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Abstract—**The behind-the-meter (BTM) battery energy storage system (BESS) is mainly utilized for providing load management. But the saved electricity bill hardly offsets the high upfront investment cost. The multi-revenue streams created by certain stackable services can offset the initial cost by reasonably designing the size and operation strategy of BESS. Therefore, to maximize the return rate on BESS investment, a two-stage optimal model for optimizing the power and energy capacity of a BTM BESS is proposed in this paper. The provided stackable services by BESS include energy arbitrage and frequency regulation. A hybrid algorithm combining the genetic algorithm and a mixed-integer linear programming model is employed to co-optimize the size and operation strategy of BESS. The real load data from the plastic manufacturing industry and the frequency regulation information from the PJM market are employed as databases to validate the availability and effectiveness of the proposed model and the hybrid algorithm.**

Keywords—size optimization, BTM BESS, energy arbitrage, frequency regulation, multi-revenue streams

I. Introduction

Behind-the-meter (BTM) battery energy storage system (BESS) is often referred to as small-scale stationary batteries, which are usually connected behind the utility meter of residential, commercial, and industrial customers [1]. The existence of BTM BESS improves the reliability of the power supply during a blackout event and reduces its owner's electricity bill by providing load management and ancillary services to system operators. Besides, it can help the grid to improve the integration of renewable energy [2] and defer the grid upgrade by reducing the peak load [3]. Considering the high upfront cost, it is essential to optimize BESS size (power rate P and energy capacity E) and operation strategy to pursue the maximum return rate of investment.

Usually, energy arbitrage is the most common service provided by the BESS [4], [5]. It reduces the electricity bill by storing energy at a low price and releasing power to the distribution network at a high price. But according to the survey's results, the revenue just from energy arbitrage is difficult to offset BESS investment cost [6], [7]. Meanwhile, the indirect benefit from deferring the grid upgrade is hard to transform into cash and pay to the BTM BESS owner due to the present market mechanism. Hence, providing stackable services to create multiple revenues and make full use of BESS is necessary to justify investments in BESS.

Frequency regulation is an ancillary service with high monetizable revenue for BTM BESS [8]. The fast and accurate response to the frequency regulation signals makes BESS the most competitive candidate to fulfill frequency regulation service. The mechanism of BESS providing frequency services by the hour makes it possible to be compatible with energy arbitrage service. However, it is not easy for BESS to provide these two stackable services from the perspective of operation and planning, because it faces challenges in carefully coordinating the time and power capacity to participate in a different market for maximizing revenue. Besides, the size requirements for BESS of these two services are exactly different, energy arbitrage prefers the BESS with high energy capacity rather than high power capacity, but frequency regulation is just the opposite. It pursues high revenue by providing high power. Hence, the size and operation strategy of BESS should be co-optimized to maximize the benefit.

At present, research pays attention to optimizing the size of BTM BESS aiming for providing load management [9], [10]. The research related to BESS providing frequency regulation and energy arbitrage mostly focuses on how to design the operation strategy [11], [12]and cost-economic analysis [13], [14]. Nevertheless, it is rare to concentrate on how to design and optimize the size of BESS that offer stackable services-energy arbitrage and frequency regulation [15], especially for BTM BESS. An optimized size method for BTM BESS providing load management was presented in [9], which established a bi-level optimization model for maximizing net income and converted it to a single-level optimization problem by using Karush–Kuhn–Tucher (KKT) conditions for solving. The factors affecting the cost and benefits of customer-sider BESS providing load management were quantitatively analyzed in [10] to design the optimal size. A three-level management framework of BTM BESS was presented for providing energy arbitrage, arbitrage, and frequency regulation in [11]. It achieved optimal operation of BESS under various operating conditions by decomposing the original problem from different time scales. Literatures [13] and [14] did the cost-benefit analysis for the BTM BESS providing energy arbitrage and frequency regulation simultaneously. It demonstrated the gain from energy arbitrage and frequency regulation was larger than that from one service. A method for sizing a BESS connected with a distribution network was described in [15], where the BESS provided energy arbitrage, frequency regulation, and power loss reduction services to maximize financial and technical

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benefits. The enumerative search method was utilized to search for the best size from the perspective of payback period, battery life span, and grid impact, but this method is time-consuming.

This paper proposed a co-optimized framework to solve the optimal size and design the operation strategy of a BTM BESS providing stackable services. With the goal of maximizing annual net present value and maximizing the daily profits, a two-stage optimization model is established aiming at the planning level and operating level. A hybrid algorithm that combines the genetic algorithm and a mixed integer linear planning (MILP) model is adopted to solve this model. It can effectively reduce the calculating time and find the optimal size.

II. FRAMEWORK OF OPTIMAL SIZING OF BESS

A. Problem description

A general framework is proposed in this section for optimizing the size of BTM BESS providing stackable services- energy arbitrage and frequency regulation. The final purpose is to discover a BESS size (*P* and *E*) to achieve maximum annual net present value (*NPV*). Therefore, not only the investment cost of BESS but the profits relying on BESS's operation strategy should be considered. Therefore, the framework, which is shown in Fig.1, including two models- the planning model and operational model is established. These two models will exchange information with each other. The planning model sends the generated sizes to the operating model, then the operating model calculates daily maximum profits R_l based on delivered sizes and then passed them to the planning model for calculating the annual NPV. In order to reduce the simulation time, the typical daily scenarios are generated based on the K-means cluster method.

B. The applications of BESS

a) Energy arbitrage revenue model

Installing BESS on consumers' sides makes the passive consumers go a step toward being prosumers who can produce, consume, and manage their energy. In the region using time-of-use electricity tariffs, users can easily achieve electricity bill saving by controlling the BESS charge/discharge strategy. During off-peak hours, a BTM BESS can store electricity at a low price. During peak hours, the BESS can provide consumers with the stored energy or inject it back into the distribution network at a high electricity price. The revenue model of energy arbitrage on the l^{th} day is shown in (1).

$$R_{PS,l}=\sum_{h=1}^{24}\lambda_{elec}(h)P(t)\Delta t \tag{1}$$

where, $\lambda_{elec}(h)$ denotes the price of electricity at h^{th} hour in the l^{th} day, \$/MWh, $P(t)$ is the power exchanging with the BESS, MW, Δt is the time interval of power dispatch.

b) Frequency regulation revenue model

Rather than conventional plants providing frequency regulation service, batteries are more efficient and lower cost to respond to system operators' instructions within milliseconds. Multiple independent system operators (ISOs) have allowed BESS to provide the frequency regulation service and made mature market mechanisms to pay for this service. Here, the policy from Pennsylvania NES Jersey Maryland (PJM) market is adopted to establish the frequency regulation revenue model.

The revenue is paid based on the performance of how a BESS responds to frequency regulation signals RegD. It includes two parts: the revenue based on the BESS successful bidding capacity C_{bid}, and the revenue based on the regulation movement, which is reflected by the mileage ratio β_h. The revenue from the frequency regulation market on the l^{th} day is given in (2). The revenue in the h^{th} hour $R_{FR,l}$ is given in (3). When $C_{bid,l}(h)$ is equal to 0, BESS does not perform the frequency regulation in the h^{th} hour.

$$R_{FR,l}=\sum_{h=1}^{24}R_{FR,l}(h) \tag{2}$$

$$R_{FR,l}(h)=\begin{cases}0 & C_{bid,l}(h)=0\\ (RMCCP_l(h)+\beta_{h,l}RMPCP_l(h))C_{bid,l}(h)\delta(h) & 0<C_{bid,l}(h)\le P_{\max}\end{cases} \tag{3}$$

where, $RMCCP(h)$ and $RMPCP(h)$ is the regulation market capacity clearing price and the regulation market performance clearing price. $\delta(h)$ is the average performance score in the h^{th} hour to evaluate the performance of the BESS following the regulation signal from three perspectives: delay, correlation and precision. Here, we focus on the precision score by neglecting other indexes, because correlation and delay scores of a BESS are usually close to 1 due to the fast-responding speed.

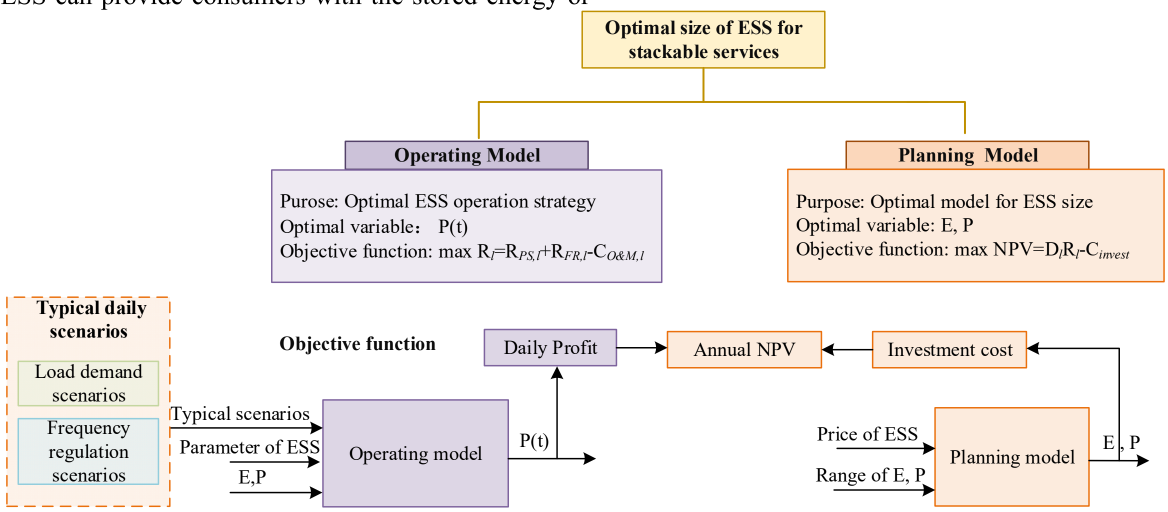

Fig. 1. Framework of optimal planning model of BTM BESS.

$$\delta(h) = 1 - \frac{1}{T}\sum_{t=1}^{T}\left|\frac{P(t,h) + C_{bid}(h) f(t,h)}{C_{bid}(h) f(t,h)}\right| \quad (4)$$

where, $f(t,h)$ is denotes the regulation signal. $P(t, h)$ is the real responding power from BESS at t time in the h^{th} hour. T is the number of intervals in an hour.

III. PROBLEM FORMULATION

A. First stage: planning level optimization model

Considering the affordability of customers and the revenue created by BESS, the BESS sizing variables including energy capacity and power rating are deserved to be carefully designed for pursuing a high return index. The planning level optimization model is described as follows.

The objective function is to maximize the annual net present value of BESS, which can be calculated as follows.

$$\max NPV = \sum_{l}^{L} D_l R_l - C_{invest} \quad (5)$$

where, D_l is the day number in a year is clustered to the l^{th} typical scenario, R_l is the profits from BESS providing stackable services in the l^{th} typical scenario. L is the number of typical scenarios in a year. C_{invest} is the annual investment cost of BESS.

$$\begin{cases} C_{invest} = (\lambda_e E_{\max} + \lambda_p P_{\max})\dfrac{r(1+r)^N}{(1+r)^N - 1} \\ R_l = R_{PS,l} + R_{FR,l} - C_{O\&M,l} \end{cases} \quad (6)$$

Where, λ_e is the cost of per energy, \$/MWh, λ_p is the cost of per power, \$/MW, $E_{\max}$ denotes the rated capacity, MWh, and $P_{\max}$ is the rated power, MW. Furthermore, r is the interest rate. N is the BESS planning time. $R_{PS,l}$ and $R_{FR,l}$ are the revenue from energy arbitrage and frequency regulation services, separately. $C_{O\&M,l}$ is the BESS operation and maintenance cost, where the linear degradation cost in [12] is adopted for calculation.

In the optimization process, the following constraints are added to ensure the settled initial size not be violated.

$$\begin{cases} 0 \le P_{\max} \le P_{ub} \\ 0 \le E_{\max} \le E_{ub} \end{cases} \quad (7)$$

Where, the subscript ub represents the upper limits setting for the variables.

B. First stage: Operation lever optimization model

The BTM BESS will not only provides energy arbitrage service, but also participates frequency regulation market to provide the ancillary service. It is essential for BESS to coordinate the participating time and the charging and discharging power for different services.

A BESS operation strategy optimization model is established to maximize the profit from the stackable services in each typical scenario, which considers the revenue from stackable services and the operation and maintenance cost. The objective function is shown in (8). The optimal variables include the charge/discharge power of BESS $P(t)$, $P_{dc}(t)$, $P_{ch}(t)$, the time BESS participate in frequency regulation market $s(h)$, and the bidding capacity in the h^{th} hour $C_{bid}(h)$, and the power $P_{fr}(t)$ released by BESS to responding frequency regulation signal.

$$\max_{l \in L} R_l = R_{PS,l} + R_{FR,l} - C_{O\&M,l} \quad (8)$$

$$C_{O\&M,l} = \frac{\lambda_e}{2N_{cycle}(SOC_{\max} - SOC_{\min})}\sum_{h=1}^{24}(|P_{dc}(h)|\eta_c + |P_{ch}(h)|/\eta_d)\Delta t \quad (9)$$

where, N_{cycle} is the cycle lifetime that ESS operates within the state of charge (SOC) limitation [$SOC_{\min}$, $SOC_{\max}$]. $P_{dc}(t)$ and $P_{ch}(t)$ are the discharging and charging power of ESS at time t, MW. η_d and η_c are the efficiencies of discharging and charging.

The SOC is used to describe how the ESS operates when it provides stackable services.

$$SOC(t) = SOC(t-1) + \frac{[P_{ch}(t)\eta_c - P_{dc}(t)/\eta_d]\Delta t}{E_{\max}} \quad (10)$$

In the operation process, BESS should satisfy the following constraints to ensure that optimal variables are not beyond the limits of energy and power.

$$SOC_{\min} \le SOC(t) \le SOC_{\max} \quad (11)$$

$$P(t) = P_{dc}(t) + P_{ch}(t) \quad (12)$$

$$-P_{\max} \le P(t) \le P_{\max} \quad (13)$$

$$0 \le P_{dc}(t) \le P_{\max} \quad (14)$$

$$-P_{\max} \le P_{ch}(t) \le 0 \quad (15)$$

$$-P_{\max} \le P_{fr}(t) \le P_{\max} \quad (16)$$

$$-P_{\max}(1 - s(h)) \le P_{fr}(t) \le P_{\max}(1 - s(h)) \quad (17)$$

$$P(t) - s(h)P_{\max} \le P_{fr}(t) \le P(t) + s(h)P_{\max} \quad (18)$$

Because the operation of BESS is under a typical scenario, the state of BESS should be the same at the start and end of one day.

$$\sum_{t=0}^{24}[P_{ch}(t)\eta_c - P_{dc}(t)/\eta_d]\Delta t = 0 \quad (19)$$

Equation (20) is supplied to ensure that the BESS cycle time will not shorter than the expected lifetime.

$$\frac{\sum_{t=0}^{24}(|P_{ch}(t)\eta_c| + |P_{dc}(t)/\eta_d|)\Delta t}{2E_{\max}(SOC_{\max} - SOC_{\min})} <= N_{cycle}/N_{year}/365 \quad (20)$$

Where, N_{year} is the calendar life of BESS.

C. Solution method

Due to the complexity of simultaneously solving planning and operation optimization models, GA combined with a MILP model are employed to find the optimal solution with the maximum objective function. The main step of the solution methods is shown in Fig.2. First, GA generates a population consisting of multiple chromosomes. Each chromosome, which includes two variables, represents a solution of BESS size to be installed. Then, the generated population in the last step is taken as the input in the operating optimization model. In order to maximize the stackable profit in every typical scenario, the optimized BESS operation strategy is designed by solving the MILP model in section III. B utilized Gurobi. Finally, the objective function of the planning level model is evaluated according to the investment cost and profits.

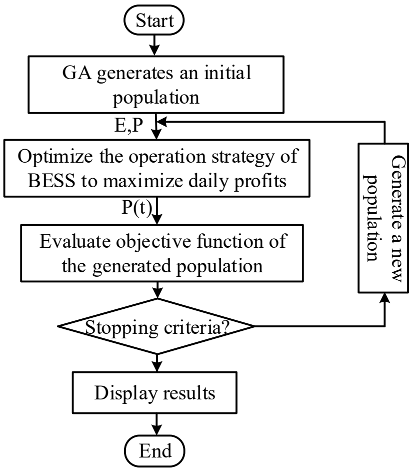

Fig. 2. Flowchart of the solving methodology.

IV. Case Study

A case study is provided to test the proposed methodology and search for the optimal size of BESS based on the real industrial load and frequency regulation information.

A. Parameters setup

The user side's power consumption data is from a plastic manufacturing industry lasting for one year [16]. The data for one month is shown in Fig.3 The information related to frequency regulation in 2020 is from the PJM market, including the regulation signal [17] and parameters [18] for calculated frequency regulation revenue. All data utilized here are converted to hourly data for reducing calculation time. The electricity price in peak period and off-peak period are assumed to be 120 \$/MWh and 50 \$/MWh. The interest rate is set to 6 %.

A method generating typical frequency information scenarios based on the K-means method in [19] is adopted here to cluster the industrial load and frequency information. It generates 8 typical scenarios consisting of load and frequency regulation information and corresponding probabilities in Table III.

From the perspective of technical characteristics, BESS is one of the best candidates to provide energy arbitrage and frequency regulation services. BESS is able to quickly respond to the frequency regulation signal, and it can be designed as the high-capacity type to satisfy the requirement of load shifting. Hence, a lithium iron phosphate (Li-LFP) battery is selected as the candidate storage technology. The concrete parameters are listed in Table II.

GA is utilized for solving the optimization problem at the planning level. The permissible ranges of power rating and energy capacity of BESS are assumed as 100 - 2000 kW, and 100 - 2000 kWh, respectively. The setting parameters and termination criteria of GA are further given in Table III.

B. Results

Based on the optimization framework in section III and the parameters in section IV.A, the optimized BESS size and its corresponding operation strategy are solved. It is worth mentioning that the optimized size of BESS searched by GA is not always the same because of the characteristic of the heuristic algorithm. Therefore, the GA algorithm is repeated 5 times to find the optimized size. The convergence process of GA with the best size is shown in Fig.3.

TABLE I. Results of Typical Daily Scenarios

Scenario	1	2	3	4
Probability	0.175	0.071	0.178	0.071
Scenario	5	6	7	8
Probability	0.181	0.071	0.181	0.071

TABLE II. Parameters of Li-FPB Battery

Li-LFP Parameters	Values
Capital power cost(\$/kW)	1000
Capital energy cost (\$/kWh)	425
Efficiency (%)	95
Number of cycles	10000
Range of SOC (%)	10-90
Lifetime(year)	10

TABLE III. GA Parameters and Stopping Criteria

GA Parameters	Values
Length of chromosome	7
Generation gap	0.9
Mutation rate	0.01
Crossover rate	0.7
Population size	50
Termination criteria and value	Stall generation-50

TABLE IV. Results of Optimal Sizing and Revenue

	Values		Values
Annual cost (\$)	3.40×10^5	Investment cost (\$)	3.17×10^5
		Operation cost (\$)	2.37×10^4
Annual revenue (\$)	4.09×10^5	Energy arbitrage revenue (\$)	9.27×10^3
		Frequency regulation revenue (\$)	4.00×10^5
Annual NPV (\$)	6.84×10^4		

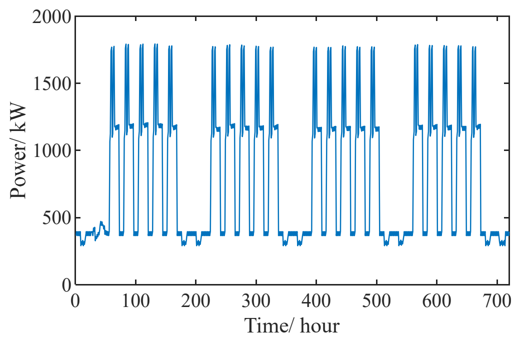

Fig. 3. Real load of one month.

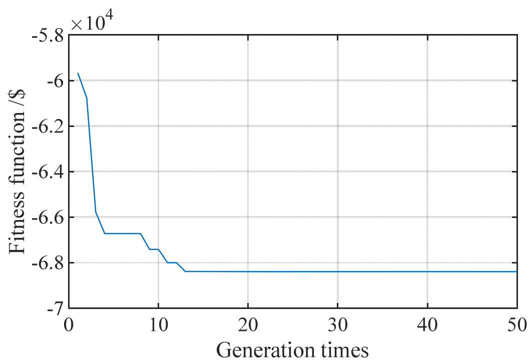

Fig. 4. GA convergence process.

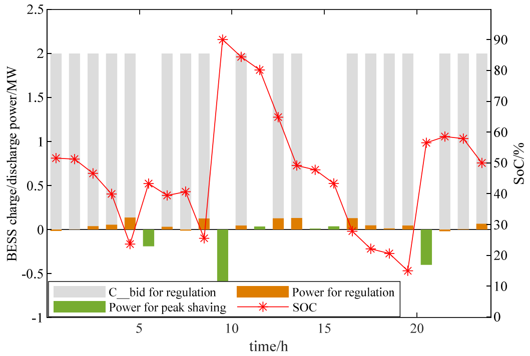

Fig. 5. Operation strategy and biding capacity of BESS on a typical scenario.

According to the calculation results, the BESS with a size of 2 MW/0.81 MWh will achieve the maximum annual NVP of ＄68, 400. The concrete cost and benefits are recorded in Table IV. And take one of the typical scenarios as an example, the BESS operation strategy is shown in Fig.4. The results indicate that the revenues can offset the investment cost and bring considerable benefits to its owner by providing stackable services. The BESS achieves higher revenue when it participates in frequency regulation markets. Hence, the size of BESS prefers to be designed with a high power to pursue high revenue, although the cost of per power unit cost is more expensive.

V. Conclusion

This paper proposes a method for optimizing the size of a BTM BESS providing stackable services: frequency regulation and energy arbitrage services. The annual maximum net present value is taken as the objective function, which considers the investment cost including initial cost and degradation cost, and revenues from a BESS providing stackable services. A two-stage model consisting of a planning optimization model and an operating optimization model is established for co-optimizing the size and operation of BESS. The genetic algorithm combined with Gurobi is used to solve this problem for finding the optimal solution. Results demonstrate that the BTM BESS with an optimized size can offset its investment cost and bring benefits by providing frequency regulation and energy arbitrage. In the condition without considering other indirect benefits, the BTM BESS should be designed with a high power capacity and low energy capacity, because the profit from the energy arbitrage service is much lower than that of frequency regulation. And most of the time, the BESS prefers to participate in the frequency regulation market.

References

[1] A. Anisie, F. Boshell, " Behind-the-meter batteries innovation landscape brief," International Renewable Energy Agency, Abu Dhabi, IRENA, 2019.

[2] T. Bowen, C. G. Welch, "Behind-the-meter battery energy storage: frequently asked questions," NREL/TP-7A40-79393. Golden, NREL,2021.

[3] X. Yang, Y. Zhang, H. He, et.al, "Real-time demand side management for a microgrid considering uncertainties," *IEEE Trans. Smart Grid*, vol. 10, no. 3, pp. 3401-3414, Apr. 2019.

[4] D. Wu, M. Kintner-Meyer, Tao Yang, et.al, "Economic analysis and optimal sizing for behind-the-meter battery storage," *IEEE PESGM*, pp. 1-5, Boston, MA, Jul. 2016.

[5] N. DiOrio, P. Denholm, W.B. Hobbs, "A model for evaluating the configuration and dispatch of PV plus battery power plants," *Appl. Energy*, vol. 5, pp. 1-12, Mar. 2020.

[6] X. Jiang, Y. Jin, X. Zheng, et al. "Optimal configuration of grid-side battery energy storage system under power marketization." *Appl. Energy*, vol. 272, pp. 1-11, Aug. 2020.

[7] S. F. Schneider, P. Novák and T. Kober, "Rechargeable batteries for simultaneous demand peak shaving and price arbitrage business," *IEEE Trans. Sus. Energy*, vol. 12, no. 1, pp. 148-157, Jan. 2021.

[8] B. Zakeri and S. Syri, "Value of energy storage in the Nordic power market- Benefits from price arbitrage and ancillary services," 13th Int. Conf. Eur. Energy Market, pp. 1–5, Porto, Portugal, Jul. 2016.

[9] Y. Ding, Q. Xu, and Y. Huang. "Optimal sizing of user-side energy storage considering demand management and scheduling cycle." *Electr. Power Syst. Res.*, vol. 184, pp. 1-10, Jul. 2020.

[10] D. Wu, M. M. Meyer, T. Yang, et al. "Analytical sizing methods for behind-the-meter battery storage." *J Energy Storage*, vol. 12, pp. 297-304, Aug. 2017.

[11] H. Su, D. Feng, Y, Zhao, et al., "Optimization of customer-side battery storage for multiple service provision: arbitrage, peak shaving, and regulation," *IEEE Trans. Ind. Appl.*, vol. 58, no. 2, pp. 2559-2573, Jan. 2022.

[12] B. Cheng and W. B. Powel, "Co-optimizing battery storage for the frequency regulation and energy arbitrage using multi-scale dynamic programming," *IEEE Trans. Smart Grid*, vol. 9, no. 3, pp. 1997-2005, May 2018.

[13] Y. Shi, B. Xu, D. Wang and B. Zhang, "Using battery storage for peak shaving and frequency regulation: Joint optimization for superlinear gains", *IEEE Trans. Power Syst.*, vol. 33, no. 3, pp. 2882-2894, May 2018.

[14] Y. Tian, A. Bera, M. Benidris and J. Mitra, "Stacked revenue and technical benefits of a grid-connected energy storage system", *IEEE Trans. Ind. Appl.*, vol. 54, no. 4, pp. 3034-3043, Jul./Aug. 2018.

[15] N. B. Arias, J. C. López, S. Hashemi, et al., "Multi-objective sizing of battery energy storage systems for stackable grid applications," *IEEE Trans. Smart Grid*, vol. 12, no. 3, pp. 2708-2721, May 2021.

[16] F. Angizeh, A. GHOFRANI, and M. Jafari, "Dataset on hourly load profiles for a set of 24 facilities from industrial, commercial, and residential end-use sectors," Mendeley Data, 2020.

[17] "PJM historical regulation market data." [Online]. Available: http://www.pjm.com/markets-and-operations/ancillary-services.aspx

[18] "PJM data miner2." [Online]. Available: https://dataminer2.pjm.com/feed/reg_market_results/definition

[19] X. Zheng, Y. Su, L. Wei, J. Zhang, et al., "Cost-benefit evaluation for battery energy storage considering degradation and data clustering in performance-based frequency regulation service," *IEEE EI2*, pp. 279-285, Wuhan, China, Oct. 2020.