Demand and Application Analysis of Large-Scale Energy Storage Technology in Power Systems (Postprint)

Authors: Wu Shengjun, Qingshan Xu, Yuan Xiaodong, Chen Bing, Li Qiang

Date: 2019-03-05T00:00:00+00:00

Abstract

Developing large-scale energy storage represents an important pathway for meeting growing electricity demand, enabling grid peak shaving and valley filling, and increasing the integration and consumption of renewable energy. The deployment of energy storage technology in power grids will substantially enhance operational safety, reliability, economy, and flexibility. This paper first introduces several energy storage technology types suitable for large-scale development, comparatively analyzes their respective advantages and disadvantages, and identifies factors influencing large-scale energy storage applications. By examining five of the most promising grid application modes for large-scale energy storage—frequency regulation, renewable energy consumption, deferral of grid investment and construction, load tracking and smoothing, and peak shaving and valley filling—the technical and economic indicator requirements for energy storage applications are presented. Finally, the problems and challenges that must be addressed for the development and application of large-scale energy storage are discussed, providing a reference for energy storage technology research and industrial development.

Full Text

An Analysis of Requirements and Applications of Grid-Scale Energy Storage Technology in Power Systems

Wu Shengjun[1],[2], Xu Qingshan[2], Yuan Xiaodong[1], Chen Bing[1], Li Qiang[1]

[1] Jiangsu Electric Power Research Institute, Nanjing 211103, China
[2] School of Electrical Engineering, Southeast University, Nanjing 210096, China

Abstract: The development of grid-scale energy storage represents a critical pathway for meeting growing electricity demand, enabling energy time-shifting, and facilitating the integration of high-penetration renewable energy sources. Energy storage applications in power grids will substantially enhance operational security, reliability, economy, and flexibility. This paper first introduces several energy storage technologies suitable for grid-scale deployment, compares their advantages and disadvantages, and identifies key factors influencing large-scale storage applications. By analyzing five of the most promising grid-scale storage application modes—frequency regulation, renewable energy accommodation, transmission and distribution upgrade deferral, load following, and peak shaving—this work delineates the required technical and economic performance targets. Finally, it outlines the problems and challenges that must be addressed for widespread deployment of grid-scale storage, providing valuable guidance for storage technology research and industrial development.

Keywords: Grid-scale energy storage technology, renewable energy grid integration, transmission and distribution upgrade deferral, load following, load shifting

1 Introduction

Power grids operate in a continuous state of dynamic balance between generation and consumption, requiring real-time power transmission and instantaneous matching of supply with demand. Traditional generation methods such as thermal, hydro, and nuclear power typically operate according to load dispatch instructions. However, renewable energy sources like wind and solar are constrained by natural conditions, exhibiting intermittent and fluctuating output characteristics that make generation control difficult. Large-scale integration of renewable energy consequently impacts grid economics, security, and stability. Meanwhile, economic and social development has driven continuous growth in peak loads and widening peak-valley differentials. In some regions, weak grid infrastructure struggles to meet load demands, making grid operation and control increasingly difficult and complex. Grid-scale energy storage can participate in short-term, medium-term, and long-term applications, representing a crucial solution to grid limitations and renewable energy integration challenges. By decoupling generation from consumption in both time and space, energy storage overcomes the traditional constraint that electricity cannot be stored, fundamentally transforming grid dispatching, operation, and planning. Deployed across generation, transmission, and distribution segments, energy storage effectively reduces brief power interruptions, alleviates peak supply pressure, defers or reduces investment in generation and grid infrastructure, enhances renewable energy accommodation capacity, and improves grid stability and flexibility. As energy storage technology advances toward higher energy density, greater conversion efficiency, lower costs, and larger scale, and with maturing demonstration projects and operational management techniques, the prospects for grid-scale storage applications are increasingly promising.

2 Overview of Grid-Scale Energy Storage Technologies

Energy storage technologies can be categorized by application into power-type and energy-type storage, and by technology into physical and electrochemical storage. Mature technologies suitable for grid-scale applications primarily include flywheel storage, compressed air energy storage, pumped hydro storage, supercapacitor storage, lead-acid batteries, lithium-ion batteries, and sodium-sulfur batteries . Each storage type offers distinct characteristics, providing diverse options for different grid-scale application requirements.

Electrochemical storage features flexible power and energy configuration according to application needs, rapid response, and suitability for large-scale deployment and mass production, making it the primary development direction for grid-scale storage. Among electrochemical technologies, lead-acid batteries offer mature technology, low cost, and high reliability, but suffer from short service life that fails to meet large-scale storage development requirements. Lithium-ion batteries provide high energy density, high conversion efficiency, and long cycle life, having achieved widespread application in electric vehicles and demonstrating suitability for grid-scale storage elements, with multiple large-scale demonstration projects already established domestically and internationally. Sodium-sulfur batteries offer high energy density and conversion efficiency with long lifespan, but require stringent operating conditions and present safety concerns. The primary challenges for electrochemical storage remain short cycle life, high costs, and environmental pollution from decommissioned batteries—critical issues requiring focused research and breakthroughs.

Supercapacitors represent typical power-type storage, suitable for high-power, low-capacity applications. They offer advantages including rapid charge/discharge rates, high power density, long cycle life, and wide operating temperature ranges, with the main limitations being low energy density and high cost.

Pumped hydro storage is the most widely deployed and mature technology for grid-scale applications, with plant capacities reaching gigawatt scale. Primarily used for peak shaving, frequency regulation, black start, and reserve capacity, pumped hydro is constrained by geographic and environmental limitations, requiring specific site conditions and long construction periods.

Compressed air energy storage ranks second only to pumped hydro in capacity, offering long discharge duration, low cost, and high safety margins with relatively mature technology that has achieved commercial application abroad. Its main drawbacks are low energy density and storage efficiency.

Flywheel storage provides high technological maturity, high power density, long lifespan, and pollution-free operation, making it suitable for grid frequency regulation and power quality management. However, it suffers from low energy density, high self-discharge rates, and high costs.

Currently, no single ideal storage technology can fully meet all grid-scale application requirements due to limitations in capacity, power, and economics. The primary research focuses for storage technologies—including safety, reliability, cost, efficiency, and lifespan—are also the key factors influencing large-scale deployment.

3 Analysis of Grid-Scale Energy Storage Applications

Increasing renewable energy penetration introduces unprecedented challenges to grid dispatch as generation becomes less controllable while still needing to meet fluctuating load demands. Grid-scale energy storage can provide voltage and frequency control, peak shaving, renewable energy integration, and other functions that enhance grid flexibility and stability. Widespread deployment requires storage to achieve specific economic and technical performance targets superior to existing generation and operational equipment. The five most promising applications are frequency regulation, renewable energy integration, transmission and distribution upgrade deferral, load following, and peak shaving. The following sections discuss the required economic and technical indicators for each application.

3.1 Grid Frequency Regulation (Short Duration)

Frequency regulation is critical for maintaining grid security and stability, requiring regulation units to respond quickly and accurately to dispatch commands. Continuous operation of large thermal power units for frequency regulation leads to reduced load factors and environmental pollution. Energy storage' s greatest advantage in frequency regulation lies in its rapid and precise response capability, delivering higher regulation efficiency per unit power. Storage technology is ideally suited to address short-term supply-demand imbalances, providing frequency regulation services with response speeds far exceeding conventional thermal units. According to U.S. electricity market analysis, storage provides 1.7 times the regulation effect of hydro units, 2.5 times that of gas units, and over 20 times that of coal units. Fast-regulating storage technologies can more effectively provide frequency regulation services. Key performance metrics for frequency regulation applications include system lifespan, continuous discharge duration, response time, and cycle efficiency . With low operating costs, rapid response, stable operation, and high reliability, storage offers superior frequency regulation characteristics. If grid-scale storage can achieve the targets in Table 2, it will have tremendous development potential for grid frequency regulation.

3.2 Renewable Energy Grid Integration (Short Duration)

Renewable energy development reduces fossil fuel consumption and environmental pollution, but the randomness and uncertainty of renewable output constrain further deployment. Using storage to modify renewable generation characteristics and transform them into controllable power sources represents a viable pathway for large-scale grid integration. Combined with renewable generation forecasting, storage systems can effectively smooth output fluctuations, improve reliability and stability, and enable large-scale renewable energy accommodation. Key performance metrics for renewable integration include cycle efficiency, system lifespan, and response time . If storage systems can meet these targets, they will see widespread application in renewable integration, increasing the proportion of renewable generation in the grid.

3.3 Deferral of Transmission and Distribution Construction and Upgrade (Long Duration)

Increasing electricity demand in load centers creates tremendous pressure on transmission and distribution infrastructure, causing local power flow imbalances and supply shortages during peak periods. Constructing and upgrading transmission and distribution facilities to meet peak demand is economically inefficient and requires long construction periods. Energy storage plants charging during off-peak periods and discharging during peaks can satisfy demand, deferring or reducing investment in transmission, distribution, and generation infrastructure—an economically viable solution. Key performance metrics include discharge duration, capacity, reliability, and system lifespan, with safety being a critical consideration requiring integration with existing grid protection systems. If grid-scale storage can achieve the performance targets in , it will be adopted as a cost-effective solution to accommodate grid intelligence and growing demand while deferring infrastructure construction.

3.4 Load Following and Smoothing (Long Duration)

In electricity bilateral markets where direct transactions occur between generators and consumers, power supply must track load fluctuations to maintain balance. Load following services, typically provided by gas units with good regulation performance, suffer from low economic efficiency and high emissions when tracking load and operating at low load factors, while increasing maintenance requirements. Storage’ s rapid response capability can track and compensate for load fluctuations before grid state changes occur, maintaining performance even at non-rated power levels. The bidirectional characteristic of storage also expands the regulation range, making it highly suitable for fast-response load following services. Key performance metrics include operation and maintenance costs and discharge duration . If utility-scale storage can achieve these targets, it will enhance the power system’ s ability to respond to load fluctuations.

3.5 Peak Shaving and Valley Filling (Long Duration)

Widening peak-valley differentials in electricity demand create supply-demand conflicts, with high prices and tight supply during peaks, and low prices with surplus supply during valleys. Energy storage systems charging during valleys and discharging during peaks can effectively balance supply-demand fluctuations. Since valley electricity prices are far lower than peak prices, peak shaving using storage plants can not only meet peak demand but also generate profit through price arbitrage, enabling economic viability. Key performance metrics include operation and maintenance costs, discharge duration, and efficiency . If grid-scale storage can achieve these targets, it will be widely deployed, enhancing grid resilience, alleviating peak demand pressure, and improving equipment utilization rates.

4 Problems and Challenges

Despite promising development potential, several issues limit the widespread deployment of grid-scale energy storage in power systems:

(1) **Lack of Market Mechanisms:** The power system comprises generation, transmission and distribution, and load segments, with storage applicable across all sectors. This multifunctionality creates market positioning ambiguity. Storage cannot self-generate electricity, distinguishing it from traditional power plants, yet as grid equipment, utilities lack operational capabilities and qualifications for power plants. This positioning ambiguity creates difficulties for construction and development, while electricity pricing issues also affect promotion. Currently in the demonstration phase, grid-scale storage development requires not only supportive policies but also clear market positioning and pricing mechanisms.

(2) **Insufficient Demonstration Projects:** Limited large-scale storage system demonstrations constrain development and deployment, as technical performance and economic viability cannot be fully validated without real-world operational data. Small-capacity experimental research offers limited insights for large-scale applications, while theoretical analysis and simulation studies cannot accurately assess key metrics such as efficiency, lifespan, reliability, and safety. Furthermore, economic benefits must support widespread deployment, and insufficient demonstration data hinders analysis and validation of economic returns, impeding commercial promotion.

(3) **Immature Technology:** Grid-scale storage technology remains insufficiently mature, with key technical issues requiring resolution for most technologies beyond pumped hydro. Among various storage types, only pumped hydro, electrochemical storage, and compressed air can simultaneously meet capacity and power requirements for grid-scale applications, while power-type technologies like flywheel, supercapacitor, and superconducting storage struggle to meet capacity demands. Efficiency and lifespan also represent technical bottlenecks, with compressed air and traditional lead-acid batteries failing to meet grid-scale requirements. Safety and reliability—fundamental power system requirements—require further research and validation for grid-scale storage systems.

(4) **Lack of Standards and Specifications:** Limited demonstrations and immature technology have resulted in absent standards and specifications, hindering technology research and healthy industrial development. The lack of technical standards for equipment, design specifications for systems, and feasible evaluation methods for various storage solutions affects system testing, operation, and control, creating safety hazards. Although various standards for batteries, converters, and grid interconnection requirements are under development domestically and internationally, standard formulation is a gradual process requiring considerable time for revision and improvement.

5 Conclusion

Grid-scale energy storage technology represents a critical pathway for enhancing grid peak shaving and frequency regulation capabilities, improving renewable energy accommodation, and increasing grid stability and flexibility—forming a key enabling technology for smart grids. Storage applications span generation, transmission, distribution, and consumption segments, addressing numerous grid limitations and challenges. Widespread deployment will fundamentally transform power systems and accelerate the green, low-carbon energy transition.

Various storage technologies offer distinct advantages and disadvantages, providing diverse options for different applications. However, many remain in the experimental demonstration phase, requiring resolution of critical issues related to safety, reliability, and economics. With current technology prospects unclear, healthy storage industry development requires policy guidance and support, strengthened fundamental research, and accelerated establishment of standards and specification systems. Mature storage technologies, comprehensive standard systems, and favorable business models constitute the necessary conditions for large-scale grid deployment.

References

[1] Consulting Group of State Grid Corporation of China to Prospects of New Technologies in Power Systems. An analysis of prospects for application of large-scale energy storage technology in power systems[J]. Automation of Electric Power Systems, 2013, 37(1): 3-8.

[2] Hu Juan, Yang Shuili, Hou Chaoyong, et al. Present condition analysis on typical demonstration application of large-scale energy storage technology and its enlightenment[J]. Power System Technology, 2015, 39(4): 879-885.

[3] Gao Xiaotao. Technical approaches for energy-saving and emission reduction of Jiangsu power[J]. Jiangsu Electrical Engineering, 2015, 34(1): 65-68.

[4] Castillo A, Gayme D F. Grid-scale energy storage applications in renewable energy integration: a survey[J]. Energy Conversion and Management, 2014, 87: 885-894.

[5] Xu Shouping, Li Xiangjun, Hui Dong. A survey of the development and demonstration application of large-scale energy storage[J]. Power System and Clean Energy, 2013, 29(8): 94-100, 108.

[6] Akinyele D O, Rayudu R K. Review of energy storage technologies for sustainable power networks[J]. Sustainable Energy Technologies and Assessments, 2014, 8: 74-91.

[7] Hameer S, Van Niekerk J L. A review of large-scale electrical energy storage[J]. International Journal of Energy Research, 2015, 39(9): 1179-1195.

[8] US Department of Energy Office of Electricity Delivery & Energy Reliability. Electric power industry needs for grid-scale storage applications[EB/OL]. 2010-12-10[2014]. http://energy.gov/oe/downloads/electric-power-industry-needs-grid-scale-storage-applications.

[9] Wang Chengmin, Sun Weiqing, Yi Tao, et al. Review on energy storage application planning and benefit evaluation methods in smart grid[J]. Proceedings of the CSEE, 2013, 33(7): 33-41, 21.

[10] Pfenninger S, Keirstead J. Renewables, nuclear, or fossil fuels? scenarios for Great Britain's power system considering costs, emissions and energy security[J]. Applied Energy, 2015, 152: 83-93.

[11] Chen Dayu, Zhang Lizi, Wang Shu, et al. Development of energy storage in frequency regulation market of United States and its enlightenment[J]. Automation of Electric Power Systems, 2013, 37(1): 9-13.

[12] Wang Zaichuang, Yuan Tiejiang, Li Yongdong, et al. Power planning based on energy storage station to improve accommodation of wind power[J]. Renewable Energy Resources, 2014, 32(7): 954-960.

[13] Cui Yang, Zhu Jiaming, Ge Yanfeng, et al. Study on capacity configuration of large-scale energy storage system under concentrated charge and discharge based on wind curtailment characteristics and economics[J]. Power System Technology, 2016, 40(2): 484-490.

[14] Xue Zhongbing, Peng Cheng. Research on the coordinated operation of renewable energy generation and EV charging storage station[J]. Jiangsu Electrical Engineering, 2014, 33(5): 36-38.

[15] Jiang Ping, Xiong Huachuan. A control scheme design for smoothing wind power fluctuation with hybrid energy storage system[J]. Automation of Electric Power Systems, 2013, 37(1): 122-127.

[16] Solomon A A, Kammen D M, Callaway D. The role of large-scale energy storage design and dispatch in the power grid: a study of very high grid penetration of variable renewable resources[J]. Applied Energy, 2014, 134: 75-89.

[17] US Department of Energy Office of Electricity Delivery & Energy Reliability. Energy storage safety strategic plan[EB/OL]. 2014-

12[2014]. http://energy.gov/oe/downloads/energy-storage-safety-strategic-plan-december-2014.

[18] Reihani E, Motalleb M, Ghorbani R, et al. Load peak shaving and power smoothing of a distribution grid with high renewable energy penetration[J]. Renewable Energy, 2016, 86: 1372-1379.

[19] Li Jianlin, Tian Liting, Lai Xiaokang. Outlook of electrical energy storage technologies under energy internet background[J]. Automation of Electric Power Systems, 2015, 39(23): 15-25.

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv —Machine translation. Verify with original.