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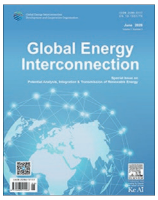

Research on the coordinated optimization of energy storage and renewable energy in off-grid microgrids under new electric power systems

Zhuoran Song [a], Mingli Zhang [a], Yuanying Chi [b], Jialin Li [c,*], Yi Zheng [b]

[a] *State Grid Liaoning Electric Power Supply Co. Ltd., Shenyang 110006, P R China*
[b] *School of Economics and Management, Beijing University of Technology, Beijing 100124, P R China*
[c] *School of Economics and Management, North China Electric Power University, Beijing 102206, P R China*

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Abstract

The supply of electricity to remote regions is a significant challenge owing to the pivotal transition in the global energy landscape. To address this issue, an off-grid microgrid solution integrated with energy storage systems is proposed in this study. Off-grid microgrids are self-sufficient electrical networks that are capable of effectively resolving electricity access problems in remote areas by providing stable and reliable power to local residents. A comprehensive review of the design, control strategies, energy management, and optimization of off-grid microgrids based on domestic and international research is presented in this study. It also explores the critical role of energy storage systems in enhancing microgrid stability and economic efficiency. Additionally, the capacity configurations of energy storage systems within off-grid networks are analyzed. Energy storage systems not only mitigate the intermittency and volatility of renewable energy generation but also supply power support during peak demand periods, thereby improving grid stability and reliability. By comparing different energy storage technologies, such as lithium-ion batteries, pumped hydro storage, and compressed air energy storage, the optimal energy storage capacity configurations tailored to various application scenarios are proposed in this study. Finally, using a typical microgrid as a case study, an empirical analysis of off-grid microgrids and energy storage integration has been conducted. The optimal configuration of energy storage systems is determined, and the impact of wind and solar power integration under various scenarios on grid balance is explored. It has been found that a rational configuration of energy storage systems can significantly enhance the utilization rate of renewable energy, reduce system operating costs, and strengthen grid resilience under extreme conditions. This study provides essential theoretical support and practical guidance for the design and implementation of off-grid microgrids in remote areas.

Keywords: Off-grid microgrid; Energy storage system; Optimal configuration; Renewable energy

0 Introduction

Amid the global energy transition, the challenge of ensuring a reliable power supply in remote areas remains particularly pronounced. These regions face significant obstacles in accessing traditional centralized power networks owing to their geographic remoteness, complex terrains, and sparse populations. The construction and maintenance of long-distance transmission lines not only incur substantial costs but are also constrained by topo-

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* Corresponding author.

E-mail addresses: zml@ln.sgcc.com.cn (M. Zhang), goodcyy@126.com (Y. Chi), iceyljl@126.com (J. Li), zy444763866@163.com (Y. Zheng).

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graphical and climatic conditions, which often hinder the stability and reliability of power supply. In extreme weather events or natural disasters, power supply disruptions can occur, severely affecting the quality of life of local residents and hindering economic development.

The integration of renewable energy sources, such as wind and solar power, introduces additional challenges for real-time power balancing. These energy sources are characterized by randomness, volatility, and intermittency, with output often misaligned with load curve fluctuations. Specifically, renewable energy tends to have low output during peak load periods and high output during off-peak times. To mitigate this imbalance, the system requires a significant number of conventional thermal power units to provide peak-shaving capabilities. As the share of renewable energy in the power system increases, the required backup capacity of these peaking units grows, complicating the maintenance of supply–demand equilibrium. Under extreme conditions, such as adverse weather events that lead to minimal or zero output from wind turbines and photovoltaic systems, insufficient standby capacity can result in a supply–demand imbalance, necessitating load restrictions to safeguard system security.

With the deepening of marketization, market dynamics, such as those associated with the upstream segments of the industrial chain, have emerged as critical factors influencing the balance power of supply and demand. Currently, coal power accounts for nearly 50% of China's installed power capacity, supplies approximately 60% of the nation's electricity generation, and is responsible for over 70% of the system's peaking tasks. As China's primary power source and the "ballast" ensuring power supply stability, coal power necessitates substantial coal consumption. Consequently, the security of coal supply significantly impacts the equilibrium of power supply and demand. Furthermore, weaknesses in local distribution network structures persist, rendering them unable to meet peak electricity demands, particularly in older urban areas, remote regions, and areas where development has outplaced planning expectations.

To address these challenges, the concept of new power systems advocates for decentralized energy supply models, particularly off-grid microgrids centered on distributed photovoltaic (PV) systems. These microgrids offer innovative solutions to these persistent issues. An off-grid microgrid is a small, self-sufficient power system capable of operating independently without reliance on external grid support. Deploying off-grid microgrids in remote regions effectively resolves power access challenges ensuring a stable and reliable power supply for local residents. Moreover, advancements in technology, especially the development of energy storage systems, have further mitigated the intermittency and volatility of renewable energy, laying a robust foundation for establishing a clean, low-carbon, safe, and efficient energy system.

1 Literature review

1.1 Research on off-grid microgrids

Research on off-grid microgrids primarily focuses on enhancing system self-sufficiency and operational efficiency. By comprehensively analyzing contributions from various scholars, an in-depth understanding can be gained regarding the design, control strategies, energy management, and optimal allocation challenges faced by off-grid microgrids.

The core of off-grid microgrid design lies in effectively integrating renewable energy sources with storage systems to achieve efficient and stable energy supply. For instance, Zhao et al. [1] proposed a fully direct current (DC)-based grid design to integrate photovoltaic (PV) systems and energy storage devices, optimizing energy flow and minimizing conversion losses. This approach significantly reduces energy losses associated with alternating current (AC) conversions, thereby improving overall energy efficiency. In the realm of control strategies, Ma [2] highlighted the use of advanced control theories to enhance the dynamic stability of off-grid power grids. Model predictive control (MPC) strategies, in particular, demonstrate the ability to predict and adjust energy output to accommodate fluctuating load demands, especially under conditions of high renewable energy volatility.

Zhang et al. [3] introduced a hybrid optimization model of off-grid PV and hydroelectricity systems, utilizing a geographic information system (GIS) for cities with abundant water resources. This model leverages water resources to meet power demands with lower economic costs and fewer storage facilities. Meng [4] emphasized the importance of inverter technology in PV systems, noting that optimizing inverter control strategies is critical for enhancing PV power generation efficiency. By improving inverter responsiveness and refining tuning algorithms, solar energy utilization can be maximized. He et al. [5] empirically compared various operation strategies, confirming the effectiveness of optimization strategies in improving system efficiency and reliability in practical applications. Their study explored the economic and environmental implications of grid extensions versus off-grid systems, highlighting the advantages of off-grid microgrids for unelectrified populations. Technologies examined included centralized fossil-fueled grid extensions and off-grid systems primarily based on solar photovoltaics and batteries. Ortega-Arriaga et al. [6] noted a lack of consistency in methodologies comparing grid extension with off-grid systems. However, they observed that off-grid power costs range from \$0.2–1.4/kWh, whereas grid extension costs vary widely, from below \$0.1/kWh to over \$8/kWh. This variability suggests that off-grid systems may already be a cost-effective option in many scenarios.

1.2 Research on energy storage capacity configuration

In the domain of energy storage, Zheng [7] was among the first to explore its role in enhancing microgrid reliability and reducing operational costs. Proper energy storage capacity allocation remains a critical factor for ensuring the continuous operation of microgrids. Energy storage systems play a pivotal role in power systems by managing energy demand and supply, integrating renewable energy sources, and providing rapid responses during emergencies. Through their unique peak-shaving and valley-filling functions, these systems release stored energy during peak demand periods and store excess energy during low-demand times. This flexibility enhances the operational efficiency and economic viability of the grid [8]. Moreover, energy storage systems play an important role in electricity price optimization by storing energy when the price of electricity is low and releasing it when the price is high, thus maximizing cost-effectiveness. This capability is particularly valuable in volatile electricity markets, as it exploits market dynamics to reduce grid burdens and minimize infrastructure investment requirements.

Energy storage systems are indispensable in facilitating the integration of renewable energy sources into power grids. As renewable energy sources, such as solar and wind, become a larger share of the energy mix, their inherent instability and intermittency pose significant challenges for grid management. Energy storage systems address these challenges by storing excess energy during periods of high output and releasing it during periods of high demand [9]. This capability enhances the utilization of renewable energy, regulates the balance between supply and demand, and stabilizes grid frequency and voltage. Such benefits are critical for large-scale integration of renewable energy, reducing waste from overcapacity and improving overall efficiency [10]. The role of energy storage systems extends beyond daily grid emergencies. During power outages or other disruptions, energy storage systems provide rapid response to maintain power supply for critical facilities [11]. This capability significantly improves grid resilience, particularly in extreme weather conditions or natural disasters. Furthermore, energy storage systems play a pivotal role in grid restoration by supporting grid restart efforts, enabling a swift return to normal operations.

Recent studies have highlighted the advantages of advanced energy storage configurations. Zhao et al. [12] demonstrated that an optimized configuration in wind-fire-storage coupled system improves wind power utilization and overall system efficiency, showcasing the benefits of multi-energy integration. Similarly, Shi et al. [13] analyzed energy storage configurations in high-ratio wind power systems, emphasizing their impact on operational economy and reliability. Chen et al. [14] proposed hybrid energy strategies for wind farms, incorporating carbon trading considerations to maximize economic and environmental benefits. Jiang et al. [8] work, on the other hand, shows how a high percentage of clean energy parks can improve system performance through optimal allocation of energy storage as well as demand response strategies.

Li et al. [15] studied energy storage configurations to address wind and solar energy dissipation, finding that optimal capacity allocation reduces renewable energy abandonment and enhances utilization rates. Zhang and Liu [16] proposed solutions for mitigating power fluctuations and energy storage lifetimes, thereby improving the environmental and economic performance of microgrid systems. Additionally, Jiang et al. [17], explored photovoltaic storage charging stations, optimizing storage capacity allocation to account for PV output variability and EV user charging behaviors, ultimately improving system performance. Zhao et al. [18] The optimized configuration of shared energy storage in a multi-virtual power plant system explored improves the operational efficiency of the system and the rate of renewable energy consumption through multi-objective optimization.

1.3 Research on energy storage capacity configuration in off-grid microgrids

Research on energy storage capacity configuration in off-grid microgrids focuses on enhancing stability, efficiency, and reliability. Ma [19] investigated advanced energy management systems in wind-solar-storage complementary systems, demonstrating their ability to mitigate supply instability and load fluctuations through precise dispatch optimization. Zhong et al. [20] highlighted the benefits of hybrid energy storage systems combining lithium batteries and supercapacitors, which improve both economic performance and power supply reliability. Liang [21] proposed optimizing energy storage allocation by leveraging wind-solar complementarity to balance supply and demand while reducing dependence on fossil fuels. Li [22] explored the potential of hydrogen production systems as a novel energy storage and conversion technology, showing their effectiveness in enhancing energy utilization in wind-solar systems. Zhu et al. [23] introduced the concept of the energy imbalance rate to evaluate correlations between wind power output and load variations, providing theoretical support for energy storage allocation in off-grid systems.

Although these studies demonstrate significant advancements, several gaps remain. Most research focuses on single energy systems or specific technologies, lacking comprehensive approaches for integrated multi-energy system management. Additionally, existing models often rely on assumptions and simplifications, which may not fully capture the complexity of real-world operating environments. Future research should prioritize integrated optimization, practical applicability of system models, and advanced multi-energy management strategies. Furthermore, decreasing renewable energy costs and advancements in grid technologies, evaluating these technologies' cost-effectiveness will be crucial in shaping the next generation of off-grid microgrids.

2 Construction of a capacity optimization configuration model for energy storage systems in off-grid microgrids

This study introduces an innovative approach to constructing a capacity optimization configuration model for energy storage systems in off-grid microgrids. The model accounts for factors such as wind and solar curtailment, load shedding, and varying electricity consumption patterns between weekdays and holidays. A dynamic objective function, coupled with a comprehensive set of constraints, is established to precisely quantify costs across different time intervals. This approach enables the model to accurately reflect the overall benefits of the system, thereby improving the optimization accuracy in complex energy scenarios. The proposed methodology offers an effective solution for achieving stable and efficient operation of off-grid microgrids.

This research leverages Python programming integrated with the Gurobi optimization solver to construct and solve the model.

2.1 Objective function

The objective function of the model is to minimize the total costs over the time period T. The function determines the optimal storage allocation capacity and scheduling scheme based on the capacity and cost parameters of the wind power, photovoltaic systems, and gas turbines incorporated in the off-grid microgrid. The specific model is formulated as follows:

$$\mathrm{Min}Z = \sum_{t \in T} \left(C_{\mathrm{ins}}(t) + C_{\mathrm{om}}(t) + C_{\mathrm{st}}^{\mathrm{mt}}(t) + C_{\mathrm{pl}}(t) + C_{\mathrm{ll}}(t) \right) \tag{1}$$

In Eq. (1), $C_{\mathrm{ins}}(t)$, $C_{\mathrm{om}}(t)$ are the installation cost, operation and maintenance cost of the wind-scenic fuel storage at time point t, respectively;$C_{\mathrm{st}}^{\mathrm{mt}}(t)$ is the start-up cost of the gas turbine at time point t;$C_{\mathrm{pl}}(t)$ and $C_{\mathrm{ll}}(t)$ represent the penalty costs for abandoned wind and abandoned load at time point t, respectively. The components of the objective function are detailed as follows:

1) installation cost $C_{\mathrm{ins}}(t)$

The installation cost at a specific time point accounts for the cumulative expenses required to procure, construct, and install equipment. This includes costs associated with design, commissioning and ensuring all power generation and energy storage equipment to operational. The installation cost is expressed as:

$$C_{\mathrm{ins}}(t) = \sum_{i \in Ng} C_{\mathrm{ins},i}(t) \times I_i + C_{\mathrm{ins},j}(t) \times I_j \tag{2}$$

$$\begin{aligned} C_{\mathrm{ins},i}(t) &= C_{\mathrm{inins},i} \times \left[\frac{r_i}{1-(1/(1+r_i))^{n_i}} \right] \div 8760 \\ C_{\mathrm{ins},j}(t) &= C_{\mathrm{inins},j} \times \left[\frac{r_j}{1-\left(1/\left(1+r_j\right)\right)^{n_j}} \right] \div 8760 \end{aligned} \tag{3}$$

where $C_{\mathrm{ins},i}(t)$ for the first i category of generating units (wind, PV, diesel generators) at the t moment of time cost (\$/kW),$C_{\mathrm{ins},j}(t)$ is the cost of energy storage j at the time t (yuan/kW). I_i and I_j represent the cost of the first i class of generating units and energy storage j of the installed capacity (kW).$C_{\mathrm{inins},i}$ and $C_{\mathrm{inins},j}$ are the installed capacity (kW) of i type of generating units and energy storage j of the initial investment cost (yuan/kW). r_i and r_j are the initial investment cost (yuan/kW) of generating sets and energy storage of category i type of generating units and energy storage j is the discount rate of n_i and n_j is the discount rate for i type of generating units and energy storage j the operating life of the generating units and energy storage [24].

2) O&M cost $C_{\mathrm{om}}(t)$

The operation and maintenance cost (O&M) cost represents the expenses incurred for repairs and routine maintenance to ensure the normal operation of generating units and energy storage systems throughout their lifetime. The O&M cost is expressed as:

$$\begin{aligned} C_{\mathrm{om}}(t) &= \sum_{i \in Ng} (C_{\mathrm{om},i}(t) \times I_i) + C_{\mathrm{om},j}(t) \times I_j \\ C_{\mathrm{om},i}(t) &= C_{\mathrm{yrom},i} \div 8760 \\ C_{\mathrm{om},j}(t) &= C_{\mathrm{yrom},j} \div 8760 \end{aligned} \tag{4}$$

$C_{\mathrm{om},i}(t)$,$C_{\mathrm{om},j}(t)$,$C_{\mathrm{yrom},i}$ and $C_{\mathrm{yrom},j}$ denote respectively the first i class of generating units and energy storage j at t point-in-time O&M cost (\$/kw. hour) and annual O&M cost (\$/kW. year). I_i and I_j denotes the O&M cost of the i rated power (kW) of the generating units and energy storage j of the class of generator sets and energy storage are rated power (kW).

3) Start-up cost $C_{\mathrm{st}}^{\mathrm{mt}}(t)$

The start-up costs are incurred when turning on the micro gas turbine from a shutdown state, which varies based on operating conditions. The start-up cost is represented as:

$$C_{\mathrm{st}}^{\mathrm{mt}}(t) = c_{\mathrm{st}}^{\mathrm{mt}}(t) \times S_{\mathrm{st}}^{\mathrm{mt}}(t) \tag{5}$$

where $c_{\mathrm{st}}^{\mathrm{mt}}(t)$ denotes the gas turbine startup cost at time point t (\$/time), and $S_{\mathrm{st}}^{\mathrm{mt}}(t)$ denotes the start-up cost of the gas turbine at time point t.$S_{\mathrm{st}}^{\mathrm{mt}}(t)$ is a 0,1 variable. The value is 1 for startup and 0 for shutdown.

4) Wind abandonment penalty cost $C_{\mathrm{pl}}(t)$

The wind penalty cost is incurred when wind or photovoltaic generation exceeds the system's maximum capacity, leading to abandonment. The cost is calculated as:

$$C_{\mathrm{pl}}(t)=C_{\mathrm{pl}}\times\sum_{i\in Ng}\left(\mathrm{PL}_i^{\mathrm{pv}}(t)+\mathrm{PL}_i^{\mathrm{wt}}(t)\right) \tag{6}$$

C_{pl} refers to the penalty cost per unit of abandoned wind power ($/kW), the $\mathrm{PL}_i^{\mathrm{wt}}(t)$ and $\mathrm{PL}_i^{\mathrm{pv}}(t)$ is the amount of abandoned wind and light at the point of time t (kW) [25].

5) Load shedding penalty cost $C_{\mathrm{ll}}(t)$

Load shedding penalty costs occur when load demand is curtailed due to renewable energy volatility or forecasting errors. The cost is expressed as:

$$C_{\mathrm{ll}}(t)=C_{\mathrm{LL}}\times\mathrm{LL}(t) \tag{7}$$

C_{LL} is the cost per unit of abandoned load penalty ($/kW);LL$(t)$ is the amount of abandoned load at the point in time t (kW).

2.2 Constraint function

1) Real-time power balance constraints

To ensure safe and stable operation, the system must balance energy generation, storage, and load demand during the operation scheduling time while accounting for wind and light abandonment [26]. The energy balance constraint at time t is formulated as:

$$\begin{aligned}&P_i^{\mathrm{pv}}(t)+P_i^{\mathrm{wt}}(t)+P_i^{\mathrm{mt}}(t)+P_j^{\mathrm{dch}}(t)-P_j^{\mathrm{ch}}(t)-\\&\left(PL_i^{\mathrm{pv}}(t)+PL_i^{\mathrm{wt}}(t)\right)+\mathrm{LL}(t)=P_{\mathrm{de}}(t)\end{aligned} \tag{8}$$

Among them,$P_i^{\mathrm{pv}}(t)$,$P_i^{\mathrm{wt}}(t)$, and $P_i^{\mathrm{mt}}(t)$ respectively represent the output power (kw) of each type of power generating equipment (photovoltaic, wind power, micro-gas turbine) at the moment of t. $P_j^{\mathrm{dch}}(t)$ and $P_j^{\mathrm{ch}}(t)$ denote the the discharge and charge power (kW) of energy storage j at time t, and $P_{\mathrm{de}}(t)$ indicates the real-time load demand at time t.

2) Wind and light output constraints

Output constraints are implemented to ensure system safety and stability by limiting generator and energy storage output to avoid overloading, underloading, or causing fluctuations in frequency and voltage. These constraints are determined by system operation and safety requirements [27].

$$\begin{aligned}&0\leqslant P_i^{\mathrm{pv}}(t)\leqslant I_i^{\mathrm{pv}}\\&0\leqslant P_i^{\mathrm{wt}}(t)\leqslant I_i^{\mathrm{wt}}\end{aligned} \tag{9}$$

In Eq. (9), I_i^{pv} and I_i^{wt} are the rated power (kW) of photovoltaic and wind power, respectively. This constraint limits the fluctuation range of wind and solar output to ensure the safe and stable operation of the power system.

3) Thermal power output constraints

$$\begin{aligned}&S_{\mathrm{st}}^{\mathrm{mt}}(t)\times P_i^{\min\mathrm{mt}}(t)\leqslant P_i^{\mathrm{mt}}(t)\leqslant S_{\mathrm{st}}^{\mathrm{mt}}(t)\times P_i^{\max\mathrm{mt}}(t)\\&P_i^{\max\mathrm{mt}}(t)=I_i^{\mathrm{mt}}\end{aligned} \tag{10}$$

In Eq. (10), $P_i^{\min\mathrm{mt}}(t)$, $P_i^{\max\mathrm{mt}}(t)$ denote, respectively, the t time ignition power minimum and maximum output limits [28].

4) Energy storage state constraints

The state of charge $\mathrm{SOC}_j(t)$ describes the ratio of the remaining energy in energy storage device j to its rated capacity at time t. The state-of-charge constraint is used to ensure that excessive or improper use of electricity causes damage to the energy storage system, and is used to guide the charging and discharging strategy of the energy storage system in order to maximize the utilization and extend the service life of the energy storage system. The state-of-charge constraints of the energy storage are limited to a minimum value $\mathrm{SOC}_j^{\min}(t)$ and maximum value $\mathrm{SOC}_j^{\max}(t)$ between the minimum and maximum values to prevent overcharging and discharging and to extend battery life.

$$\begin{aligned}&E_j\times\mathrm{SOC}_j(t)-E_j\times\mathrm{SOC}_j(t-1)=\\&\left(P_j^{\mathrm{ch}}(t)\times u_{\mathrm{ch}}-\frac{P_j^{\mathrm{dch}}(t)}{u_{\mathrm{dch}}}\right)\times\Delta t\end{aligned} \tag{11}$$

$$\mathrm{SOC}_j^{\min}(t)\leqslant\mathrm{SOC}_j(t)\leqslant\mathrm{SOC}_j^{\max}(t) \tag{12}$$

In the above equation, the u_{ch} and u_{dch} are the charging and discharging efficiency (%) of the energy storage, respectively, and E_j is the rated capacity of the energy storage (kWh).

$$\begin{aligned}&0\leqslant P_j^{\mathrm{ch}}(t)\leqslant I_j\\&0\leqslant P_j^{\mathrm{dch}}(t)\leqslant I_j\end{aligned} \tag{13}$$

The above equation limits the maximum and minimum values of the charging and discharging power of the energy storage device.

$$P_j^{\mathrm{dch}}(t)\times P_j^{\mathrm{ch}}(t)=0 \tag{14}$$

Charging and discharging processes cannot occur simultaneously.

5) Abandoned load, abandoned wind and light volume constraints

$$\begin{aligned}&0\leqslant\mathrm{PL}_i^{\mathrm{pv}}(t)\leqslant P_i^{\mathrm{pv}}(t)\\&0\leqslant\mathrm{PL}_i^{\mathrm{wt}}(t)\leqslant P_i^{\mathrm{wt}}(t)\\&0\leqslant\mathrm{LL}_{(t)}\leqslant P_{\mathrm{de}}(t)\\&\left(\mathrm{PL}_i^{\mathrm{pv}}(t)+\mathrm{PL}_i^{\mathrm{wt}}(t)\right)\times\mathrm{LL}(t)=0\end{aligned} \tag{15}$$

The above equation on the one hand limits the maximum and minimum values of the abandoned wind and load power. On the other hand, it ensures that the abandoned load and abandoned wind power do not occur at the same time.

6) Gas turbine start-stop constraints

$$0 \leqslant c_{st}^{mt} \geqslant \varepsilon_{st}^{mt}\left(S_{st}^{mt}(t) - S_{st}^{mt}(t-1)\right) \tag{16}$$

ε_{st}^{mt} is the startup cost of the gas turbine. This constraint indicates that the startup cost of the gas turbine is not significant if and only if $S_{st}^{mt}(t) = 1$, and $S_{st}^{mt}(t-1) = 0$, the gas turbine starts at the t moment startup, there exists t moment-to-moment startup cost $c_{st}^{mt}(t) = \varepsilon_{st}^{mt}$. For other combinations of scenarios $c_{st}^{mt}(t)$ the value of is 0.

7) Gas unit creep constraints

Thermal power units are subject to mechanical and thermal constraints in adjusting their generation capacity and cannot immediately reach the set target value, requiring a gradual adjustment process, i.e., the creeping constraints of the thermal power system.

$$\begin{aligned}
&P_i^{mt}(t) - P_i^{mt}(t-1) \leqslant S_{st}^{mt}(t-1) \times P_i^{up} + P_i^{minmt}(t)\left(S_{st}^{mt}(t) - S_{st}^{mt}(t-1)\right) + \\
&P_i^{max\,mt}(t)\left(1 - S_{st}^{mt}(t)\right) \\
&P_i^{mt}(t-1) - P_i^{mt}(t) \leqslant S_{st}^{mt}(t) \times P_i^{down} - \\
&P_i^{min\,mt}(t)\left(S_{st}^{mt}(t) - S_{st}^{mt}(t-1)\right) + P_i^{max\,mt}(t)\left(1 - S_{st}^{mt}(t-1)\right)
\end{aligned} \tag{17}$$

P_i^{up},P_i^{down} are the upward and downward climb capacities of the unit, respectively. The formula ensures that the gas turbine is limited by the upper and lower climbing capacities during continuous startup. When the unit starts and stops, it is not affected by the climbing capacity, and it is used at the lowest thermal power output power $P_i^{min\,mt}(t)$ starting and stopping.

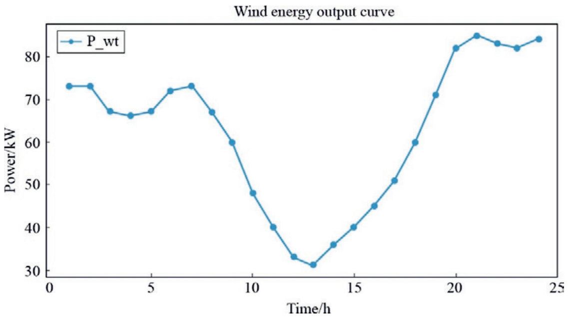


Fig. 1. Wind energy output curve (kW) [34].

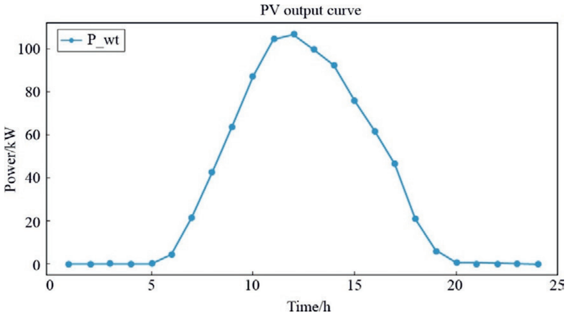


Fig. 2. PV output curve (kW).

2.3 Decision-making variables

The decision-making variables in the model include parameters for corner markers, sets, and decision variables. The detailed parameter definitions and corresponding data are specified in Table 1 and Figs. 1, 2.

Table 1
Basic data.

Notation	Hidden meaning	Notation	Hidden meaning
r_i,r_j	Discount rate for wind, PV, and diesel (8 %) [29]	C_{LL}	Cost of abandoned load ($1/kWh) [30]
n_i,n_j	Operational life of wind, diesel, and storage systems (20 years for wind, 40 years for diesel, 10 years for storage)	$P_i^{pv}(t)$,$P_i^{wt}(t)$	Hourly output curves for wind and PV (kW) (Fig. 2,3)
$C_{inins,i}$,$C_{inins,j}$	Initial investment cost of wind power, diesel fuel and energy storage [31] (yuan/kW): wind power investment cost: 7719, photovoltaic investment cost: 7258, diesel investment cost: 3384, energy storage investment cost: 7960	$P_{de}(t)$	Hourly load power demand (kW) for microgrid users (Fig. 4)
I_i, which are respectively I_i^{wt}, I_i^{pv}, I_i^{mt}	Installed capacity (kW) of various types of wind and diesel units (wind 100, PV 120, thermal 20)	$P_i^{min\,mt}(t)$	Minimum output limit for thermal power operation (kW): 10
$C_{yrom,i}$,$C_{yrom,j}$	Annual operation and maintenance cost of wind, diesel and storage (yuan/kW): photovoltaic: 73, diesel: 61, storage: 80, and wind power: 20 [32]	$P_i^{max\,mt}(t)$	Maximum output limit during thermal power operation (kW): 20
ε_{st}^{mt}	Gas turbine start-up cost: $2/kW	u_{ch},u_{dch}	Energy storage charging and discharging efficiency: 0.86 [32]
C_{pl}	Cost of penalizing abandoned wind power: 1 yuan/kWh	P_i^{up},P_i^{down}	Gas turbine up and down climbing capacity at time t, speed (kW/h): 5 [33]

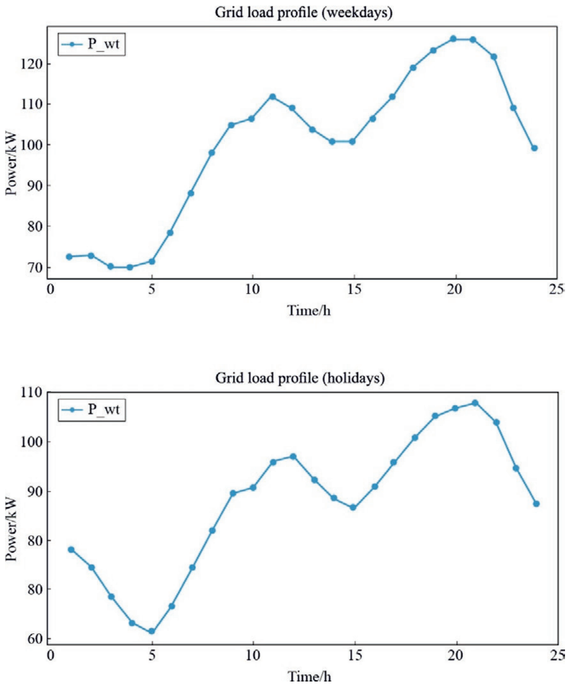


Fig. 3. Grid load profile (kW).

3 Example analysis

This example evaluates an off-grid microgrid project in Liaoning, characterized by seasonal and fluctuating energy resources. Electricity load patterns differ significantly between weekdays and holidays. The objective is to verify the model's effectiveness in such complex scenarios and demonstrate its capability to achieve optimal energy storage configuration based on local energy resources, load characteristics, and cost structures. This analysis provides valuable insights for planning and operating similar projects.

3.1 Basic parameters

Fig. 3 highlights significant differences in load characteristics between weekdays and holidays in the daily power system operations. Electricity demand patterns on weekdays are typically more complex and variable than on holidays. On weekdays, commercial activities, industrial production, and utility operations are at their peak, and the demand for electricity from these activities is both high and urgent. Electricity loads show significant peak-to-valley differences on weekdays, especially during the morning and evening commuter peaks, when loads rise rapidly, resulting in increased stress on the grid. In contrast, electricity demand during holidays is mainly focused on residential electricity use, such as home entertainment, cooking and air-conditioning use. While these uses may increase during certain hours (e.g., in the evening), overall holiday electricity demand is relatively smooth and lacks the sharp peak variations found on weekdays. In addition, overall electricity demand on holidays is also typically lower than on weekdays.

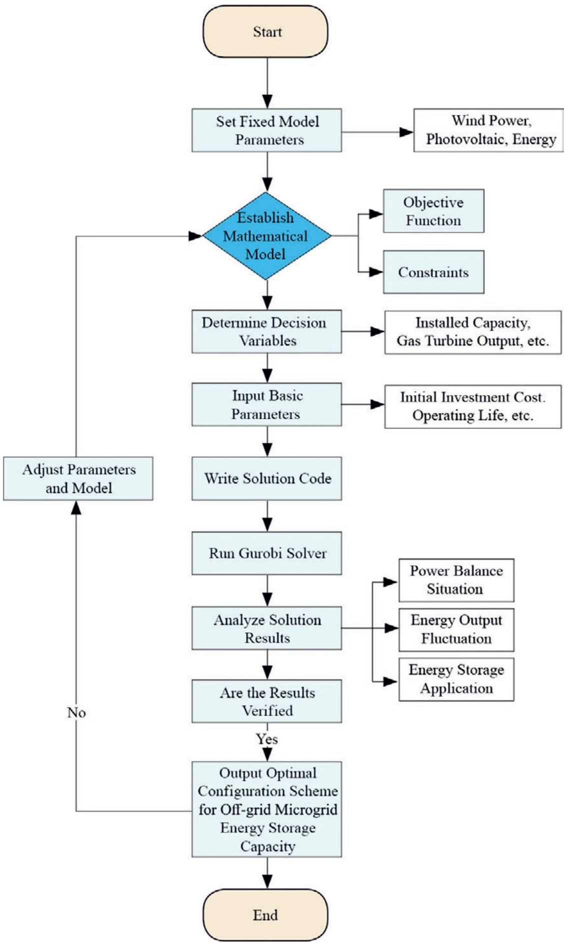
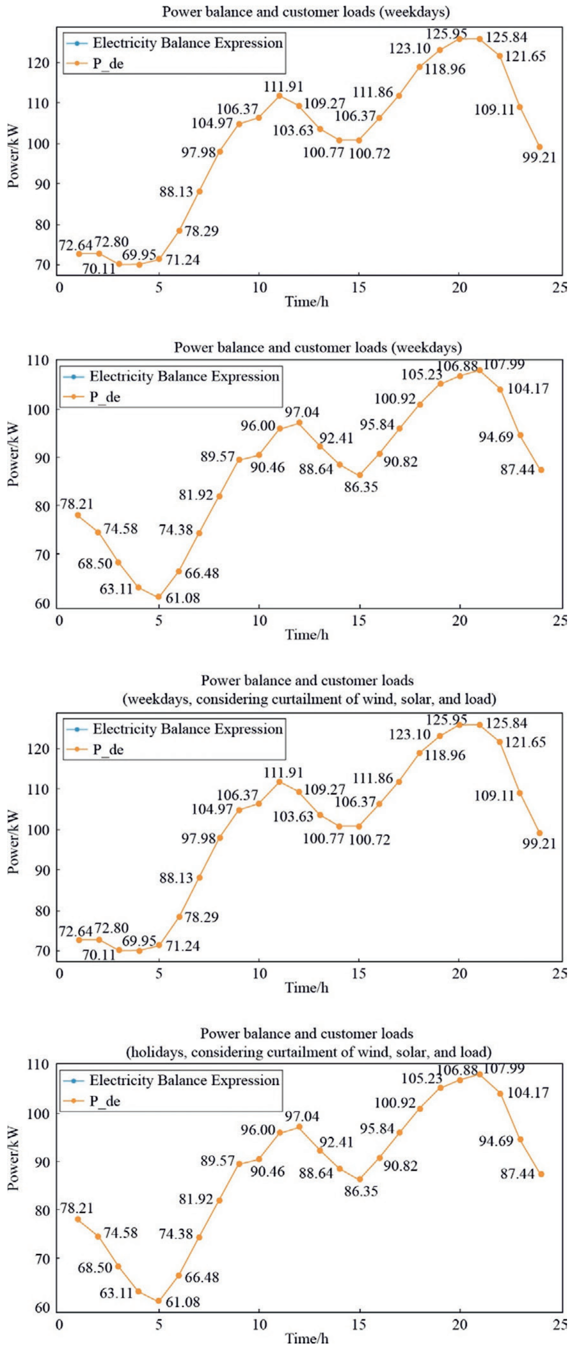


Fig. 4. Optimization process.

3.2 Results analysis

This study examines an off-grid microgrid project in Liaoning to validate the effectiveness of the proposed energy storage optimization model. By analyzing energy storage application scenarios and cooperative operation modes, the study explores various operational scenarios including weekdays and holidays, wind and solar curtailment scenarios and load shedding scenarios. The optimization employs the mixed-integer quadratic constraint programming (MIQCP) method, aiming to evaluate the impact of integrated wind and PV systems on grid balance under intraday scenarios and analyze output fluctuations of wind and PV systems during different time periods and their effect on grid stability. The optimization results and process were solved by Gurobi Optimizer in Fig. 4 as follows.

Fig. 5 illustrates the optimization process, demonstrating how the energy storage system effectively balances sup-


Power balance and customer loads (weekdays)

Power balance and customer loads (weekdays)

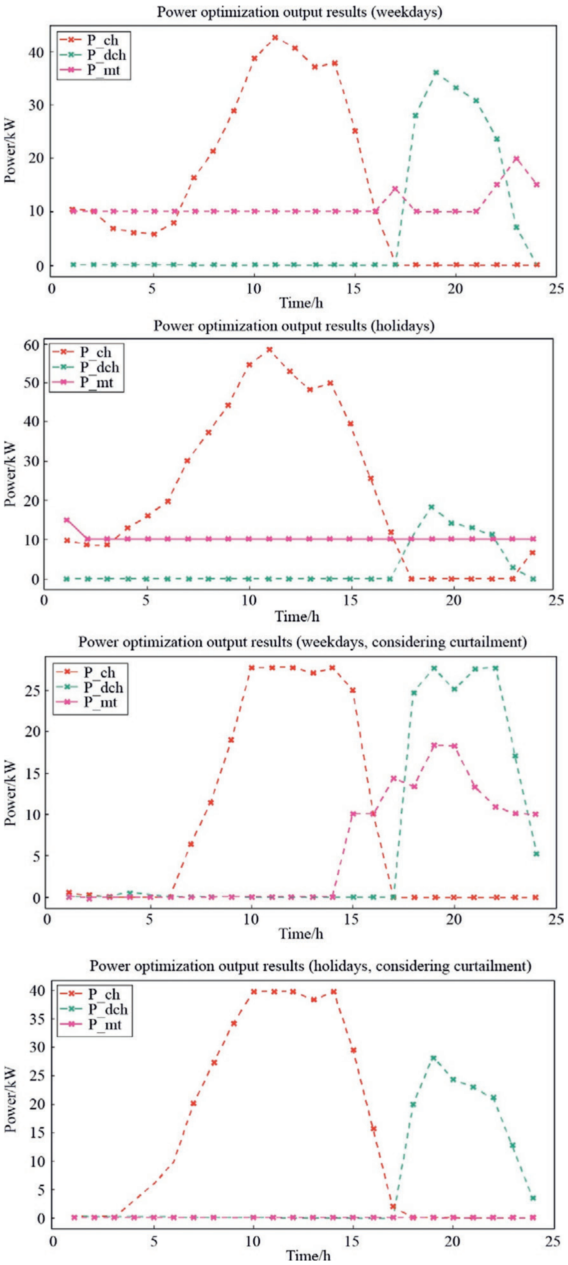
Power balance and customer loads (weekdays, considering curtailment of wind, solar, and load)

Power balance and customer loads (holidays, considering curtailment of wind, solar, and load)

Fig. 5. Power balance and customer loads.

ply and demand across multiple scenarios. The graphs show that supply and demand remain essentially balanced over all time periods. This equilibrium is achieved through the rational application of the energy storage system, guided by the optimization strategy. The near-overlapping curves highlight the effectiveness of the model in achieving power balance and ensuring system stability.

Fig. 6 illustrates the collaborative operation of various power sources and energy storage systems under the optimization model. It shows how fluctuations in the output of


Power optimization output results (weekdays)

Power optimization output results (holidays)

Power optimization output results (weekdays, considering curtailment)

Power optimization output results (holidays, considering curtailment)

Fig. 6. Power optimization output results.

each energy source are balanced by the energy storage system, particularly when wind and solar generation are highly variable, where energy storage plays a crucial role in regulation.

Combining the data from four charts with the final optimization results, it is evident that while considering economic factors, the model effectively balances the utilization of renewable energy sources with the economical operation of the energy storage system. Specifically, in Fig. 5, it is observed that on weekdays, the charging and discharging of the energy storage system are relatively balanced without considering the curtailment of wind and

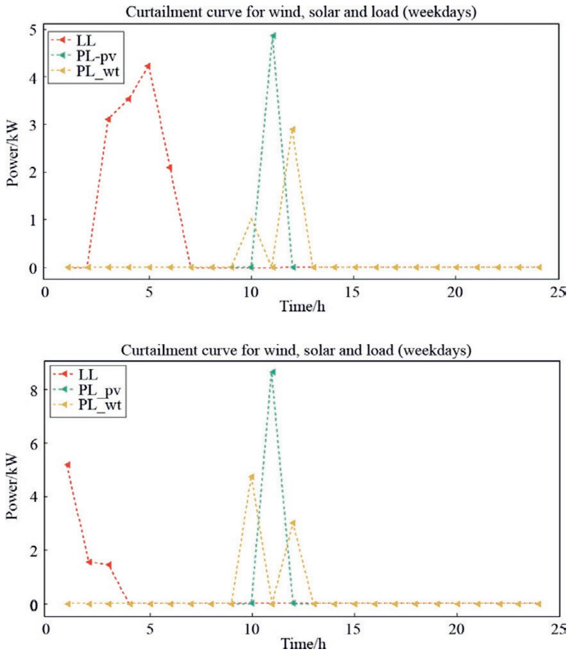


Fig. 7. Curtailment curve for wind, solar, and load.

solar power. However, during holidays, there may be excessive charging and insufficient discharging due to lower loads unable to fully absorb wind and solar power. When curtailment is not considered, the surplus wind and solar power is entirely absorbed by the storage system. This leads to lower utilization efficiency of renewable resources and increases the storage costs of the energy system. Therefore, incorporating the curtailment of wind, solar, and load remains essential. Under the goal of minimizing costs, it can be seen that both on weekdays and holidays, the charging of energy storage decreases, and the balance between charging and discharging improves. This proves that the model effectively balances the costs of curtailing wind and solar power and operating energy storage.

Additionally, gas turbines operate more steadily when curtailment is not considered. However, when curtailment is factored in, there is a noticeable increase in output from gas turbines during weekday afternoons. This is because after balancing costs, the model curtails a certain amount of wind and solar output, leading to insufficient energy in storage to support power balance during high-load times. On low-load holidays, there is no need for gas turbines to balance the power.

As shown in Fig. 7, the amount of wind and solar power curtailed on weekdays is generally less than on holidays, but there is more load shedding during the early morning hours from 3 AM to 7 AM compared to holidays. This occurs because the electrical load on the grid begins to increase during the early morning hours on weekdays, primarily due to the startup of certain industrial and commercial activities. Although most residential and commercial areas still experience low demand during these nighttime hours, specific industries such as manufacturing and continuous production lines might have already begun or are about to start their production activities. This initial rise in demand may not be enough to cause a significant peak load but is sufficient to affect the load balance on the grid. In this case, grid operators must predict and adjust the power supply to meet this gradually increasing demand. However, forecasting has its inherent uncertainties, especially during off-peak periods. If the actual load is lower than the predicted load, operators might need to implement load shedding to maintain grid stability. This operation often involves temporarily cutting off certain non-essential loads or reducing supply to prevent grid frequency and voltage issues due to excess power supply. Since the weekday daytime load is higher than on holidays, as known from Fig. 7, it can absorb more wind and solar power, thus reducing the occurrence of curtailment.

Additionally, the operation of the electricity market also significantly impacts load shedding during this period. The power market on weekdays might already be active in the early morning hours in anticipation of high daytime demand, and fluctuations in electricity prices might prompt operators to adjust power supply through market mechanisms. For example, if market prices indicate that reducing supply is cost-effective, operators might choose to reduce supply during economically sensible periods, even if it means implementing load shedding during low-demand periods.

As shown in Table 2, the final optimization results show that without considering the curtailment of wind, solar, and load, the optimal installed capacity of the battery storage system (I_es) on weekdays is 42.61 kW, and the storage capacity (E_es) is 360.63 kWh. On holidays, it is 58.52 kW and 557.23 kWh, respectively. When considering the curtailment, the optimal installed capacity on weekdays is 27.75 kW, with a storage capacity of 429.58 kWh, and on holidays, it is 39.88 kW and 557.72 kWh.

The results reveal that, regardless of whether curtailment is considered, holidays. Despite lower average loads on holidays, the required storage capacity is higher due to reduced commercial and industrial activity, which lowers overall power demand, increased domestic and recreational electricity use during certain periods, such as evenings and holiday events. These factors necessitate an energy storage system with higher output capacity and larger reserves to ensure a stable and reliable power supply, particularly in grids with limited dispatchable infrastructure, such as gas turbines.

Moreover, according to conclusions from Fig. 6, more wind and solar energy is absorbed on holidays, thus requiring an energy storage system with higher power output capacity and larger energy reserves. This not only ensures the continuity and reliability of power supply but also optimizes the economic operation of electric power

Table 2
Optimization results.

Consideration	Time	Optimal installed capacity (I_es) /kW	Storage capacity (E_es) /kWh
Without curtailment	Weekdays	42.61	360.63
Without curtailment	Holidays	58.52	557.23
With curtailment	Weekdays	27.75	429.58
With curtailment	Holidays	39.88	557.72

resources, especially when not considering curtailment. The energy storage system effectively absorbs and releases excess renewable energy, such as wind and solar, reducing reliance on traditional power resources and enhancing grid flexibility and environmental friendliness. These capabilities are particularly important on holidays when renewable energy output may be more unstable, and the unpredictability of electricity demand is more pronounced.

The results also indicate that both on weekdays and holidays, the required installed capacity of the energy storage decreases significantly after considering curtailment, while the change in storage capacity is minimal. The curtailment strategy enables system operators to selectively avoid absorbing excess wind and solar capacity during low-demand periods, reducing the instantaneous power requirements of the energy storage system. This makes the system more economical and efficient while maintaining grid stability. Although some energy can be discarded at the time of production, the energy storage system still needs to manage and balance energy at different times. Especially during periods when renewable resources are abundant but demand is relatively low, the storage system still needs to absorb a large amount of energy and store it for release during peak demand periods. Even when adopting a curtailment strategy, a significant amount of energy needs to be stored in storage facilities for extended periods to ensure a rapid response when demand rises. This not only ensures the stability of the grid but also optimizes the overall efficiency of resource use, as the energy storage system can release energy during periods of high electricity prices, thereby achieving cost savings.

In summary, the curtailment strategy allows grid operators to optimize costs, improve resource utilization efficiency, and maintain grid stability. The power demand of the energy storage system can thus be reduced because the sharpness of demand peaks is mitigated. Meanwhile, the energy demand increases because it is necessary to manage and balance the flow of energy within the grid over a longer time frame, ensuring supply–demand balance and reliable operation under various conditions. The implementation of this strategy helps to drive the power system towards a more sustainable and economically efficient direction.

These findings validate the effectiveness of the proposed optimization model in enhancing economic efficiency and system stability. The peaks and troughs in the charts align with the code output for energy storage needs and cost calculations, showing the effectiveness of the optimization algorithm in practical applications. Future research could further explore improvements, including more advanced forecasting tools, more detailed energy storage management strategies, and optimization models that consider market price dynamics.

4 Conclusion

This paper presents an in-depth study of the capacity allocation of energy storage systems in off-grid microgrids, focusing on analyzing the energy structure, output characteristics, and their integration with renewable energy sources. By examining application scenarios and synergistic operation modes, the study emphasizes the importance of optimizing the energy mix to enhance the integration of renewables. Additionally, it highlights the critical role of advanced energy storage solutions in improving grid stability and reliability, catering to the diverse power load demands of industrial and residential sectors.

Through a detailed analysis of energy storage systems capacity configuration, the study demonstrates the necessity of diversifying the energy mix and increasing the share of renewable energy in off-grid microgrids. Accurate analysis of power output and load demand is identified as essential for guiding the optimal allocation of energy storage systems. This not only enhances grid operational efficiency but also strengthens the system's adaptability to the inherent volatility and uncertainty of renewable energy sources. In the context of global carbon neutrality goals and sustainable development challenges, the findings underscore the need for innovative energy storage technologies and management strategies. Future research should focus on integrating diversified energy resources, leveraging advanced forecasting tools, and employing intelligent control systems to optimize energy storage and dispatch. These efforts aim to achieve a balanced, reliable, and environmentally friendly energy supply.

This paper also discusses the capacity allocation of energy storage systems in off-grid microgrids, by constructing an energy storage capacity-setting model and verifying the validity of the model through example analysis. This paper first analyzes the critical factors to be considered for energy storage system capacity allocation, including power load demand, grid transmission capacity, storage economics, technology characteristics, and policy factors. These analyses provide a holistic perspective on optimal energy storage system configuration. Subsequently, the construction process of the energy storage capacity-setting model is described in detail, including the model's objective function, decision variables, and constraints, like real-time power balance constraints, wind power output constraints, thermal power output; and energy storage state. These constraints ensure the feasibility of the model's practical applicability and settlement.

In the example analysis section, the MIQCP method is used to analyze the optimal configuration of the energy storage system based on the actual data of various scenarios in the Liaoning area. The results obtained by Gurobi Optimizer solving show the optimal installed capacity and scheduling scheme for energy under various scenarios, effectively demonstrating the role of the energy storage system's regulatory role, particularly in mitigating fluctuations in renewable energy output.

Comprehensive research in this paper leads to the conclusion that the economy and stability of the power system can be significantly improved and the phenomena of curtailment of wind and solar power can be reduced through rational energy storage system configuration and optimal scheduling. Future work should further explore more advanced forecasting tools and energy storage management strategies, as well as comprehensive optimization models for better cost-effectiveness and decision-making. Building models that combine technical, economic, and environmental aspects to support efficient and sustainable power system development.

CRediT authorship contribution statement

Zhuoran Song: Writing – original draft. **Mingli Zhang:** Supervision, Resources. **Yuanying Chi:** Project administration, Conceptualization. **Jialin Li:** Supervision, Methodology. **Yi Zheng:** Writing – review & editing, Data curation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Zhuoran Song and Mingli Zhang are currently employed by State Grid Liaoning Electric Power Supply Co. Ltd. The other authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Zhuoran Song graduated from Shanghai Jiao Tong University with a major in Power System and Automation. He currently works at the New-type Power Systems Division of the Development Department, State Grid Liaoning Electric Power Company Limited.

Mingli Zhang graduated from Northeast Electric Power University with a major in Power System and Automation. He currently serves as the Deputy Director of the Development Department at State Grid Liaoning Electric Power Company Limited.

Yuanying Chi graduated from Jilin University with a major in Technology Economy and Management. She currently serves as Director of the Beijing Industrial Energy Policy Research Center.

Jialin Li is a Ph.D. Candidate at School of Economics and Management, North China Electric Power University, with research interests in energy economics, management, and sustainable energy development.

Yi Zheng is a Ph.D. Candidate at School of Economics and Management, Beijing University of Technology, with research interests in low-carbon economy and energy economics.

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