Gaithersburg, MD.
5. Technical University of Dortmund, Dortmund, Germany.
6. University of Michigan, Ann Arbor, MI.
7. Florida International University, Miami, FL.
8. Denmark's Technical University, Copenhagen, Denmark.
9. Greentown Labs, Boston, MA
10. DeltaClime VT, Burlington, Vermont
11. Cleantech to Market, Haas School of Business, UC Berkeley, Berkeley, CA.

I. Websites Featuring Project Work Results

1. Just have a think, *How to balance renewable grids WITHOUT energy storage!* https://www.youtube.com/watch?v=NU3woCaFSZs
2. Website of PI (Mads Almassalkhi's publications): https://madsalma.github.io/publications.html

J. Other Products (e.g. Databases, Physical Collections, Audio/Video, Software, Models, Educational Aids or Curricula, Equipment or Instruments)

None.

K. Awards, Prizes, and Recognition

- L. Richard Fisher Chair in Electrical Engineering (Mads Almassalkhi), 2022.
- Eminent Scholar Chaired Associate Professor in Electrical Engineering (Sumit Paudyal, FIU), 2020.
- NSF CAREER Awards:
  - Mads R. Almassalkhi, "Enabling grid-aware aggregation and real-time control of distributed energy resources in electric power distribution systems", 2021.
  - Sumit Paudyal, Operation of Distribution Grids in the Context of High-Penetration Distributed Energy Resources and Flexible Loads, 2018.
- Awards from the University of Vermont
  - UVM College of Engineering and Mathematical Sciences Junior Faculty of the Year (Mads Almassalkhi), 2016

    - 3 x UVM Innovation Hall of Fame Awards for licensing IP (Mads Almassalkhi, Jeff Frolik, and Paul Hines), 2019
    - 3 x First UVM Startup Acquired Awards, (Mads Almassalkhi, Jeff Frolik, and Paul Hines), 2022
- Best Professor of the Year (Sumit Paudyal, Michigan Tech), Eta Kappa Nu (HKN) Society, 2018.
- “Microenterprise of the Year” (Packetized Energy), US Small Business Administration (Vermont office), 2020.
- “Gamechanging startups 2019” (Packetized Energy), CB Insights, 19 Nov, 2018.

Follow-On Funding

Table 2: Follow-on Funding Received

Source	Funds Committed or Received
Various angel investors, 2016	1,050,000 in seed investment in Packetized Energy
DOE Argonne National Labs, “Beyond DERMS”, 2020	$775,000
DOE SLAC National Accelerator Lab, Grid Resilience and Intelligence (GRIP) project, 2017.	$425,000
DOE BENEFIT program, “Grid-interactive Efficient Building Equipment Performance Dataset”, 2020.	$125,000 (full scope not completed as a result of acquisition)
ARPA-E PERFORM, ”An Integrated Paradigm for the Management of Delivery Risk in Electricity Markets: From Batteries to Insurance and Beyond”, 2020.	$420,00 (full scope not completed as a result of acquisition)
DOE EERE ENERGISE, “Robust and resilient coordination of feeders with uncertain distributed energy resources: from real-time control to long-term planning”, 2017.	$2,500,000
VELCO, “Stochastic Receding Horizon Optimal Power Flow Given High-resolution Weather Forecasts”, 2017.	$297,000
California Energy Commission (BRIDGE)	$2,000,000
NSF CMMI EAGER, “Collaborative Research: Real-Time: Hybrid Control Architectures Combining Physical Models and Real-time Learning”, 2018	$300,000
NSF EPCN CAREER, “Enabling grid-aware aggregation and real-time control of distributed energy resources in electric power distribution systems”, 2021	$500,000
Sloan Foundation, “Integrated renewable energy community microgrid transitions in remote rural and Indigenous communities in Alaska”, 2022.	$500,000

DOE SETO, “Hybrid Energy System Platform for Cold Weather Climates”, 2023	$4,000,000
DOE EERE, “Enabling Place-Based Power Generation using Community Energyshed Design”, 2023	$4,300,000
NIST, “Constraint-aware Control of Distributed Resources in the Electric Grid”, 2019	$300,000
NSF EPCN CAREER, “ Operation of Distribution Grids in the Context of High-Penetration Distributed Energy Resources and Flexible Loads”, 2018	$500,000
NSF CRISP Type 2 “Collaborative Research: Understanding the Benefits and Mitigating the Risks of Interdependence in Critical Infrastructure Systems”, 2018	$979,525
DOE SETO ASSIST, “Optimal Reconfiguration and Resilient Control Framework for Real-Time Photovoltaic Dispatch to Manage Critical Infrastructure,” awarded to FIU, 2019	$600,000