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Coordinated Control Strategy of Source-Grid-Load-Storage in Distribution Network Considering Demand Response

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Abstract: This study aims to minimize the overall cost of wind power, photovoltaic power, energy storage, and demand response in the distribution network. It aims to solve the source-grid-load-storage coordination planning problem by considering demand response. Additionally, the study includes a deep analysis of the relationship between demand response, energy storage configuration, and system cost. A two-level planning model is established for wind power and photovoltaic power grid connection, including demand response, wind power, photovoltaic power, and energy storage. The model minimizes the sum of the differences between the total load and the total new energy generation after demand response in each time period as the bottom-level objective and minimizes the overall cost of the distribution network as the top-level objective, achieving the coordinated configuration of wind power, photovoltaic power, and energy storage. The simplex method is used to solve the model, and the improved IEEE33 node system is used as an example for verification. The simulation results fully prove the model's correctness and the algorithm's effectiveness, supporting the coordinated planning of distribution networks.

Keywords: distribution network; demand response; source-grid-load-storage; simplex method



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1. Introduction

The interaction between the power grid and the power communication network has become increasingly close due to advancements in power grid construction and communication technology [1]. The power grid's reliable performance is closely linked to the effective functioning of secondary systems such as protection, security, and monitoring, which rely heavily on the robust support the communication network provides. The modern power grid is a complex network system that tightly couples the power grid and the power communication network, each highly dependent on the other [2]. The concept of a Cyber-Physical Power System (CPPS), mentioned in literature [3,4], integrates physical world sensing with computational, communication, and control capabilities. It combines power generation, transmission, and distribution equipment with communication and control modules to achieve system monitoring, control, and optimization. CPPS significantly enhances power system efficiency and cost reduction by utilizing physical world perception, computational power, communication capabilities, and control functions.

The traditional dispatching of conventional Cyber-Physical Power Systems (CPPS) typically follows a “generation follows load, with centralized generation adjustment” paradigm, where load and energy storage are not included in the dispatching scope. In recent years, driven by the national “dual carbon” strategy [5] and supported by policies and market forces, the installed capacity of wind and photovoltaic power generation in China has steadily increasing. However, wind and photovoltaic power generation is

subject to weather conditions, resulting in fluctuating and stochastic output power characteristics. This power generation uncertainty significantly affects the grid's power quality and stable operation [6,7]. The traditional "generation follows load" dispatching mode is no longer sustainable. To address these issues, there is an urgent need to transition from the traditional "generation follows load" dispatching mode to an "integration of generation, grid, load, and storage" collaborative interaction mode [8–11]. To address the challenges of integrating wind and photovoltaic power into the grid, it has become effective to plan the coordination of wind and photovoltaic power generation units alongside energy storage facilities. This approach helps mitigate the high peak-valley difference in grid load and resolves the issues related to wind and photovoltaic power integration. This coordinated planning not only enhances the stability of the grid but also positively impacts its economic operation. By adjusting control strategies in different scenarios, precise control of load and energy storage can be achieved, ensuring system security and promoting the integration of new energy sources. Literature [12] discusses the signal distortion between input and output, which is used to meet the requirements of a new type of PV wattrouter designed to control the energy consumption of photovoltaic households and prevent potential energy overflow into the distribution network. Literature [13] addresses the challenge of the impact of high proportions of photovoltaic (PV) integration on the grid by developing a control strategy that includes high proportions of PV, direct current modulation, user loads, and energy storage systems, promoting coordinated interaction between generation, grid, load, and storage. Literature [14] proposes an optimal dispatching model for the interaction between generation, grid, load, and storage by studying the operational characteristics of conventional power sources, controllable loads, and energy storage systems, aiming to minimize the costs associated with new energy losses and the comprehensive operating costs of the power system. To achieve a low-carbon economy, literature [15] presents an improved generation-grid-load-storage transfer reinforcement learning algorithm using K-means clustering and dual-structure experience pool technology, effectively reducing the system's economic and carbon processing costs and enhancing the absorption capacity of new energy. Literature [16] utilizes Nash equilibrium theory and reinforcement learning methods, employing the Nash-Q algorithm to maximize the benefits of multiple intelligent agents, thereby reducing the economic costs and carbon emissions of the system.

The advancement in energy storage technology has enabled the integration of wind and photovoltaic devices into distribution networks [17]. Firstly, by coordinating and configuring wind power, photovoltaic power, and energy storage systems, the frequency and voltage of the distribution network can be effectively regulated. This facilitates the smooth integration of wind and photovoltaic resources, thereby improving electric power quality [18]. Secondly, energy storage systems possess bidirectional energy and power flow capabilities [19]. Enabling them to respond rapidly to the energy demands of distribution networks, providing convenient and efficient support to the grid, enhancing system flexibility, and ensuring reliable power supply. Energy storage technology also addresses the issue of uncontrollable output power from wind and photovoltaic sources, improving wind power utilization and maintaining grid stability. However, the costs of energy storage devices are high. Since distributed energy sources are close to the user load side, considering only the impact on the system side is insufficient to meet the future needs of the grid. Therefore, research on demand response is receiving increasing attention. Demand response can alleviate grid load pressure by adjusting user energy usage patterns, enhancing power system stability, reducing energy consumption peaks, promoting energy utilization efficiency, and driving sustainable energy development. Literature [20] proposes a demand management method that coordinates adjustable loads with energy storage. Literature [21] analyzes three demand response load types and proposes a method for assessing the impact of various flexible loads on distribution network operations. Literature [22] optimizes the performance of distributed energy sources using demand response, selecting the optimal capacity and location of distributed energy sources in the network

based on actual power losses, reactive power losses, and voltage distribution to ensure both environmental conditions and economic operation of the system.

With the widespread application of new energy in power systems, many studies have explored energy storage devices and demand response in power systems, proposing various coordinated planning methods to meet the demands of new power systems [23]. References [24–26] all consider energy storage devices and demand response, and through coordinated planning, improve the grid's ability to integrate solar and wind power while ensuring safe and stable grid operation. However, they almost do not consider the economic impact on the grid. Reference [27] proposes a virtual power plant model that considers wind energy, photovoltaic power generation, and price-based demand-side response, coordinating various energy storage devices to enhance the revenue of the virtual power plant. Reference [28] constructs a State of Charge (SOC) output characteristic model of energy storage, considering different types of demand response to minimize system operating costs and pollution emissions, and employs a genetic algorithm to analyze a specific region. Reference [29] establishes a power system optimization model that considers shared energy storage and a refined demand response mechanism, effectively improving energy storage utilization and operational economy. Reference [30] proposes a source-grid-load-storage multi-coordinated distribution network virtualization grid partition method to reduce the economic impact of distributed source-load on distribution network operations, and validates it on the IEEE33 node system, improving source-load matching, grid power supply rate, and economic efficiency. Reference [31] analyzes and models the uncertainty of new energy generation in a park energy system, considering various demand responses such as controllable loads and energy storage, and improves the operational reliability and economy of the park through coordinated planning. Reference [32] uses a robust optimization method to handle the uncertainties of wind turbine and photovoltaic power output, establishing a mixed-integer linear programming problem, and the results show reduced power system operating costs. Reference [33] improves the BP neural network algorithm to predict new energy generation, enhancing the economic efficiency of the distribution system and the consumption capacity of renewable energy through accurate dispatching. Reference [34] provides evaluation indicators for the source-grid-load-storage distribution network system, and through coordinated optimization, simulates specific implementation schemes, reducing the comprehensive operating cost of the grid. Reference [35] considers various generation technologies, energy storage technologies, and demand-side responses, establishing a power planning mathematical model that reduces investment and operating costs of the power system. However, In existing research on distribution grid planning considering demand response, the integration of demand response resources with wind, photovoltaic, and energy storage technologies, as well as the economic analysis of how demand response can reduce coordination planning costs for wind, photovoltaic, and energy storage, is relatively scarce and incomplete. More comprehensive and in-depth research is needed to promote the economic benefits and sustainable development of distribution grid planning.

In summary, the Cyber-Physical Power System (CPPS) integrates traditional power, communication, and control systems, enabling real-time monitoring of system data and achieving more intelligent scheduling. This effectively enhances system security and robustness. Meanwhile, the source-grid-load-storage interactive technology can better coordinate and balance the energy supply and load demand within the system, achieving efficient energy scheduling and improving energy utilization. As a critical technology, energy storage devices can store excess electricity during peak periods and then release it during demand peaks or insufficient power supply, thus balancing the load and supply-demand differences in the power grid. This helps reduce grid operating costs, decreases reliance on traditional power generation resources, and improves the stability and reliability of the power system. With demand response technology, the system can monitor user load in real-time, flexibly adjust the active power of load nodes based on changes in user energy demand, adapt to user actual needs, and improve user satisfaction. Coordinated scheduling

and intelligent management can optimize power system operations, reduce energy waste, and efficiently utilize energy storage devices. This avoids excessive energy demand during peak periods, helps smooth the load curve, and improves system economics.

This study optimizes power system operating strategies by comprehensively considering the coordination between energy storage devices and demand response technology to minimize the operating costs of the power network. This promotes the development of the power system towards greater intelligence and efficiency and provides essential technical support and empirical analysis foundations for the future integration of sustainable energy and the sustainability of power systems.

The main contributions of the paper can be summarized as follows:

1. Through in-depth research on the impact of demand response on the coordinated planning of wind power, photovoltaic power, and energy storage in distribution networks, a bi-level planning model that includes the costs of demand response, wind power, photovoltaic power, and energy storage was established, aiming to minimize the comprehensive cost of the distribution network.
2. The impact of demand response and coordinated energy storage configuration on the comprehensive cost of the system was analyzed, and the superiority of the proposed method in the paper was verified through four comparative schemes.
3. The relationship between the demand response percentage, energy storage configuration capacity, and system cost was studied. This research is of great significance for reducing system costs and promoting the sustainable development of the power system.

The remainder of the paper is provided as follows. Section 2 introduces the system model. Section 3 presents the problem's planning transformation and solution process. Section 4 introduces the simulation parameter settings and simulation analysis. In Section 5, the paper is concluded.

2. System Model

Considering the interrelationships and coupling characteristics among the distribution network, information network, control center, and main grid, a multi-network coordinated control model has been developed based on integrating source-grid-load-storage and demand response technology. As shown in Figure 1, the distribution network realizes the "generation, transmission, transformation, and distribution" of electrical energy, completing information collection, transmission, and command execution. The communication network links the distribution network and the control center, facilitating the transfer of information between them. The control center serves as the automated control hub of the entire system, monitoring the operation status of the distribution network, analyzing and computing distribution network data, and generating control instructions. The main grid is an important regulatory means for achieving supply-demand balance, providing energy trading and grid interconnection functions. By integrating control computing systems, large-scale communication networks, extensive sensor networks, and power physical equipment, the distribution network, communication network, main grid, and control center are comprehensively analyzed as a whole. All devices in the system collaborate and influence each other, jointly determining the functionality and behavioral characteristics of the entire system.

The distribution network consists of user-side load nodes, power lines, wind and photovoltaic (PV) power generation units, energy storage units, and remote terminal devices. Considering the coordinated interaction of source, grid, load, and storage technologies, Remote Terminal Units (RTUs) are installed at each load node, enabling the selective installation of wind power, photovoltaic power generation, and energy storage units. Nodes are interconnected via power lines. Considering the grid connection of new energy devices, wind power generators, and photovoltaic power generators are regarded as the primary energy sources for the distribution network. This change not only better reflects the actual operating status of the power system but also helps improve the system's adaptability to and utilization of new energy. Energy storage units are introduced for energy storage

and release to improve energy utilization further and maintain system safety. new energy generation and storage units collectively provide energy to the load, achieving synergistic energy utilization. During system operation, when new energy generation units and energy storage units are insufficient or surplus in supplying power, the system will conduct power purchase or sale operations with the main grid to meet demand. The system's optimization and adjustment improve its alignment with the actual power system operation, enhancing sustainability and adaptability. This provides more comprehensive support for the future intelligentization and integration of new energy sources in power systems. Finally, the numbers of photovoltaic power generation units, wind power generation units, load nodes, and energy storage units are defined as M_1 , M_2 , M_3 , and M_4 , respectively, and node numbering is represented by sets A_1 , A_2 , A_3 , A_4 .

The communication network nodes are critical in connecting various distribution network components with the control center. Communication nodes connect with the RTU devices in the distribution network and the control center, facilitating data transmission and communication functions. Each communication node is linked to an RTU device in a point-to-point connection. There is a one-to-one correspondence between communication and distribution network nodes, with an equal number of communication and distribution network nodes. The RTU collectors are responsible for collecting data from the distribution network nodes connected to them and transmitting this data to the communication nodes through the upstream communication channel. All communication nodes aggregate and transmit the collected data to the control center, supporting subsequent data analysis and decision-making processes. The control center broadcasts control commands to the communication nodes to remotely control the distribution network. Upon receiving the instructions, the communication nodes transmit them to the respective RTU actuators through the downstream communication channel to execute the corresponding control operations. This system architecture ensures effective communication and coordination among the various components of the microgrid system, enabling the system to respond promptly to external environmental changes and control instructions, thereby ensuring the microgrid's stable operation and optimized scheduling.

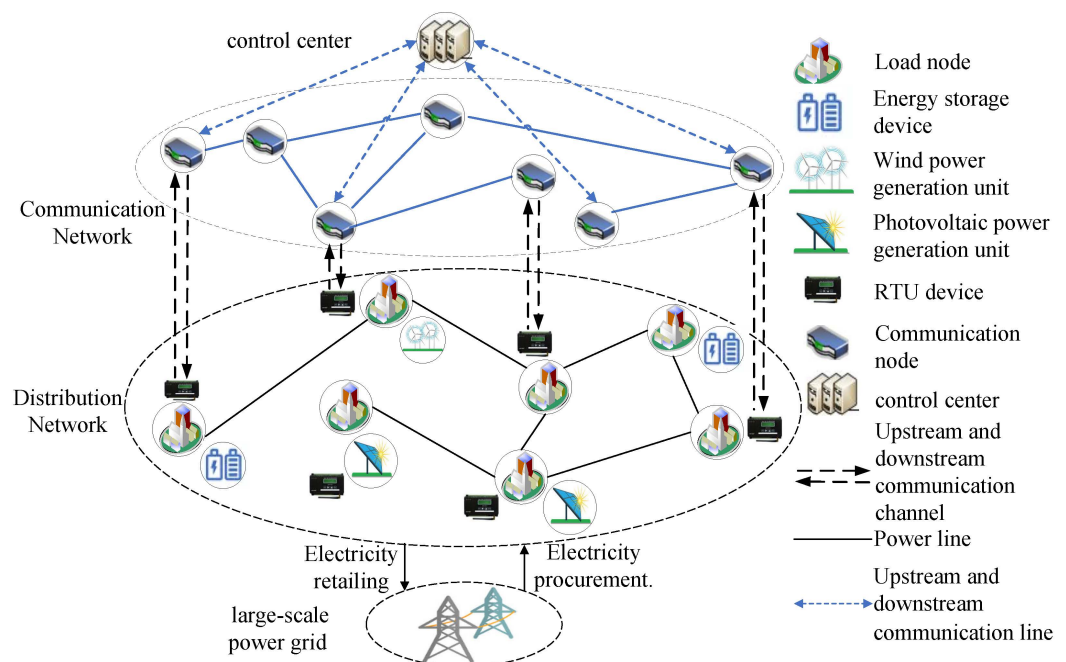


Figure 1. The coordinated control model of source-grid-load-storage in distribution network considering demand response.

This model organically integrates the distribution network, information network, control center, and the main power grid to perform comprehensive analysis and regulation

as a whole, demonstrating high feasibility for installation. The collectors in the RTU devices can gather real-time data from the distribution network, while the actuators in the RTU devices can execute the control commands issued by the control center. Standardized data interfaces (such as RESTful API and OPC UA) are used for communication to ensure smooth and compatible data exchange. To ensure uniformity in data formats between the new model and existing systems, common data formats (such as JSON and XML) are used for transmission. Standardized communication protocols (such as IEC 61850 and DNP3) are employed for data transmission and system integration, ensuring interoperability. The model has good scalability, allowing for the addition or removal of distribution network nodes, communication nodes, as well as new energy generation and storage devices according to actual needs. Additionally, with the advancement of technology, the effectiveness of this model in practical applications will continue to improve, providing strong support for the widespread adoption of smart grids and renewable energy.

This model has a very wide range of practical applications:

1. **Smart Grids:** The model can optimize demand response strategies in smart grids, achieving power system balance and stability through reasonable load dispatching of users, thus enhancing grid operation efficiency. It is suitable for smart grids that include a large amount of distributed energy resources, such as wind and photovoltaic power generation, improving energy utilization and supply reliability through optimized scheduling of these resources.
2. **Microgrids:** In off-grid microgrids, the model can effectively regulate local energy production and storage, ensuring self-sufficiency and enhancing the reliability and stability of energy. In grid-connected microgrids, it can optimize interactions with the main grid, reducing electricity purchase costs and achieving economical and efficient operation.
3. **Energy Internet:** In the energy internet, the model can collaboratively optimize the supply-demand balance of multiple forms of energy, increasing the overall flexibility and reliability of the energy system. It is applicable to cross-regional energy dispatching by optimizing energy flow between different regions, reducing energy waste, and improving overall efficiency.

3. Problem Formulation

Both demand response and energy storage units can smooth the net load curve and increase the utilization of wind and photovoltaic power. Due to the higher cost of energy storage operations than demand response, demand response operations are prioritized in the lower-level planning model. After determining the capacity for load reduction and the generation curves of wind and photovoltaic units at each user side, demand response is implemented, ensuring that the difference between user electricity consumption and the generation of new energy units is minimized while balancing the total load reduction capacity within the system's operational period. The optimization results are then distributed to the distribution network, enabling it to operate in the newly optimized state. In the upper-level planning, based on the lower-level planning, the compensation cost of demand response and the cost of wind and photovoltaic power generation devices, energy storage devices, and purchasing electricity from the main grid are comprehensively considered to optimize the configuration of energy storage, ultimately minimizing the total economic cost of the distribution network. The structure of the bilevel planning model is shown in Figure 2.

3.1. Demand Response Planning

The article selects Interruptible Loads (IL) as representatives of load shedding and models them for demand response. IL refers to loads that can be conditionally interrupted, managed through contracts, and used to alleviate system deficits through demand response mechanisms.

The study adopts a daily cycle for demand response, with each hour serving as a response period. For the load shedding within the distribution network, the requirement is to meet the load reduction demand within 24 h. The process of demand response is outlined as follows:

- Step 1: Users determine the capacity for load shedding and whether it will participate in demand response. They also set the initial operating time for this part of the load shedding.
- Step 2: Unified load management merchants collect the information users send in Step 1 and upload it to the distribution network's control system. The control system analyzes the load curve and wind/photovoltaic data over 24 h to temporally align the load with wind/photovoltaic power, scheduling the transfer time for load shedding.
- Step 3: If the designated users receive the instruction signal for load shedding, the load shedding operates automatically during the specified period as scheduled. The load operates normally according to the initial schedule if the designated users do not receive the transfer signal.

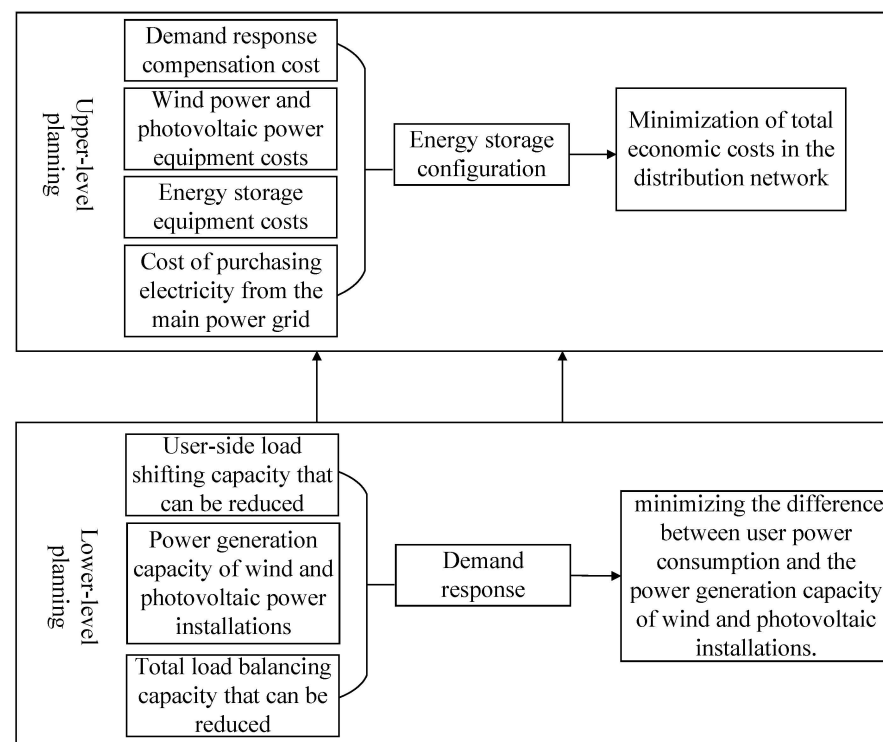


Figure 2. Optimal economic bilevel planning model structure diagram for distribution networks considering demand response.

The demand response planning model aims to minimize the difference between user electricity consumption and the power generation of new energy generation devices during the system operating cycle, formulated as follows:

$$\min \sum_{t=1}^T |P_{LM}(t) - P_{W\&P}(t)| \quad (1)$$

where $P_{LM}(t)$ is the load quantity after the demand response for the period, T is the demand response cycle, and $P_{W\&P}(t)$ is the total power of wind and photovoltaic energy in period t of the distribution network.

$$P_{LM}(t) = P_{LO}(t) + P_{LC}(t) \quad (2)$$

where $P_{LO}(t)$ is the original total load of the distribution network during period t , and $P_{LC}(t)$ is the change in the total load of the distribution network during period t .

$$P_{W\&P}(t) = \sum_{i \in A_1} P_{w,i}(t) + \sum_{i \in A_2} P_{p,i}(t) \quad (3)$$

$$P_{LO}(t) = \sum_{i \in A_3} P_{LO,i}(t) \quad (4)$$

$$P_{LC}(t) = \sum_{i \in A_3} P_{LC,i}(t) \quad (5)$$

where $P_{LC,i}(t)$ is the change in load at node i , after demand response during period t .

Transfer capacity constraints are established to meet the user's basic electricity demand.

$$-P_{LC,i,\max} \leq P_{LC,i}(t) \leq P_{LC,i,\max}, i \in A_3 \quad (6)$$

where $P_{LC,i,\max}$ is the maximum power limit for demand response that can occur at load node i .

$$P_{LC,i,\max} = P_{LO,i} \cdot a_L, i \in A_3 \quad (7)$$

where a_L is the percentage of demand response at the load node.

The total electricity consumption of users within the operating cycle remains constant; only the timing of electricity consumption for certain loads has been shifted. However, it is necessary to ensure that the total amount of reducible load remains unchanged.

$$\sum_{t=1}^T \sum_{i \in A_3} P_{LC,i}(t) = 0 \quad (8)$$

Demand response affects the net load curve of the power system by adjusting user electricity consumption behaviors. During periods of high electricity demand, users are encouraged to reduce or delay their electricity consumption through economic incentives, thereby lowering the peak load. During periods of low electricity demand, users are encouraged to increase their electricity consumption to enhance the electricity consumption during off-peak periods, thus smoothing the load curve.

3.2. Optimal Economic Planning of Distribution Network

The upper-level optimization model considers the investment and operational costs of wind power, photovoltaic power, and energy storage devices, along with the purchasing or selling cost of electricity from/to the main grid, while also considering the impact of demand response. The cost of purchasing or selling electricity from/to the main grid is influenced by the output of new energy generation units, the demand response, and the output of energy storage. Suppose the coordination between demand response and energy storage is strong. In that case, new energy generation resources can be maximally integrated, leading to a corresponding reduction in the purchasing or selling cost of electricity for the distribution network. The objective function of the upper-level planning includes the construction costs, operational costs, demand response costs, energy storage costs, and purchasing or selling costs of electricity from/to the main grid for wind power and photovoltaic power devices in the distribution network and can be represented as follows:

$$\min C_{ESS} + C_{W\&P} + C_C + C_B \quad (9)$$

where C_{ESS} is the cost of energy storage, $C_{W\&P}$ is the cost of photovoltaic and wind power devices, C_C is the compensation cost of demand response, and C_B is the cost of purchasing or selling electricity from the main grid for the distribution network.

The cost of energy storage takes into account the entire lifecycle from installation, commissioning, and maintenance to decommissioning. It mainly consists of initial installation

costs, maintenance costs during operation, benefits from peak shaving, and disposal costs after decommissioning. Specifically, it can be represented as follows:

$$C_{ESS} = C_{cap} + C_{pe} + C_{dc} - C_s \quad (10)$$

where C_{cap} is the initial installation cost, C_{pe} is the operation and maintenance cost, C_{dc} is the disposal cost, and C_s is the peak shaving benefit.

$$C_{cap} = (M_p \cdot \sum_{i \in A_4} P_{ESS,max,i} + M_c \cdot \sum_{i \in A_4} E_{rate,i}) \cdot \frac{1}{T_E \cdot T_C} \quad (11)$$

where, M_p and M_c respectively represent the investment cost per unit power and per unit capacity of energy storage devices, $P_{ESS,max,i}$ is the maximum output power of energy storage device i , $E_{rate,i}$ is the maximum installed capacity of energy storage device i , T_E is the service life of energy storage devices, and T_C is the number of days in a year.

$$C_{fe} = C_f \cdot P_{ESS,max,i} \cdot \frac{1}{T_E \cdot T_C} + C_e \cdot \sum_{i \in A_4} W_{E,i} \quad (12)$$

where C_f and C_e respectively represent the cost coefficients of fixed and variable costs of the energy storage device, $W_{E,i}$ is the total charge and discharge amount of energy storage device i in one day.

$$W_{E,i} = \sum_t^T |d_i(t)| \quad (13)$$

where $d_i(t)$ is the active power of energy storage device i at time t .

$$C_{dc} = \frac{C_{pscr} \cdot \sum_{i \in A_4} P_{ESS,max,i} + C_{escr} \cdot \sum_{i \in A_4} E_{rate,i}}{T_E \cdot T_C} \quad (14)$$

where C_{pscr} and C_{escr} respectively represent the decommissioning costs of energy storage unit power and unit capacity.

$$C_s = \sum_{t=1}^T \sum_{i \in A_4} c_{cost} \cdot (d_i^{dch}(t) - d_i^{ch}(t)) \cdot \Delta t \quad (15)$$

$$C_{cap_w\&p} = \sum_{i \in A_1} C_p \cdot P_{rate,i}^p \cdot \frac{1}{T_p \cdot T_C} + \sum_{i \in A_2} C_w \cdot P_{rate,i}^w \cdot \frac{1}{T_w \cdot T_C} \quad (16)$$

where T_p and T_w respectively represent the service life of photovoltaic and wind power devices. The operation and maintenance costs of new energy devices:

$$C_{om_w\&p} = \sum_{i \in A_1} C_{pm} \cdot P_{rate,i}^p + \sum_{i \in A_2} C_{wm} \cdot P_{rate,i}^w \quad (17)$$

where C_{pm} and C_{wm} respectively represent the maintenance cost coefficients per unit capacity of photovoltaic and wind power devices.

Users and load management merchants will generally sign contracts that specify the conditions for load interruption and compensation measures. Users participating in demand response can enjoy economic incentives. In this study, if users participate in a demand response, they will receive an economic compensation of m_c per unit of electricity after the demand response occurs. Therefore, according to the agreement, the demand response compensation paid by the grid is:

$$C_c = \sum_{t=1}^T \sum_{i \in A_3} m_c \cdot P_{LC,i}(t) \quad (18)$$

When demand response, wind power, photovoltaic power, and energy storage are coordinated for regulation and still cannot meet the distribution network's electricity demand, or there is surplus electricity, the cost of purchasing or selling electricity to the main grid is:

$$C_b = \sum_{t=1}^T C_{\text{cost}} \cdot P_1(t) \quad (19)$$

where $P_1(t) > 0$ represents the amount of electricity purchased by the distribution network from the main grid in period t , $P_1(t) < 0$ represents the amount of electricity sold by the distribution network to the main grid in period t , and C_{cost} is the unit price of purchasing or selling electricity from/to the main grid.

For energy storage devices, their charging and discharging power during operation are limited and can be represented as:

$$0 \leq d_i^{\text{ch}}(t) \leq P_{\text{ESS,max},i}, i \in A_4 \quad (20)$$

$$0 \leq d_i^{\text{dch}}(t) \leq P_{\text{ESS,max},i}, i \in A_4 \quad (21)$$

The remaining electricity of an energy storage device at the next moment is dependent on its remaining energy at the previous moment, charging/discharging power, charging/discharging efficiency, and the time interval between the two moments. This relationship can be expressed as:

$$q_i(t + \Delta t) = q_i(t) + \eta^{\text{ch}} \cdot \Delta t \cdot d_i^{\text{ch}}(t) - \Delta t \cdot d_i^{\text{dch}}(t) / \eta^{\text{dch}}, i \in A_4 \quad (22)$$

where Δt is the time interval between two consecutive adjustments of the energy storage device, while η^{ch} and η^{dch} respectively represent the charging and discharging efficiency of the energy storage device.

To ensure the sustainability and safety of the energy storage device, the remaining electricity of the device at the next moment must meet the following requirements:

$$\beta_{\min} \cdot E_{\text{rate}} \leq q_i(t + \Delta t) \leq \beta_{\max} \cdot E_{\text{rate}}, i \in A_4 \quad (23)$$

where β_{\min} and β_{\max} respectively represent the upper and lower limits ratio coefficients of the energy storage device's remaining electricity.

To maintain the supply-demand balance between power generation and consumption in the system, add the power balance constraint for the distribution network as follows:

$$\sum_{i \in A_1} P_{P,i}(t) + \sum_{i \in A_2} P_{W,i}(t) - \sum_{i \in A_3} P_{\text{LM},i}(t) + \sum_{i \in A_4} d_i(t) + P_1(t) = 0 \quad (24)$$

3.3. Optimization Problem Transformation and Solving

According to the description in Section 3.1, the objective function of demand response can be expressed as:

$$\min \sum_{t=1}^T \left| \sum_{i \in A_3} P_{\text{LO},i}(t) + \sum_{i \in A_3} P_{\text{LC},i}(t) - \sum_{i \in A_1} P_{W,i}(t) - \sum_{i \in A_2} P_{P,i}(t) \right| \quad (25)$$

Expanding the range of all i values to include A_3 for wind power generation devices, $P_{W,i}(t) = 0, i \in A_3 \&\& i \notin A_1$, and for photovoltaic power generation devices, $P_{P,i}(t) = 0, i \in A_3 \&\& i \notin A_2$, Formula (25) can be transformed into:

$$\min \sum_{t=1}^T \sum_{i \in A_3} |P_{\text{LO},i}(t) + P_{\text{LC},i}(t) + P_{W,i}(t) + P_{P,i}(t)| \quad (26)$$

Setting $P_{LC,i}(t) = x_i(t)$ and $P_{LO,i}(t) - P_{W,i}(t) - P_{P,i}(t) = A_i(t)$, Formula (26) can be transformed into:

$$\min \sum_{t=1}^T \sum_{i \in A_3} |x_i(t) + A_i(t)| \quad (27)$$

For $\forall x_i(t) \in R, \exists u_i(t), v_i(t) \geq 0$, it leads to:

$$x_i(t) + A_i(t) = u_i(t) - v_i(t) \quad (28)$$

$$|x_i(t) + A_i(t)| = u_i(t) + v_i(t) \quad (29)$$

Simply taking $u_i(t) = \frac{x_i(t) + A_i(t) + |x_i(t) + A_i(t)|}{2}$ and $v_i(t) = \frac{|x_i(t) + A_i(t)| - (x_i(t) + A_i(t))}{2}$, this optimization problem is ultimately simplified to:

$$\text{minimize} \quad \sum_{t=1}^T \sum_{i \in A_3} (u_i(t) + v_i(t)) \quad (30)$$

$$\text{subject to} \quad -P_{LC,i,\max} \leq u_i(t) - v_i(t) - A_i(t) \leq P_{LC,i,\max}, \quad i \in A_3, t \in T \quad (30a)$$

$$\sum_{t=1}^T \sum_{i \in A_3} (u_i(t) - v_i(t) - A_i(t)) = 0 \quad (30b)$$

$$u_i(t), v_i(t) \geq 0 \quad (30c)$$

The simplex method is used to solve linear programming problems and is widely employed to find optimal solutions to such problems. Linear programming is an optimization problem where the objective is to find a set of variable values that optimize a linear objective function subject to a series of linear constraints. Below are the basic principles and steps of the simplex method:

- Step 1: Formulate the linear programming problem into standard form, which involves minimizing the linear objective function subject to equality constraints.
- Step 2: Initialize a basic feasible solution, which is a solution that satisfies all equality constraints.
- Step 3: Compute the simplex table, which represents the linear programming problem in a matrix form and includes information such as objective function coefficients, basic variables, and non-basic variables.
- Step 4: Select an entering variable from the non-basic variables to improve the objective function value. This selection is typically based on the principle of maximum gain, meaning choosing the variable that results in the greatest decrease in the objective function value.
- Step 5: Select a departure variable from the basic variables to maintain the solution's feasibility. This selection is typically based on the principle of minimum ratio, meaning choosing the variable that minimizes the violation of constraints.
- Step 6: Update the simplex table by replacing basic variables.
- Step 7: Repeat Steps 1 to 6 until an optimal solution is found. The optimality condition is usually when all coefficients of non-basic variables are non-positive.
- Step 8: Interpret the optimal solution based on the final simplex table and determine the optimal value.

4. Simulation Results and Analysis

To verify the effectiveness of the coordinated planning strategy based on optimal economics and demand response in distribution networks proposed in this chapter, numerical simulations are conducted using MATLAB. Firstly, the demand response results are analyzed, comparing the changes in load active power considering demand response and the optimization effect of demand response on the net load curve. Secondly, an analysis of the comprehensive cost results of the distribution network is conducted, further exam-

ining the impact of four scenarios on the optimization model, including the installation of energy storage systems and the consideration of demand response. By analyzing the simulations of these schemes, the effectiveness of the proposed model is evaluated and the best system configuration scheme is determined. The simulation results will provide an important reference for the deployment and operation of actual systems, assisting in achieving intelligent management and optimization operation of power systems.

4.1. Simulation Parameter Settings

This case study is based on the IEEE 33-node distribution network system with appropriate modifications. The distribution network comprises 32 branches and five tie-switch branches. The network's primary-end reference voltage is 12.66 kV, and the total active power load of the distribution network is 3715 kW. Wind power generation units are installed at nodes 20, 22, and 29, represented by WT. Photovoltaic power generation units are installed at nodes 10, 15, and 25, represented by PV. Energy storage units are installed at nodes 6 and 13, represented by ESS. The overall system structure is illustrated in Figure 3.

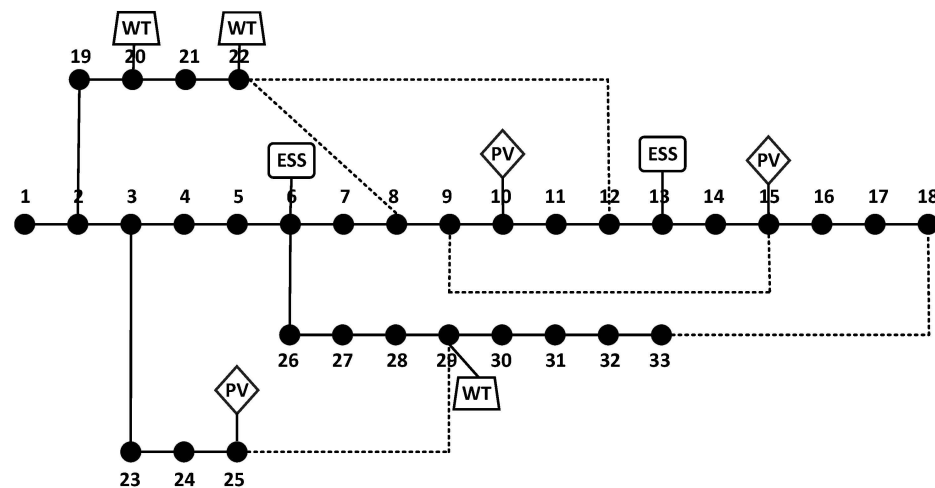


Figure 3. Simulation model diagram of distribution network based on enhanced IEEE 33-Node system.

The standard IEEE 33-node system does not consider new energy generation devices such as wind and photovoltaic power generation units nor the regulatory role of energy storage units. By installing the devices mentioned above, the system can effectively increase the proportion of new energy, reduce carbon emissions, and make the grid more flexible and stable. These improvements not only optimize the system's operational efficiency and economic viability but also support the development of microgrids and smart grids, driving the power system towards a cleaner and more sustainable direction.

Table 1 details the node numbers of the IEEE 33-bus system and their corresponding active power values. These data are crucial for analyzing system load, calculating power balance between nodes, performing power flow analysis, and assessing system stability. By comprehensively analyzing these data, one can better understand the load distribution within the system, the power exchanges between nodes, and provide a basis for the optimized scheduling and planning of the system.

Table 2 provides the key parameters of the topological structure and electrical parameters model of the system's power lines.

According to the statistical data results from the referenced [36], Figure 4 illustrates the curves of the generated power of photovoltaic and wind power generation units over time, ranging from hour 1 to hour 24, $t = 1, 2, \dots, 24$. Additionally, the figure presents the curves of the total generated power from three PV generation units and three wind power generation units in the distribution network over time. It can be observed from the figure that the generated power from PV and wind power generation units exhibit randomness and uncertainty over time. photovoltaic radiation intensity significantly influences the

generation capacity of PV units, while wind speed largely influences the generation capacity of wind power units. Generally, wind speed tends to be high when photovoltaic radiation intensity is low, and vice versa. The generation from PV and wind power units exhibits complementary characteristics, and coordinating the operation of these two methods can provide electricity to the distribution network.

Table 1. IEEE 33-node system node parameters.

Node Number	Active Power/kW	Node Number	Active Power/kW	Node Number	Active Power/kW
1	0	12	60	23	90
2	100	13	60	24	420
3	90	14	120	25	420
4	120	15	60	26	60
5	60	16	60	27	60
6	60	17	60	28	60
7	200	18	60	29	120
8	200	19	90	30	200
9	60	20	90	31	150
10	60	21	90	32	210
11	45	22	90	33	60

Table 2. IEEE 33-node system branch parameters.

Branch Number	Starting Node	Ending Node	Branch Resistance/ Ω	Branch Reactance/ Ω	Branch Number	Starting Node	Ending Node	Branch Resistance/ Ω	Branch Reactance/ Ω
1	1	2	0.0922	0.047	17	17	18	0.372	0.574
2	2	3	0.493	0.2511	18	2	19	0.164	0.1565
3	3	4	0.366	0.1864	19	19	20	1.5042	1.3554
4	4	5	0.3811	0.1941	20	20	21	0.4095	0.4784
5	5	6	0.819	0.707	21	21	22	0.7089	0.9373
6	6	7	0.1872	0.6188	22	3	23	0.4512	0.3083
7	7	8	0.7114	0.2351	23	23	24	0.898	0.7091
8	8	9	1.03	0.74	24	24	25	0.896	0.7011
9	9	10	1.044	0.74	25	6	26	0.203	0.1034
10	10	11	0.1966	0.065	26	26	27	0.2842	0.1447
11	11	12	0.3744	0.1238	27	27	28	1.059	0.9337
12	12	13	1.468	1.155	28	28	29	0.8042	0.7006
13	13	14	0.5416	0.7129	29	29	30	0.5075	0.2585
14	14	15	0.591	0.526	30	30	31	0.9744	0.963
15	15	16	0.7463	0.545	31	31	32	0.3105	0.3619
16	16	17	1.289	1.721	32	32	33	0.341	0.5362

Table 3 provides the other necessary simulation parameters.

4.2. Analysis of Demand Response Results

In Figure 5, the black curve represents the variation of power generation in the distribution network over time. The green curve represents the variation of the total load of the system at different time intervals in the simulation period when no demand response occurs. Due to the fixed initial parameters at each node, it is represented as a straight

line that does not change over time in the figure. The blue curve represents the variation of the total load of the system at different time intervals in the simulation period when demand response occurs. The figure shows that after a demand response occurs, the overall curve closely approximates the original load curve. High-power energy storage charging and discharging are necessary when new energy generation significantly exceeds or falls below the original load. The maximum charging and discharging power and the rated energy storage capacity must be increased to meet the system requirements. This will result in a higher basic installation cost of energy storage and increased expenditure on purchasing electricity from the main grid. After demand response occurs, the overall curve closely approximates the original load curve, and only a partial increase in demand response costs is needed to effectively reduce energy storage costs and purchase electricity from the main grid, providing positive feedback to the overall cost of the subsequent distribution network.

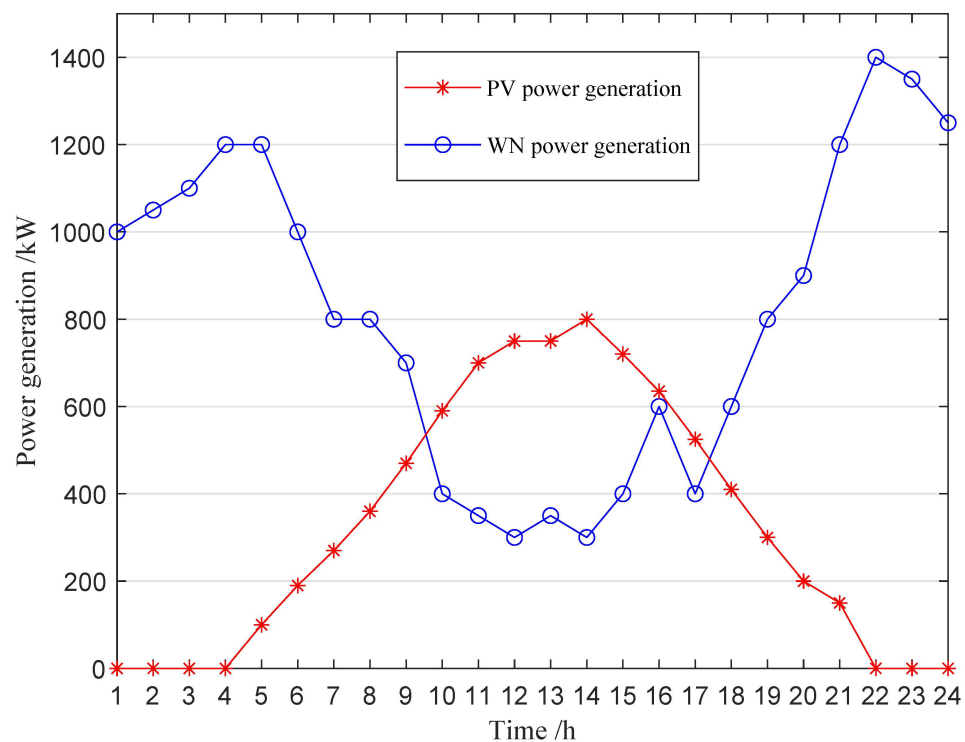


Figure 4. The power generation curves of photovoltaic and wind power devices vary with time.

Table 3. Basic parameter settings.

Category	Value	Category	Value
M_p /RMB/kW	600	C_w	1200
M_c /RMB/kW	400	T_p /year	15
T_E /year	5	T_W /year	15
T_C /day	365	m_c /RMB/kW	0.4
C_f /RMB/kW	86.8	C_{cost} /RMB/kW	0.68
C_e /RMB/kW	10	η^{ch}	0.95
C_{pscr} /RMB/kW	930	η^{dch}	0.95
C_{escr} /RMB/kW	10	β_{min}	0.2
C_p /RMB/kW	1000	β_{max}	0.8

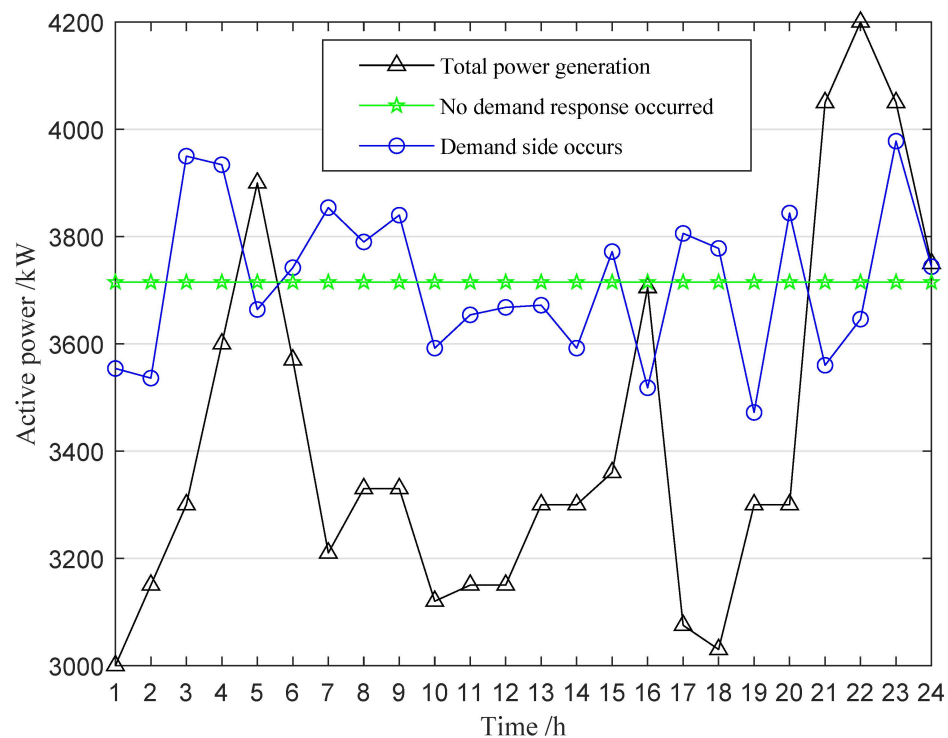


Figure 5. Total power generation of the distribution network, and the system active power variation curve with time when demand response occurs and does not occur.

Figure 6 displays the curves of the net load of the distribution network over time, represented by blue and black curves for when demand response occurs and when it does not, respectively. By observing the curves in the figure, the changes in the net load of the system before and after implementing demand response can be seen. When demand response is not implemented, the peak net load of the system is 748 kW, whereas after implementing demand response, the peak net load decreases to 715 kW. This indicates that the system successfully reduces the peak load by implementing demand response measures, effectively smoothing the load curve and improving the stability and reliability of the system. Additionally, since a portion of the load is shifted from peak periods to off-peak periods, the total net load of the system over the entire simulation period also decreases from 10,020 kW to 9680 kW. This further demonstrates the effectiveness of demand response in optimizing load distribution and improving energy utilization efficiency without increasing system costs. In summary, the simulation results in Figure 6 demonstrate the adjustment effect of demand response on the net load of the system, providing intuitive validation for the effectiveness of the coordinated planning strategy based on optimal economy and demand response in the distribution network.

4.3. Analysis of Comprehensive Cost Results of Distribution Network

Four schemes are set for comparison in the following text to study the impact of energy storage and demand response on this optimization model and its effectiveness. Comparing the various costs of the distribution network throughout a day, Scheme 1 considers energy storage devices and demand response, including the configuration of energy storage and the overall costs of the distribution network. Scheme 2 only considers energy storage devices without demand response, including the configuration of energy storage and the overall costs of the distribution network. Scheme 3 only considers demand response without installing energy storage devices, including the overall costs of the distribution network. Scheme 4 considers neither energy storage devices nor demand response, including the

overall costs of the distribution network. The cost values of the distribution network under different schemes are shown in Table 4.

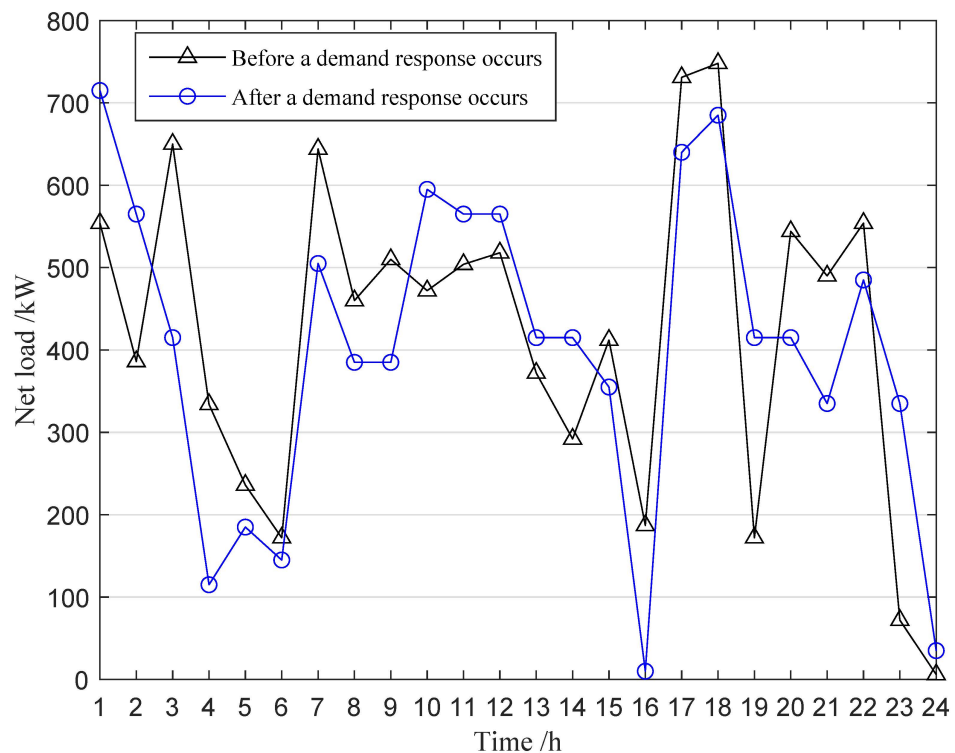


Figure 6. System net load curve before and after demand response occurs in System net load curve before and after demand response occurs in the distribution network.

Without considering demand response, Scheme 2, which involves energy storage, compared to Scheme 4, leads to a decrease in the output from the main grid from 7050 kWh to 5252 kWh, representing a reduction of 25.5%. This reduction in purchased electricity from the main grid results in a decrease of 1223 yuan in purchasing costs, and the total daily cost of the system decreases from 5247 yuan to 5053 yuan. This is attributed to the absence of energy storage regulation when the generation from wind and photovoltaic units exceeds the system load consumption, wasting surplus generation. This results in a significant increase in curtailed wind and photovoltaic power. When the system generation is insufficient, a large amount of electricity needs to be purchased from the main grid, ultimately leading to a substantial cost increase. Considering demand response, Scheme 1, compared to Scheme 3, increases the regulating effect of energy storage, leading to a significant decrease in purchased electricity from the main grid by 1582 kWh, a reduction in electricity procurement cost by 1075 yuan, and a daily total cost decrease of 190 yuan. Comparing these two sets of schemes (2 and 4, and 1 and 3), it is evident that energy storage facilities effectively mitigate peak loads and reduce curtailed wind and photovoltaic power.

Without considering energy storage devices, Scheme 3, compared to Scheme 4, incorporates demand response, which reduces the amount of electricity purchased from the grid by the system from 7050 kWh to 6280 kWh in a day, resulting in a cost reduction of 524 yuan in purchasing electricity. After deducting the compensation cost for demand response, the total daily cost of the system still decreases by 111 yuan. With the introduction of demand response, a portion of the load is shifted from peak loads to off-peak loads in the distribution network, improving the overall net load curve and reducing electricity demand during peak periods.

Table 4. The cost values of distribution networks under different schemes.

Index	Scheme 1	Scheme 2	Scheme 3	Scheme 4
Energy storage configuration node	6/13	6/13	/	/
Maximum energy storage capacity/kWh	310/350	550/300	/	/
Energy storage charge and discharge power limit/kW	120/110	150/135	/	/
Percentage of load capacity that can be reduced	20	0	20	0
Cost of wind and photovoltaic power installations/RMB	453	453	453	453
Cost of energy storage/RMB	4698	5252	6280	7050
Cost of purchasing electricity	3195	3571	4270	4794
from the main power grid/RMB	413	0	413	0
Total cost/RMB	4946	5053	5136	5047

Furthermore, compared to Scheme 2, Scheme 1 involves the coordinated cooperation of demand response and energy storage devices, reducing the number of charge-discharge cycles and the configuration capacity of energy storage devices. This results in a total cost reduction of 144 yuan for the energy storage devices and a decrease of 376 yuan in electricity purchasing costs from the grid, leading to a total system cost reduction of 107 yuan. Scheme 1, compared to Scheme 4, considers demand response and the coordinated cooperation of energy storage, reducing the electricity purchased from the grid from 7050 kWh to 4698 kWh, decreasing the system's electricity demand by 2352 kWh, a reduction of 33.4%. The cost of purchasing electricity is reduced by 1599 yuan. Even after deducting the energy storage and demand response costs of 1298 yuan in Scheme 1, the total system cost still decreases by 301 yuan.

Schemes 2 and 3 only consider energy storage devices and demand response, respectively. In both cases, the total system costs are lower than in Scheme 4, demonstrating that both energy storage devices and demand response can reduce system costs. However, the total cost of Scheme 2 is less than that of Scheme 3, indicating that the regulatory effect of energy storage devices within a certain range is superior to demand response alone. Nonetheless, the coordinated cooperation of both is even more efficient.

It can be concluded that both energy storage devices and demand response mechanisms effectively reduce the total system costs in the power system. The coordinated cooperation between energy storage devices and demand response is particularly noteworthy, effectively reducing the system's total costs. This coordination is theoretically feasible and practically achieved through optimization, significantly reducing the system's total costs. This provides a feasible technical pathway and effective economic means for the intelligent regulation of future power systems.

Figure 7 shows the variation curves of load shedding over time for four schemes when the system is disconnected from the main power grid. Load shedding is the last line of defense to maintain system operation, characterized by its rapid responsiveness and flexibility, which can quickly reduce the load and prevent system overload, thereby ensuring the stable operation of the power system. From the figure, it can be observed that Scheme 1, which is the method proposed in this paper, can effectively reduce the total load shedding at each time scale, ensuring power balance at any given moment and effectively protecting system security.

4.4. Analysis of the Relationship between Demand Response, Energy Storage Configuration, and System Cost

With the transformation of the energy supply structure and the change in energy consumption patterns, demand response and energy storage technologies serve as important means to regulate the balance between electricity supply and demand. They play a significant role in reducing system costs and promoting the sustainable development of power systems. Researching the relationship between demand response percentage and energy

storage capacity can provide a scientific basis for planning and designing energy storage systems. Understanding the impact of demand response on energy storage requirements can help determine the capacity and configuration of energy storage systems and improve their efficiency and economic viability. Furthermore, analyzing the relationship between energy storage capacity and total costs under different demand response percentages helps comprehensively understand the synergistic mechanism between demand response and energy storage systems. By optimizing energy storage capacity and demand response percentages, it is possible to minimize system costs to the greatest extent, enhance the intelligence and flexibility of power systems, and achieve an economical, reliable, and clean energy supply.

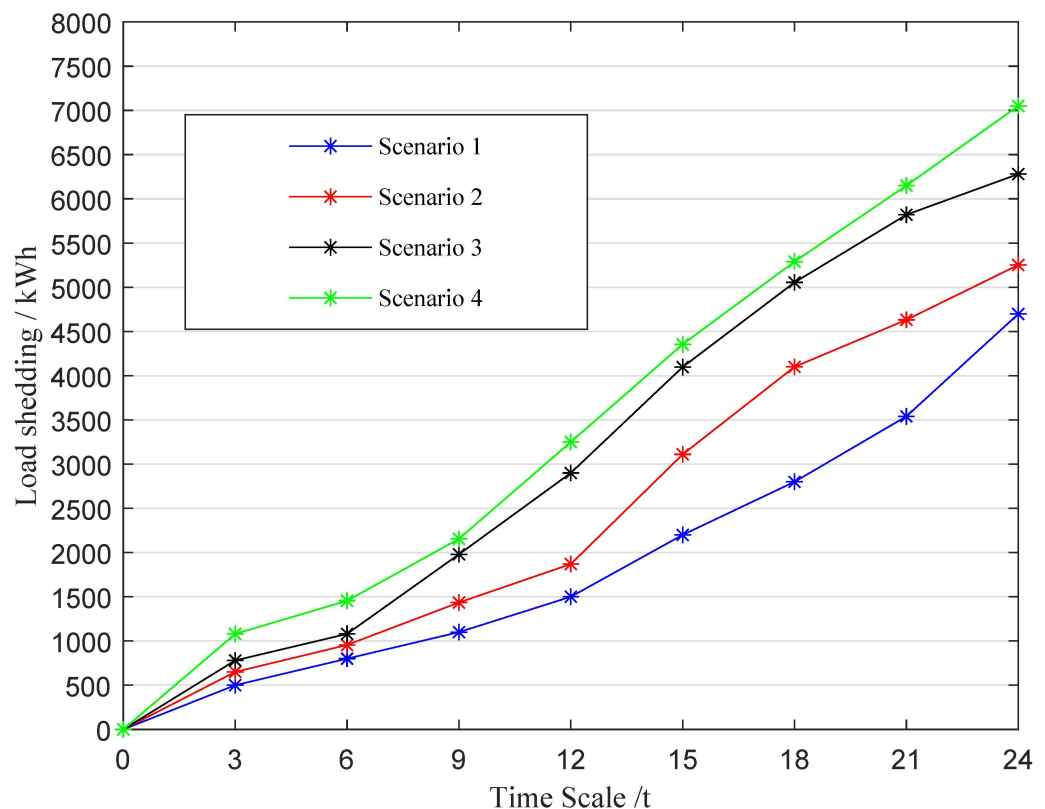


Figure 7. Load shedding curves for four schemes in off-grid mode.

The relationship between demand response percentage and total system costs is depicted in Figure 8. Typically, the proportion of demand response is constrained and does not exceed 20%. This limitation is due to the essential nature of many loads, which cannot be arbitrarily adjusted. Such restrictions ensure system stability and reliability while maximizing the utilization of adjustable load resources. As the percentage of energy storage demand response configuration capacity increases, the total costs of the distribution network gradually decrease. Initially, with demand response configuration capacity at 0%, the total system costs are relatively high. However, as the percentage gradually increases to 20%, the total system costs gradually decrease to a more economically reasonable level. Specifically, as the demand response percentage increases, the total system costs decrease from 5365 yuan to 4775 yuan. This trend can be attributed to the various advantages brought about by the synergistic effect of demand response and energy storage technologies. As the demand response percentage increases, the system's flexibility and responsiveness to load changes gradually strengthen. Demand response can smooth the load curve by adjusting user electricity consumption behavior, reducing electricity demand during peak periods and increasing it during off-peak periods, thereby reducing the volatility of the net load curve. The smoothing of the net load curve enables energy storage systems to more effectively respond to the fluctuations in power generation from new energy. As a result,

the demand for energy storage within the system decreases correspondingly, reducing the configuration costs of the energy storage system. Additionally, with the implementation of demand response, the system's demand for energy storage systems' maximum charging and discharging power decreases accordingly. By effectively managing demand response, the system can more reasonably schedule charge and discharge operations, reducing the need for high charge and discharge power in the energy storage system and consequently reducing its design and operation costs.

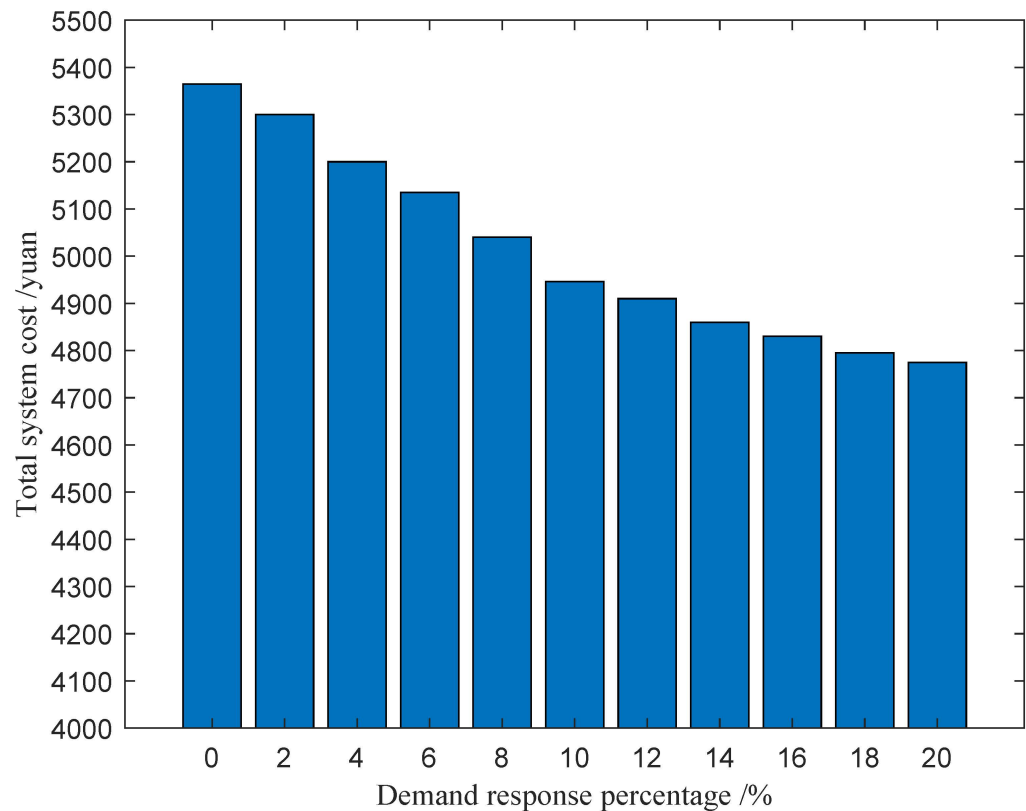


Figure 8. Impact of demand response percentage on total system cost.

Figure 9 presents the optimal energy storage capacity variation under different demand response percentage conditions. The figure shows that as the demand response percentage increases from 0 to 20%, the optimal energy storage capacity gradually decreases from 1900 kWh to 155 kWh. This trend is due to the impact of demand response on power system operations. With the increase in the percentage of demand response, users have more flexibility in electricity consumption, allowing them to reduce electricity demand during peak load periods and increase it during off-peak periods. Consequently, the system's load curve becomes smoother, decreasing the peak-to-valley difference. This smoothing of the load curve reduces the system's peak load demand, alleviating the pressure on the power system. Due to the smoothing of the load curve, the required energy storage capacity during peak periods decreases since the system no longer needs to cope with drastic load fluctuations. In other words, as demand response increases, the system becomes more stable, with a reduced range of load variations, leading to a decrease in the required energy storage capacity.

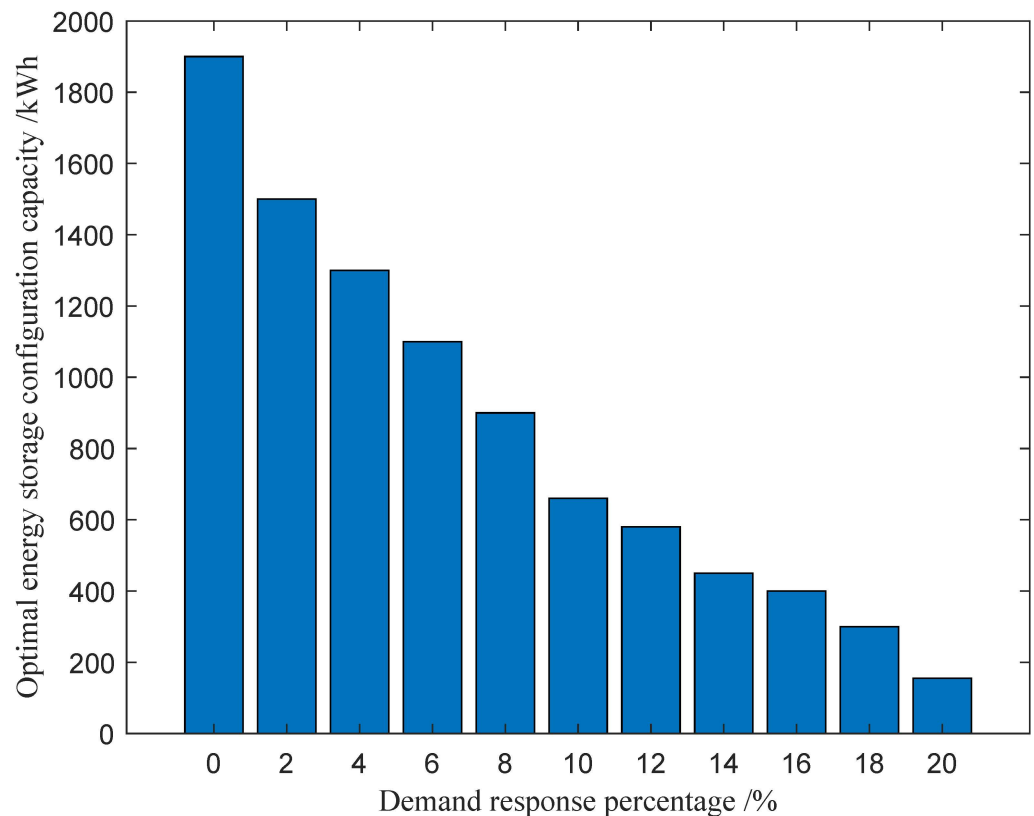


Figure 9. Optimal energy storage configuration capacity under different demand response percentages.

Figure 10 illustrates the variation of total system cost with energy storage capacity under three different demand response percentage conditions. When the demand response percentage is fixed, the total system cost initially decreases and then increases with the increase in energy storage capacity. This changing trend primarily stems from the peak-shaving and valley-filling characteristics of the energy storage system. Initially, as the energy storage capacity increases, the energy storage system can fully utilize its peak-shaving and valley-filling functions, resulting in benefits outweighing the configuration costs and decreasing total system costs. However, as the energy storage capacity continues to increase, the energy storage system's configuration costs gradually increase, while the benefits realized cannot cover the configuration costs, leading to an overall increase in total system costs. Therefore, the total system cost rises when the energy storage capacity exceeds a critical value.

On the other hand, at the same energy storage capacity, as the demand response percentage of the distribution network increases, the total system cost gradually decreases. This is because the increasing demand response brings additional benefits to the distribution network, thereby reducing operating costs. Additionally, implementing demand response can reduce the capacity requirement for the peak-to-valley difference in the distribution network load, thereby decreasing the system's need for energy storage capacity configuration and further lowering the overall system cost. Therefore, with the increase in demand response percentage, the changing trend of the total system cost is influenced by the energy storage capacity and demand response.

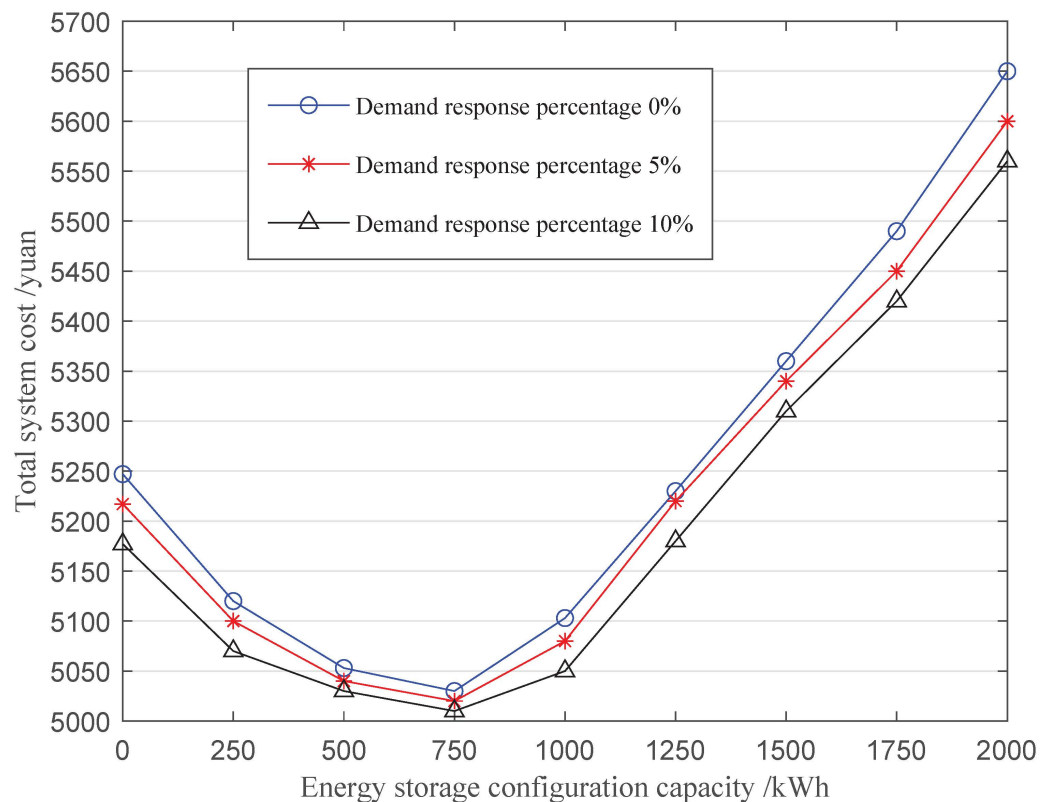


Figure 10. Relationship curve between energy storage configuration capacity and total cost under different demand response percentages.

5. Conclusions

In the context of grid connection of wind power and photovoltaic devices, a study on coordinated planning strategies integrating source-grid-load-storage with consideration of demand response was conducted. The main research results are as follows:

1. The paper establishes a coordinated planning model for wind power and photovoltaic power devices, energy storage devices, and demand response and analyzes their cost-benefit characteristics. Demand response adjusts the net load characteristics by motivating users. Its implementation can effectively reduce the distribution network's energy storage regulation capacity demand. Demand response is more economically advantageous compared to energy storage.
2. A dual-layer planning model is established considering demand response in coordinating source-grid-load-energy storage planning. By iterating the optimization values of the upper-layer and lower-layer planning using a dual-layer planning method, the model can reflect the impact of cost-benefit among wind power, photovoltaic devices, energy storage, and demand response. The model considers the coordination and cooperation among wind power, photovoltaic devices, energy storage, and demand response from the perspective of the overall economic viability of the distribution network.
3. The optimization model and calculation methods proposed in this paper are verified by improving the IEEE-33 node system example, and four optimization configuration Schemes considering whether energy storage devices and demand response are considered are analyzed. The results show that energy storage devices can effectively reduce overall costs. Demand response can replace the demand for energy storage regulation at a lower cost, effectively reducing the demand for energy storage configuration capacity in the distribution network, reducing the charge and discharge cycles of energy storage to reduce investment and operating maintenance costs, and has better economic benefits.

4. Studying the relationship between demand response, energy storage deployment, and system costs can help power system operators and policymakers better understand how to optimize the operation of the power system through demand management and energy storage technologies. By effectively deploying energy storage systems and promoting demand response, the flexibility and stability of the power system can be enhanced, reducing energy supply uncertainty, operational costs, and environmental impact, thereby facilitating the power system's transition towards greater sustainability and intelligence.

Based on the above research content, we believe the future research directions are as follows:

1. By leveraging big data and artificial intelligence technologies, particularly through deep learning neural network models [37,38], it is possible to account for different weather conditions such as sunny, cloudy, and rainy days. By analyzing historical weather data, real-time weather forecast data, and power generation data, precise power generation prediction models can be established. These models can accurately predict the power generation curves of new energy generation devices, ensuring more reliable predictions. Furthermore, advanced machine learning algorithms such as immune-based machine learning algorithms [39], time series forecasting models, and reinforcement learning can be used for coordinated planning, enabling the grid to make intelligent decisions. By optimizing demand response strategies, the grid can manage and allocate power resources more efficiently, significantly improving the utilization of power resources and promoting the grid towards greater stability, efficiency, and economy.
2. Instead of setting user compensation amounts to fixed values, it is recommended to research dynamic pricing mechanisms such as real-time pricing, time-of-use pricing, and critical peak pricing. These mechanisms incentivize users to reduce electricity consumption during peak demand periods and increase usage during off-peak periods, thereby better balancing the grid load. The real-time pricing mechanism adjusts electricity prices in real-time based on supply and demand conditions, encouraging users to consume electricity when prices are lower. The time-of-use pricing mechanism divides the day into different periods with varying electricity prices, allowing users to adjust their consumption based on the price. The critical peak pricing mechanism significantly increases electricity prices when demand approaches peak levels, strongly incentivizing users to reduce consumption. These dynamic pricing mechanisms can effectively balance the grid load, promote reasonable electricity consumption habits, and improve overall energy efficiency.

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