SAND2021-10740C

# Energy Storage-based Packetized Delivery of Electricity

Tu A. Nguyen, *Senior Member, IEEE*, and Raymond H. Byrne, *Fellow, IEEE*
Sandia National Laboratories, Albuquerque, NM 87185
Email: tunguy@sandia.gov, rhbyrne@sandia.gov.

***Abstract*—This paper presents Energy Storage-based Packetized Delivery of Electricity (ES-PDE) that is radically different from the operation of today's grid. Using ES-PDE, the loads are powered by the energy storage systems (ESS) the majority of the time and only receive packets of electricity periodically to charge the ESSs. Therefore, the grid operators can schedule the delivery of electricity packets to utilize the existing grid infrastructure. Since the customers are powered by the co-located ESSs they are not impacted by the grid operation in short term. Therefore, when grid outages occur, the customers still have power for some time, giving the grid more time to be fully restored.**

***Index Terms*—Energy storage, packetized energy.**

## I. Introduction

In today's power grid, electricity demand must be matched instantaneously by electricity generation due to the lack of storage capacity. To ensure grid reliability, the generation, transmission and distribution systems must have sufficient capacity to meet the peak demand. In the future, as the number of electric vehicles (EV) increases, the peak demand is anticipated to increase sharply since EV charging tends to coincidentally occur in the evening when drivers arrive home from work. That will require tremendous investment to upgrade grid infrastructure just to meet the peak demand. Furthermore, as more and more renewable energy (RE) resources are integrated into the grid, the variability and uncertainty from those resources will create many technical challenges in maintaining grid reliability and stability. Therefore, to help mitigate these problems, the peak demand, the variability and uncertainty from RE must be effectively managed.

Among the recent technologies, energy storage has shown to be one of the most effective solutions for the above problems as it can provide the needed flexibility to both the grid operators and the customers. In the literature, many studies have investigated the use of energy storage systems (ESS) for different applications and services. These studies often access the technical and economic benefits of ESSs for multiple services in electricity markets [1–3], for Transmission and Distribution (T&D) upgrade deferral and congestion relief [4, 5] and for behind-the-customer-meter applications [6–8]. Many papers also study the optimal control of ESSs for the above applications. An optimal control for frequency regulation using behind-the-meter battery energy storage systems (BESS) is proposed in [9]. Model predictive control (MPC) for the management of building demand with BESS and heating ventilation air conditioning (HVAC) is used in [10]. An optimal BESS control is proposed in [11] for mitigating solar PV variability while reducing transformer losses. An optimization framework is proposed in [12] to maximize the benefit of ESSs for utilizing the existing fossil-fueled generation fleet.

Beside energy storage, many other technologies and solutions are also developed to help manage the highly decentralized, distributed and transactive grid in the future, among which *Packetized Energy* (or *Energy-as-packet*, *Energy Internet*) introduces a completely different way in balancing electricity supply and demand [13]. In a packetized-energy system, energy is delivered to consumers as packets during certain times [14, 15]. In the literature, packetized energy has been studied extensively. Most recent studies focus on the energy management and control of the packetized energy systems. For example, [16] presents a plug-and-play energy internet where energy packets are routed using energy routers (similar to internet modems). In [17], an energy-router-based architecture is proposed using a continuous-time Markov chain that models and monitors system behaviors.

Nevertheless, most of the above works do not investigate the use of energy storage in packetized networks. Only in [18] is store-then-consume mechanism for local packetized power networks proposed. While this approach aims to reduce the aggregated load fluctuation in the distribution system, it does not consider distributed RE systems that can be significant in the future grid. Therefore, in this paper we propose Energy Storage-based Packetized Delivery of Electricity (ES-PDE) that is radically different from the previous packetized energy frameworks by using distributed ESSs to decouple electricity generation and demand while considering the high penetration of RE in the distribution system. Specifically, under ES-PDE, the loads are powered by the ESS the majority of the time and only receive packets of electricity periodically to charge the ESSs. In essence, ES-PDE decouples electricity generation and consumption using distributed ESSs, which will allow both generation and consumption to follow their own schedules that maximize their benefits. Using ES-PDE, the grid operators can schedule the delivery of electricity packets to the customers' ESSs in a manner that fully utilizes the existing grid infrastructure thereby minimizing the system operating cost and neglecting or deferring the need for infrastructure upgrade. On the other side, the customers are powered by the co-located ESSs and not being impacted by the grid operation in short term. Therefore, when grid outages occur, the customers can be self-powered for some period of time, giving the grid more time to be fully restored. This advantage is particularly

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

helpful during natural disasters or physical- and cyber-attacks when the utility grid restoration might be delayed due to some critical damages.

## II. Electricity Packet Delivery Scheme

In this work, specified are the electricity packet delivery schemes that are based on the following principles:

- The customers' hourly load profiles are forecasted by the system operators ahead of time (e.g., day ahead).
- The operators then specify the size of each packet to be delivered to the customers' ESSs at each hour in the next day. This schedule is based on an optimization to minimize an objective function under the system's constraints. For example, the objective can be minimizing the daily peak of a load or a load aggregation.
- At each hour in operation, the size of the electricity packet to be delivered to a customer will be adjusted by the difference between the customer's actual and forecasted consumption in the previous hour.

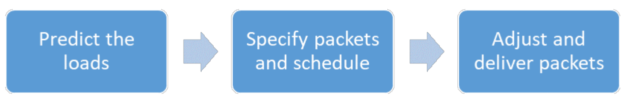


Fig. 1. ES-PDE Workflow

Two packet delivery schemes are proposed that include a one-battery delivery scheme and a two-battery delivery scheme, as described below.

### A. One-battery delivery scheme

Under this packetized delivery scheme, each customer's power system must be equipped with one ESS and inverter (see Fig. 2). For the continuous operation of the customer's loads the power rating of the inverter must be high enough to cover the peak load and power losses. This delivery scheme allows the loads to be powered by ESSs most of the time and only receive packets of electricity periodically to charge the ESSs.

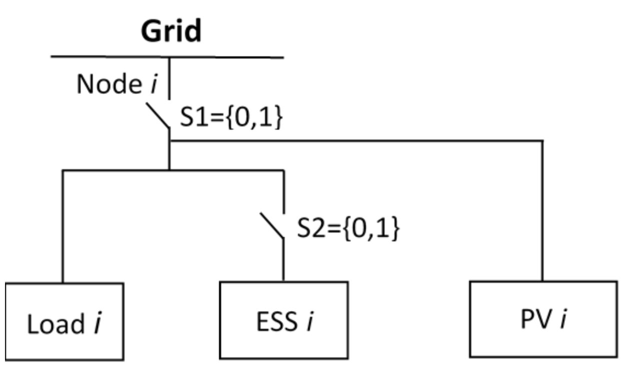


Fig. 2. One-battery configuration

The operation modes of the customer's ESS are defined as follows:

- Grid-connected mode (S1 and S2 are closed): occurs when the inverter is connected to the utility grid to receive energy packets. In this operation mode, the grid energy and on-site distributed generation (optional) are used to power the load and charge the ESSs.
- Stand-alone mode (S1 is open and S2 is closed): occurs when the inverter is disconnected to the utility grid. In this operation mode, the customer's loads are powered by the ESS and the on-site distributed generation.

This delivery scheme allows the loads to be powered by ESSs most of the time and only receive packets of electricity periodically to charge the ESSs.

### B. Two-battery delivery scheme

Under this packetized delivery scheme, each load or load cluster is coupled with two ESSs that are alternatively switching between the load and the grid (see Fig. 3). At any time, one of the associated ESS discharges to power the load while the other ESS charges to receive the electricity packet from the grid. The ESSs at different loads and load clusters will be coordinated in a centralized manner by the grid operators to meet specific objectives or requirements. The operation modes

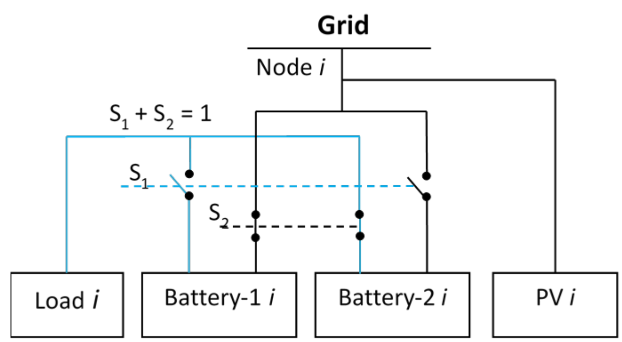


Fig. 3. Two-battery configuration

of the customer's ESS are defined as follows:

- Normal mode (S1, S2 are alternatively open and closed): occurs one of the battery charges from the grid and on-site generation while the other battery discharges to power the load.
- Emergency mode (S1 is closed and S2 is closed): occurs when long outages occur on the grid. In this mode, the batteries discharge the entire time to power the load.

This delivery scheme can fully decouple the loads and the grid by using a two-storage configuration. Therefore, the grid operators can observe the uncertainties in load before making changes in the packet delivery schedule. Similarly, grid outages cannot be seen immediately by the load thereby improving grid resilience significantly.

## III. Optimization Problem Formulation

In this section, we formulate the optimization problems to optimally schedule the energy packets considering all storage and configuration constraints. The objectives of these problems are to minimize the peak load of a given feeder (i.e., flatten out the feeder's load profile). The physical limits of the devices

TABLE I
NOMENCLATURE

| Constants | Description | Unit |
|---|---|---|
| $\tau$ | Time step duration | hour |
| $h$ | Time step index | - |
| $i$ | Node index | - |
| $x$ | ESS index $\in \{1,2\}$ | - |
| H | Time horizon | - |
| $\overline{S}^{i,x}$ | Energy capacity of ESS-x at $i$ | kWh |
| $\overline{P}^{i,x}$ | ESS's power rating of ESS-x at $i$ | kW |
| $\eta_{\text{s}}$ | ESS's self-discharge efficiency $\in [0,1]$ | - |
| $\eta_{\text{c}}$ | ESS's round-trip efficiency $\in [0,1]$ | - |
| $P_{\text{l}}^{i,h}$ | Load forecast at $i$ during $h$ | kW |
| $P_{\text{pv}}^{i,h}$ | PV forecast at $i$ during $h$ | kW |
| **Variables** | **Description** | **Unit** |
| $P_{\text{max}}$ | Peak load of the feeder over time horizon H | kW |
| $P_{\text{g}}^{i,h}$ | Grid power at $i$ during $h$ | kW |
| $P_{\text{c}}^{i,h,x}$ | Charge power of ESS-x at $i$ during $h$ | kW |
| $P_{\text{d}}^{i,h,x}$ | Discharge power of ESS-x at $i$ during $h$ | kW |
| $\alpha_{\text{c}}^{i,h,x}$ | Binary charge status of ESS-x at $i$ during $h$ | - |
| $\alpha_{\text{d}}^{i,h,x}$ | Binary discharge status of ESS-x at $i$ during $h$ | - |
| $S^{i,h,x}$ | The state of energy of ESS-x at $i$ during $h$ | kWh |

and the characteristics of the configurations are described in the constraints. The results of these optimizations will provide a deterministic schedule for energy packet delivery since perfect foresight of the load and PV data are used.

Specifically, followings are the formulations of the optimization problems. Nomenclature is given in Table I.

### A. Formulation for one-battery configuration

$$\text{minimize: } P_{\text{max}} = \max_h \left\{ \sum_i P_{\text{g}}^{i,h} \right\} \tag{1}$$

with the followings constraints:

- **State of energy (SOE) constraints:**

$$S^{i,h} = \eta_s S^{i,h-1} + \tau \left( \eta_c P_{\text{c}}^{i,h} - P_{\text{d}}^{i,h} \right), \tag{2}$$
$$0 \le S^{i,h} \le \overline{S^{i}}, \tag{3}$$
$$S^{\text{i,0}} = S^{\text{i,H}}. \tag{4}$$

These constraints calculate and make sure the SOEs of ESSs are in within their energy capacity limits and the initial SOE is equal to the final SOE.

- **Power balance constraint:**

$$P_{\text{d}}^{i,h} - P_{\text{c}}^{i,h} + P_{\text{g}}^{i,h} + P_{\text{pv}}^{i,h} \ge P_{\text{l}}^{i,h}. \tag{5}$$

- **Charge and discharge constraints:**

$$0 \le P_{\text{c}}^{i,h} \le \alpha_{\text{c}}^{i,h} \overline{P}^{i}, \tag{6}$$
$$0 \le P_{\text{d}}^{i,h} \le \alpha_{\text{d}}^{i,h} \overline{P}^{i}, \tag{7}$$
$$\alpha_{\text{c}}^{i,h} + \alpha_{\text{d}}^{i,h} \le 1. \tag{8}$$

Constraints (6) and (7) describe the power limit of the ESS at node $i$. Constraint (8) makes sure the ESS at node $i$ do not simultaneously charge and discharge during time step $h$.

- **Linearization constraint:**

$$\sum_i P_{\text{g}}^{i,h} \le P_{\text{max}}, \ \forall h. \tag{9}$$

Since $P_{\text{max}} = \max_h \left\{ \sum_i P_{\text{g}}^{i,h} \right\}$ is nonlinear, it is linearized by constraint (9).

### B. Formulation for two-battery configuration

The objective function is also given in (1). The constraints are as follows:

- **State of energy constraints:**

$$S^{i,h,x} = \eta_s S^{i,h-1,x} + \tau \left( \eta_c P_{\text{c}}^{i,h,x} - P_{\text{d}}^{i,h,x} \right), \tag{10}$$
$$0 \le S^{i,h,x} \le \overline{S^{i,x}}, \tag{11}$$
$$S^{\text{i,0,x}} = S^{\text{i,H,x}}. \tag{12}$$

- **Power balance constraints:**

$$\sum_{x \in \{1,2\}} \left\{ P_{\text{d}}^{i,h,x} \right\} \ge P_{\text{l}}^{i,h}, \tag{13}$$
$$\sum_{x \in \{1,2\}} \left\{ P_{\text{c}}^{i,h,x} \right\} \le P_{\text{g}}^{i,h} + P_{\text{pv}}^{i,h}. \tag{14}$$

In the two-battery configuration, the load and the grid are fully decoupled using ESSs. Therefore, power must be balanced on both the load side and the grid side.

- **Charge and discharge constraints:**

$$0 \le P_{\text{c}}^{i,h,x} \le \alpha_{\text{c}}^{i,h,x} \overline{P}^{i}, \tag{15}$$
$$0 \le P_{\text{d}}^{i,h,x} \le \alpha_{\text{d}}^{i,h,x} \overline{P}^{i}, \tag{16}$$
$$\alpha_{\text{c}}^{i,h,1} = \alpha_{\text{d}}^{i,h,2}, \tag{17}$$
$$\alpha_{\text{d}}^{i,h,1} = \alpha_{\text{c}}^{i,h,2}, \tag{18}$$
$$\alpha_{\text{c}}^{i,h,x} + \alpha_{\text{d}}^{i,h,x} \le 1, \tag{19}$$

where constraint (17), (18) and (19) make sure the two ESSs at node $i$ alternatively charge from the grid and discharge to the load during time step $h$.

- **Linearization constraint:** is also given in (9).

## IV. CASE STUDIES

In this example, a hypothetical utility feeder is considered (see Fig. 4) that powers one large hotel, one primary school, one large office building, 20 large houses, 20 medium houses and 20 small houses. The load consumptions are taken from OpenEI database [19] that includes simulated load data for Albuquerque, New Mexico. Since the residential loads are relative small, they are clustered together in three groups including large house load, medium house load and small house load. For ES-PDE to work, batteries are associated with each load or load cluster. The size of the batteries are selected so that they can power the associated loads the whole day. In this example, we assume the operator wants to minimize the peak load of the feeder. The load profiles in a day are given in Fig. 5.

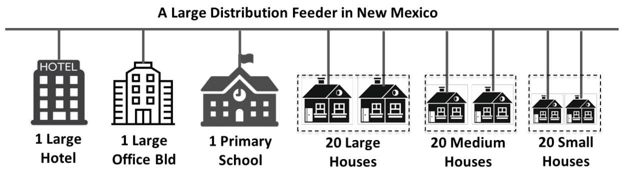


Fig. 4. A Large Feeder in New Mexico

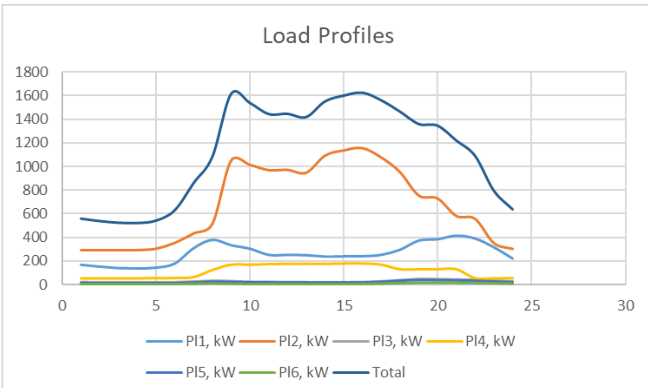


Fig. 5. Load profile

### A. One-battery delivery scheme results

Using one-battery delivery scheme, the operators can schedule the delivery of energy packets to the customers' ESSs to achieve their objective (e.g., minimize the peak load of the feeder as we assume in this case study). As a result of the operators' optimization problem, energy packets are specified in Fig. 6. As one can see from the schedule, different electricity

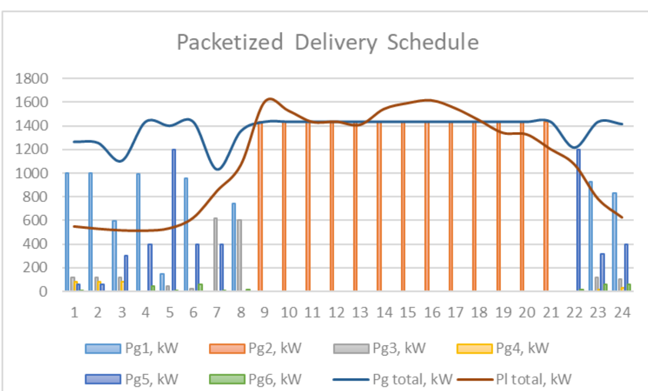


Fig. 6. One-battery Scheme: Packet Delivery Schedule

packets can be scheduled at different time in order to minimize the total peak load of the feeder. While the packets for each customer are discrete, the total load seen from the feeder is continuous and specified by the sum of all energy packets. Given the load profiles and the packet delivery schedule, the normalized SOE (i.e., the state of charge (SOC)) of the customers' ESSs are specified in Fig. 7. It is shown that at any time during this scenario the SOCs are always above 20%. That means in the worst-case scenario when a grid outage occurs between 21:00 and 23:00, all of the ESSs would be able to maintain their full loads for more than 4.8 hours (or 20 % of 24 hours). This demonstrates the grid resilience enhancement of ES-PDE.

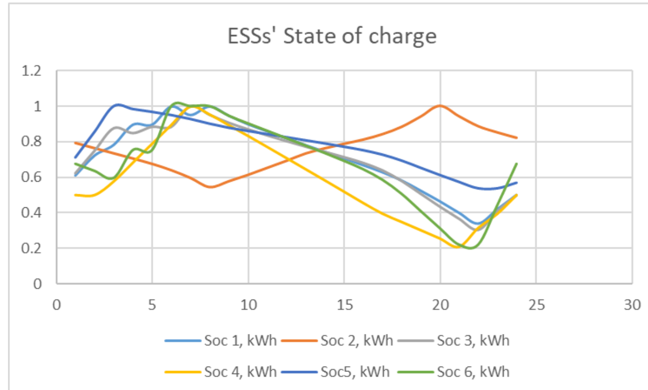


Fig. 7. One-battery Scheme: ESSs' State of charge

### B. Two-battery delivery scheme results

In contrast to the one-battery delivery scheme, the two-battery delivery scheme allows much more flexibility in scheduling the packet delivery to the customers. The two batteries can alternatively charge and discharge making the load profile look flat to the grid while maintaining the real load. As a result of the operator's optimization problem, energy packets are shown in Fig. 8. We also see that the total SOE of the two batteries at any site is high at any time. For example, the total SOE of the batteries at the primary school is always above 1400 kWh which is enough to power the load for 12 hours if outages occur.

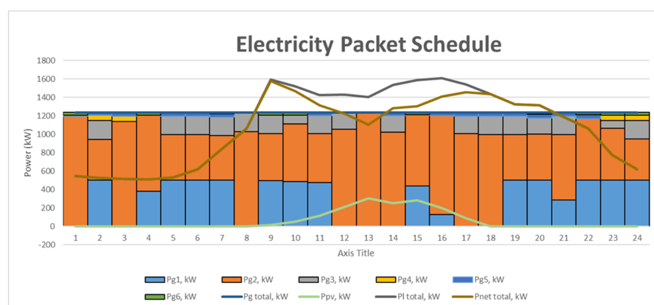


Fig. 8. Two-battery Scheme: Packet Delivery Schedule

## V. Conclusions

In this paper, the packetized energy concept has been realized using ESSs. Two configurations including one-battery and two-battery configurations are proposed for the delivery of energy packets to the customers. While the one-battery configuration is easier and more economical for realization, the two-battery configuration can fully decouple the load and the utility

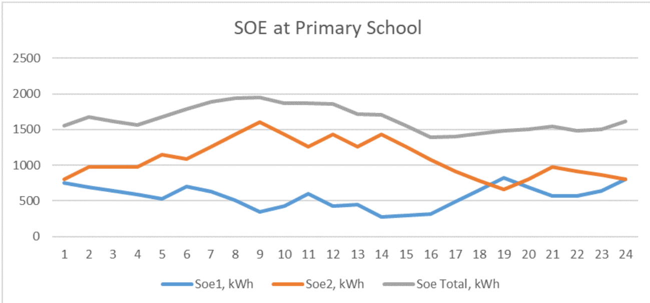


Fig. 9. Two-battery Scheme: ESSs' State of energy

grid by adding another battery. As seen in the case studies, the main advantage of this decoupling is that the grid operators can schedule the delivery of electricity packets to the customers' ESSs in a manner that fully utilizes the existing grid and at the same time the customers are not affected by the short-term outages since they are being powered by their co-located ESSs. Future work in this topic will include uncertainty in the optimization problems to describe the stochastic characteristics of both the load and the renewable generations.

## Acknowledgment

This study was funded by the Laboratory Directed Research & Development (LDRD) program at Sandia National Laboratories. Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525. This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government. Special thanks to Dr. David Wilson at Sandia, for his technical review and leadership for this LDRD project. This paper approved as SAND2021-XXXXC.

## References

[1] R. J. Concepcion, F. Wilches-Bernal, and R. H. Byrne, "Revenue opportunities for electric storage resources in the southwest power pool integrated marketplace," in *Proceedings of the 2019 IEEE Power and Energy Society General Meeting (PESGM)*, Atlanta, GA, August 2019, pp. 1–5.

[2] T. Nguyen, R. Byrne, R. Concepcion, and I. Gyuk, "Maximizing revenue from electrical energy storage in MISO energy & frequency regulation markets," in *Proceedings of the 2017 IEEE Power Energy Society General Meeting*, Chicago, IL, July 2017, pp. 1–5.

[3] T. A. Nguyen, D. A. Copp, R. H. Byrne, and B. R. Chalamala, "Market evaluation of energy storage systems incorporating technology-specific nonlinear models," *IEEE Transactions on Power Systems*, vol. 34, no. 5, pp. 3706–3715, Sep. 2019.

[4] S. R. Deeba, R. Sharma, T. K. Saha, D. Chakraborty, and A. Thomas, "Evaluation of technical and financial benefits of battery-based energy storage systems in distribution networks," *IET Renewable Power Generation*, vol. 10, no. 8, pp. 1149–1160, 2016.

[5] H. Khani, M. R. D. Zadeh, and A. H. Hajimiragha, "Transmission congestion relief using privately owned large-scale energy storage systems in a competitive electricity market," *IEEE Transactions on Power Systems*, vol. 31, no. 2, pp. 1449–1458, March 2016.

[6] D. Wu, M. Kintner-Meyer, T. Yang, and P. Balducci, "Economic analysis and optimal sizing for behind-the-meter battery storage," in *2016 IEEE Power and Energy Society General Meeting (PESGM)*, July 2016, pp. 1–5.

[7] T. Nguyen and R. Byrne, "Maximizing the cost-savings for time-of-use and net-metering customers using behind-the-meter energy storage systems," in *Proceedings of the 2017 North American Power Symposium (NAPS)*, Morgantown, WV, Sept 2017, pp. 1–5.

[8] ——, "Optimal time-of-use management with power factor correction using behind-the-meter energy storage systems," in *Proceedings of the 2018 IEEE Power Energy Society General Meeting*, Portland, OR, Aug 2018, pp. 1–5.

[9] Y. Kim, G. Del-Rosario-Calaf, and L. K. Norford, "Analysis and experimental implementation of grid frequency regulation using behind-the-meter batteries compensating for fast load demand variations," *IEEE Transactions on Power Systems*, vol. 32, no. 1, pp. 484–498, Jan 2017.

[10] D. T. Vedullapalli, R. Hadidi, and B. Schroeder, "Combined hvac and battery scheduling for demand response in a building," *IEEE Transactions on Industry Applications*, vol. 55, no. 6, pp. 7008–7014, Nov 2019.

[11] A. Nagarajan and R. Ayyanar, "Design and strategy for the deployment of energy storage systems in a distribution feeder with penetration of renewable resources," *IEEE Transactions on Sustainable Energy*, vol. 6, no. 3, pp. 1085–1092, July 2015.

[12] T. Nguyen, R. Byrne, and R. D. Trevizan, "Utilization of existing generation fleets using large-scale energy storage systems," in *Proceedings of the 2020 IEEE Power Energy Society General Meeting*, Montreal, Canada, Aug 2020, pp. 1–5.

[13] R. Abe, H. Taoka, and D. McQuilkin, "Digital grid: Communicative electrical grids of the future," *IEEE Transactions on Smart Grid*, vol. 2, no. 2, pp. 399–410, 2011.

[14] K. Wang, J. Yu, Y. Yu, Y. Qian, D. Zeng, S. Guo, Y. Xiang, and J. Wu, "A survey on energy internet: Architecture, approach, and emerging technologies," *IEEE Systems Journal*, vol. 12, no. 3, pp. 2403–2416, 2018.

[15] P. H. J. Nardelli, H. Alves, A. Pinomaa, S. Wahid, M. D. C. Tomé, A. Kosonen, F. Kühnlenz, A. Pouttu, and D. Carrillo, "Energy internet via packetized management: Enabling technologies and deployment challenges," *IEEE Access*, vol. 7, pp. 16 909–16 924, 2019.

[16] A. Q. Huang, M. L. Crow, G. T. Heydt, J. P. Zheng, and S. J. Dale, "The future renewable electric energy delivery and management (FREEDM) system: The energy internet," *Proceedings of the IEEE*, vol. 99, no. 1, pp. 133–148, 2011.

[17] M. Gao, K. Wang, and L. He, "Probabilistic model checking and scheduling implementation of an energy router system in energy internet for green cities," *IEEE Transactions on Industrial Informatics*, vol. 14, no. 4, pp. 1501–1510, 2018.

[18] J. Ma, N. Zhang, and X. Shen, "Elastic energy distribution of local area packetized power networks to mitigate distribution level load fluctuation," *IEEE Access*, vol. 6, pp. 8219–8231, 2018.

[19] Commercial and residential hourly load profiles for all TMY3 locations in the united states. [Online]. Available: https://data.openei.org/submissions/153