Front. Eng. Manag. 2025, 12(2): 305–329
https://doi.org/10.1007/s42524-025-4190-3

RESEARCH ARTICLE

Huadong MO, Chaojie LI, Nina LIU, Bo ZHAO, Haoxin DONG, Hangyue LIU, Enrico ZIO

Energy storage systems for carbon neutrality: Challenges and opportunities

Abstract In recent years, improvements in energy storage technology, cost reduction, and the increasing imbalance between power grid supply and demand, along with new incentive policies, have highlighted the benefits of battery energy storage systems. These systems offer long life, low cost, and high energy conversion efficiency. While energy storage is gradually transitioning from demonstration projects to commercial operations, its technical and economic performance is still limited, and it lacks economies of scale. Research on the design and operational optimization of energy storage systems is crucial for advancing project demonstrations and commercial applications. Therefore, this paper aims to provide insights into system configuration and operational optimization. It first summarizes the optimal configuration of energy storage technology for the grid side, user side, and renewable energy generation. It then analyzes and reviews the economic optimization and cybersecurity challenges in power system operations. Finally, this paper discusses unresolved issues in energy storage applications and highlights important considerations for future implementation and expansion.

Keywords energy storage technology, battery energy storage, configuration planning, operation optimization, economics and security

1 Introduction

Global energy consumption is increasing due to population growth, technological advancements, and post-pandemic recovery. This has led to significant concerns regarding energy supply and environmental issues. Fossil fuels are heavily relied upon, resulting in substantial carbon emissions and resource depletion. In response, renewable energy sources are being actively developed. One of the United Nations' Sustainable Development Goals (SDGs) aims to significantly increase the share of renewable energy in the global energy mix by 2030 (SDGs, 2019). However, renewable energy sources are intermittent and unpredictable. Their large-scale integration into the grid adds uncertainty and complexity, threatening the reliability and stability of power systems.

This is why energy storage technology is gaining significant interest for its potential to address the challenges of widespread renewable energy adoption. An energy storage system (ESS) can help smooth the output of renewable energy sources and reduce the impact of their intermittency on system stability. It can also store excess energy during periods of high availability, which can then be used to meet demand during peak hours (Zhou et al., 2022). Additionally, energy storage technology enhances the resilience of the energy system by improving its self-healing capabilities and enabling faster recovery after disasters and accidents (Cheng, 2013; Xu et al., 2013). More specifically, energy storage technology plays a crucial role in several areas. It supports the development of smart grids, enhances distributed generation systems, and facilitates the integration of Electrical Vehicles (EVs). This technology helps manage energy demand more effectively by balancing peak and off-peak usage. It also smooths energy consumption, increases the efficiency

Received Jun. 11, 2024; revised Dec. 19, 2024; accepted Jan. 1, 2025

Huadong MO (✉)
School of Systems and Computing, University of New South Wales, Canberra ACT 2612, Australia
E-mail: huadong.mo@unsw.edu.au

Chaojie LI (✉), Nina LIU, Bo ZHAO, Haoxin DONG
State Key Laboratory of Alternate Electrical Power System with Renewable Energy Sources, North China Electric Power University, Beijing 102206, China
E-mail: cjlee.cqu@163.com

Hangyue LIU
Sungrow Australia Group Pty Ltd, North Sydney NSW 2060, Australia

Enrico ZIO
Center for Research on Risks and Crises, Mines-Paris, PSL, France; Department of Energy, Politecnico di Milano, Italy

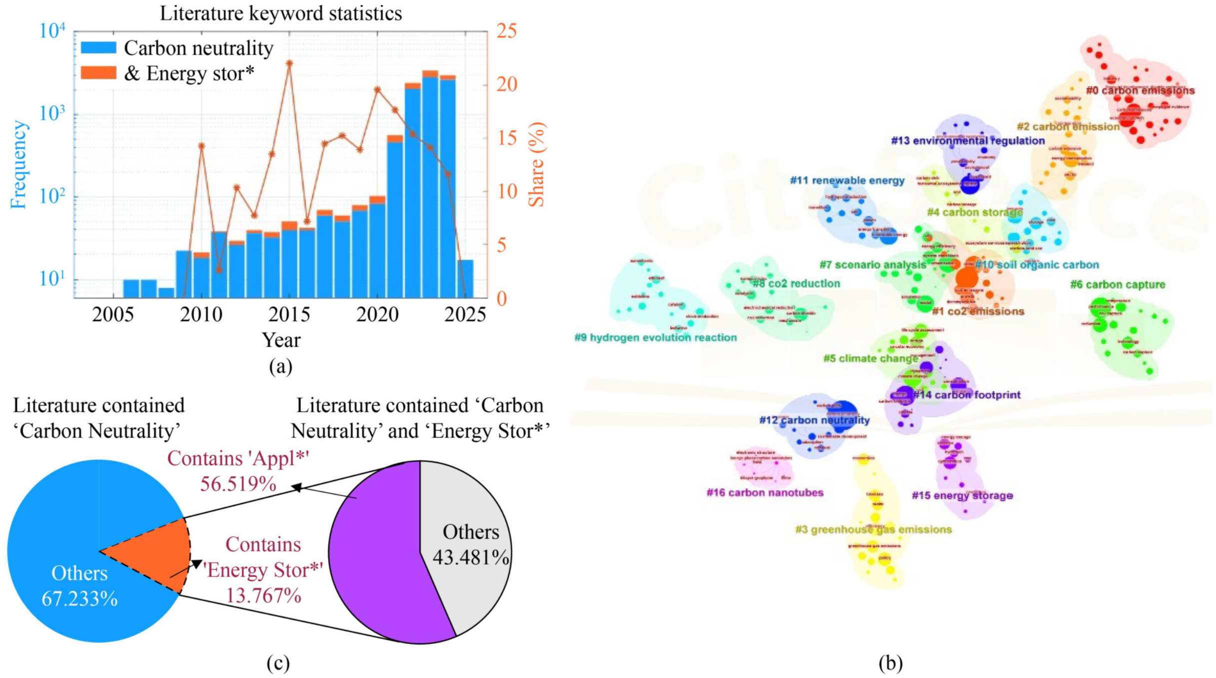
Open Access funding enabled and organized by CAUL and its Member Institutions.

of power equipment, and reduces the overall cost of power supply.

Currently, the battery energy storage system (BESS) is the storage technology with the largest installed capacity, apart from pumped storage. Pumped storage has significant limitations, including high geographic requirements, high initial investment costs, and potential environmental impacts. Additionally, pumped storage has a power response rate of several minutes, making it challenging to provide responses within seconds. The inertia of the power system is expected to decline rapidly in the future due to increased renewable energy installations and a reduced share of synchronous generators. According to Fernández-Guillamón et al. (2019), from 1996 to 2016, the equivalent inertia constant in Europe decreased from 4 to 3.3 s – nearly a 20% drop – due to rising wind power penetration. In Denmark, which has a high share of renewable energy, it decreased from 4 to 1.6 s. The European Network of Transmission System Operators (ENTSO-E) predicts that, under rapid renewable energy development scenarios, the grid equivalent inertia in the UK and Italy will drop to zero by 2040 (ENTSO-E, 2021). As a result, future power systems will require more fast-response devices to ensure frequency stability. BESS is considered a key energy storage technology for future power systems due to its high energy density, high cycle efficiency, and rapid response speed. Therefore, this paper focuses on BESS as the primary research subject.

With a steady decline in energy storage technology costs, the economic advantages of BESS, such as long life, high energy conversion efficiency, and low cost, are becoming more evident (Li et al., 2016a; Deeba et al., 2016). Regarding profitability, BESS offers significant flexibility compared to traditional power units. It can provide high-slope, large-volume, and bidirectional power, enabling it to take advantage of profitable opportunities, such as price spikes. In terms of feasibility, a Virtual Power Plant (VPP) that aggregates multiple Distributed Energy Resources (DERs) offers a reliable platform for distributed BESSs to profit from energy trading and ancillary services markets (Han et al., 2021). As for market growth, the global battery market was valued at \$108.4 billion in 2019 and is expected to grow at a rate of 14.1% from 2020 to 2027 (Grand View Research, 2023). With the increasing share of EVs in new vehicle sales, it is likely that EV fleets will also be aggregated into dynamic BESSs and participate in markets using Vehicle-to-Grid (V2G) technology (Mwasilu et al., 2014).

To provide a comprehensive view of previous related literature, we conducted a bibliometric analysis of carbon neutrality research using Citespace. First, we searched the Web of Science Core Collection using the keyword ‘Carbon Neutrality’ and selected papers from 2000 to the present. The search yielded a total of 10,525 papers. After filtering out ‘Artistic’ and ‘Review’ articles, we obtained 9,973 valid papers. The results of the bibliometric analysis are shown in Fig. 1. Figure 1(a) displays the number of papers published over time, indicating that interest in ‘Carbon Neutrality’ has been steadily increasing over the past decade, with a notable spike in 2021. Figure 1(b) highlights the main research areas within the ‘Carbon Neutrality’ literature, showing that energy storage is a key pathway to achieving carbon neutrality.



(a) (c) (b)

Fig. 1 The result of the bibliometric analysis on the carbon neutrality literature.

Figure 1(c) presents the percentage of energy storage research within the 'Carbon Neutrality' literature, focusing on energy storage applications. It is clear that achieving economical and efficient energy storage applications is a major concern for researchers.

Nevertheless, compared to most other energy resources, one of the main obstacles to the widespread commercial deployment of BESS is the high cost, particularly for configuration and operation. These costs make it challenging to unlock the economic potential of BESS. This requires evaluating factors, such as system degradation, energy roundtrip efficiency, and energy market bidding strategies. Additionally, careful planning and design are needed throughout the entire BESS life cycle, covering both configuration and operation phases. Furthermore, due to technical, economic, and regulatory limitations, an effective system for analyzing and evaluating the practical benefits of BESS has not yet been established. As energy storage technology transitions from engineering demonstrations to commercial operations, research on the configuration design and operational optimization of BESS in power systems presents both challenges and opportunities. This paper focuses on exploring how energy storage in different application scenarios can be efficiently energy managed through optimization techniques to reduce the cost of energy storage.

To date, the applications of BESS in power systems can be classified into five categories: (1) ancillary services, (2) power reserve, (3) energy trading, (4) investment delay and grid support, and (5) combined applications, as summarized in Table 1. Depending on the application type, duration, and value stream, the optimization objectives for the configuration design or operational optimization of BESS can be determined.

On the other hand, artificial intelligence (AI) is becoming an essential tool in developing information technology applications in the power industry, supporting the transformation and growth of the energy sector (Hu et al., 2023). With the introduction of concepts like smart grids and the energy Internet, AI has been widely applied across various power system fields. The application route for AI technology is shown in Fig. 2. For example, the Hornsdale Power Reserve in South Australia uses an AI-powered trading system, demonstrating the potential of AI in the power sector. This large-scale battery saved consumers over $150 million in its first two years of operation, showcasing the value of grid-scale batteries in electricity markets and proving that integrating AI into BESS can be highly profitable (Neoen, 2024). Therefore, applying AI technology to optimize BESS configuration and operation to overcome high costs and enhance economic viability is a promising approach.

To fill the above gaps and provide valuable references to potential researchers, we will conduct research according to the technical route and ideas shown in Fig. 3. To address the gaps mentioned above and provide valuable insights for future researchers, this review paper makes the following contributions:

- General optimization models, including objective functions and constraints, for BESS configuration design and operational optimization in power systems are provided.
- Typical optimization methods and objectives for BESS configuration design are illustrated.
- The optimization methods are classified based on configuration design and operational optimization, with further sub-classification according to specific BESS applications in power systems. Innovations, strengths, and limitations of these methods are also analyzed.
- The cybersecurity challenges in BESS operation, particularly under AI and blockchain technology, are summarized.
- Opportunities for future research are discussed.

2 Energy storage technologies in power system

In modernizing the power system, energy storage technology has become essential for enhancing grid flexibility and achieving carbon neutrality. As renewable energy is integrated on a large scale, the importance of energy storage

Table 1 Different optimization categories, applications, and value streams of BESS

Optimization category	Application	Duration	Value stream
Ancillary service	Frequency regulation	Long-Term	Gain auction profits from power grid enterprises
	Peak shaving and valley filling	Long-Term	Reduce peak cost for related departments
	Black start	Short-Term	Get rewards from contracts with system operators
Power reserve	Uninterrupted power supply	Short-Term	Improve power supply reliability
	Ramp rate control	Long-Term	Stabilize the fluctuation and obtain relevant rewards
Energy trading	Energy arbitrage	Long-Term	Low charge and high discharge can obtain benefits
Investment delay and grid support	Voltage support	Long-Term	Reduce utility costs for distribution network/enterprises
	EV-Grid integration	Long-Term	Reduce the cost of the distribution network
Combined application	Multiple applications	Short-Term/Long-Term	Value accumulation in many aspects

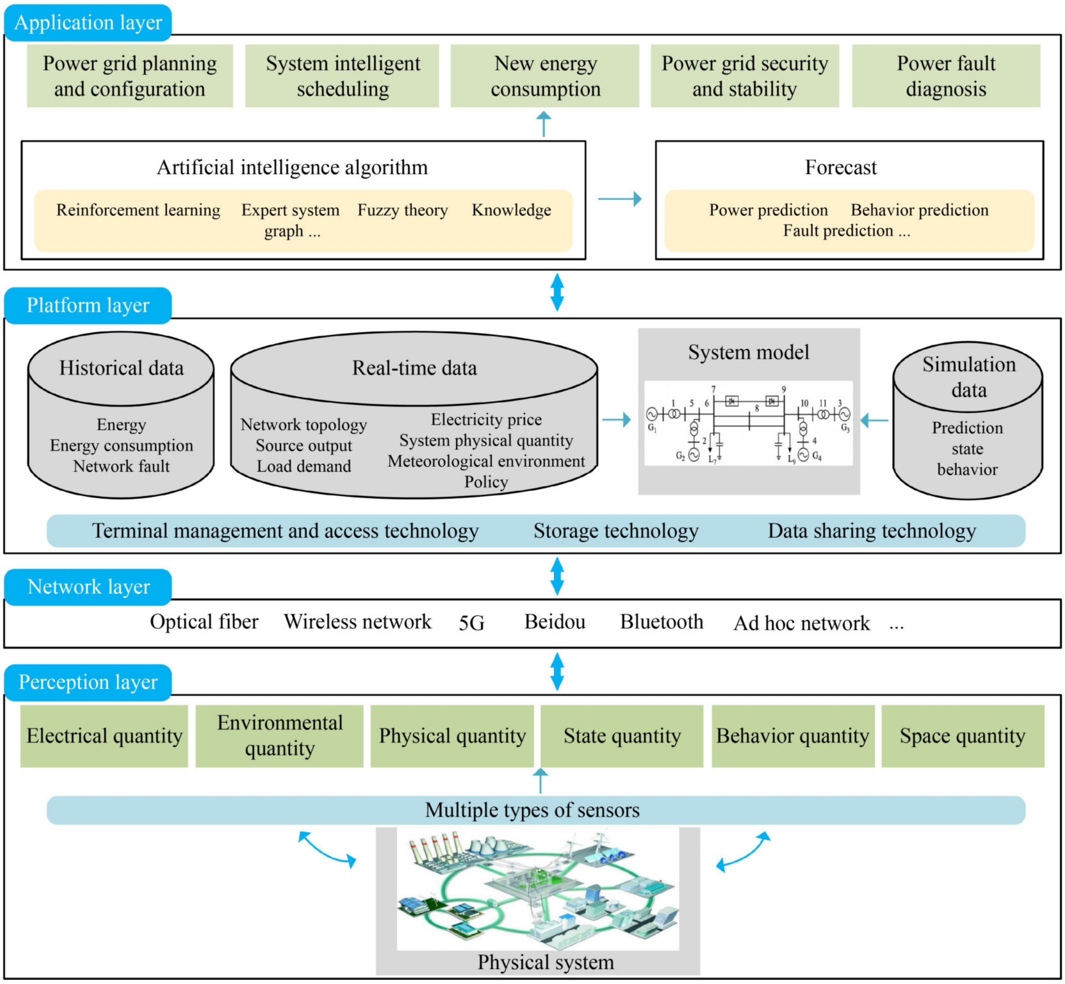


Fig. 2 The application technology route of artificial intelligence technology.

has grown significantly. This section provides an in-depth review of current energy storage technologies, including their types, characteristics, application scenarios, and techno-economic aspects.

2.1 Types and technical features

Energy storage technologies can be categorized into physical energy storage, electrochemical energy storage, and electromagnetic energy storage based on the form of energy storage and the conversion mechanism. Physical energy storage includes technologies such as pumped storage, compressed air energy storage, and flywheel energy storage. These technologies are known for their large-scale, long-duration storage capacity, making them suitable for grid peak shaving and emergency backup. Electrochemical energy storage technologies, including lithium-ion batteries, lead-acid batteries, flow batteries, and hydrogen energy storage, are characterized by fast response times and flexible configurations. They are crucial for frequency regulation, backup, and integrating renewable energy into the power system. Electromagnetic energy storage, such as superconducting magnetic energy storage and supercapacitors, offers high power density and fast charging and discharging capabilities. These technologies are well-suited for instantaneous power support and maintaining energy balance in the grid. Table 2 presents the specific classification of energy storage technologies, while Table 3 summarizes the key technical characteristics of each technology.

2.2 Application scenarios

Energy storage technologies have diverse application scenarios, ranging from large-scale grid operations to distributed energy management. In areas rich in renewable energy, physical energy storage is used to shift energy over time and ensure stable grid operation through the ‘renewable energy + storage’ model. Electrochemical energy storage is applied in urban power grids and microgrids for commercial operations, providing frequency regulation, peak-valley arbitrage, and demand-side response services. Electromagnetic energy storage is valuable in scenarios requiring a fast response, such as instantaneous power compensation in power grids and fast charging stations for EVs. Meanwhile, phase change

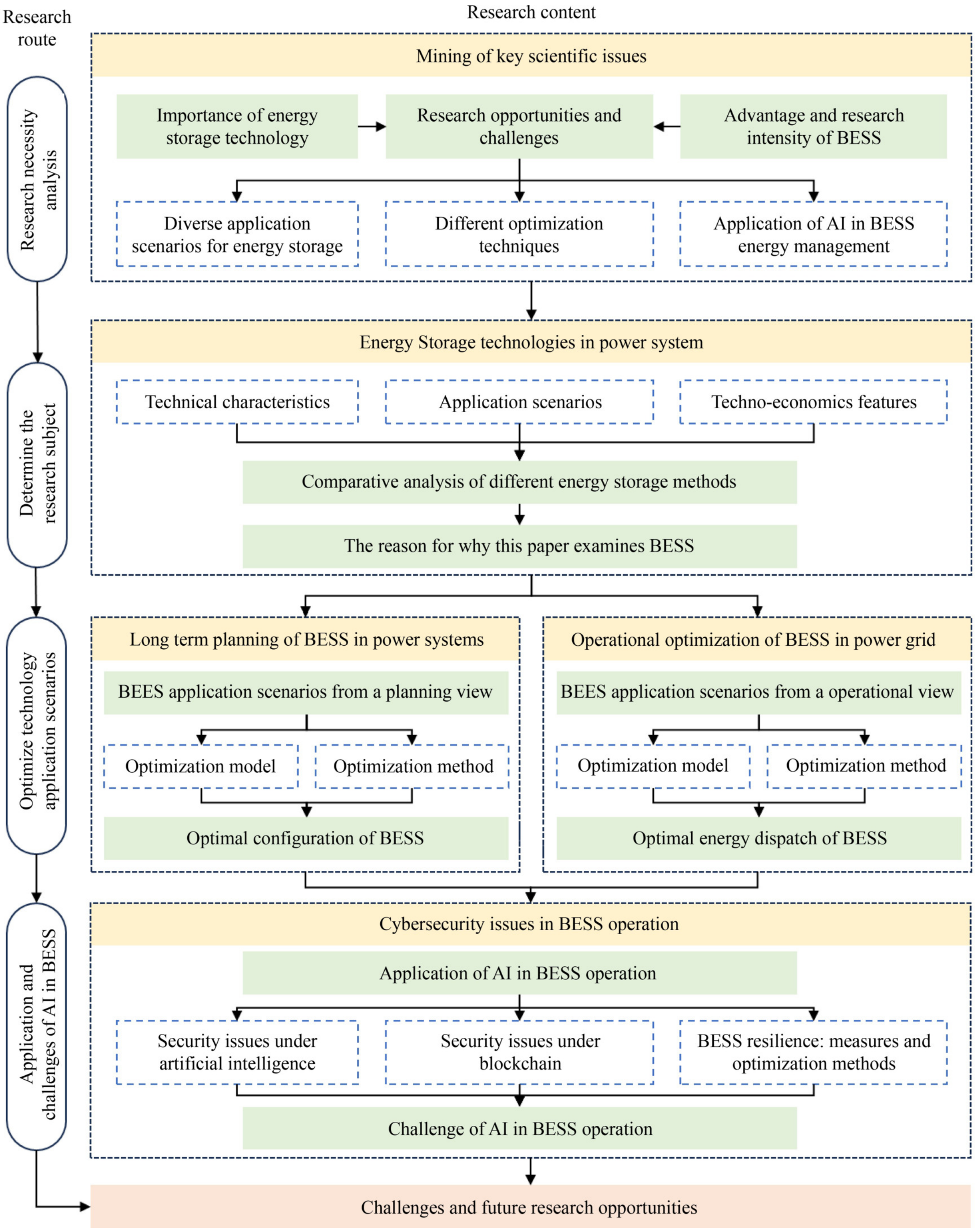


Fig. 3 The research route and content of this paper.

energy storage is used in solar thermal power generation and industrial waste heat recovery to provide a stable supply of thermal energy, improving energy efficiency. Table 4 summarizes the advantages and disadvantages of each energy storage technology.

2.3 Technical and economic analysis

In terms of techno-economics, physical energy storage offers better cost efficiency due to its large-scale, long-duration characteristics. However, it is limited by geographic requirements and potential environmental impacts. The cost of electrochemical energy storage is decreasing due to technological advances and large-scale production, and its flexibility and high efficiency make it competitive in the power market. Electromagnetic energy storage has high power density, but its current high cost limits its use to specific applications requiring extremely

Table 2 Energy storage systems based on the form of energy storage and conversion mechanism

Energy Storage Systems	Form of energy	Abbreviation
Electrochemical energy storage system	Lithium-ion batteries	Li-ion
	Lead-acid batteries	LA
	Liquid current batteries	NaS
	Hydrogen energy storage	HES
Physical energy storage system	Pumped storage	PHES
	Compressed air energy storage	CAES
	Flywheel energy storage	FES
Electromagnetic energy storage system	Superconducting magnetic energy storage	SMES
	Supercapacitors energy storage	SCES

Table 3 Technical characteristics of various energy storage technologies (Elalfy et al., 2024; Domínguez et al., 2025).

Type	Power density (kW/m^3)	Energy density		Lifetime cycles (times)	Round-trip efficiency (%)	Self-discharge per day (%)
		(kW·h/m^3)	(kW·h/kg)			
Li-ion	1300–10000	140–630	75–200	1000–10000	90–97	0.1–0.3
LA	10–400	50–80	30–50	500–2000	70–80	0.1–0.4
NaS	140–180	150–250	150–240	2 500–4 500	<90	0.1–0.3
HES	>500	500–3000	800–10000	>1000	20–50	<0.0001
PHES	N. A	N. A	0.5–1.5	20000–50000	70–87	0.005–0.02
CAES	0.04–10.00	0.4–20	30–60	10000–30000	60–90	0.003–0.03
FES	1000–5000	20–80	10–30	>20000	75–95	55–100
SMES	1000–4000	0.2–13.8	0.3–75.0	10000–100000	80–99	10–15
SCES	40000–120000	10–20	0.05–15	>50000	60–97	20–40

Table 4 Advantages and disadvantages of various energy storage technologies (Elalfy et al., 2024; Domínguez et al., 2025)

Type	Advantage	Disadvantage	Application status
Li-ion	High power and energy density, rapid response	The lifecycle depends on the discharge level and high cost	Suitable for power supplies that require high response speed and mobility
LA	Low cost, mature technology	Low energy and power density, short lifecycle, high maintenance costs, and toxic materials	The most mature BESS
NaS	High energy storage capacity	Complex structure, low energy and power density	Suitable for public utilities with long discharge duration
HES	High energy density, long discharge time, and good environmental compatibility	The overall energy conversion efficiency is low, and the investment cost is high	Hydrogen production, storage, and transportation are restricted
PHES	Mature technology, high energy storage capacity, long service life cycle	Geographical location limitation, high cost, low power density, and potential environmental impact	Costs vary by location, with high initial infrastructure costs and variable operation and maintenance costs
CAES	Mature technology and high energy storage capacity	Efficiency fluctuations, safety hazards, and geographical limitations	The cost varies depending on the site, with high initial infrastructure costs and variable operation and maintenance costs
FES	High energy storage capacity, environmentally friendly, small space occupancy, mature technology	Noise pollution, safety issues, and high unit energy storage costs	Commonly used for uninterruptible power supply
SMES	Fast response speed, high energy storage capacity, and high reliability	High cost, cooling issues, and high magnetic field requirements	Low temperature refrigeration system needs to be configured
SCES	High energy density	The interdependence, safety issues, and environmental impacts of battery component characteristics	Suitable for power sources that require high response speed and fixed power supply

fast response times. Phase-change energy storage is limited economically due to material costs and the complexity of thermal management systems, yet it has unique advantages in certain applications. Table 5 summarizes the techno-economic characteristics of each energy storage technology.

Table 5 Techno-economics characteristics of various energy storage technologies (Elalfy et al., 2024; Domínguez et al., 2025; Lieskoski et al., 2024; De Carne et al., 2024)

Type	Average capital cost		Rated power (MW)	Rated energy (MW·h)	Suitable storage duration	Response time
	($/kWh)	($/kW)				
Li–ion	546	2512	0.1–50	10^{-5}–100	min–day	ms
LA	437	2140	1–100	0.01–100	min–day	ms
NaS	343	2254	0.1–50	0.1–100	min–day	ms
HES	540	3243	0.1–1000+	100–1000+	h–months	s–min
PHES	58	1413	100–5000	1000+	h–months	~3 min
CAES	77.8	980	5–300+	1000+	h–months	~10 min
FES	4791	867	0.01–20	0.01–5	s–min	ms–s
SMES	5350	322	0.01–10	10^{-4}–0.1	min–h	ms
SCES	540	3243	0.1–1000+	100–1000+	h–months	s–min

Note: Capital costs are calculated based on the typical discharge time for each technology. The average value represents the median of the entire price range, following the method outlined by Zakeri and Syri (2015).

2.4 Future development

The rapid growth of renewable energy generation makes deploying large-scale, cost-effective energy storage systems essential for maintaining power system reliability. Since there are various types of renewable energy sources, a diverse range of storage systems is needed to meet the specific requirements of each source. In the long-term, it is challenging to predict which type of energy storage system will dominate the market, but electrochemical energy storage technology, particularly BESS, is currently experiencing significant growth. Lithium-ion batteries are seen as a highly competitive option for grid-scale energy storage applications due to their high energy density, low mass, high efficiency, and fast response time. However, the actual deployment of BESS is still limited and has not yet reached the level required for large-scale, regulated commercialization, largely due to the insufficient exploitation of market potential and benefits. Optimizing the configuration and operation of energy storage systems is crucial for increasing the annual utilization of batteries and maximizing the benefits of BESS demonstration projects. For future energy storage projects, BESS capacity should be optimally configured, and efficient operation strategies should be developed based on the specific flexibility requirements of different scenarios. The goal is to reduce construction costs while better meeting the varying needs of the power grid. This approach will contribute to establishing a new power system that is environmentally friendly, low in carbon emissions, economically efficient, and both flexible and responsive.

3 Long-term planning of BESS in power systems

An effective configuration of BESS significantly impacts the overall economy and operational security of power systems. If the BESS capacity is too small, it cannot effectively improve power quality and grid performance. Conversely, an oversized BESS can lead to unnecessarily high investment and maintenance costs. Additionally, different BESS applications may require specific locations, as the placement of BESS within the grid can influence its effectiveness. Therefore, both the capacity and location of the BESS must be carefully considered during the system planning and design stages to achieve optimal configuration.

To optimize the capacity and location of BESS, it is necessary to first represent the optimization problem as a mathematical model. This model can then be solved using optimization techniques such as branch-and-bound and interior-point methods to determine the optimal BESS configuration. This chapter will begin by introducing the generalized BESS configuration planning model. It will then present the relevant optimization methods and conclude with a review of research on BESS configuration planning across different application scenarios.

3.1 Optimization model for BESS configuration design

During the BESS configuration design process, both the capacity and location of the BESS must be determined. Additionally, BESS operation should be considered within a two-stage planning framework. The planning period typically spans several years, such as 10 years, and should include representative scenarios of renewable generation and load demands. Generally, the BESS configuration planning process involves defining an objective function and corresponding constraints, which are as follows:

$$\min \textstyle\sum_{i\in I} f_1\left(E_i^{\mathrm{cap}}\right) + \sum_{i\in I}\sum_{t\in T} f_2\left(P_{i,t}^{\mathrm{ch}}, P_{i,t}^{\mathrm{dis}}\right), \tag{1}$$

$$0 \leqslant P_{i,t}^{\mathrm{ch}}, P_{i,t}^{\mathrm{dis}} \leqslant E_i^{\mathrm{cap}}/\tau, \forall i, t, \tag{1a}$$

$$E_i^{\mathrm{cap}} \leqslant E_i^{\mathrm{max}}, \tag{1b}$$

$$P_{i,t}^{BS} = P_{i,t}^{\mathrm{ch}}\eta_i^{\mathrm{ch}} - P_{i,t}^{\mathrm{dis}}/\eta_i^{\mathrm{dis}}, \forall i,t, \tag{1c}$$

$$E_{i,t}^{\mathrm{BS}} = E_{i,t-1}^{\mathrm{BS}} + P_{i,t}^{\mathrm{BS}}\tau, \forall i,t, \tag{1d}$$

$$SoC_i^{\mathrm{min}}E_i^{\mathrm{cap}} \leqslant E_{i,t}^{\mathrm{BS}} \leqslant SoC_i^{\mathrm{max}}E_i^{\mathrm{cap}}, \forall i,t, \tag{1e}$$

$$\text{Network power flow constraints,} \tag{1f}$$

$$\text{Network operation constraints.} \tag{1g}$$

I, i Buses in the distribution network candidate for BESS installation.
$P_{i,t}^{\mathrm{ch/dis}}$ BESS charging/discharging power.
$P_{i,t}^{BS}$ BESS internal power.
$E_i^{\mathrm{cap/max}}$ BESS planning capacity/Maximum capacity (kWh).
$E_{i,t}^{\mathrm{BS}}$ Stored energy in BESS (kW·h).
$SoC_i^{\mathrm{min/max}}$ State of charge limits.
$f_1(\cdot)$ BESS capacity cost in the planning stage.
$f_2(\cdot)$ BESS operation cost in the operation stage.
τ Time interval length.
$\eta^{\mathrm{ch/dis}}$ BESS charging/discharging efficiency (%).

The objective Function (1) aims to minimize the total cost, which includes both the investment cost of BESS capacity and the operating cost. Constraint (1a) limits the charging and discharging power of the BESS to stay within the planned capacity. Constraint (1b) restricts the planning capacity to not exceeding the maximum allowable capacity. Internal power, accounting for inverter efficiency, is represented by (1c). Equation (1d) calculates the remaining energy in the BESS after charging or discharging. The state-of-charge (*SoC*) of the BESS is limited by constraint (1e). Finally, constraints (1f) and (1g) introduce the network power flow constraints related to BESS charging/discharging and network operation.

Studies (Schleifer et al., 2022; Dong et al., 2023a; Dong et al., 2023b) provide empirical cases of such operational optimization models. From a practical standpoint, some manufacturers sell BESS as modular units, with each module having a fixed capacity (Wang et al., 2021). Therefore, constraints (1a), (1b), and (1e) in Model (1) can be replaced by the following constraints in Model (2):

$$\min \textstyle\sum_{i\in I} f_1(\alpha_i) + \sum_{i\in I}\sum_{t\in T} f_2(P_{i,t}^{\mathrm{ch}}, P_{i,t}^{\mathrm{dis}}), \tag{2}$$

s.t. (1c), (1d), (1g), (1f)

$$\alpha_i \in \{1, 2, 3 \cdots K_i\}, \forall i, \tag{2a}$$

$$0 \leqslant P_{i,t}^{ch}, P_{i,t}^{dis} \leqslant \alpha_i E^{\mathrm{mod}}/\tau, \forall i, p, t, \tag{2b}$$

$$\textstyle\sum_{i\in I}\alpha_i \leqslant N_{BS}^{\mathrm{max}}, \forall i, \tag{2c}$$

$$SoC_i^{\mathrm{min}}\alpha_i E^{\mathrm{mod}} \leqslant E_{i,t}^{BS} \leqslant SoC_i^{\mathrm{max}}\alpha_i E^{\mathrm{mod}}, \forall i,t, \tag{2d}$$

where α_i represents an integer variable indicating the number of BESS modules at candidate bus i, and E^{mod} denotes the capacity of a single BESS module (kWh). Constraint (2a) specifies that the number of BESS modules is an integer, with a maximum of K_i BESS modules at each candidate bus. The charging and discharging power of BESS are limited by (2b), where E^{mod} is a known parameter. Constraint (2c) defines the range of the total number of BESS modules. Finally, constraint (2d) restricts the SoC of the BESS.

3.2 Optimization approaches

AI technology is generally used in BESS configuration design through two types of optimization methods: model-based and non-model-based, as shown in Fig. 4.

For the model-based optimal configuration method, intelligent prediction algorithms, such as neural networks, are first used to predict application scenarios. Then, an optimal configuration model is established based on specific configuration objectives. Finally, intelligent solution methods like genetic algorithms, particle swarm optimization, or ant colony algorithms are applied to optimize the configuration strategy.

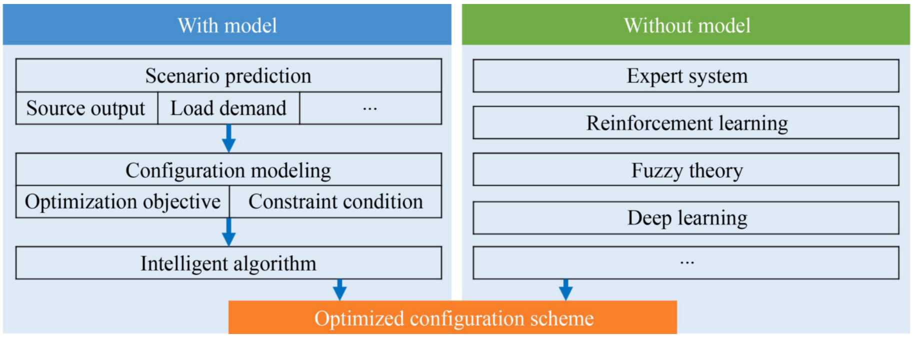


Fig. 4 Configuration planning method.

In contrast, the model-free optimal configuration method does not require the establishment of an optimization model. Instead, the optimal configuration of BESS can be directly achieved using methods like expert systems, reinforcement learning, or fuzzy theory based on the configuration objectives.

Although the two types of methods differ, their optimization objectives are largely consistent. Considering the positive impacts of BESS on economic performance, system reliability, and renewable energy utilization, the optimization objectives can be categorized into economic objectives, reliability objectives, and multiple-objective optimizations (Liu et al., 2019; Tao et al., 2016). These categories take into account a range of factors, as illustrated in Fig. 5.

Economic objectives are often key optimization goals. By creating mathematical models for the investment, operation, and maintenance costs of BESS, the aim is to minimize these costs, maximize operational efficiency, and ensure optimal configuration of the BESS.

Ensuring the safe and stable operation of power networks is also a priority for energy storage capacity planning. Distribution networks, which are directly connected to end users, play a critical role in power supply reliability and quality. In the event of a fault or power shortage in the distribution system, BESS with appropriate capacity should be used to provide continuous power. This ensures that user demands are met for a sufficient duration and that power fluctuations remain within safe limits, thus maintaining the overall reliability and stability of the power system.

It is important to note that the economic and reliability objectives of BESS often conflict with each other. Focusing solely on one objective may not lead to an optimal overall configuration plan. Therefore, it is essential to consider both economic and reliability objectives comprehensively. Additionally, factors such as renewable energy utilization, energy supply-demand balance, and environmental benefits should be taken into account to further enhance the overall performance of BESS.

3.3 Configuration design for the active distribution networks

The application of BESS in the distribution network offers several benefits. It can delay power network upgrades, reduce transmission congestion, provide ancillary services, and improve power supply reliability. Additionally, under the peak-valley tariff mechanism, BESS can profit through arbitrage by storing energy during low-demand periods and discharging during peak demand.

To achieve optimal configuration of energy storage plants in active distribution networks, Abou El-Ela et al. (2022) establish a model that considers both operational costs and equivalent life loss. The location and capacity of BESS are optimized using the Hybrid Particle Swarm Optimization Algorithm for both grid-connected and off-grid scenarios.

To mitigate the adverse effects of the randomness and volatility of PV power generation on the power system, Abdelkader et al. (2018) analyze the characteristics of PV power output from the perspective of system probabilistic power flow. They develop an optimization model for BESS location and capacity, aiming to minimize investment costs, limit the probability of power branch overloads, and reduce network losses. A genetic algorithm is employed to effectively solve this optimization problem.

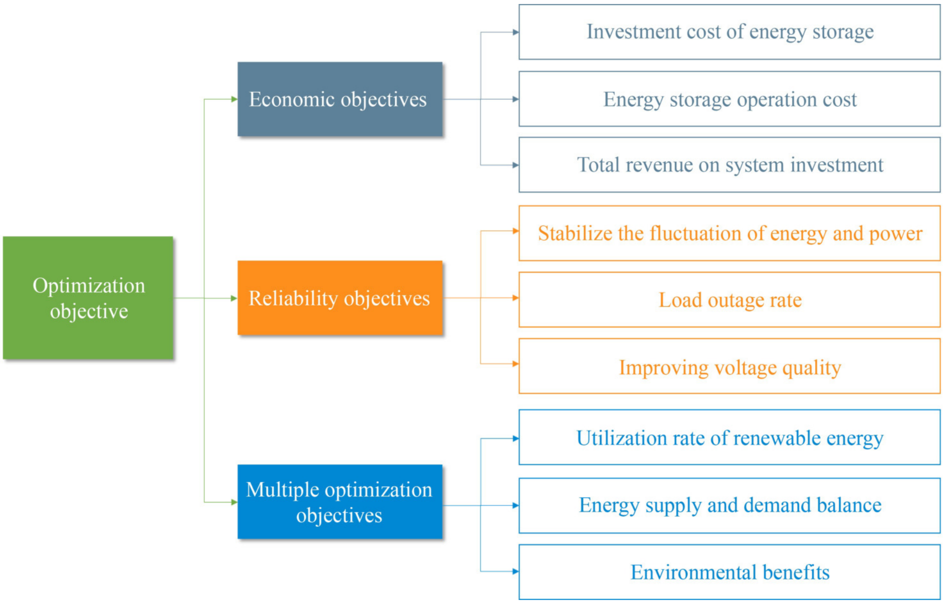


Fig. 5 Classification of optimization objectives.

From the perspective of grid-side energy storage investors, Wang et al. (2020a) propose a double-layer model for the optimal configuration of grid-side BESS, considering multiple market trading modes. The objective of the model is to maximize the overall benefit of energy storage investment by accounting for market income from energy storage, frequency regulation, peak regulation, and investment costs. The inner layer of the model aims to minimize the total system operation cost, taking into consideration the costs of power generation, frequency regulation services, peak regulation services, and wind curtailment."

Jiang et al. (2019) present a model that uses mixed-integer linear programming to determine the optimal configuration for large-scale energy storage. This model is specifically designed for regions with combined wind and solar power. The objective is to minimize energy storage costs while maximizing the integration of renewable energy into the power grid.

Although BESS provides many benefits to the distribution network, investors often cannot directly profit from these. Moreover, much of the existing research focuses on BESS applications without adequately considering investors' interests. Therefore, conducting a comprehensive evaluation of BESS value, i.e., measuring both social and economic benefits and identifying beneficiaries, to help investors achieve better returns is a promising area for future research.

3.4 Configuration planning for the coordination with renewable energy generations

The variability and unpredictability of renewable energy sources can hinder their large-scale integration into the grid. Energy storage facilities help stabilize the fluctuations in renewable energy generation, providing more consistent power to the system (Barton and Infield, 2004). Energy storage applications in renewable energy mainly include wind power storage (Hessami et al., 2011; Monjean et al., 2010; Castronuovo and Lopes, 2004; Liu et al., 2020b; Ma et al., 2015; Paul et al., 2020; Kazari et al., 2019), photovoltaic energy storage (Li et al., 2023; Luo et al., 2021; Liang et al., 2017), and independent power supply systems with storage, such as microgrids. The optimal energy storage capacity is closely tied to the renewable energy generation curve. Therefore, most planning optimizations rely on generation prediction curves to determine the optimal BESS configuration.

Revenue from renewable energy–BESS–mainly comes from arbitrage, where BESS stores energy during low-demand periods and discharges it during high-demand periods under peak-valley tariffs. This is of primary interest to renewable energy power generation companies. However, there is an overlooked aspect in the literature: the installation of BESS reduces the additional reserve capacity required for renewable energy grid connection, resulting in significant social benefits. The allocation of these benefits depends on policies related to renewable energy generation in the power market. In literature (Hessami et al., 2011; Monjean et al., 2010; Castronuovo and Lopes, 2004), BESS planning for wind power grid connections aims to optimize storage capacity to maximize net income over the study period. Zhang et al. (2018a) use a fuzzy control strategy for BESS connected to the grid to optimize the charging capacity of the wind farm.

Ma et al. (2015) introduce a method for configuring a hybrid energy storage system to mitigate fluctuations in wind power. This approach aims to reduce the costs of combining supercapacitors and batteries by considering the unique attributes of each storage technology and the specific needs of managing wind power variability. The solution is computed using a quantum genetic algorithm based on the Bloch sphere model. Paul et al. (2020) propose a multi-objective framework to optimally configure energy storage for offshore wind farms. It takes into account factors such as battery cost, lifespan, wind turbine availability, expected energy output, risk of power shortages, and the potential to reduce wasted wind energy. This framework helps determine the optimal BESS size for efficient operation in such environments. Kazari et al. (2019) consider the layout and power fluctuations of wind turbines to achieve joint optimization of wind power generation and energy storage capacity.

Li et al. (2023) evaluate the engineering economics of off-grid photovoltaic-driven electrolytic hydrogen systems with energy storage. Luo et al. (2021) develop a mixed-integer linear programming model to calculate the levelized cost of energy for PV systems integrated with energy storage. This model identifies the optimal operational strategy and uses a Shapley value-based approach to adjust for externalities, allowing for fair distribution of system costs among governments, utility grids, and residents in 15 Chinese cities. In the work (Liang et al., 2017), a joint capacity configuration model for photovoltaic energy storage is proposed to minimize investment costs. This model considers factors such as the load power shortage rate and energy spillover ratio to optimize the capacity of the PV-storage system.

For large power supply systems or microgrids, the power supply often includes multiple units, such as traditional thermal power, wind power, diesel generators, biomass power, and photovoltaic generation. Energy storage planning in these systems typically uses costs, such as total power generation cost (Benitez et al., 2008), unit power generation cost (Diaf et al., 2008; Kaldellis and Zafirakis, 2007; Kaldellis et al., 2009), and total operation cost (Bahmani-Firouzi and Azizipanah-Abarghooee, 2014; Fossati et al., 2015; Liu et al., 2010), as the objective function for optimizing BESS integration. In addition, Marchenko (2010) considers the construction costs of both the power supply and BESS. The constraints include maintaining supply-demand balance within the system, managing charging/discharging power, and meeting BESS power limitations.

To minimize the total generation cost of the system, Benitez et al. (2008) establish a nonlinear optimization model for a wind power pumped storage system. This model is used to analyze the optimal energy storage scale under different wind speed characteristics. Diaf et al. (2008) develop a numerical simulation model to optimize the operation of a combined wind, solar, and storage power supply system from a techno-economic perspective. The objective is to minimize the cost of unit power generation, resulting in the optimal power structure and storage configuration. Kaldellis et al. (2007) and Kaldellis et al. (2009) evaluate the energy storage requirements for independent power systems utilizing wind, solar, and diesel generators. They analyze various storage technologies, including pumped hydro, compressed air, and batteries, to determine which technology offers the lowest unit cost for power generation, thus identifying the optimal energy storage solution for these systems.

Bahmani-Firouzi and Azizipanah-Abarghooee (2014) aim to minimize total operating costs by proposing a capacity optimization method for BESS in microgrids using an improved bat algorithm. Fossati et al. (2015) present a capacity configuration method for microgrids based on a genetic algorithm, which takes battery capacity degradation into account. Liu et al. (2010) set up a dynamic economic dispatch model for a microgrid and solves it using a dynamic programming algorithm. The study analyzes the economic dispatch results for a microgrid that includes wind power, photovoltaic generation, fuel cells, diesel engines, and storage batteries to determine the optimal storage size. Marchenko (2010) focuses on optimizing an independent power supply system that incorporates a diesel engine, biomass power generation, wind power, and compressed air storage. The study establishes a mathematical optimization model to minimize the annual discounted cost, and it uses the General Algebraic Modeling System (GAMS) to solve the model.

When energy storage is integrated with renewable energy generation systems, such as PV and wind power, both sources exhibit intermittent and fluctuating power output. However, they have different power characteristics over different time scales. Therefore, time division should be taken into account when modeling. Additionally, the energy storage characteristics of different battery technologies must be considered to ensure that the response speed of the storage system matches the power fluctuation characteristics of the renewable energy sources.

3.5 Configuration planning for BESS on the demand side

On the demand side, BESS is primarily used to reduce electricity bills and provide an uninterrupted power supply. Most of the current research focuses on the value of BESS for saving electricity bills rather than its value in reducing the cost of power shortages by ensuring an uninterrupted power supply. Lee (2007) optimizes BESS for industrial users who are equipped with wind turbines for power generation. The study aims to minimize users' monthly electricity charges and employs a multi-channel iterative particle swarm optimization algorithm to determine the optimal charging/discharging strategy and energy storage capacity. Lee and Chen (1995) examine how BESS can reduce electricity and capacity charges for users. It proposes a BESS planning model to maximize users' investment returns. This model uses a combination of multi-step dynamic planning and expert knowledge base rules to determine the optimal energy storage size and contract capacity. With the goal of maximizing net benefits from electricity savings, Oudalov et al. (2007) apply a dynamic programming method to optimize the storage size and operation strategy for BESS used in load adjustment.

With the rapid growth of EVs, charging stations have emerged as a new type of user in the distribution network. The significant power fluctuations at fast-charging stations can heavily impact distribution networks, increasing power supply costs and consumption. To mitigate this load impact, installing a centralized or distributed energy storage system at charging stations is often considered. The use of BESS helps to shift peak loads at charging stations. Additionally, BESS can participate in providing ancillary services for the distribution network. This can assist in increasing the utilization of renewable energy with variable output and improve overall economic efficiency.

Currently, energy storage for EV charging stations is still in the early stages of development (Hong et al., 2004), and there are relatively few studies on the optimal storage capacity configuration for such stations. Li et al. (2021) propose an energy storage optimization method for PV charging stations along expressways in a grid-connected state. This method utilizes hybrid energy storage to optimize system configuration and combines HOMER with the tabu algorithm to solve the problem. Based on factors such as charging costs, basic capacity, BESS, transformer and converter costs, and energy losses due to efficiency, Wang et al. (2017) present an optimal configuration strategy for hierarchical BESS. This strategy addresses the challenges of high short-term charging power demands and low load utilization at fast EV charging stations.

4 Operational optimization of BESS in power grid operation

Energy storage is a key controllable resource in power systems. It plays a vital role in promoting renewable energy integration, enhancing the regulation capacity of the power grid, and ensuring its safe and economical operation. The applications of energy storage in power systems are illustrated in Fig. 6. During power system operation, energy storage owners may pursue different objectives, leading to varying operational scheduling strategies. The goals of energy storage applications are to maximize the use of storage resources, optimize the operation process, and achieve high operational efficiency.

Similar to the BESS configuration planning chapter, this chapter begins with a generalized BESS operational optimization model. Since the mathematical optimization methods for solving the model have been covered in Chapter 2, this chapter will focus on the application of BESS in power system operations and power market operations.

4.1 Optimization model for BESS operational optimization

BESS operational optimization can be represented by Model (1), which considers BESS operations during the planning stage. The model typically includes both the operational costs of BESS and the potential benefits (e.g., revenue from the energy market or ancillary services). Therefore, the BESS operational optimization model (single-phase) is formulated as follows:

$$\min \sum\nolimits_{i\in I} \sum\nolimits_{t\in T} f_2\left(P^{\text{ch}}_{i,t}, P^{\text{dis}}_{i,t}\right) - f_3(P^{\text{ch}}_{i,t}, P^{\text{dis}}_{i,t}), \tag{3}$$

s.t. (1c)–(1g)

$$0 \leqslant P^{\text{ch}}_{i,t}, P^{\text{dis}}_{i,t} \leqslant P^{BS_{\max}}_{i}, \forall i,t, \tag{3a}$$

where $P^{BS_{\max}}_{i}$ is the maximum BESS charging/discharging power. $f_2(\cdot)$ denotes the BESS operation cost. $f_3(\cdot)$ denotes the profit from the markets such as the energy market or ancillary service based on the price predictions. Also, E^{cap}_{i} is a known parameter in the BESS operation model.

Studies (Rashedi et al., 2024; Yi et al., 2024; Taghizad-Tavana et al., 2024) provide empirical cases of such operational optimization models. In practice, large-scale BESS systems are configured as three-phase systems. Therefore, a binary variable is introduced to prevent simultaneous charging and discharging. The complete three-phase BESS operation model is formulated as follows (Wang et al., 2022):

$$\min \sum\nolimits_{i\in I} \sum\nolimits_{t\in T} \sum\nolimits_{p\in P} f_2\left(P^{\text{ch}}_{i,p,t}, P^{\text{dis}}_{i,p,t}\right) - f_3(P^{\text{ch}}_{i,p,t}, P^{\text{dis}}_{i,p,t}), \tag{4}$$

s.t. (1d)–(1g)

$$0 \leqslant P^{\text{ch}}_{i,p,t} \leqslant \beta_{n,t} P^{BS_{\max}}_{i,p}, \forall i,p,t, \tag{4a}$$

$$0 \leqslant P^{\text{dis}}_{i,p,t} \leqslant (1-\beta_{n,t}) P^{BS_{\max}}_{i,p}, \forall i,p,t, \tag{4b}$$

$$P^{\text{BS}}_{i,t} = \sum\nolimits_{p\in P} P^{\text{ch}}_{i,p,t}\eta^{\text{ch}} - P^{\text{dis}}_{i,p,t}/\eta^{\text{dis}}, \forall i,t, \tag{4c}$$

where $\beta_{n,t}$ represents a binary decision variable for the BESS charging or discharging decision. This ensures that only one state, either charging or discharging, can be activated for all three phases at each time interval.

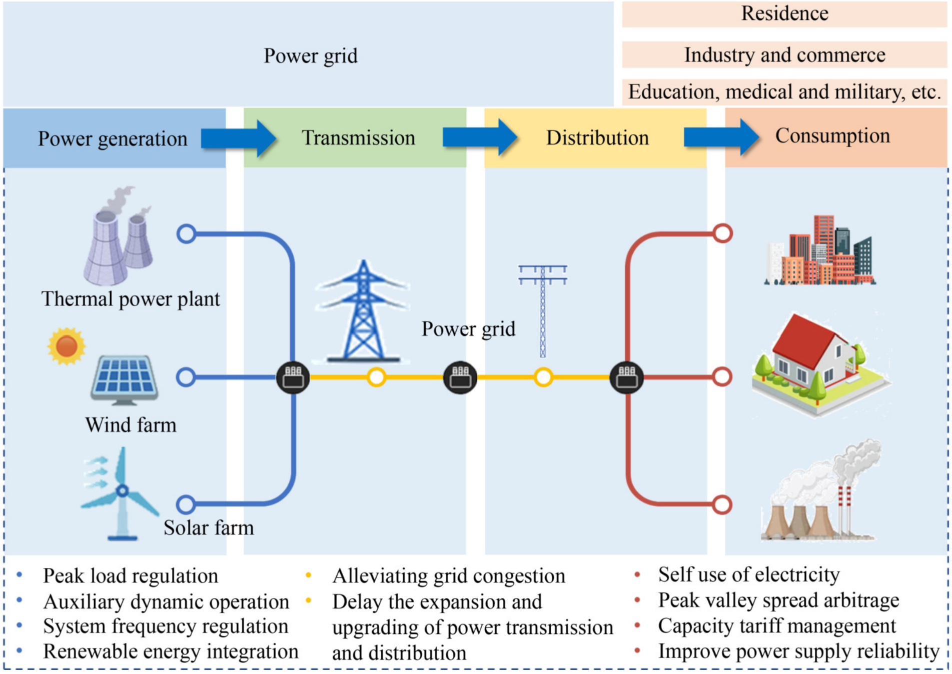


Fig. 6 Applications of energy storage in power systems.

4.2 The role of BESS in the power system operation

Recent studies have shown that energy storage equipment owners can enhance the value of energy storage by optimizing across different markets, such as frequency regulation and spinning reserve (Cheng and Powell, 2018). In this section, BESS operational optimization is categorized into five types based on different applications: ancillary services, power reserve, energy trading, investment delay and grid support, and combined applications.

4.2.1 Ancillary service

(1) Frequency regulation

To counteract the reduced ability of the power grid to regulate frequency due to the integration of large amounts of renewable energy, energy storage systems can be deployed. Their rapid response capabilities enhance grid frequency control, effectively addressing this issue. In 2011, the Federal Energy Regulatory Commission (FERC) of the United States issued Act No. 755, introducing the concept of energy storage frequency regulation mileage and incorporating frequency regulation performance into the compensation mechanism. Following this, Germany, the UK, and other countries also introduced action plans for energy storage to participate in the power ancillary services market (Ullah et al., 2024; Telaretti and Dusonchet, 2017). Despite variations in market systems globally, reserve demand for frequency control is typically met through a bidding process overseen by the system operator (Telaretti and Dusonchet, 2017; Hesse et al., 2017). Li et al. (2016b) reviewed research on large-scale energy storage participating in frequency regulation, covering the necessity and feasibility analysis, energy storage control strategy, capacity configuration, economic evaluation, and joint operation with traditional frequency regulation power supply, demonstrating the feasibility and necessity of energy storage in frequency regulation.

Vasudevan et al. (2021) presented a comprehensive control strategy for BESS in frequency regulation. This strategy includes virtual inertia and virtual droop control to optimize the timing and capacity of BESS deployment, ensuring effective support for system frequency stability. Compared to centralized access, research on distributed BESS participating in frequency regulation through aggregation is less developed. Falabretti et al. (2017) introduced a method for distributed BESS to participate in primary frequency regulation. It extracts typical frequency fluctuation conditions of the Italian grid using a fast Fourier transform and tests the performance of the proposed distributed BESS, showing promising results in primary frequency regulation. Additionally, Lee et al. (2016) proposed a coordinated control scheme for distributed BESS with regional hosts. Under the coordination of regional hosts, each distributed BESS effectively supports system frequency and voltage through aggregation."

(2) Peak shaving and valley filling

BESS can also be used for peak shaving and valley filling, helping to reduce additional operating costs associated with peak load demands. In this work (Wen et al., 2016), a battery model for peak shaving and valley filling is developed, considering factors such as battery capacity, voltage, and current. Li et al. (2020b) addressed the challenge of limited peak shaving capacity in power systems after integrating renewable energy. It proposes an optimal scheduling strategy for a wind-solar-hydrothermal BESS system to enhance peak shaving. This strategy analyzes peak shaving compensation while considering the operational limits of thermal power units and the capabilities of BESS in peak shaving and valley filling.

(3) Black start

BESS also supports the potential application of the black start capability of distributed generation systems. In the event of supply failures, such as technical defects or network attacks, individual components or the entire power system may collapse. In such situations, BESS can assist in restarting existing generator units. System operators may reward the black start capability of distributed generators, as it facilitates the coordinated recovery of the system (Giorgio et al., 2017). Li et al. (2020a) designed a black start scheme for wind farms using multiple BESS units, which aligns with black start scheme specifications. It proposes four main stages for the black start process of the combined wind-storage system. The feasibility of this black start process is initially verified at the transient level through simulations of the combined wind-storage system using PSCAD. Li et al. (2018) presented a coordinated optimization strategy for the black start process based on predictive model control. It designs both the operation and control modes of the system, considering its operational state and characteristics.

4.2.2 Power reserve

(1) Uninterrupted power supply

In addition to the ancillary services mentioned above, energy storage can also provide power backup applications. To ensure power quality during grid fluctuations and to prevent power loss during failures, some customers rely on BESS for an uninterrupted power supply (UPS). This is particularly important for key users, such as hospitals and data centers, where a highly reliable local power supply is crucial. Weicker (2013) proposed a topology and control strategy for a Li-ion battery energy storage UPS system with a dual-active bridge (DAB) interface for high-power applications. The effectiveness of the proposed scheme is verified through EMTDC/PSCAD modeling and simulation. Aamir et al. (2016) presented a design method for UPS in medical settings, considering factors such as the nature of the load, power input requirements, and dynamic output characteristics, which align with relevant standards.

However, generalized cost-benefit analysis for the UPS application of BESS may be ineffective, as the value generated by UPS is difficult to quantify and largely depends on customer requirements for safe operation after system failures and the quality of the local grid.

(2) Ramp rate control

BESS can also be used to control the ramp rate (i.e., smooth the output power) of generator units with large fluctuations, such as intermittent wind or photovoltaic generators (Kargarian et al., 2016; Atzeni et al., 2013). Liu et al. (2016) proposed an optimal bidding strategy for BESS to maximize profit by jointly optimizing participation in the energy market and the flexible slope product market.

However, this application only provides rewards in selected regions and is highly dependent on specific regulations or conventions.

4.2.3 Energy trading

(1) Energy arbitrage

Changes in power demand and supply in the electricity market can lead to price fluctuations. Peak-valley energy arbitrage is the most widely used method in user-side energy storage. Profits are primarily made through peak-valley arbitrage and reducing electricity prices during peak load demand. The difference in peak and valley electricity prices leads to varying economic outcomes for different regions and types of energy storage projects. He et al. (2011) aimed to maximize arbitrage in the day-ahead and balanced service markets. It simulates the optimal operation and scheduling model of BESS in a French grid and compares economic benefits under different business models. Xin et al. (2019), Jin et al. (2019) and Esfahani et al. (2019) used various game theories and optimization schemes to determine the optimal energy storage scheduling strategy for a multi-microgrid distribution network, thereby improving the system economy.

However, the user load curve does not always align with local peak and valley periods, causing peak-valley spread income to fall short of expectations. Additionally, factors such as battery life and grid connection management often lead to higher actual operating costs than estimated. To overcome the challenges faced by the user-side energy storage market, it is necessary to further reduce energy storage costs and improve market mechanisms, including demand-side response and the spot market (Dong et al., 2020).

4.2.4 Investment delay and grid support

(1) Voltage support

BESS can also support the local power grid in performing various tasks. It can act as a delay measure or even an alternative to traditional power grid enhancements. The power grid also needs the ability to control voltage fluctuations caused by changes in renewable energy output and residential or industrial loads. Proper control of energy storage, such as coordinating active and reactive power at specific local demand points or community scales, can help reduce such voltage fluctuations (Huang et al., 2020; Akram et al., 2020).

In many countries or regions, regulations do not provide direct compensation for voltage services, preventing private enterprises from entering this market. However, if the cost of alternative measures exceeds the cost of BESS, distribution network operators (DNOs) responsible for stabilizing the local grid may consider integrating energy storage (Alam et al., 2015). Poudineh and Jamasb (2014) and Spiliotis et al. (2016) systematically analyzed the technical limitations and potential profitability of using BESS to delay local grid investments.

(2) EV-Grid integration

The electrification of road transportation requires upgrading the charging infrastructure, significantly impacting grids at all levels. The emergence of EV charging stations has placed higher demands on grid infrastructure; however, upgrading the grid can be very costly. Yang et al. (2021) introduced battery energy storage into high-power fast charging stations to optimize their design and reduce their impact on the grid. In the work (Zhang et al., 2020), a two-stage optimization model is proposed to enhance flexibility in the distribution network (DN). This model includes EV charging, energy storage, and the dispatch of interruptible loads.

While energy storage can help stabilize system voltage and delay the need for distribution network upgrades, several technical, economic, and regulatory challenges must be addressed to utilize this resource fully. A significant obstacle is the lack of an effective market mechanism for efficient management.

4.2.5 Multiple services in the power grid

(1) Multiple services

Analysis of BESS usage for specific applications reveals significant idle time, often resulting in wasted energy storage resources. Combining multiple applications can improve BESS utilization and enhance the value of corresponding applications.

In the work (Leou, 2008), a profit maximization model is developed, considering benefits such as delaying grid upgrades, reducing congestion costs, and arbitrage from low storage and high generation. This model is solved using a genetic algorithm combined with linear programming. Zhu et al. (2019) proposed a combined operational energy storage mode for arbitrage and power backup, considering the appropriate capacity ratio between the battery and converter. Moghaddam and Saeidian (2010) and Kazempour and Moghaddam (2009) determine optimal operation strategies for vanadium and sodium sulfur battery energy storage power stations using the General Algebraic Modeling System (GAMS). The strategies account for revenues from arbitrage, reserve, and frequency regulation for low storage and high generation.

In the work (Badeda et al., 2017), BESS, such as UPS, is studied to provide additional services during stable grid operation. The goal is to allocate battery capacity and power based on the current state of health (SoH) to provide the best operation strategy over the entire life of the BESS. Tang and Yang (2019) presented an optimization approach for Virtual Power Plants (VPPs) incorporating energy storage. This method aims to optimize market operations and bidding strategies for VPPs, ensuring the most favorable energy and reserve capacity deals in the day-ahead market while maintaining transaction equilibrium in the real-time market.

(2) Service with microgrid clusters

With the rapid development of renewable energy power generation, energy storage multi-application optimization research is being conducted for both microgrids (Tang and Yang, 2019; Sortomme and EI-Sharkawi, 2009; Che et al., 2019) and renewable energy power stations (Zhao et al., 2015; Zhang et al., 2018b; González-Garrido et al., 2018; González-Garrido et al., 2019). Badeda et al. (2017) and Tang and Yang (2019) point out that BESS in microgrids can be used for frequency regulation, voltage support, and power backup to optimize system operation. Sortomme and EI-Sharkawi (2009) and Che et al. (2019) proposed a two-stage BESS energy optimization control strategy for grid-connected microgrids with wind power, considering both energy optimization and power fluctuation smoothing in response to the randomness and fluctuation of wind power.

For renewable energy power generation systems, Zhao et al. (2015) proposed an optimal BESS scheduling model based on bilevel programming in integrated wind power systems. In this model, BESS optimizes the net load curve through effective charging and discharging while using its remaining capacity as part of the system power reserve, thereby reducing the total reserve needed for thermal power generation. Additionally, a SoC control strategy is introduced to ensure the rationality of SoC management.

Zhao et al. (2015) and Zhang et al. (2018b) proposed a multi-level hybrid BESS wind farm optimal scheduling strategy. It optimizes the energy storage operation strategy across three stages: the day-ahead market (to enhance wind power generation profit), the real-time market (to eliminate day-ahead prediction errors and smooth wind power fluctuations), and the standby market (to provide ancillary services). This approach improves both power supply reliability and market profit. Zhang et al. (2018b), González-Garrido et al. (2018) and González-Garrido et al. (2019) presented optimization methods for managing energy storage in photovoltaic power plants within the energy market (day-ahead market) and the secondary reserve market (frequency regulation service). The goal is to find the best trade-off between profits and to determine the optimal operation strategy.

(3) Service with V2G technology

With the development of EVs and the adoption of grid-connected V2G technology, energy storage in the V2G scenario is also considered part of multi-application research for energy storage. Wong et al. (2011) demonstrated that, with the help of a communication network in the smart grid, the mobile battery systems in EVs and plug-in hybrid EVs can serve as energy storage and provide ancillary services for the smart grid. In the work (Wang et al., 2014), a method is proposed for the orderly charging and discharging of EVs. This method leverages the advantages of both power plants and grids, significantly reducing fuel costs and unit start-up/shutdown costs while also contributing to peak shaving and valley filling.

Luo et al. (2012) examined the potential economic returns of using plug-in EVs as grid resources. It calculates and compares the expected profits and the profits from providing ancillary services, taking into account the uncertainty of driving behavior. The results indicate that participating in the frequency regulation business is more profitable than in the reserve business. In the work (Han et al., 2018), the use of EVs as power sources to mitigate voltage fluctuations and provide backup power is considered. The study investigates the optimal scheduling of multiple EVs connected to an active distribution network, providing a reference for distribution network operation planning.

Although multiple applications have significant potential to enhance the value of energy storage, it can be challenging to control BESS for multiple tasks while meeting regulatory constraints, particularly when multiple stakeholders are involved.

(4) Reuse of second-life power battery

Some research focuses on the economic aspects of using retired power batteries in energy storage configurations. By reusing battery energy storage, the investment cost in system energy storage can be reduced, and the overall economy of system operation can be improved while still meeting energy storage requirements. To compare and analyze the life cycle cost differences between echelon utilization batteries and new batteries, a cost analysis model per kilowatt-hour of power consumption is established, considering battery life and operational characteristics (Tao et al., 2020). This model is used to assess the feasibility of using retired batteries in energy storage power stations. In studies (Tao et al., 2020; Viswanathan and Kintner-Meyer, 2011), a benefit evaluation method for the echelon utilization of retired power batteries in the power system is proposed. This method analyzes key parameters such as the impact of ancillary peak shaving services, the depth of charging and discharging, battery health status, and the utilization life of the batteries.

Heymans et al. (2014) examined the technical feasibility and economic viability of using retired power batteries in BESS for energy storage, specifically for participating in peak shaving on the user side, considering both the cost and functionality of the retired batteries. Chennaif et al. (2021) studied the economic viability of echelon utilization batteries in photovoltaic energy storage, using a household power load as an example. The research shows that, due to low household electricity prices, small peak-valley price differences, and the high initial cost of batteries, household photovoltaic BESS is still less competitive than standalone photovoltaic systems. However, the study indicates that echelon utilization batteries are more economical than new lithium-ion batteries in photovoltaic BESS.

Zhu et al. (2023) proposed a method for integrating and applying decommissioned power lithium batteries in an optimal storage microgrid system. The research demonstrates that these batteries maintain normal charging and discharging performance after proper screening and grouping, providing value for echelon utilization. Zhang et al. (2014) developed a mathematical model based on typical load curves to assess the benefits of energy storage for peak shaving and reducing network losses at fast-charging stations. This model evaluates the cost-effectiveness and practicality of using second-life batteries for BESS in such stations. In the work (Wu et al., 2022), the echelon utilization of retired batteries is applied to scenarios such as EV charging stations and home BESS under gradually milder service conditions. The study proposes an economic operation method for cascading the utilization of retired batteries across multiple energy storage scenarios. The results indicate that the residual value of retired batteries is maximized when used across multiple scenarios compared to a single scenario.

As the number of retired power batteries continues to grow, the echelon utilization industry for these batteries is expected to become a significant new industry. Research on echelon utilization technology shows that battery management systems and application economics are key factors for successful utilization. Therefore, the focus of future research should be on efficiently utilizing retired batteries and achieving effective battery management.

(5) The recycling of aging battery

Considering the negative impact of aging batteries on the reliability and performance of BESS connected to the grid, some researchers have proposed optimizing the disassembly of aging batteries to enhance overall BESS performance in smart grid applications. Akhavan-Hejazi et al. (2021) explored how the characteristics of the weakest battery affect the operation of grid-connected BESS with aging batteries. It develops a model for disassembling aging batteries. Hardware-in-the-loop (HIL) tests demonstrate the effectiveness of the proposed method in improving the effective capacity of BESS. A case study further evaluates the impact of aging battery disassembly on the performance of energy storage for peak-shaving applications. The results also indicate that the increase in effective capacity depends on the composition and aging condition of the batteries. Currently, related research is still in its early stages and remains relatively limited.

4.3 Optimization of peer-to-peer electricity trading

Localized electricity market

As the power market continues to develop and investor interests in BESS and renewable energy systems diversify, the autonomy of market participants is increasing. As a result, power market transactions are evolving from a traditional, single approach to a more complex and diverse model. Figure 7 illustrates these changes in the trading modes of the power market.

(1) The participation mode of the power market

Some research focuses on optimizing the operation and

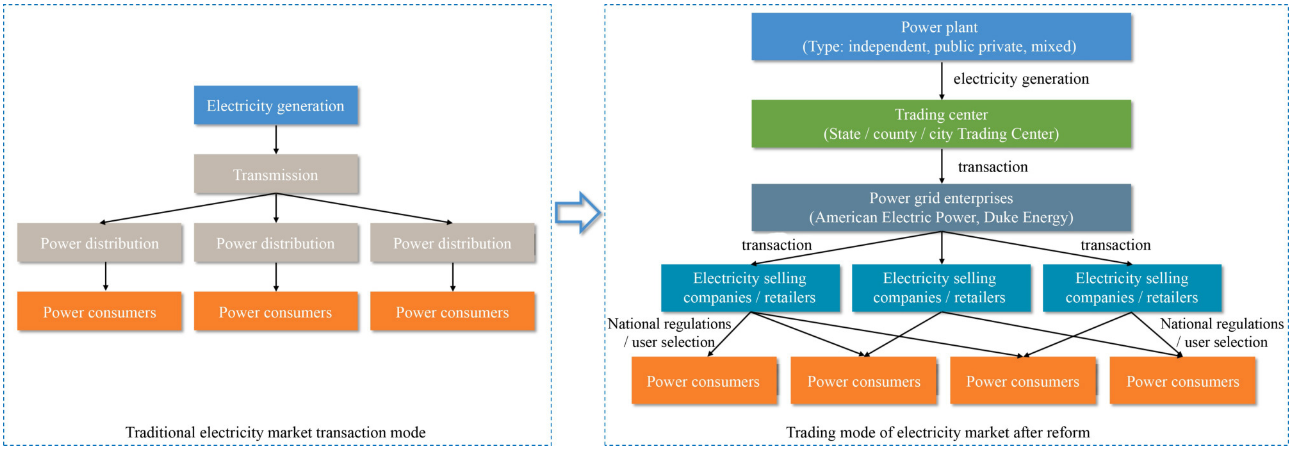


Fig. 7 Change of trading mode in the power market.

dispatch of power systems based on the participation modes of power market participants. One key area of research is the participation of BESS in peer-to-peer (P2P) transactions, with particular interest in the economic benefits of such participation. Guo et al. (2018) presented a pricing decision model based on economic surplus optimization for energy storage consumers in the P2P transaction mode. The study verifies that this approach reduces the cost of electricity for users. Chen et al. (2020) considered a distribution network composed of consumers with BESS and high renewable penetration to enable P2P transactions. The simulation results indicate that consumers with BESS not only increase their scheduling flexibility but also provide economic benefits to the entire distribution network. Yebiyo et al. (2020) and Liu et al. (2020a) analyze the benefits of P2P transactions in the context of distributed energy storage sharing. The results verify that BESS can effectively reduce electricity costs for consumers and operating costs for producers during P2P transactions. Paudel et al. (2019) proposed a P2P transaction model for community microgrids with BESS using game theory. The simulation results demonstrate that the operating costs of microgrid participants using BESS as a transaction medium are significantly reduced under this transaction mode.

(2) Energy storage community

Another prominent area of research involves forming an energy storage community using regional BESS and studying transactions in the local power market. Walker and Kwon (2021) show that, compared to individual energy storage systems, shared energy storage in residential communities can effectively reduce electricity costs for users and improve the utilization rate of the energy storage system. Hossain et al. (2021) proposed an energy management strategy for uncertain environments, optimizing the operation of community energy storage and significantly reducing the operation costs of grid-connected microgrids.

Wang et al. (2018) proposed a daily distribution plan for residential electricity consumption, incorporating shared energy storage, combined heat and power, and photovoltaic power supply to reduce user energy consumption. In the work (Lockley and von Hippel, 2021), a design and operation scheme for a micro-energy network based on liquid air energy storage was introduced. Using community energy consumption data, the study provides a detailed design and analysis of the energy storage subsystem, effectively improving overall energy utilization efficiency. The research demonstrates that involving BESS in P2P transactions and local electricity market transactions in various forms can significantly enhance the economic benefits for participants, as well as improve renewable energy consumption and energy storage utilization rates.

(3) Blockchain-based P2P energy trading

Furthermore, blockchain technology, considered a potential solution to energy Internet development bottlenecks, has been widely studied for P2P transactions due to its decentralization and traceability. In blockchain-based P2P power transactions, there are only buyers and sellers, with no central node involved (Yang et al., 2017), as shown in Fig. 8. Before the transaction, the buyer and seller agree on the contract terms. During the transaction, the smart contract is automatically executed according to both parties' quotations, eliminating the need for price negotiation. Onyeka Okoye et al. (2020) examined the economic dispatch of microgrids using an energy blockchain network. It proposes a multi-time scale economic dispatch method for microgrids based on smart contracts, considering energy storage and user-side response.

Bing et al. (2019) proposed a blockchain-based photovoltaic trading mechanism that incentivizes users to freely and flexibly settle individual transactions. Using a credit value trading mechanism, users can achieve more satisfactory transactions. Van Cutsem et al. (2020) introduced a decentralized cooperative demand response framework. Ma et al. (2018) established a game model for market participant competition using blockchain. In this model, information about energy storage is not sent

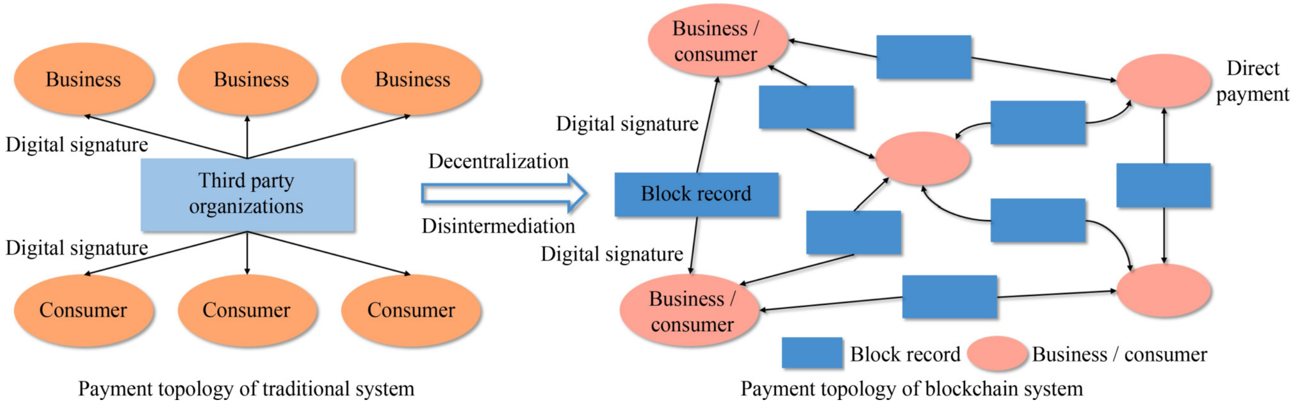


Fig. 8 Prosumer in blockchain-based P2P energy trading.

back to a central control center. Still, it is instead exchanged directly through point-to-point information interaction and asset transfers with other participants. In the work (Wang et al., 2020b), a distributed energy trading model was proposed based on contract orders, where users match transactions through contract orders.

5 Cybersecurity issues in BESS operation

At the beginning of this century, several power system network security incidents occurred worldwide. These incidents, directly and indirectly, drove the development of secondary security systems for power grids in various countries. Over the past two decades, the power monitoring network security system has evolved significantly from single-dimensional protection to a comprehensive protection system and from passive measures to active defense strategies. However, with the advent of the energy Internet, new cybersecurity challenges have emerged.

5.1 Security issues under artificial intelligence

The application of AI plays an important role in improving the operational efficiency of power grids and enhancing service quality for power companies. However, it also increases the risk of data loss and poses significant threats to information security. One reason AI brings network security risks is the immaturity of the technology. This includes limitations, such as a lack of explainability in algorithms and strong dependence on data. Additionally, while AI can enhance network security, it also has the potential to expand the scale of network attacks.

For example, deep learning, a key AI technology, relies on artificial neural networks. In pursuing accuracy, neural networks often sacrifice transparency and controllability. In many cases, even the creators of deep learning algorithms find it challenging to explain their internal workings. These characteristics of AI can be exploited for adversarial attacks or to amplify existing network attacks. Therefore, it is crucial to use AI positively to secure power grid monitoring networks. This can be achieved through data mining, security risk analysis, abnormal event detection, and early warning systems.

5.2 Security issues under blockchain

Currently, blockchain technology is being used to address various issues in energy and power market transactions. However, its application in power systems is still in its early stages due to ongoing security and privacy concerns, which remain core challenges for blockchain technology. The main security challenges for implementing blockchain in the energy trading market include private key loss, privacy breaches, and smart contract vulnerabilities.

(1) Private key loss

Information on the blockchain is tamper-proof, but it relies on the security of private keys. The common method for private key storage is for each user in the blockchain system to encrypt the private key and store it on their device. However, this approach cannot withstand offline dictionary attacks if the user's device is compromised, exposing the blockchain to the risk of private key theft. In general, there is still a lack of a trusted environment for private key authentication. Additionally, the distributed storage structure of the blockchain complicates the process of managing private key re-issuance.

(2) Privacy disclosure

Currently, transaction data transmitted and stored on the blockchain is open and transparent. Bitcoin only provides privacy protection for the identities of both parties by separating the transaction address from the real identity of the address holder. However, relationships between accounts and transactions can still be traced through information such as address IDs and IP addresses (Ding et al., 2018). For the energy Internet, which involves the privacy of many trading users in energy subsystems, data transparency may not meet regulatory requirements, particularly for sensitive data that requires a balance between privacy protection and compliance. Not only must transaction privacy for participants in the energy Internet be protected on the blockchain, but the system must also prevent illegal activities by unauthorized participants.

(3) Smart contract security

Blockchain technology must ensure the automatic execution of smart contracts to facilitate smooth distributed energy transactions. However, if there is a coding error in the contract, it is often challenging to perform a rollback or create a fork. Smart contracts also have other issues, such as the absence of a clear accountability entity, timestamp attacks, and re-entry vulnerabilities. In distributed energy transactions, participants use virtual accounts, which can lead to accountability issues due to a lack of responsible parties (Zhao et al., 2020). Some malicious nodes may exploit the timestamp in the contract as a trigger to gain improper benefits. Additionally, when one contract calls another, the current contract may be suspended, allowing multiple re-entries, which can cause security vulnerabilities.

5.3 BESS resilience: measures and optimization methods

To evaluate the resilience of power networks integrated with BESS, it is crucial to examine the system's performance transition curve under cyber-physical risks originating from BESS. This investigation forms the basis for quantifying and optimizing BESS resilience (Wu and Li, 2021). Understanding the coupling dependencies between power networks and BESS, as well as establishing cascading failure models (Aziz et al., 2019), are prerequisites for quantifying the system performance curve.

Based on the system performance transition curve and the curve-based quantitative measure for assessing BESS resilience outlined by Nguyen et al. (2019), existing optimization methods for BESS resilience are studied from three perspectives: a) Enhancing BESS resilience against Denial-of-Service (DoS) cyber-attacks using centralized control (Chlela et al., 2018); b) Protecting BESS from Fault Data Injection Attacks via a fault-tolerant and distributed control approach (Raeispour et al., 2022); c) Improving resilience against cyber-attacks using an agent-based secure distributed optimal control scheme (Sharma et al., 2017).

6 Challenges and future research opportunities

The application of energy storage technology holds great potential for power systems and is proving its value to grid operators worldwide. However, the development and use of BESS are still primarily concentrated in economically developed countries and regions with robust regulatory frameworks for energy storage projects. This chapter provides an in-depth analysis of the existing technological challenges faced by energy storage systems, using BESS as the focus of the study. It also summarizes the potential of AI to help overcome these barriers.

6.1 Current challenges

1) **Technical Performance Limitations**: BESS have limitations in terms of energy conversion efficiency and lifecycle. Battery degradation over time impacts both system reliability and the return on investment.

2) **Economic Viability**: High initial costs and operational expenses are significant barriers to BESS adoption. Current models do not adequately address the total cost of ownership or present compelling business cases for investors.

3) **Integration with Power Grid**: Integrating BESS into the existing grid infrastructure poses challenges, such as managing the variability of renewable energy sources and maintaining grid stability and reliability.

4) **Operational Optimization**: The development of optimal configuration designs and operational strategies for BESS is in its early stages. The advantages and disadvantages of different optimization algorithms for BESS optimization have been summarized in Table 6. More advanced methodologies are required to ensure efficient use of these systems.

5) **Cybersecurity Risks**: The digital nature of modern BESS makes them vulnerable to cybersecurity threats, highlighting the need for robust protection mechanisms that are currently insufficient.

6.2 Opportunities for future research

1) **Advanced Materials and Technologies**: Future research should focus on developing new materials and chemistries to improve energy density, power density, and the overall lifecycle of BESS.

2) **Economic Models and Incentive Policies**: Future research should focus on developing comprehensive economic models that address multiple optimization

Table 6 Advantages and disadvantages of existing optimization approaches for BESS configuration design and operation optimization (Bamisile et al., 2024; Hossain Lipu et al., 2022).

Optimization algorithm	Application scenario	Advantage	Disadvantage
Linear programming (LP)	Charge/discharge scheduling scheme development for BESS	1. Easy to use; 2. Computationally efficient. 3. Global optimal solution reachability.	1 Applicability limited by linearity assumptions.
Mixed-integer linear programming (MILP)	Optimal number of installed batteries of BESS	1. Solving problems with discrete variables; 2. global optimal solution reachability.	1. Computational time is positively correlated with the number of discrete variables
Mixed-integer second-order cone programming (MISOCP)	BESS operation and planning considering AC power flow constraints	1. Active-reactive characteristics of the real grid are considered; 2. Global optimal solution reachability	1. Relaxation errors in a toroidal grid cannot be neglected; 2. Calculation time is much longer.
Semidefinite programming (SDP)	BESS operation and planning considering the three-phase unbalance problem	1. Three-phase characteristics of the real grid are considered 2. Global optimal solution reachability	1. Calculation time is very long.
Swarm intelligence algorithm	BESS optimization under dynamic pricing market model	1. Easy to implement; 2. Great for finding a nice workable solution; 3. Not dependent on gradient information; 4. Generalized and not concerned with the form of the optimization problem.	1. Long iteration time; 2. The optimality of the resulting solution cannot be guaranteed.
Artificial intelligence technology	Health state estimation of BESS and real-time scheduling decisions in uncertain environments	1. Strong real-time decision-making capabilities; 2. Generalized and not concerned with the form of the optimization problem.	1. long model training time; 2. Sensitive parameterization; 3. Poor decision interpretability 4. The optimality of the resulting solution cannot be guaranteed.

objectives and accommodate the interests of various stakeholders. This includes examining the impact of policy incentives on BESS adoption and operation, designing market mechanisms that value the flexibility and reliability services provided by BESS, and studying financial risk mitigation strategies for BESS projects.

3) **Artificial Intelligence**: Leveraging AI and machine learning for predictive analytics, operational optimization, and health monitoring of BESS can significantly enhance their performance and reduce operational costs. Future research should focus on developing self-learning algorithms that adapt to real-time data and improve decision-making for BESS operation.

4) **Cybersecurity Solutions**: As BESS become increasingly digitalized, there is a growing need for advanced cybersecurity frameworks to protect against evolving threats. This includes developing intrusion detection systems, secure communication protocols, and robust access control mechanisms.

5) **Grid Integration Strategies**: Research should focus on innovative strategies for integrating BESS with the power grid to enhance grid stability and accommodate higher penetrations of renewable energy sources. This could involve developing advanced control algorithms, energy management systems, and exploring the role of BESS in providing ancillary services.

6) **Second-Life Applications and Recycling**: Research into second-life applications for retired BESS and battery recycling can support a circular economy and reduce the environmental impact of BESS. Future research should focus on developing efficient repurposing strategies, designing batteries for easy disassembly and recycling, and assessing the economic viability of second-life applications.

7) **Peer-to-Peer Energy Trading**: Exploring the role of BESS in facilitating peer-to-peer energy trading can create new business models and improve the economic viability of distributed energy resources. Future research should focus on developing platforms and mechanisms that enable direct energy transactions between consumers, supported by BESS.

7 Summary

With the ongoing growth of the social economy, energy resources are becoming increasingly scarce, necessitating efficient and sustainable solutions. The development of renewable energy has emerged as a critical component of future energy strategies due to its potential to provide clean and sustainable power. However, integrating renewable energy sources into the existing power grid presents significant challenges, including grid stability issues due to the intermittent nature of renewables like solar and wind. The variability and unpredictability of renewable energy generation can lead to substantial fluctuations, posing risks to grid reliability.

Simultaneously, the increasing peak-to-valley difference in grid load has created substantial inefficiencies, adversely affecting the economy of the power system. This variability results in higher operational costs and underutilization of grid assets, thereby reducing the overall economic viability of the energy sector. To address these issues, the adoption and effective utilization of energy storage technology are essential, as it has great potential to stabilize the energy supply, balance the grid load, and support the integration of renewable energy sources.

Therefore, this paper provides a comprehensive analysis of existing technologies and research related to energy storage planning and operational optimization. It evaluates the effectiveness of current energy storage solutions in addressing the key challenges faced by modern power systems. Additionally, it highlights future research directions and identifies unresolved problems that need to be tackled to enhance energy storage applications. These insights serve as valuable references for configuring and optimizing power systems to ensure efficient integration and operation of energy storage technologies. By accelerating the adoption of energy storage technologies in power grids, this work aims to contribute to the sustainable and balanced growth of power systems, fostering the healthy and rapid development of renewable energy while improving grid stability and economic efficiency.

Competing Interests The authors declare that they have no competing interests.

References

Aamir M, Ahmed Kalwar K, Mekhilef S (2016). Uninterruptible power supply (UPS) system. Renewable & Sustainable Energy Reviews, 58: 1395–1410

Abdelkader A, Rabeh A, Mohamed Ali D, Mohamed J (2018). Multi-objective genetic algorithm based sizing optimization of a stand-alone wind/PV power supply system with enhanced battery/super-capacitor hybrid energy storage. Energy, 163: 351–363

Abou El-Ela A A, El-Sehiemy R A, Shaheen A M, Wahbi W A, Mouwafi M T (2022). A multi-objective equilibrium optimization for optimal allocation of batteries in distribution systems with lifetime maximization. Journal of Energy Storage, 55: 105795

Akhavan-Hejazi H, Taylor Z, Mohsenian-Rad H (2021). Optimal cell removal to enhance operation of aged grid-tied battery storage systems. IEEE Transactions on Sustainable Energy, 12(1): 739–742

Akram U, Nadarajah M, Shah R, Milano F (2020). A review on rapid responsive energy storage technologies for frequency regulation in modern power systems. Renewable & Sustainable Energy Reviews, 120: 109626

Alam M J E, Muttaqi K M, Sutanto D (2015). Community energy storage for neutral voltage rise mitigation in four-wire multigrounded LV feeders with unbalanced solar PV allocation. IEEE Transactions on Smart Grid, 6(6): 2845–2855

Atzeni I, Ordóñez L G, Scutari G, Palomar D P, Fonollosa J R (2013). Demand-side management via distributed energy generation and storage optimization. IEEE Transactions on Smart Grid, 4(2): 866–876

Aziz T, Masood N A, Deeba S R, Tushar W, Yuen C (2019). A methodology to prevent cascading contingencies using BESS in a renewable integrated microgrid. International Journal of Electrical Power & Energy Systems, 110: 737–746

Badeda J, Kwiecien M, Schulte D, Rüwald T, Sauer D U Adaptive battery steering and management system for the optimized operation of stationary battery energy storage systems in multi-use applications. 2017 IEEE International Telecommunications Energy Conference (INTELEC), 287–293

Bahmani-Firouzi B, Azizipanah-Abarghooee R (2014). Optimal sizing of battery energy storage for micro-grid operation management using a new improved bat algorithm. International Journal of Electrical Power & Energy Systems, 56: 42–54

Bamisile O, Cai D, Adun H, Dagbasi M, Ukwuoma C C, Huang Q, Johnson N, Bamisile O (2024). Towards renewables development: Review of optimization techniques for energy storage and hybrid renewable energy systems. Heliyon, 10(19): e37482

Barton J P, Infield D G (2004). Energy storage and its use with intermittent renewable energy. IEEE Transactions on Energy Conversion, 19(2): 441–448

Benitez L E, Benitez P C, van Kooten G (2008). The economics of wind power with energy storage. Energy Economics, 30(4): 1973–1989

Bing Q, Xia Y, Li B, Li D Z, Zhang Y (2019). Photovoltaic trading mechanism design based on blockchain-based incentive mechanism. Power System Automation, 43(9): 132–139 (in Chinese)

Castronuovo E D, Lopes J A P (2004). On the optimization of the daily operation of a wind-hydro power plant. IEEE Transactions on Power Systems, 19(3): 1599–1606

Che Q Q, Yang X W, Zhang Y, Li Q S, Zhao Q M. An energy optimization and control strategy of microgrids considering the hybrid energy storage system. In: 2019 9th International Conference on Power and Energy Systems (ICPES), 1–5

Chen X P, Li G Y, Zhou M, Xia Y (2020). Distributed optimal scheduling for prosumers in distribution network considering uncertainty of renewable sources and P2P trading. Power System Technology, 44(9): 3331–3338 (in Chinese)

Cheng B, Powell W B (2018). Co-optimizing battery storage for the frequency regulation and energy arbitrage using multi-scale dynamic programming. IEEE Transactions on Smart Grid, 9: 1997–2005

Cheng S J (2013). An analysis of prospects for application of large-scale energy storage technology in power systems. Power System Automation, 37: 3–8 (in Chinese)

Chennaif M, Zahboune H, Elhafyani M, Zouggar S (2021). Electric System Cascade Extended Analysis for optimal sizing of an autonomous hybrid CSP/PV/wind system with Battery Energy Storage System and thermal energy storage. Energy, 227: 120444

Chlela M, Mascarella D, Joos G, Kassouf M (2018). Fallback control for isochronous energy storage systems in autonomous microgrids under Denial-of-Service cyber-attacks. IEEE Transactions on Smart Grid, 9(5): 4702–4711

De Carne G, Maroufi S M, Beiranvand H, De Angelis V, D'Arco S, Gevorgian V, Waczowicz S, Mather B, Liserre M, Hagenmeyer V (2024). The role of energy storage systems for a secure energy supply: A comprehensive review of system needs and technology solutions. Electric Power Systems Research, 236: 110963

Deeba S R, Sharma R, Saha T K, Chakraborty D, Thomas A (2016). Evaluation of technical and financial benefits of battery-based energy storage systems in distribution networks. IET Renewable Power Generation, 10(8): 1149–1160

Diaf S, Belhamel M, Haddadi M, Louche A (2008). Technical and economic assessment of hybrid photovoltaic/wind system with battery storage in Corsica island. Energy Policy, 36(2): 743–754

Ding W, Wang G, Xu A D, Chen H J, Hong C (2018). Research on key technologies and information security issues of energy blockchain. Zhongguo Dianji Gongcheng Xuebao, 38(4): 1026–1034 (in Chinese)

Domínguez M, Fernández-Cardador A, Fernández-Rodríguez A, Cucala A P, Pecharromán R R, Urosa Sánchez P, Vadillo Cortázar I (2025). Review on the use of energy storage systems in railway applications. Renewable & Sustainable Energy Reviews, 207: 114904

Dong H, Shan Z, Zhou J, Xu C, Chen W (2023b). Refined modeling and co-optimization of electric-hydrogen-thermal-gas integrated energy system with hybrid energy storage. Applied Energy, 351: 121834

Dong H, Xu C, Chen W (2023a). Modeling and configuration optimization of the rooftop photovoltaic with electric-hydrogen-thermal hybrid storage system for zero-energy buildings: Consider a cumulative seasonal effect. Building Simulation, 16(10): 1799–1819

Dong L, Heng N, Fan Y, Zhao J Y, Zhang Z (2020). Exploration and practice of business model of shared energy storage in energy Internet. Electric Power Construction, 41: 38–44

Elalfy D A, Gouda E, Kotb M F, Bureš V, Sedhom B E (2024). Comprehensive review of energy storage systems technologies, objectives, challenges, and future trends. Energy Strategy Reviews, 54: 101482

ENTSO-E (2021). The inertia challenge in Europe—Present and long-term perspective

Esfahani M M, Hariri A, Mohammed O A (2019). A multiagent-based game-theoretic and optimization approach for market operation of multimicrogrid systems. IEEE Transactions on Industrial Informatics, 15(1): 280–292

Falabretti D, Moncecchi M, Brivio C, Delfanti M, Merlo M, Musolino V IoT-oriented management of distributed energy storage for the primary frequency control. In: 2017 IEEE International Conference on Environment and Electrical Engineering and 2017 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe), 1–6

Fernández-Guillamón A, Gómez-Lázaro E, Muljadi E, Molina-García Á (2019). Power systems with high renewable energy sources: A review of inertia and frequency control strategies over time. Renewable & Sustainable Energy Reviews, 115: 109369

Fossati J, Galarza A, Martín-Villate A, Fontan L (2015). A method for optimal sizing energy storage systems for microgrids. Renewable Energy, 77: 539–549

Giorgio A D, Giuseppi A, Liberati F (2017). Pietrabissa A Controlled electricity distribution network black start with energy storage system support. In: 25th Mediterranean Conference on Control and Automation (MED), 781–786

González-Garrido A, Saez-de-Ibarra A, Gaztañaga H, Milo A, Eguia P (2018). Comparison of market operation strategies for photovoltaic power plants with storage systems providing frequency ancillary services. In: 13th International Conference on Ecological Vehicles and Renewable Energies (EVER), 1–8

González-Garrido A, Saez-de-Ibarra A, Gaztañaga H, Milo A, Eguia P (2019). Annual optimized bidding and operation strategy in energy and secondary reserve markets for solar plants with storage systems. IEEE Transactions on Power Systems, 34(6): 5115–5124

Grand View Research (2020–2027) Battery market size, share & trends analysis report by product (Lead Acid, Li-ion, Nickle Metal Hydride, Ni-cd), by application (Automotive, Industrial, Portable), by region, and segment forecasts

Guo L, Chen X, Deng H, He Y, Chen Q (2018). A framework of operating mechanism based on peer-to-peer transaction among distributed energy resources in community microgrid. Electric Power Construction, 39: 1–9 (in Chinese)

Han Q I, Gao X J, Gao Y F, Zhong Y F, Li Z P (2018). Optimization of the active distribution network operation considering the V2G mode of electric vehicles. In: International Conference on Power System Technology (POWERCON), 4488–4493

Han Y, Wang W, Yu T, Huang Y, Liu D, Jia H (2021). Analysis of economic operation model for virtual power plants considering the uncertainties of renewable energy power generation. In: IEEE Sustainable Power and Energy Conference (iSPEC), 1980–1995

He X, Lecomte R, Nekrassov A, Delarue E, Mercier E Compressed air energy storage multi-stream value assessment on the french energy market. 2011 IEEE Trondheim PowerTech, 1–6

Hessami M A, Bowly D R (2011). Economic feasibility and optimisation of an energy storage system for Portland Wind Farm (Victoria, Australia). Applied Energy, 88(8): 2755–2763

Hesse H C, Schimpe M, Kucevic D, Jossen A (2017). Lithium-ion battery storage for the grid—A review of stationary battery storage system design tailored for applications in modern power grids. Energies, 10(12): 2107

Heymans C, Walker S, Young S, Fowler M (2014). Economic analysis of second use electric vehicle batteries for residential energy storage and load-levelling. Energy Policy, 71: 22–30

Hong L S, Zeng Z L, Huang Z K, Shi X W, Bie Y M (2004). Joint optimization of electric bus charging and energy storage system scheduling. Frontiers of Engineering Management, 1–16

Hossain M A, Chakrabortty R K, Ryan M J, Pota H R (2021). Energy management of community energy storage in grid-connected microgrid under uncertain real-time prices. Sustainable Cities and Society, 66: 102658

Hu Y, Kuang W, Qin Z, Li K, Zhang J, Gao Y, Li W, Li K (2023). Artificial intelligence security: Threats and countermeasures. ACM Computing Surveys, 55(1): 1–36

Huang J Y, Huang K Q, Yang J, Huang Z G, Zhang B Y, Zeng L J (2020). Coordination control strategy of energy storage participating in grid voltage regulation and dynamic reactive power support. Electrical & Energy Management Technology, 30(10): 77–83

Jiang X, Zheng X, Hu G, Chen G Y, Zeng Q S (2019). Optimization of battery energy storage system locating and sizing for the grid. Transactions of China Electrotechnical Society, 34: 10

Jin Z, Cuangang H, Tao R (2019). Nash bargaining model for direct energy transaction on distribution side with multi-microgrid participation. Storage Science and Technology, 4: 645–653

Kaldellis J, Zafirakis D (2007). Optimum energy storage techniques for the improvement of renewable energy sources-based electricity generation economic efficiency. Energy, 32(12): 2295–2305

Kaldellis J, Zafirakis D, Kavadias K (2009). Techno-economic comparison of energy storage systems for island autonomous electrical networks. Renewable & Sustainable Energy Reviews, 13(2): 378–392

Kargarian A, Hug G, Mohammadi J (2016). A multi-time scale co-optimization method for sizing of energy storage and fast-ramping generation. IEEE Transactions on Sustainable Energy, 7(4): 1351–1361

Kazari H, Oraee H, Pal B C (2019). Assessing the effect of wind farm layout on energy storage requirement for power fluctuation mitigation. IEEE Transactions on Sustainable Energy, 10(2): 558–568

Kazempour S J, Moghaddam M P (2009). Economic viability of NaS battery plant in a competitive electricity market. In: International Conference on Clean Electrical Power, 453–459

Lee S J, Kim J H, Kim C H, Kim S K, Kim E S, Kim D U, Mehmood K K, Khan S U (2016). Coordinated control algorithm for distributed battery energy storage systems for mitigating voltage and frequency deviations. IEEE Transactions on Smart Grid, 7(3): 1713–1722

Lee T Y (2007). Operating schedule of battery energy storage system in a Time-of-Use rate industrial user with wind turbine generators: A multipass iteration Particle Swarm Optimization approach. IEEE Transactions on Energy Conversion, 22(3): 774–782

Lee T Y, Chen N M (1995). Determination of optimal contract capacities and optimal sizes of battery energy storage systems for time-of-use rates industrial customers. IEEE Transactions on Energy Conversion, 10(3): 562–568

Leou R C (2008). An economic analysis model for the energy storage systems in a deregulated market. In: IEEE International Conference on Sustainable Energy Technologies, 744–749

Li C, Zhang S, Zhang J, Qi J, Li J, Guo Q, You H (2018). Method for the energy storage configuration of wind power plants with energy storage systems used for black-start. Energies, 11(12): 3394

Li C P, Zhang S N, Li J H (2020a). Black-start scheme for wind-power generation based on multiple energy storage system. Journal of Global Energy Interconnection, 3: 643–652

Li J L, Ma H Y, Dong H (2016a). Present development condition and trends of energy storage technology in the integration of distributed renewable energy. Transactions of China Electrotechnical Society, 31: 1–10

Li J X, Zhao F, Gao F Y (2021). Hierarchical optimization for capacity of PV-integrated EV charging stations on expressway based on HOMER and Tabu algorithm. Journal of Power Supply, 1–13

Li T, Li Z, Yang J, Cui D, Wang Z, Ma K, Hu W (2020b). Coordination and optimal scheduling of multi-energy complementary system considering peak regulation initiative. Power System Technology, 44(10): 3622–3630

Li X, Huang J, Chen Y, Liu W J (2016b). Review on large-scale involvement of energy storage in power grid fast frequency regulation. Power System Protection and Control, 44: 145–153 (in Chinese)

Li X M, Lv X Y, Zhang W Z, Xu C B (2023). Can energy storage make off-grid photovoltaic hydrogen production system more economical? Frontiers of Engineering Management, 10(4): 672–694

Liang C, Wang P, Han X (2017). Economic selection of energy storage system for PV station considering dynamic reliability evaluation. Power System Technology, 41(8): 2639–2646

Lieskoski S, Koskinen O, Tuuf J, Björklund-Sänkiaho M (2024). A review of the current status of energy storage in Finland and future development prospects. Journal of Energy Storage, 93: 112327

Hossain Lipu M, Ansari S, Miah M S, Hasan K, Meraj S T, Faisal M, Jamal T, Ali S H, Hussain A, Muttaqi K M, Hannan M A (2022). A review of controllers and optimizations based scheduling operation for battery energy storage system towards decarbonization in microgrid: Challenges and future directions. Journal of Cleaner Production, 360: 132188

Liu C, Zhao J K, Zhao D M, Li B Q, Chen J S, Wang J X, Yao Q (2019). Review on the research of flexible and safe operation of renewable energy microgrids using energy storage systems. Zhongguo Dianji Gongcheng Xuebao, 37(4): 1–18 (in Chinese)

Liu J, Zou D P, Chen Y C, Chu Z J, Gao Z, Teng Z S (2020a). Discussions on operation mechanism and benefits of customer-side distributed energy storage P2P sharing mode of "Internet+. Power System and Clean Energy, 36: 97–105 (in Chinese)

Liu W, Guo H, Li J, Chen Y, Chen Q (2016). Optimal bidding strategy for energy storage systems in energy and flexible ramping products markets. In: IEEE Innovative Smart Grid Technologies - Asia (ISGT-Asia), 776–780

Liu X P, Ming D, Han J H, Han P P, Peng Y L (2010). Dynamic economic dispatch for microgrids including battery energy storage. In: 2nd International Symposium on Power Electronics for Distributed Generation Systems, 914–917

Liu Y, Wu X, Du J, Song Z, Wu G (2020b). Optimal sizing of a wind-energy storage system considering battery life. Renewable Energy, 147: 2470–2483

Lockley A, von Hippel T (2021). The carbon dioxide removal potential of Liquid Air Energy Storage: A high-level technical and economic appraisal. Frontiers of Engineering Management, 8(3): 456–464

Luo X, Liu X J, Liu Y F, Liu J P, Wang Y X (2021). Benefit-based cost allocation for residentially distributed photovoltaic systems in China: A cooperative game theory approach. Frontiers of Engineering Management, 8(2): 271–283

Luo Z, Hu Z, Song Y, Xu Z, Liu H, Jia L, Lu H (2012). Economic analyses of plug-in electric vehicle battery providing ancillary services. In: IEEE International Electric Vehicle Conference, 1–5

Ma S, Ma H, Jiang X (2015). Capacity configuration of the hybrid energy storage system based on bloch spherical quantum genetic algorithm. Proceedings of the CSEE, 592–599

Ma T, Peng L, Du Y, Gou Q F, Wang C, Guo X F (2018). Competition game model for local multi-microgrid market based on block chain technology and its solution algorithm. Electric Power Automation Equipment, 38: 191–203 (in Chinese)

Marchenko O (2010). Mathematical modeling and economic efficiency assessment of autonomous energy system with production and storage of secondary energy carriers. International Journal of Low Carbon Technologies, 5(4): 250–255

Moghaddam I G, Saeidian A (2010). Self scheduling program for a VRB energy storage in a competitive electricity market. In: International Conference on Power System Technology, 1–6

Monjean P, Sprooten J, Robyns B (2010). Inuence of technical-economic energy context for the management of wind farms and storage systems in a constrained network. In: IEEE International Symposium on Industrial Electronics, 2420–2425

Mwasilu F, Justo J J, Kim E K, Do T D, Jung J W (2014). Electric vehicles and smart grid interaction: A review on vehicle to grid and renewable energy sources integration. Renewable & Sustainable Energy Reviews, 34: 501–516

Neoen (2024). Hornsdale Power Reserve

Nguyen H T, Muhs J W, Parvania M (2019). Assessing impacts of energy storage on resilience of distribution systems against hurricanes. Journal of Modern Power Systems and Clean Energy, 7(4): 731–740

Onyeka Okoye M, Yang J, Cui J, Lei Z, Yuan J, Wang H, Ji H, Feng J, Ezeh C (2020). A blockchain-enhanced transaction model for microgrid energy trading. IEEE Access: Practical Innovations, Open Solutions, 8: 143777–143786

Oudalov A, Cherkaoui R, Beguin A (2007). Sizing and optimal operation of battery energy storage system for peak shaving application. In: IEEE Lausanne Power Tech, 621–625

Paudel A, Chaudhari K, Long C, Gooi H B (2019). Peer-to-Peer energy trading in a prosumer-based community microgrid: A game-theoretic model. IEEE Transactions on Industrial Electronics, 66(8): 6087–6097

Paul S, Nath A P, Rather Z H (2020). A multi-objective planning framework for coordinated generation from offshore wind farm and battery energy storage system. IEEE Transactions on Sustainable Energy, 11(4): 2087–2097

Poudineh R, Jamasb T (2014). Distributed generation, storage, demand response and energy efficiency as alternatives to grid capacity enhancement. Energy Policy, 67: 222–231

Raeispour M, Atrianfar H, Davari M, Gharehpetian G B (2022). Fault-tolerant, distributed control for emerging, VSC-based, islanded microgrids—An approach based on simultaneous passive fault detection. IEEE Access: Practical Innovations, Open Solutions, 10: 10995–11010

Rashedi B, Abdollahi A, Rashidinejad M (2024). Flexibility-based operation and construction of energy hub considering battery aging and deep-learning for participation in demand response programs.

Energy Conversion and Management, 315: 118803

Schleifer A H, Murphy C A, Cole W J, Denholm P (2022). Exploring the design space of PV-plus-battery system configurations under evolving grid conditions. Applied Energy, 308: 118339

Sharma D D, Singh S N, Lin J, Foruzan E (2017). Agent-based distributed control schemes for distributed energy storage systems under cyber attacks. IEEE Journal on Emerging and Selected Topics in Circuits and Systems, 7(2): 307–318

Sortomme E, El-Sharkawi M A (2009). Optimal power flow for a system of microgrids with controllable loads and battery storage. In: IEEE/PES Power Systems Conference and Exposition, 1–5

Spiliotis K, Claeys S, Gutierrez A R, Driesen J (2016). Utilizing local energy storage for congestion management and investment deferral in distribution networks. In: 13th International Conference on the European Energy Market, 1–5

Taghizad-Tavana K, Tarafdar-Hagh M, Nojavan S, Yasinzadeh M, Ghanbari-Ghalehjoughi M (2024). Operation of smart distribution networks by considering the spatial–temporal flexibility of data centers and battery energy storage systems. Sustainable Cities and Society, 114: 105746

Tang W, Yang H T (2019). Optimal operation and bidding strategy of a virtual power plant integrated with energy storage systems and elasticity demand response. IEEE Access: Practical Innovations, Open Solutions, 7: 79798–79809

Tao Q, Sang B Y, Ye J L, Xue J H (2016). Optimal configuration method of distributed energy storage systems in distribution network with high penetration of photovoltaic. High Voltage Engineering, 42(7): 2158–2165 (in Chinese)

Tao Y, Xue J, Xia M, Tao J, Zhang Q, Li X, Liao Q, Li C, Tang H (2020). Economic feasibility of echelon utilization battery in photovoltaic energy storage. In: E3S Web of Conferences, 194: 02001

Telaretti E, Dusonchet L (2017). Stationary battery technologies in the US: Development trends and prospects. Renewable & Sustainable Energy Reviews, 75: 380–392

Ullah F, Zhang X, Khan M, Mastoi M S, Munir H M, Flah A, Said Y (2024). A comprehensive review of wind power integration and energy storage technologies for modern grid frequency regulation. Heliyon, 10(9): e30466

United Nations (2019). Sustainable Development Goals (SDGs) United Nations

Van Cutsem O, Ho Dac D, Boudou P, Kayal M (2020). Cooperative energy management of a community of smart-buildings: A Blockchain approach. International Journal of Electrical Power & Energy Systems, 117: 105643

Vasudevan K R, Ramachandaramurthy V K, Venugopal G, Ekanayake J B, Tiong S K (2021). Variable speed pumped hydro storage: A review of converters, controls and energy management strategies. Renewable & Sustainable Energy Reviews, 135: 110156

Viswanathan V V, Kintner-Meyer M (2011). Second use of transportation batteries: Maximizing the value of batteries for transportation and grid services. IEEE Transactions on Vehicular Technology, 60(7): 2963–2970

Walker A, Kwon S (2021). Analysis on impact of shared energy storage in residential community: Individual versus shared energy storage. Applied Energy, 282: 116172

Wang B, Zhang C, Dong Z Y, Li X (2021). Improving hosting capacity of unbalanced distribution networks via robust allocation of battery energy storage systems. IEEE Transactions on Power Systems, 36(3): 2174–2185

Wang B, Zhang C, Li C, Li P, Dong Z Y, Lu J (2022). Hybrid interval-robust adaptive battery energy storage system dispatch with SoC interval management for unbalanced microgrids. IEEE Transactions on Sustainable Energy, 13(1): 44–55

Wang H, Jiang J, Huang M, Zhang W, Bao Y (2017). Hierarchical energy storage configuration method for pure electric vehicle fast charging station. In: IEEE Transportation Electrification Conference and Expo, Asia-Pacific, 1–6

Wang L Y, Jiang Y W, Wang J (2020a). Optimization of grid-side energy storage considering multi-market transaction. Power System and Clean Energy, 36: 30–38

Wang Q, Gao Y, Zhang J (2014). Research on electric vehicle orderly charging and discharging considering unit running cost and effectiveness of power system operation. In: International Conference on Power System Technology, 996–1000

Wang S J, Ping C, Xue G B (2018). Synergic optimization of community energy internet considering the shared energy storage. Electric Power, 51: 77–84

Wang Y, Zhao H, Hou X, Sun H, Zheng K, Li S, Ye J (2020b). Distributed electricity trading model in microgrid based on contract orders. Power System Technology, 44(10): 3291–3297 (in Chinese)

Weicker P (2013). A systems approach to lithium-ion battery management. Artech house

Wen Y, Li W, Huang G, Liu X (2016). Frequency dynamics constrained unit commitment with battery energy storage. IEEE Transactions on Power Systems, 31(6): 5115–5125

Wong Y S, Lai L L, Gao S, Chau K T (2011). Stationary and mobile battery energy storage systems for smart grids. In: 4th International Conference on Electric Utility Deregulation and Restructuring and Power Technologies (DRPT), 1–6

Wu G Y, Li Z J (2021). Cyber–Physical Power System (CPPS): A review on measures and optimization methods of system resilience. Frontiers of Engineering Management, 8(4): 503–518

Wu Y, Tian P, Xiao X, Cao Y, Yu L (2022). Multi-scenario safe operation method of energy storage system for cascade utilization of retired power batteries. In: Frontier Academic Forum of Electrical Engineering Singapore, 925–935

Xin T, Cungang H, Tao R (2019). Master-slave game-based economic optimization method for multi-microgrid system. Electric Power, 52: 68–76 (in Chinese)

Xu S P, Li X J, Dong H (2013). A review of development and demonstration application of large-scale electrochemical energy storage. Electric Power Contruction, 34: 73–80 (in Chinese)

Yang D C, Zhao X Y, Xu Z X, Li Y, Li Q (2017). Developing status and prospect analysis of blockchain in energy internet. Zhongguo Dianji Gongcheng Xuebao, 37: 3664–3671 (in Chinese)

Yang M, Zhang L, Zhao Z, Wang L (2021). Comprehensive benefits analysis of electric vehicle charging station integrated photovoltaic and energy storage. Journal of Cleaner Production, 302: 126967

Yebiyo M, Mercado R A, Gillich A, Chaer I, Day A R, Paurine A (2020). Novel economic modelling of a peer-to-peer electricity market with the inclusion of distributed energy storage—The possible case of a more robust and better electricity grid. Electricity Journal, 33(2): 106709

Yi T, Li Q, Zhu Y, Shan Z, Ye H, Xu C, Dong H (2024). A hierarchical co-optimal planning framework for microgrid considering hydrogen energy storage and demand-side flexibilities. Journal of Energy Storage, 84: 110940

Zakeri B, Syri S (2015). Electrical energy storage systems: A comparative life cycle cost analysis. Renewable & Sustainable Energy Reviews, 42: 569–596

Zhang J G, Jiao D, Wang X, Zhu J, He J (2014). Analysis on economic operation of energy storage based on second-use batteries. Power System Technology, 38(9): 2551–2555 (in Chinese)

Zhang L, Kuang J, Sun B, Li F, Zhang C (2020). A two-stage operation optimization method of integrated energy systems with demand response and energy storage. Energy, 208: 118423

Zhang Y, Xu Y, Guo H, Zhang X, Guo C, Chen H (2018a). A hybrid energy storage system with optimized operating strategy for mitigating wind power fluctuations. Renewable Energy, 125: 121–132

Zhang Z, Zhang Y, Huang Q, Lee W J (2018b). Market-oriented optimal dispatching strategy for a wind farm with a multiple stage hybrid energy storage system. CSEE Journal of Power and Energy Systems, 4(4): 417–424

Zhao S, Xu X, Wu Z (2020). Innovative application of blockchain technology in field of distributed energy trading. Electrical & Energy Management Technology, 1–10

Zhao S Q, Wang Y, Xu Y, Yin J F (2015). Optimal scheduling of energy storage system in wind power integrated system based on bi-level programming. In: IEEE Power & Energy Society General Meeting, 1–5

Zhou K L, Zhang Z H, Liu L, Yang S L (2022). Energy storage resource management: Planning, operation, and business model. Frontiers of Engineering Management, 9(3): 373–391

Zhu H, Zhang L, Liu G J (2019). Study on multiple functional operation of demand side storage. Power Supply, 36: 77–84 (in Chinese)

Zhu Z B, Sun S M, Ding Y M, Huang S P (2023). Research on control strategy of hybrid energy storage system with optical storage microgrid. Journal of Electrical Engineering & Technology, 18(4): 2835–2845