Energy Proceedings
Vol 48, 2024
ISSN 2004-2965

A Review of Optimization Models for Battery Sizing in Utility-scale Photovoltaic Power Plants

Wenqian Zhang[1], Mingkun Jiang[2], Wenxiao Jiang[3], Haoran Zhang[3*]
1 School of Urban Planning and Design, Peking University, Shenzhen, Guangdong, 518055, China
2 PV Industry Innovation Center, State Power Investment Corporation, Shannxi, 710061, China
3 LocationMind Inc., 701, 3-5-2, Iwamoto-cho, Chiyoda-ku, Tokyo 101-0032, Japan
(Corresponding Author: h.zhang@pku.edu.cn)

ABSTRACT

The rapid growth of photovoltaic (PV) power generation has led to an increasing need for effective battery energy storage systems to address the intermittency and variability of PV output. This comprehensive review focuses on the optimization models used for battery sizing in photovoltaic power stations. It presents an in-depth analysis of various approaches, including mathematical programming, heuristic algorithms, and hybrid methods. The review examines the objective functions, constraints, and key parameters considered in these models. Additionally, it discusses the performance evaluation metrics and the impact of different factors such as load profiles, PV generation patterns, and cost structures on battery sizing decisions. The findings of this review provide valuable insights for researchers and practitioners aiming to optimize battery sizing in PV power stations to enhance system reliability and economic viability.

Keywords: Photovoltaic (PV) Power Generation, Battery Sizing, Optimization Models, PV Generation Patterns, Economic Viability

NONMENCLATURE

Abbreviations	
PV	Photovoltaic
BESS	Battery energy storage system
SOC	State of charge
DC/AC ratio	Direct Current/Alternating Current ratio
n	The number of Year
INV	Inverter

1. INTRODUCTION

The rapid growth of photovoltaic (PV) power generation has led to an increasing need for effective battery energy storage systems to address the intermittency and variability of PV output. This comprehensive review focuses on the optimization models used for battery sizing in photovoltaic power stations. It presents an in-depth analysis of various approaches, including mathematical programming, heuristic algorithms, and hybrid methods. The review examines the objective functions, constraints, and key parameters considered in these models. Additionally, it discusses the performance evaluation metrics and the impact of different factors such as load profiles, PV generation patterns, and cost structures on battery sizing decisions.

Based on Fig.1 and Fig.2, it can be inferred that the photovoltaic (PV) storage optimization model is primarily applied in significant areas of research within regions such as China, India, and Australia, focusing on fields like energy, engineering, and mathematics. Additionally, mathematical modeling and simulation are highlighted as crucial in energy conversion and energy storage processes, indicating the model's relevance in mathematical applications within the energy sector.

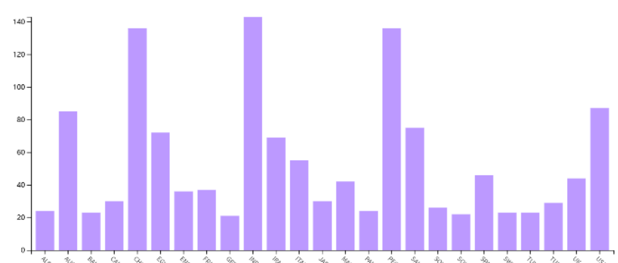

Fig. 1 Research areas in recent years

This is a paper for the 10th Applied Energy Symposium: Low Carbon Cities & Urban Energy Systems (CUE2024), May. 11-13, 2024, Shenzhen, China.

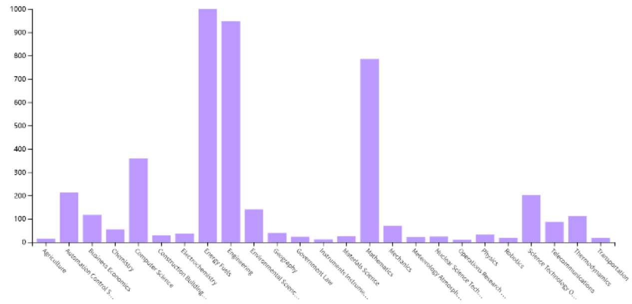

Fig. 2 Fields of study in recent years

The growing adoption of photovoltaic (PV) power stations as a sustainable source of energy has brought significant attention to efficient energy storage systems, particularly batteries, which play a critical role in balancing supply and demand. Battery sizing optimization is essential to enhance the economic viability, operational efficiency, and reliability of PV systems. This paper provides a comprehensive review of optimization models and methodologies for battery sizing in photovoltaic power stations. The review categorizes existing approaches into techno-economic optimization, reliability-focused models, and hybrid methodologies, and highlights key factors such as load demand, solar irradiance variability, battery characteristics, and market conditions. Furthermore, emerging trends, including machine learning techniques, multi-objective optimization, and the integration of hybrid energy systems, are discussed. This review aims to serve as a reference for researchers and practitioners seeking to develop advanced optimization models to improve battery sizing in PV power stations, ultimately contributing to the advancement of renewable energy systems.

2. CONFIGURATION OF BATTERY ENERGY STORAGE SYSTEM

2.1 Selection of energy storage technologies

Among the various types of energy storage technologies available, lithium-ion batteries, lead-acid batteries, and emerging technologies such as redox flow batteries, sodium-sulfur batteries, and zinc-hybrid cathode batteries have been extensively studied. The economic feasibility of battery energy storage systems, including lithium-ion and lead-acid batteries, has been evaluated for commercial consumers looking to replace peak power plants under energy time-of-use tariffs [1,2]. Hybrid energy storage systems combining lithium-ion and lithium-sulfur battery modules have been proposed to enhance specific energy and power capabilities. These systems utilize Gallium Nitride-based DC-DC converters to link the battery modules efficiently [3]. Research efforts continue to focus on improving the performance, cost-effectiveness, and safety of various energy storage technologies to facilitate their widespread adoption in different applications[4] .

2.2 Control strategy of BESS

The control strategy of battery energy storage systems plays a crucial role in various applications such as peak shaving, load shifting, frequency regulation, and voltage support. Reddy et al. (2020) utilized an Adaptive Neuro-Fuzzy Inference System (ANFIS) to prioritize and manage load flattening and voltage regulation in residential distribution networks, enhancing grid stability[5]. Li et al. (2021) proposed a virtual synchronization control strategy for integrating optical storage with BESS[6]. This approach is effective in mitigating output fluctuations and providing the necessary synchronous support for grid stability. Recent studies have made significant strides in enhancing BESS control and operation within distribution networks abundant with renewable energy. A multi-objective control strategy optimizes BESS for both benefit maximization and safe operation[7]. A composite BESS, combining hydrogen/bromine redox flow batteries and supercapacitors, addresses pulse power regulation in grid-tied PV systems. State-space modeling has been utilized to develop load frequency control strategies, coordinating wind turbines, HVDC, ESS, and synchronous generators for improved frequency regulation[8]. These advancements collectively bolster BESS role in renewable energy integration and grid stability.

2.3 Optimization constraints

The energy storage optimization model's constraints are categorized into internal and external factors (Fig.3). Internal constraints include energy balance to prevent loss, energy capacity which is the maximum energy the battery can store, state of charge indicating current battery charge level, and battery lifetime concerning its operational lifespan. External constraints encompass power constraints affecting rapid charge/discharge capabilities, grid load demand aligning battery operation with electricity needs, economic constraints considering operational costs and benefits, and emission constraints to limit environmental impact, particularly greenhouse gas emissions. These constraints ensure the battery operates efficiently, meets performance needs, and aligns with economic and environmental sustainability goals.

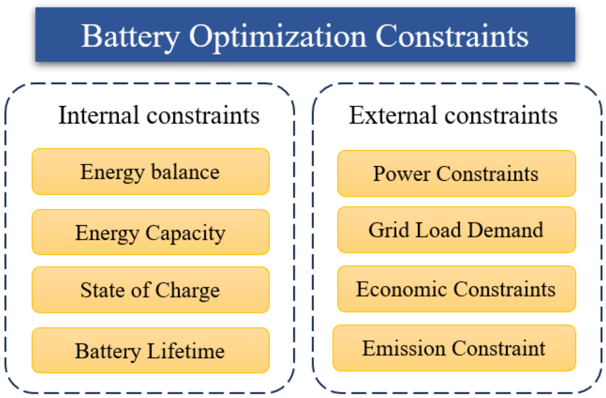

Fig. 3 Battery optimization constraints

3. OPTIMIZATION METHODS

3.1 Mathematical Programming Methods

Mathematical programming methods play a crucial role in optimizing battery sizing in PV stations. (Mirhoseini et. al., 2020) utilized convex methods for economic battery sizing and power dispatch in a grid-connected charging station[9]. (Sayfutdinov et. al., 2020) employed the Alternating Direction Method of Multipliers for optimal siting, sizing, and technology selection of Li-ion battery storage[10]. (Achiluzzi et. al., 2020) proposed a stochastic mixed integer linear programming formulation for optimal asset planning for prosumers with energy storage and PV units[11]. (Chen et. al., 2021) introduced a two-layer model for optimal scheduling of FTPSS with PV and HESS, considering the online degradation of battery capacity[12]. (Taslimi et. al., 2021) optimized an off-grid solar-based energy system for a Conex using mixed-integer linear programming techniques[13]. These studies highlight the importance of mathematical programming methods in determining the optimal battery sizing for PV stations, considering various factors such as economic feasibility, energy indicators, and profit maximization.

3.2 Heuristic and Metaheuristic Algorithms

The optimization of battery sizing in photovoltaic (PV) systems has been a topic of interest in recent literature. (Maleki et. al., 2020) utilized the Harmony Search Optimization algorithm for the optimum sizing of hybrid solar schemes with battery storage units[14]. (Ashtiani et. al., 2020) conducted a techno-economic analysis of a grid-connected PV/battery system using the Teaching-learning-based Optimization Algorithm[15]. (Arfeen et. al., 2021) provided a comprehensive review of modern trends in optimization techniques applied to hybrid microgrid systems, categorizing metaheuristic algorithms into evolutionary, swarm intelligence, physics, and human intelligence-based algorithms[16]. (Kharrich et. al., 2021) proposed a new IWO/BSA algorithm for the economic and ecological design of hybrid renewable energy systems, focusing on minimizing the net present cost and considering various operating constraints[17]. (Ridha et. al., 2020) proposed a multi-objective particle swarm optimization (MOPSO) method for sizing standalone photovoltaic systems, optimizing the number of PV modules and storage batteries[18]. (Gerlach et. al., 2021) developed an energy management system for autonomous PV hybrid systems using a fuzzy logic approach combined with metaheuristic particle swarm optimization[19]. (Abdel-Mawgoud et. al., 2021) applied the Archimedes optimization algorithm to determine the optimal size of PVs and battery energy storage systems in distribution networks, reducing energy losses significantly[20]. (Eltamaly, 2021) introduced a Musical Chairs Algorithm for maximum power point tracking (MPPT) in PV systems[21]. (Diab et. al., 2022) optimized the sizing of stand-alone microgrids with PV plants, fuel cells, and battery storage systems, considering a real case study in Egypt[22]. Overall, the literature highlights the use of various heuristic and metaheuristic algorithms for battery sizing in PV systems, aiming to optimize system performance, reduce costs, and enhance reliability.

3.3 Multi-Objective Optimization

The optimization of battery sizing in PV power stations is a crucial aspect of ensuring efficient energy storage and utilization. Various optimization methods have been explored in recent research to address this issue. (Hussain et. al., 2020) proposed a two-step approach involving optimality analysis and performance evaluation using cost and power indices[23]. (Wu et. al., 2020) proposed a double-layer optimization method for BESS sizing analysis in fast-charge stations, utilizing genetic algorithms for optimal solutions[24]. Consider a variety of renewable energy sources, energy storage systems, and demand-side management to find the best solution for energy storage configuration under uncertain conditions[25]. (Oton et. al., 2020) focused on optimal sizing of a DC microgrid for a rural base transceiver station, emphasizing sustainability and environmental impact mitigation[26]. Similarly, (Bukar et. al., 2020) developed a methodology to optimize the size of ESS, PV, and diesel generator in a ship power system to minimize CO_2 emissions and costs.[27] In addition, the flexibility and anti-risk ability of the system can be effectively balanced by designing a two-stage optimization method, that is, the optimal size of the system is determined in the first stage, and the optimal operation strategy is determined in the second stage[28]. These methods offer valuable insights into improving energy efficiency and storage capacity in renewable energy systems.

4. EVALUATION METHODS

The optimal configuration of batteries in a photovoltaic (PV) station is crucial for maximizing energy efficiency and ensuring reliable power supply. Various studies have focused on evaluating different methods for determining the optimal battery configuration in PV systems. (Masih et. al., 2020) also presented an optimization and reliability analysis of hybrid solar-wind energy systems using a grasshopper optimization algorithm (GOA) for selecting the optimal energy system configuration[29]. Furthermore, (Ryu et. al., 2020) investigated the evaluation of business continuity for a grid-connected microgrid with a photovoltaic system and Battery Energy Storage System (BESS), emphasizing the importance of BESS operation planning during power outages[30]. (Hou et. al., 2020) focused on the optimal capacity configuration of a wind-photovoltaic-storage hybrid power system, highlighting the significance of gravity energy storage systems[31]. Additionally, (Peng et. al., 2021) conducted research on optimal configuration with capacity analysis of PV-plus-BESS for behind-the-meter applications, demonstrating the importance of considering load demand and electricity prices in determining PV system and BESS capacities[32]. (Pei et. al., 2021) also emphasized the importance of considering battery characteristics when configuring energy storage for photovoltaic power stations[33]. Overall, these studies underscore the importance of evaluating different methods for determining the optimal battery configuration in PV stations to enhance energy efficiency, reliability, and cost-effectiveness in renewable energy systems.

5. DISCUSSION

This review has underscored the critical role of battery energy storage systems in mitigating the intermittency and variability inherent in photovoltaic (PV) power generation. The exploration of optimization models for battery sizing in large PV power stations has revealed a diverse landscape of methodologies, each with its strengths and applications. Techno-economic optimization models have been instrumental in ensuring that battery systems are not only technically feasible but also economically viable. Reliability-focused models have highlighted the importance of battery systems in maintaining grid stability and power quality. Hybrid methodologies, which combine the precision of mathematical programming with the flexibility of heuristic algorithms, have emerged as a powerful tool for addressing complex, multi-objective optimization challenges.

The review has also brought to light the significance of performance evaluation metrics in assessing the effectiveness of battery sizing. Factors such as load profiles, PV generation patterns, and cost structures have been identified as pivotal in influencing battery sizing decisions. The impact of these factors has been analyzed across various models, demonstrating their crucial role in the optimization process. Emerging trends, including the integration of machine learning techniques and multi-objective optimization, have shown promise in further enhancing the accuracy and efficiency of battery sizing. The integration of hybrid energy systems, which combine PV with other renewable sources, presents new opportunities and challenges for optimization models.

6. CONCLUSIONS

The optimization of battery sizing in photovoltaic power stations is a multifaceted challenge that requires a nuanced approach. This review has provided a comprehensive overview of the current state of the art in optimization models, emphasizing the need for a holistic consideration of technical, economic, and reliability factors. The categorization of existing approaches into techno-economic, reliability-focused, and hybrid methodologies offers a structured framework for understanding and advancing the field.

The review has also highlighted the potential of emerging trends to further refine battery sizing optimization. Machine learning techniques offer new avenues for predicting PV output and load demand with greater accuracy, while multi-objective optimization frameworks allow for a more balanced consideration of competing objectives. The integration of hybrid energy systems will likely become increasingly important as the renewable energy sector continues to evolve. As the renewable energy sector continues to grow, the insights and methodologies discussed in this review will play a critical role in shaping the future of sustainable energy storage solutions.

ACKNOWLEDGMENT

We gratefully acknowledge the support from the JICA and the MOST of China for the Japan-China Cooperative Project on "Research on Human-Source-Load-Carbon Synergy Optimization Technology for Carbon Neutral City Energy System Driven by Population Trajectory Big Data.

REFERENCE

(1) Mongird, K.; Viswanathan, V. V.; Balducci, P. J.; Alam, J. E.; Fotedar, V.; Koritarov, V.; Hadjerioua, B. An Evaluation of Energy Storage Cost and Performance Characteristics. *ENERGIES* **2020**.

(2) Martinez-Bolanos, J. R.; Udaeta, M. E.; Gimenes, A. L. V.; Silva, V. O. da. Economic Feasibility of Battery Energy Storage Systems for Replacing Peak Power Plants for Commercial Consumers Under Energy Time of Use Tariffs. *JOURNAL OF ENERGY STORAGE* **2020**.

(3) Avila, A.; Lucu, M.; Garcia-Bediaga, A.; Ibarguren, U.; Gandiaga, I.; Rujas, A. Hybrid Energy Storage System Based on Li-Ion and Li-S Battery Modules and GaN-Based DC-DC Converter. *IEEE ACCESS* **2021**.

(4) Mahesh, M.; Bhaskar, D.; Reddy, T. N.; Sanjeevikumar, P.; Holm-Nielsen, J. Evaluation of Ancillary Services in Distribution Grid Using Large-scale Battery Energy Storage Systems. *IET RENEWABLE POWER GENERATION* **2020**.

(5) Reddy, K. R.; Meikandasivam, S. Load Flattening and Voltage Regulation Using Plug-In Electric Vehicle's Storage Capacity With Vehicle Prioritization Using ANFIS. *IEEE TRANSACTIONS ON SUSTAINABLE ENERGY* **2020**.

(6) Li, Z.-X.; Qiu, X.; Han, W. Simulation Research on Virtual Synchronization Control Strategy of Optical Storage Integration Based on DIgSILENT Platform. *2021 IEEE SUSTAINABLE POWER AND ENERGY CONFERENCE (ISPEC)* **2021**.

(7) Meng, G.; Sun, Y.; Yu, T.; Wang, C.; Sun, K.; An, P. A Multi-Objective Control Strategy of The Energy Storage System in Distribution Networks with A High Proportion of Renewable Energy. *JOURNAL OF PHYSICS: CONFERENCE SERIES* **2023**.

(8) Trinh, D.-T.; Wu, Y.-K.; Pham, M.-H. A Novel Load Frequency Control Strategy for A Modern Power System By Considering State-Space Modeling and Stability Analysis. *IEEE ACCESS* **2024**.

(9) Mirhoseini, P.; Ghaffarzadeh, N. Economic Battery Sizing and Power Dispatch in a Grid-Connected Charging Station Using Convex Method. *Journal of Energy Storage* **2020**, *31*, 101651.

(10) Sayfutdinov, T.; Ali, M.; Khamisov, O. Alternating Direction Method of Multipliers for the Optimal Siting, Sizing, and Technology Selection of Li-Ion Battery Storage. *Electric Power Systems Research* **2020**, *185*, 106388.

(11) Achiluzzi, E.; Kobikrishna, K.; Sivabalan, A.; Sabillon, C.; Venkatesh, B. Optimal Asset Planning for Prosumers Considering Energy Storage and Photovoltaic (PV) Units: A Stochastic Approach. *Energies* **2020**, *13* (7), 1813.

(12) Chen, M.; Liang, Z.; Cheng, Z.; Zhao, J.; Tian, Z. Optimal Scheduling of FTPSS with PV and Hess Considering the Online Degradation of Battery Capacity. *IEEE Transactions on Transportation Electrification* **2021**, *8* (1), 936–947.

(13) Taslimi, M. S.; Maleki Dastjerdi, S.; Bashiri Mousavi, S.; Ahmadi, P.; Ashjaee, M. Assessment and Multi-Objective Optimization of an off-Grid Solar Based Energy System for a Conex. *Energy Equipment and Systems* **2021**, *9* (2), 127–143.

(14) Maleki, A.; Nazari, M. A.; Pourfayaz, F. Harmony Search Optimization for Optimum Sizing of Hybrid Solar Schemes Based on Battery Storage Unit. *ENERGY REPORTS* **2020**.

(15) Ashtiani, M. N.; Toopshekan, A.; Astaraei, F. R.; Yousefi, H.; Maleki, A. Techno-Economic Analysis of A Grid-Connected PV/Battery System Using The Teaching-Learning-Based Optimization Algorithm. *SOLAR ENERGY* **2020**.

(16) Arfeen, Z. A.; Sheikh, U. U.; Azam, M. K.; Hassan, R.; Shehzad, H. M. F.; Ashraf, S.; Abdullah, M. P.; Aziz, L. A Comprehensive Review of Modern Trends in Optimization Techniques Applied to Hybrid Microgrid Systems. *CONCURRENCY AND COMPUTATION: PRACTICE AND EXPERIENCE* **2021**.

(17) Kharrich, M.; Kamel, S.; Ellaia, R.; Akherraz, M.; Alghamdi, A. S.; Abdel-Akher, M.; Eid, A.; Mosaad, M. I. Economic and Ecological Design of Hybrid Renewable Energy Systems Based on A Developed IWO/BSA Algorithm. *ELECTRONICS* **2021**.

(18) Ridha, H. M.; Gomes, C.; Hizam, H.; Ahmadipour, M. Optimal Design of Standalone Photovoltaic System Based on Multi-Objective Particle Swarm Optimization: A Case Study of Malaysia. **2020**.

(19) Gerlach, L.; Bocklisch, T. Experts Versus Algorithms? Optimized Fuzzy Logic Energy Management of Autonomous PV Hybrid Systems with Battery and H2 Storage. *ENERGIES* **2021**.

(20) Abdel-Mawgoud, H.; Kamel, S.; Tostado-Véliz, M.; Elattar, E. E.; Hussein, M. M. Optimal Incorporation of Photovoltaic Energy and Battery Energy Storage Systems in Distribution Networks Considering Uncertainties of Demand and Generation. *APPLIED SCIENCES* **2021**.

(21) Eltamaly, A. M. A Novel Musical Chairs Algorithm Applied for MPPT of PV Systems. *RENEWABLE & SUSTAINABLE ENERGY REVIEWS* **2021**.

(22) Diab, A.; El-Rifaie, A.; Zaky, M.; Tolba, M. Optimal Sizing of Stand-Alone Microgrids Based on Recent Metaheuristic Algorithms. *MATHEMATICS* **2022**.

(23) Hussain, A.; Bui, V.-H.; Baek, J.-W.; Kim, H.-M. Stationary Energy Storage System for Fast EV Charging Stations: Optimality Analysis and Results Validation. *ENERGIES* **2020**.

(24) Wu, D.; Qiang, G.; Zhao, W.; Wang, J.; Shi, S.; Zhou, Y. Battery Energy Storage System (BESS) Sizing Analysis of Bess-Assisted Fast-Charge Station Based on Double-

Layer Optimization Method; 2020; pp 658–662. https://doi.org/10.1109/SCEMS48876.2020.9352324.

(25) Luo, L.; Abdulkareem, S. S.; Rezvani, A.; Miveh, M. R.; Samad, S.; Aljojo, N.; Pazhoohesh, M. Optimal Scheduling of a Renewable Based Microgrid Considering Photovoltaic System and Battery Energy Storage under Uncertainty. *Journal of Energy Storage* **2020**, *28*, 101306.

(26) Oton, C.; Iqbal, M. T. Design and Analysis of A Stand-Alone DC Hybrid Microgrid for A Rural Base Transceiver Station in Nigeria. *2020 IEEE ELECTRIC POWER AND ENERGY CONFERENCE (EPEC)* **2020**.

(27) Bukar, A. L.; Tan, C. W.; Lau, K. Y.; Dahiru, A. T. Optimal Planning of Hybrid Photovoltaic/Battery/Diesel Generator in Ship Power System. *INTERNATIONAL JOURNAL OF POWER ELECTRONICS AND DRIVE SYSTEMS* **2020**.

(28) Aghamohamadi, M.; Mahmoudi, A.; Haque, M. H. Two-Stage Robust Sizing and Operation Co-Optimization for Residential PV–Battery Systems Considering the Uncertainty of PV Generation and Load. *IEEE Transactions on Industrial Informatics* **2021**, *17* (2), 1005–1017. https://doi.org/10.1109/TII.2020.2990682.

(29) Masih, A.; Verma, H. Optimization and Reliability Evaluation of Hybrid Solar-Wind Energy Systems for Remote Areas. *INTERNATIONAL JOURNAL OF RENEWABLE ENERGY RESEARCH* **2020**.

(30) Ryu, A.; Ishii, H.; Hayashi, Y. Multi-Objective Optimal Operation Planning for Battery Energy Storage in A Grid-Connected Micro-Grid. **2020**.

(31) Hou, H.; Xu, T.; Wu, X.; Wang, H.; Tang, A.; Chen, Y. Optimal Capacity Configuration of The Wind-Photovoltaic-Storage Hybrid Power System Based on Gravity Energy Storage System. *APPLIED ENERGY* **2020**.

(32) Peng, C.-Y.; Kuo, C.-C.; Tsai, C.-T. Optimal Configuration with Capacity Analysis of PV-Plus-BESS for Behind-the-Meter Application. *APPLIED SCIENCES* **2021**.

(33) Pei, S.; Han, C.; Zhang, P.; Xu, J. Energy Storage Configuration Considering Battery Characteristics for Photovoltaic Power Station. *2021 4TH INTERNATIONAL CONFERENCE ON ENERGY, ELECTRICAL AND ...* **2021**.