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Research article

The application effect of the optimized scheduling model of virtual power plant participation in the new electric power system

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ABSTRACT

To build a comprehensive framework for virtual power plant (VPP) development aligned with market dynamics and to devise effective strategies to foster its growth, this study undertakes several key steps. Firstly, it constructs a VPP development framework based on market conditions, to drive the evolution of new power systems and facilitating energy transformation. Secondly, through a blend of theoretical analysis and model construction, the fundamental principles of VPP are systematically elucidated, and a decision model for the VPP development framework, focusing on price demand response, is formulated. Lastly, an optimal scheduling model for the new power system is developed, with its efficacy validated across three distinct scenarios. The findings underscore the critical importance of integrating energy storage technologies, particularly pumped storage hydropower systems, for achieving balance and optimization within new power systems. Model verification reveals that the incorporation of energy storage power stations significantly enhances system stability and efficiency, particularly in addressing the volatility associated with renewable energy sources. Additionally, the analysis indicates that while the adoption of energy storage technologies may marginally increase overall power generation costs, the total power generation cost declines with the integration of battery storage and pumped storage hydropower stations. This suggests that leveraging energy storage technologies not only enhances system operational reliability but also contributes to reducing the overall cost of power production to a certain extent. In summary, this study presents an economic and environmentally sustainable scheduling model for new power systems within the context of market trading environments. By offering both theoretical insights and practical guidance, it aims to support sustainable development and energy transformation initiatives. Ultimately, the study is poised to foster the adoption of clean energy, facilitate the establishment of smart grids, and bolster the sustainable utilization of energy resources, thereby advancing environmental conservation efforts.

1. Introduction

Scheduling within an electric power system (EPS) constitutes a pivotal aspect of EPS operation, conventionally centered on achieving cost minimization while ensuring adherence to EPS balance and generator set constraints. The primary aim involves

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determining power generation levels across various EPS stages, with the goal of minimizing total power generation fuel or emission costs, meeting load demand, and mitigating transmission losses [1]. However, the advent of innovative EPS models, emphasizing recycled energy, poses challenges due to the inherent randomness and volatility associated with recycled energy generation systems. These challenges have significant implications for system safety, reliability, and economic operation [2]. Consequently, EPS scheduling mandates a reevaluation of dispatch objectives and constraints, particularly in light of the integration of a substantial proportion of new energy power units [3].

Initially, microgrid technology emerges as a pivotal solution to tackle challenges associated with recycled energy [4]. Within a microgrid, generator sets operate within the traditional distribution network, enabling direct power flow from the generation side to the load side without transmission through the network, thus enhancing energy utilization [5]. Microgrid systems play a crucial role in absorbing dispersed generation and increasing the penetration of recycled energy [6]. Secondly, energy storage system scheduling emerges as a significant method through energy storage system configuration and forecasting of new energy generation [7]. Integrating wind power and energy repositioning into the EPS mitigates operational risks associated with new energy generation systems to an acceptable level [8]. Lastly, solar power plant scheduling is underscored. Through the thermal repositioning system of the solar thermal power plant (STPP), the STPP output can be controlled to maximize power generation benefits. Operating akin to thermal power units with favorable climbing characteristics, the power generation actively engages in power grid frequency regulation, voltage regulation, and other measures [9]. In recent years, with the rapid development of the energy internet and the deepening integration of complementary coupling among various energy sources, the concept of a multi-energy virtual power plant (VPP) has emerged. However, research on optimal scheduling of multi-energy VPPs under multiple uncertainty conditions remains insufficient. Kong et al. (2020) employed a robust stochastic optimal scheduling method to address scheduling problems under multiple uncertainty conditions. They utilized generative adversarial networks to generate scenarios for electricity, heat, cooling, and natural gas loads. Through the application of the K-medoids clustering method, typical load scenarios were obtained, allowing for the formulation of scheduling plans that minimize operating costs under worst-case scenarios, thereby assisting in reducing the overall scheduling costs of the system [10]. Corinaldesi et al. (2019) highlighted that automated demand response (DR) could enhance the stability of distribution systems and increase the proportion of renewable energy but required high computational power and a complex coordination architecture. Hence, smart grid technology plays a crucial role in the future development of power systems [11]. VPP technology, as an intelligent solution integrating multiple energy sources and flexibly managing energy supply, plays a significant role in the development of the energy industry. With the promotion of concepts such as comprehensive energy systems and energy internet, along with the advancement of electrification levels and the development of "electrification substitution" technology, the coupling relationships between various energy sources are gradually strengthening. Traditional independent planning and operation models are no longer applicable. Consequently, technologies like VPP have emerged to achieve coordinated operation and optimized scheduling of various energy sources. Nevertheless, as energy types expand and energy markets evolve, VPP technology faces numerous challenges. These include handling the uncertainty of renewable energy outputs, the impact of electricity market price fluctuations on optimization scheduling, and the uncertainty introduced to the load side by the development of demand-side management technologies. Therefore, to adapt to the increasingly complex energy environment and enhance energy utilization efficiency, continuous innovation and refinement of VPP technology are essential to meet the challenges of future energy systems [12].

In summary, scholars have extensively researched the power system scheduling field, achieving significant advancements from various perspectives. However, challenges and key issues persist in the power systems of the VPP. These issues include, but are not limited to, effectively constructing the development framework of the VPP to meet the requirements of novel power systems and devising effective strategies to promote the development of the VPP, enhancing their role and efficiency in energy production and management. Building upon prior research, this study utilizes VPP theory to re-optimize the scheduling of novel power systems. Initially, the theoretical foundation of the VPP is presented, followed by the introduction of a decision model that combines price DR with the VPP integrated into power system operations. Finally, based on this foundation, an optimization scheduling model for novel power systems is constructed, and experiments are conducted to validate the model. This study aims to address a series of specific problems and challenges in VPP-based power systems. Firstly, according to the role and function of VPP in the new power system, this study discusses how to effectively construct the VPP development framework to meet the new power system's requirements. Secondly, this study focuses on developing effective strategies to promote the development of VPP and improve its role and efficiency in energy production and management. In addition, special attention is paid to the key issue of addressing the impact of renewable energy volatility on the grid and improving the utilization of renewable energy sources. In this study, the dispatching of new power systems is re-optimized by integrating VPP theory into a decision model that combines price disaster recovery and VPPs. The resulting optimal scheduling model is constructed and validated through experiments. The innovation of this study lies in its analysis of the effectiveness of the optimal scheduling model in various scenarios, providing a theoretical basis for formulating VPP-related policies in system scheduling. Overall, this study addresses key issues facing VPP in new power systems, offering crucial support for achieving the sustainable development of energy systems and energy transformation. The proposed cost-optimal scheduling model based on VPP introduces pumped storage power stations and concentrated solar photovoltaic (PV) power generation, effectively increasing the proportion of renewable energy consumption while reducing the total system power generation cost. This contribution presents innovative solutions for intelligent energy management and sustainable energy system development. Furthermore, it offers practical guidance and theoretical support for promoting the utilization of clean energy and the establishment of a smart grid, thereby advancing the goal of sustainable energy use and environmental protection.

2. Literature review

Several scholars, both domestically and internationally, have been actively exploring the establishment of an integrated control management system to integrate demand-side and supply-side electricity facilities. The main objective is to achieve optimized dispatching of the EPS by seamlessly integrating available VPP resources and actively participating in EPS resource allocation. In their work, Dayalan and Rathinam (2021) proposed a control strategy specifically tailored for recycled energy access. This strategy facilitated remote access control and device optimization for all devices following the scheduling optimization scheme, enabling automatic reconfiguration of devices [13]. Khosravi et al. (2021) categorized the involvement of recycled energy in EPS dispatch into three levels: data collection, dispersed control, and system supervision, along with allocation management [14]. Kai et al. (2021) introduced a staged dispersed energy dispatch scheme, leveraging multi-agent theory to integrate dispersed microgrid systems [15]. Guisández and Pérez-Díaz (2021) incorporated wind power, thermal power, and DR into EPS resource allocation. Their EPS optimization dispatch model, constructed under the dual constraints of economic goals and carbon emission targets, utilized a united scheduling mode for power generation and carbon emissions, resolved through combined integer linear programming [16].

In summary, VPPs demonstrate clear advantages in promoting energy conservation, waste mitigation in the power industry, and achieving comprehensive electricity resource allocation. However, the operational uncertainties inherent in the system demand careful consideration. Therefore, it is imperative to establish appropriate scheduling allocation goals aligned with national plans and prevailing industrial trends in the power sector, realistically incorporating these uncertainties into the optimized scheduling model.

3. An optimized scheduling model for DR-VPP participation in EPS operation

3.1. VPP and DR

(1) The theory of VPP

The concept of VPPs originates from the scholarly work titled “Virtual Utilities: Description, Technology, and Competitiveness of Emerging Industries.” In this publication, a virtual utility is defined as a dynamic cooperative arrangement involving several relatively independent market-oriented entities. The primary objective of this collaboration is to provide consumers with desired electricity services. Notably, these entities are not required to possess physical assets of the requisite magnitude [17].

A VPP is an intelligent energy system that integrates distributed energy resources, energy storage devices, and demand-side resources. It achieves coordinated optimization of energy production, storage, and consumption through intelligent control and management. The core concept of VPP revolves around utilizing an advanced energy management system to integrate distributed energy resources, demand-side resources, and energy storage devices, thereby achieving coordinated optimization of energy production, storage, and consumption. Through intelligent control and management, a VPP can realize real-time monitoring of power system demand, adapt to market conditions, and flexibly adjust energy production and consumption strategies to maximize system operation efficiency and stability. Key features of VPP include flexibility, intelligence, and diversity. Flexibility allows VPP to adjust energy supply and demand in real-time according to actual demand, thereby adapting to different market conditions. Intelligence facilitates real-time monitoring and response of the system through advanced control technology, thereby enhancing system reliability and response speed. Diversity enables VPP to integrate various energy resources and demand-side resources to meet the diverse needs of users and systems. In general, the core concept of VPP aims to achieve intelligent management of the power system by integrating and optimizing the utilization of energy resources, thereby promoting sustainable development and optimization of the energy system.

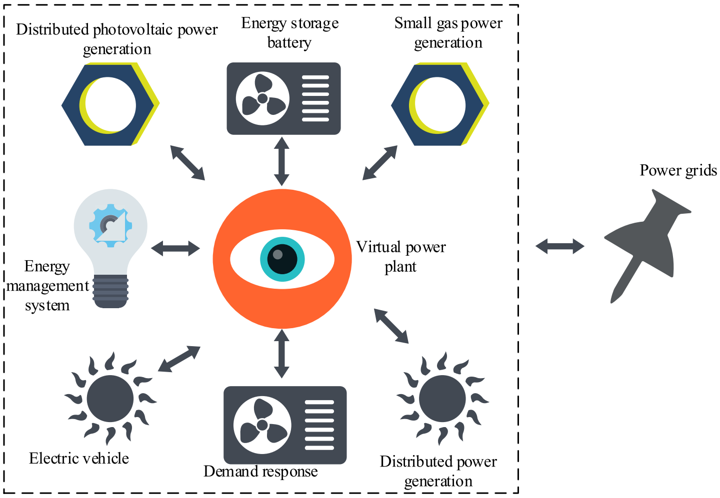


Fig. 1. Composition of a VPP.

The VPP embodies several distinctive characteristics that underscore its pivotal role in modern energy systems. Firstly, VPP exhibits remarkable flexibility, allowing for the dynamic adjustment of energy production and consumption strategies in response to the evolving needs of the power system and prevailing market conditions. This adaptive capability optimizes system operation to its fullest potential. Secondly, leveraging advanced intelligent control technology, VPP can monitor and swiftly respond to changes within the power system in real-time, thereby enhancing system responsiveness and stability. Furthermore, the inherent diversity of VPP facilitates the seamless integration of a wide array of energy resources and demand-side resources, including wind power, PV, energy storage devices, and DR. This versatility ensures the fulfillment of diverse requirements within the power system. The fundamental premise of VPP entails the comprehensive consolidation of disparate energy resources distributed across a specific geographical area. This consolidation aims to facilitate flexible control and centralized scheduling, enabling the aggregation and grid-connected consumption of substantial volumes of regional energy. The overarching objective is to realize market-oriented operations for decentralized energy systems [18]. Fig. 1 illustrates the composition and classification of VPP components.

Fig. 1 illustrates the primary components of a VPP, encompassing dispersed wind power plants, distributed PV power generation, micro-gas turbines, energy storage systems, supplementary generation-side resources, and demand-side resources, symbolized by DR. Central to the functioning of a VPP is the energy management system, responsible for the supervision and control of dispersed power supply, DR, and energy repositioning equipment. Its principal objective is to optimize system efficiency or minimize costs for operators, all while ensuring the secure and stable operation of the VPP [19].

VPP can be categorized based on various criteria. Firstly, from a technological standpoint, VPPs can be classified into different types, such as wind power-based, PV-based, and hybrid VPPs, depending on the types of energy resources integrated into them. Secondly, considering the scale and capacity of the VPP, it can be classified as large-scale, medium-scale, or small-scale VPP. Additionally, based on the diverse services and functionalities offered by the VPP, it can be categorized into different service types, such as grid-supportive, user-side service-oriented, and energy-trading VPP. The VPP can provide a range of operational management and technical services for system operations. For instance, it can offer services such as power flow control, voltage load control, and frequency control to meet the needs of both distribution system operators and transmission system operators (TSOs), thereby ensuring the reliability and safety of system operations. Based on the distinct functions of VPP in the market, it can be classified into two categories: Commercial virtual power plant (CVPP) and technical virtual power plant (TVPP) [20]. The operational mechanisms of these two VPP types are displayed in Fig. 2.

Fig. 2 illustrates that a VPP is an intelligent energy system that integrates distributed energy resources, energy storage devices, and demand-side resources to achieve coordinated optimization of energy production, storage, and consumption. Within this framework, the TVPP stands out as a specialized type of VPP focused on enhancing the technical performance and operational efficiency of energy systems. TVPP aims to bolster the reliability, stability, and efficiency of energy systems by incorporating advanced energy management systems and intelligent control technologies. Unlike the economic orientation of the CVPP, TVPP prioritizes technical operation and engineering practices, typically managed by technical professionals. Its operational objectives encompass optimizing energy production, storage, and consumption processes, as well as enhancing system responsiveness and flexibility to address dynamic changes and challenges within the power system. Consequently, TVPP plays a critical role in providing technical support and solutions for sustainable energy management and the construction of smart grids. The roles of CVPP and TVPP are outlined in Table 1.

Overall, VPP is an innovative energy management system, harmonizing decentralized energy resources, energy storage equipment, and demand-side management to realize optimal scheduling of energy production, storage, and consumption through intelligent control and management. Its foundational concept revolves around maximizing the utilization of distributed energy and storage technologies in an integrated manner to fulfill the requirements of the power system while garnering economic benefits within market frameworks. The inherent flexibility of VPP enables dynamic adjustments to energy production and consumption strategies, tailoring them to diverse market conditions and user demands. By orchestrating the intelligent management of the energy system, VPP offers crucial technical support and solutions for enhancing energy utilization efficiency, fostering the development of renewable energy sources, bolstering the stability and flexibility of the power system, and propelling forward energy transformation and smart grid construction initiatives.

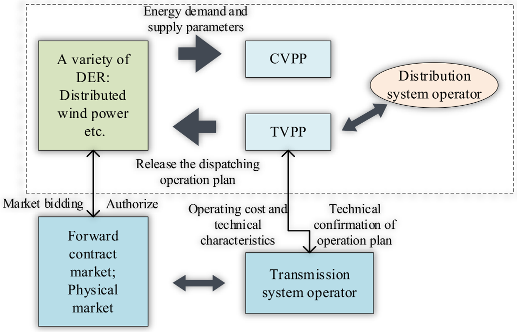


Fig. 2. Operation mechanism of two VPP types.

Table 1
Roles of CVPP and TVPP.

Module name	Role
CVPP	Provides the operating parameters of distributed energy resources, energy supply and demand measurement data, cost data, and other relevant information for predicting energy supply and demand within the VPP.
TVPP	Supplies the system with visual operational attributes of all distributed energy resources, along with system balancing services and supporting services tailored to the operational requirements of both distribution system operators and transmission system operators within the power grid.

(2) DR

DR entails the strategic guidance of consumers in judiciously utilizing electricity through economic, technical, legal, and administrative measures within the market environment, with the primary aim of ensuring the reliable, economical, and consistent operation of the EPS [21]. Evolving alongside the progression of the smart grid, DR has traversed three distinct developmental stages: manual DR, semi-automatic DR, and fully automatic DR. Additionally, DR can be categorized based on its mechanism into price-based demand response (PBDR) and incentive-based demand response (IBDR) [22]. The specific details of these two DR types are outlined in Table 2:

3.2. A decision model for PBDR for VPP in EPS operation

The decision model for the market operation mechanism based on Price-Based Demand Response for Virtual Power Plant (PBDR-VPP) is formulated using a multi-objective optimization approach. Its objective is to balance the supply-demand relationship within the EPS while advancing energy conservation and emission reduction objectives. Initially, the model encompasses various objective functions, including total coal consumption of the system, average load difference during peak and off-peak periods, and consumer electricity expenditure. These functions aim to minimize system operating costs, stabilize load fluctuations, and enhance customer satisfaction with electricity consumption, thereby fostering economic and social benefits for the EPS. Regarding model constraint conditions, it mandates that the system's daily load before and after implementing peak-off-peak TOU pricing remains unchanged to ensure power supply stability. Additionally, restrictions are imposed on peak, off-peak, and flat load levels to prevent the emergence of new load peak periods, thereby ensuring the system's stable operation. Additionally, constraints are imposed on the electricity price during peak, off-peak, and flat periods to prevent excessive expansion of the peak-to-off-peak electricity price ratio. This ensures that consumer electricity expenditure does not significantly increase following the implementation of peak-off-peak TOU pricing. The model employs various optimization algorithms, such as mixed integer programming algorithms, to identify the optimal solution considering multiple objective functions and constraints. During the optimization process, several variables are taken into account, including electricity consumption during peak, off-peak, and flat periods, total coal consumption of the system, and customer satisfaction with electricity consumption. By adjusting these variables reasonably, the model aims to achieve the market operation goal of PBDR-VPP.

(1) PBDR-VPP

PBDR-VPP entails consumers responding to various HEP change strategies, modifying their electricity consumption behavior, and facilitating load reduction or transfer. The loads that are diminished or shifted can be conceptualized as a form of VPP providing “negative output” to the system during peak periods [23]. PBDR-VPP serves as a conduit for transmitting electricity market price fluctuations to end consumers, prompting alterations in their electricity consumption habits. Strategies employed encompass TOU, real-time, and peak tariffs [24]. A prevalent strategy within TOU pricing is peak-to-valley TOU pricing. Based on the characteristics of electricity load during specific periods, the electricity sales company divides the day into peak, valley, and flat periods, establishing distinct electricity sales prices for each time segment. Consumers adjust their electricity consumption patterns in response to price fluctuations in each period, strategically adopting staggered peak electricity consumption to conserve or shift a portion of the peak load [25].

Table 2
Classification and content of DRs.

Classification	Specific content	Response measures
PBDR	Varied electricity pricing strategies direct consumers to optimize energy consumption behavior, adjusting electricity demand for peak reduction, valley filling, and load fluctuation mitigation.	Time-of-use (TOU) pricing mechanism, real-time hourly electric price (HEP) mechanism, peak price mechanism
IBDR	Ensures power supply stability within the system. Administrators transmit DR signals to the market using preferential HEP or financial incentives, attracting eligible participants for conditional response involvement. Subsequently, contracts enable electricity load adjustments as per agreed-upon terms and periods, leading to corresponding subsidies acquisition.	Direct load control, demand-side bidding/buyback programs, disrupted loads, emergency DR mechanisms, capacity service items, and ancillary services market items.

(2) Market operation mechanism of PBDR-VPP

In the market operational strategy employed by PBDR projects, VPP operators assume the primary role of electricity sellers. Operating as price takers, these operators procure electricity within the multi-level market to fulfill the electricity demand of consumer entities. Within the framework of the electricity market, the transaction and dispatch procedures undertaken by VPP operators are illustrated in Fig. 3.

Fig. 3 illustrates that within the trading domain, the electricity sales entity, operating as a VPP operator, establishes a strategic TOU pricing framework aimed at encouraging consumer participation in load reduction responses. Additionally, the entity conducts medium- and long-term transactions and spot trading with power generation entities via the power scheduling and trading center. This facilitates electricity procurement to fulfill the needs of consumer entities while generating revenue through power transactions.

(3) Peak-valley TOU electricity pricing model based on multi-objective optimization

1) Objective function

The primary objective of promoting the adoption of peak-valley TOU electricity pricing on the consumer side is to optimize power generation costs by moderating peaks and filling valleys. This strategic approach aims to enhance energy conservation and minimize wastage. Currently, a significant portion of China's standby units comprises coal-fired units characterized by modest capacity and elevated energy consumption, resulting in relatively high operating costs. The implementation of peak-valley HEP serves to mitigate consumer load fluctuations, thereby reducing the operational output of these coal-fired standby units, particularly during peak electricity demand periods. Peak-valley TOU electricity pricing effectively redistributes power load from peak and flat periods to off-peak (valley) times, consequently diminishing the frequency of starts and stops in system operation units. Consequently, the total coal consumption cost across peak, flat, and valley periods is established as the objective function to assess the impact of peak-valley TOU electricity pricing on energy conservation and waste minimization. This evaluation is quantified by the expression provided in Eq. (1).

$$\min B = \sum_{t \in T_p} \left(\alpha_p + \beta_p L_{t,PB} \right) + \sum_{t \in T_f} \left(\alpha_f + \beta_f L_{t,PB} \right) + \sum_{t \in T_v} \left(\alpha_v + \beta_v L_{t,PB} \right) \tag{1}$$

In Eq. (1), B represents the total coal consumption of the EPS. The parameters α_p, α_f, and α_v signify the baseline coal consumption levels during peak, flat, and valley periods, respectively. Additionally, β_p, β_f, and β_v represent the coal consumption coefficients per unit of power generation during peak, flat, and valley periods.

The primary consequence of implementing peak-valley TOU electric pricing is the reduction in load fluctuations during peak-valley hours. The optimization objective is to minimize the mean load difference throughout the peak-valley period, serving as a metric for evaluating the efficacy of peak-valley HEP in mitigating system load fluctuations. This evaluation is quantified by the expression provided in Eq. (2).

$$\min \Delta L = \frac{\sum\limits_{t \in T_p} L_{t,PB}}{T_p} - \frac{\sum\limits_{t \in T_v} L_{t,PB}}{T_v} \tag{2}$$

Following the implementation of peak and valley HEP, consumers adjust their electricity consumption behavior in response to variations in HEP across different periods. In comparison to the scenario of unrestricted electricity consumption, consumer satisfaction with electricity usage experiences a certain degree of influence. Hence, the consumer entity relinquishes a portion of the freedom to utilize electricity in exchange for enhanced economic efficiency. When this concession of electricity freedom leads to greater cost savings, it has the potential to attract more consumers to engage in DR-VPP initiatives. In the initial phase of VPP operations, the electricity sales company must ensure that the electricity expenses incurred by consumer entities are minimized, thereby enticing active participation from these resources. Consequently, the electricity expense (R) of the consumer entity becomes the focal point for

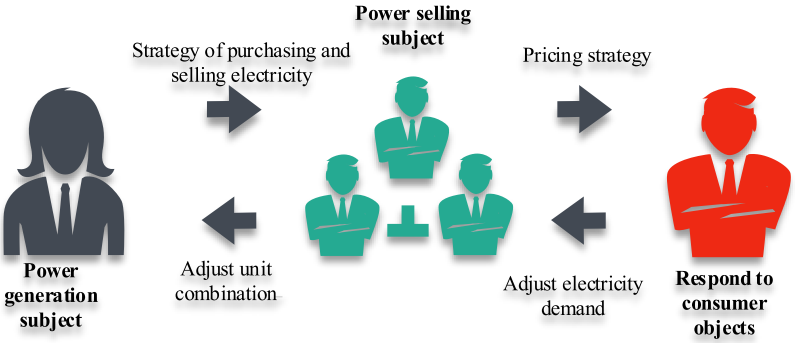


Fig. 3. Market operation mechanism of PBDR-VPP.

system optimization goals.

$$\boldsymbol{minR} = \rho_p \sum_{t \in T_p} \boldsymbol{L}_t^{PB} + \rho_f \sum_{t \in T_f} \boldsymbol{L}_t^{PB} + \rho_v \sum_{t \in T_v} \boldsymbol{L}_t^{PB} \tag{3}$$

2) Constraints

The implementation of PBDR necessitates adherence to various constraints to ensure the effective functioning of the system. Firstly, there is a requirement for compliance with the daily load parameters both before and after the adoption of peak-valley TOU electricity pricing. This ensures the stability of the power supply throughout the day. Additionally, specific constraints are imposed on peak and valley load levels, as well as on the HEP thresholds. Careful management of these thresholds is essential to prevent excessive increases in electricity prices. Furthermore, constraints are imposed on load levels during peak, flat, and valley periods to prevent the emergence of new peak load periods, thus maintaining system stability. VPP operators are tasked with ensuring that their profitability remains stable or improves following the implementation of peak-valley TOU electricity pricing, thereby incentivizing their active participation in the system.

The methodology proposed in this study demonstrates effectiveness and reliability across several dimensions. Firstly, it is underpinned by a thorough comprehension and analysis of critical factors, including the operational dynamics of the power system, consumer behavior, and electricity pricing policies. This foundation enables the establishment of a robust optimization model that accounts for the influence of peak-valley TOU pricing on the system's overall coal consumption while capturing consumer responses to price fluctuations and their impact on electricity satisfaction. Secondly, the methodology mitigates the risk of producing irrational outcomes or overly optimized solutions by incorporating rational constraints. These constraints include maintaining the daily load nearly constant, constraining load fluctuations during peak, flat, and valley periods, and keeping electricity prices within reasonable bounds. Furthermore, the methodology leverages real-time data monitoring and dynamic adjustment strategies, ensuring the model's adaptability to evolving real-world conditions. This proactive approach enhances the reliability and practical applicability of the results generated by the model. In summary, this methodology offers a comprehensive consideration of diverse factors and employs scientific modeling techniques combined with stringent constraints to ensure the accuracy and credibility of its results.

3.3. Design of the multi-objective optimized scheduling model for EPS with VPP participation

This section presents the detailed design of the multi-objective optimized scheduling model of the EPS with VPP participation. Firstly, the output modeling of various distributed power sources, such as wind power, PV systems, and gas generator sets, is elaborated. This involves utilizing Weibull and Beta distributions to characterize the volatility of wind speed and light radiation, and considering factors like power generation efficiency and cost for gas generator sets. Secondly, the modeling of storage equipment, including batteries and pumped storage systems, is outlined. This encompasses describing the charge and discharge characteristics and cost model of batteries, along with the operational characteristics and income model of pumped storage systems. Thirdly, the optimization objective of the VPP, focusing on maximizing economic income and optimizing environmental value, is detailed. This objective considers various factors such as sales income, generation cost, storage cost, and purchased power cost. Finally, the optimal scheduling model includes constraints such as power balance, distributed power output, interruptible load, and operation constraints for batteries and pumped storage systems. The model employs a multi-objective stochastic optimization algorithm based on scenario theory to optimize solutions, ensuring robustness and reliability.

Aligned with the economic dynamics of the system, the VPP achieves harmonized and optimized management of diverse dispersed power sources, energy repositioning equipment, and consumer load entities within its operational framework, utilizing both economic and technical approaches. In the context of the ongoing electricity marketization reform and the deregulation of the electricity sales sector, the VPP emerges as a pivotal mechanism for advancing the load management of consumer entities, experiencing widespread development. This section aims to construct a VPP system-based scheduling operation model encompassing controllable and uncontrollable loads, energy repositioning equipment, and interruptible loads, building upon the insights provided in the preceding section regarding VPP functionality. The dispatch model is formulated to maximize the operating revenue of the VPP while optimizing environmental value. Leveraging scenario theory, a multi-objective stochastic optimization model for the economic environment scheduling of VPP, accounting for wind-solar uncertainty, is developed. Simulation analysis is employed to validate the efficacy of the model.

(1) Dispersed power output modeling
  1) Dispersed wind power modeling

Wind power generation is intricately linked to the variability of wind speed. Describing the fluctuation of wind speed through probability distribution forms the foundation for deducing the output characteristics of wind power. The Weibull distribution function, being a continuous probability distribution function, offers flexibility and reliability in parameter settings. In this context, the Weibull distribution is employed to articulate the fluctuations in wind speed.

$$\boldsymbol{f}(\boldsymbol{v}, \boldsymbol{k}, \boldsymbol{b}) = \frac{\boldsymbol{k}}{\boldsymbol{b}}\left(\frac{\boldsymbol{v}}{\boldsymbol{b}}\right)^{\boldsymbol{k}-1} \boldsymbol{e}^{-(\boldsymbol{v}/\boldsymbol{b})^{\boldsymbol{h}}} \tag{4}$$

Here, v is the wind speed, k is the shape parameter, and b is the scale parameter.

Accordingly, the probability function of the Weibull distribution is defined as Eq. (3).

$$P(v) = \int_0^v f_v(v)dv = 1 - \exp\left(-\left(\frac{v^k}{b}\right)\right) \tag{5}$$

2) Dispersed PV

PV power generation relies on the PV effect at semiconductor interfaces, a technology that directly converts solar energy absorbed by semiconductors into electrical power. Its primary components include solar panel elements, control devices, and inverters. The power output from PV power generation exhibits characteristics of randomness, intermittency, and fluctuations, closely tied to the intensity of light radiation. The Beta distribution function is a conventional choice for characterizing the probability distribution of light radiation. Consequently, the probability distribution function representing solar radiation intensity is expressed as Eq. (3).

$$P(\varphi) = \int_{\varphi\ min}^{\varphi\ max} f(\varphi)d\varphi \tag{6}$$

In Eq. (3), $\varphi\ min$ and $\varphi\ max$ are the upper and lower limits of solar radiation intensity, respectively.

3) Gas generator unit

Gas-dispersed units primarily utilize Gas Turbine units to drive high-speed generators for electricity generation. The efficiency of gas-fired combined cooling, heating, and power units, commonly employed, typically exceeds 70 %.

The power generation efficiency of the gas-dispersed generator unit, denoted as θ^{FC}, can be assumed. Its actual output, G_t^{FC} is represented by Eq. (7):

$$G_t^{FC} = \theta^{FC} \times LHV \times V_t^{FC} \tag{7}$$

In Eq. (7), LHV denotes the calorific value of natural gas, which is 34.12 MJ/m^3, and V_t^{FC} represents the volume of natural gas used in the t period in cubic meters.

The costs associated with the gas-dispersed generator unit encompass both investment operation expenses and start-stop costs. Therefore, the cost function of the generator set at time t is represented by Eq. (8):

$$C_t^{FC} = C_{a,t}^{FC} + C_{b,t}^{FC} \tag{8}$$

$C_{a,t}^{FC}$ represents the investment operating cost.

4) Energy repositioning battery

The VPP commonly integrates energy repositioning equipment with limited capacity to balance the irregularly dispersed power of loads. Such equipment can be categorized based on different methods, including chemical energy repositioning equipment such as lead-acid batteries and lead-sulfur batteries, mechanical energy repositioning equipment like pumped storage, and electromagnetic energy repositioning equipment such as super capacitors.

The operational status of the battery is divided into charging mode and power supply mode, contingent upon factors such as the charging status, voltage condition, and the energy repositioning equipment's demand within the system. The battery's charge and discharge properties are characterized by three key parameters: battery capacity, state of charge, and discharge degree.

Typically, the battery discharges energy to the system during peak hours and charges during off-peak hours. Accordingly, the operational costs and revenues associated with the battery are outlined as follows:

$$C^{SB} = \rho_v \sum_{t=1}^{T} \mu_t^{SB,chr} G_t^{SB,chr} \tag{9}$$

$$R^{SB} = \rho_p \sum_{t=1}^{T} \mu_t^{SB,dis} G_t^{SB,dis} \tag{10}$$

Here, ρ_v and ρ_p denote the prices of electricity during peak and off-peak hours, respectively. $G_t^{SB,chr}$ and $G_t^{SB,dis}$ represent the charging and discharge powers for the time period t. $\mu_t^{SB,chr}$ and $\mu_t^{SB,dis}$ signify the state of charge and discharge of the battery at time t.

5) Pumped storage

The pumped storage system consists of essential components including a water turbine, upper and lower dams, and a generator. Its operational principle involves pumping water from the lower dam to the upper dam using electricity during periods of low valley load. Conversely, during peak load hours, water is released from the upper dam to the lower dam, harnessing the potential energy to generate electricity via turbines.

During power generation, the pumped storage system must maintain a minimum output level, constrained by the volume of water in the upper reservoir. Its electrical power output during this period is fixed and cannot be adjusted arbitrarily. Thus, the revenue $\boldsymbol{R}^{CW}$ generated by the pumped storage system during peak load hours is expressed as follows in Eq. (11):

$$\boldsymbol{R}^{CW} = \rho_p \sum_{t=1}^{T} \mu_t^{CWg} G_t^{CWp} \tag{11}$$

In Eq. (11), μ_t^{CWg} refers to the discharge state of the pumped storage system.

(2) New EPS optimization scheduling model based on VPP

The development of the model proposed in this study encompasses several key aspects, including defining the objective function, establishing constraints, and selecting optimization algorithms. The objective function serves as the focal point of optimization, indicating the goal of the scheduling process. In this context, the primary objective is to maximize the economic benefits derived from the VPP across various time periods, considering the diverse sources of income and costs associated with the operation of distributed energy resources. The objective function aims to maximize the economic benefits of the VPP, which consist of multiple components reflecting revenue generation and operational costs of distributed energy resources. Specifically, the objective function incorporates eight distinct components. These components encompass revenue generated from selling electricity to end consumer objects within specific regions and various operational management costs associated with distributed energy resources. Conversely, cost components encompass economic compensations to consumer objects subsequent to the activation of interruptible loads, operational costs linked to distributed wind power and PV, expenses associated with gas distributed generation, charging expenditures for batteries, pumping costs for pumped storage systems, and expenses related to external electricity purchases.

During the optimization scheduling process, it is crucial to consider various constraints to guarantee the safe and stable operation of the system. These constraints encompass power balance constraints, limitations on the output of distributed energy sources, restrictions on interruptible loads, operational constraints on batteries, constraints on pumped storage systems, and additional constraints as necessary. By imposing these constraints, the behavior of individual components is regulated to ensure they operate within acceptable ranges, thereby safeguarding the overall system's integrity and reliability.

In the optimization process, selecting an appropriate algorithm is pivotal for effectively solving the objective function while adhering to the constraints. Various optimization algorithms are available, including linear programming, integer programming, dynamic programming, genetic algorithms, and particle swarm optimization, among others. Linear programming, in particular, is a commonly employed method, well-suited for problems characterized by linear objective functions and constraints. Given that the objective function and constraints in this study's model exhibit linearity, linear programming emerges as the preferred optimization algorithm. This choice is substantiated by linear programming's efficacy in solving such problems, offering notable computational efficiency and interpretability. Utilizing linear programming facilitates the derivation of an optimal scheduling plan, considering diverse constraints, thereby maximizing the economic benefits for the VPP across different periods. The advantages of linear programming stem from its robust mathematical foundation, straightforward solving process, and capacity to identify global optimal solutions or approximate optimal solutions.

Regarding the inherent uncertainty associated with renewable energy sources like wind and solar, it is imperative to modify the objective function of the optimized scheduling model for the VPP. Instead of solely focusing on maximizing economic benefits, the objective function should aim to maximize expected returns. This adaptation is crucial due to the unpredictability inherent in renewable energy sources, leading to fluctuations in actual returns. Consequently, the optimal scheduling plan must consider the expected returns across various scenarios to effectively manage uncertainty and optimize outcomes.

4. The experimental settings

(1) Experimental equipment and parameter settings

The experimental apparatus and its specifications, as detailed in Table 3, are presented to validate the optimized dispatch model of

Table 3
Experimental equipment.

Equipment Name	Quantity and Specification (Number × Size)
Wind Turbine	4 × 110 MW
Photovoltaic Unit	2 × 10 MW
Turbine Unit	10 × 40 MW
Energy Storage System	5 × 10 MW
Pumped Storage	1 × 100 MW

the VPP.

In addition, the parameters set in the experiment are presented in Table 4.

(2) Experimental scenario design

This section formulates three scenarios to assess the impact of new energy generation on the dispatch of traditional energy production systems and investigates the role of STPP within the system. The non-dispatchable recycled energy generator sets encompass wind power generation and PV power generation.

Scenario 1. Equipped with conventional units and non-dispatchable recycled energy generator sets.

Scenario 2. Considering demand-side response alongside conventional units and non-dispatchable recycled energy generator sets.

Scenario 3. Incorporating demand-side response with conventional units, wind power, PV, energy reposition power plants, and pumped storage systems.

Furthermore, the optimized model is formulated as a combined integer programming model, and its solution is achieved using the YALMIP platform in MATLAB by invoking CPLEX.

The Mixed Integer Linear Programming (MILP) model is a mathematical optimization model designed to solve linear optimization problems involving integer and continuous variables. In the MILP model, the objective function and the constraints are linear, but some of the variables are restricted to integer values. These integer variables typically represent discrete choices or assignments in decision variables. In a given problem, an optimization model can be classified as a MILP if it aims to optimize integer and continuous variables. For example, when resources are either allocated or not allocated, and the allocation of these resources is based on linear relationships, the model can be classified as MILP. In other words, the MILP model considers the properties of linear and integer programming, allowing for efficient optimization between discrete and continuous decision variables. In this study, the optimization model is described as a mixed integer programming model. It involves integer variables (e.g., decision variables representing choices for the allocation of different resources in a power generation system) and linear relationships (e.g., the balance between energy production and consumption). Therefore, the model proposed in this study is classified as MILP.

This simulation involves various parameters, including the technical parameters and operating characteristics of solar thermal, PV, wind power stations, etc. Among them, the maximum installed capacity of the STPP is 100 MW, with a maximum heat storage capacity of 1000 MWh. The PV power station also has a maximum installed capacity of 100 MW, with each PV panel covering an area of 15.7 m^2 and priced at 21,000 US dollars per MW. The wind power station comprises 40 wind turbines, each with a rated power of 2400 kW and a power generation price of $24 per MW. The simulation runs for one day, from 0 to 24 h, using hours as the time unit for the system layer and minutes for the station layer. The simulation run time of the system layer is 24 h, while that of the station layer is 1440 min. In the system layer, scheduling occurs hourly, while in the station layer, dispatching operates at a minute-by-minute granularity. The optimization period is set to 15 min to ensure the system's ability to flexibly schedule and optimize power generation resources in a short time frame. Through comprehensive simulation and analysis of the entire simulation process, the coordination and operational efficiency of different energy systems can be thoroughly evaluated, providing valuable insights for optimizing EPS scheduling.

Application effect of optimized scheduling model based on VPP in new EPSs.

4.1. Day-ahead power forecast results

Before conducting the experiment, a power forecast for both the wind power system and the PV power generation system is performed. The results of this prediction are depicted in Fig. 4.

As depicted in Fig. 4, the power forecast reveals distinct disparities in the power generation profiles of the wind power system and the PV power generation system prior to the day of operation. Notably, during noon hours, the PV power generation system exhibits a pronounced peak in power output, reaching its maximum capacity. Conversely, the wind power system registers relatively lower power output during this period. The power variation trend of the PV power generation system follows a pattern reminiscent of a quadratic function, steadily increasing with solar illumination before gradually declining post-noon peak. In contrast, the power variation trend of the wind power system demonstrates an inverse relationship, peaking close to midnight, presenting characteristics

Table 4
Experimental parameter settings.

Parameter Name	Specific Settings
Wind Turbine Output Power	2.5 MW
Wind Turbine Cut-in and Cut-out Wind Speeds	1 m/s; 10 m/s
Photovoltaic Conversion Efficiency	15 %
Gas Turbine Generator Ramp Rate Limits	30 kW/min; 100 kW/min
Battery Energy Storage System Charging and Discharging Efficiency	95 %
Operating Power of the Pumped Storage System	100 MW
External Grid Selling Price	0.09 USD/kWh
Transmission and Distribution Price	0.03 USD/kWh
Virtual Power Plant Grid Connection Price	0.09 USD/kWh

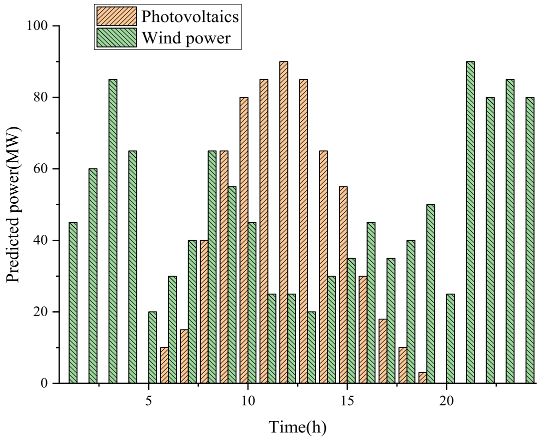
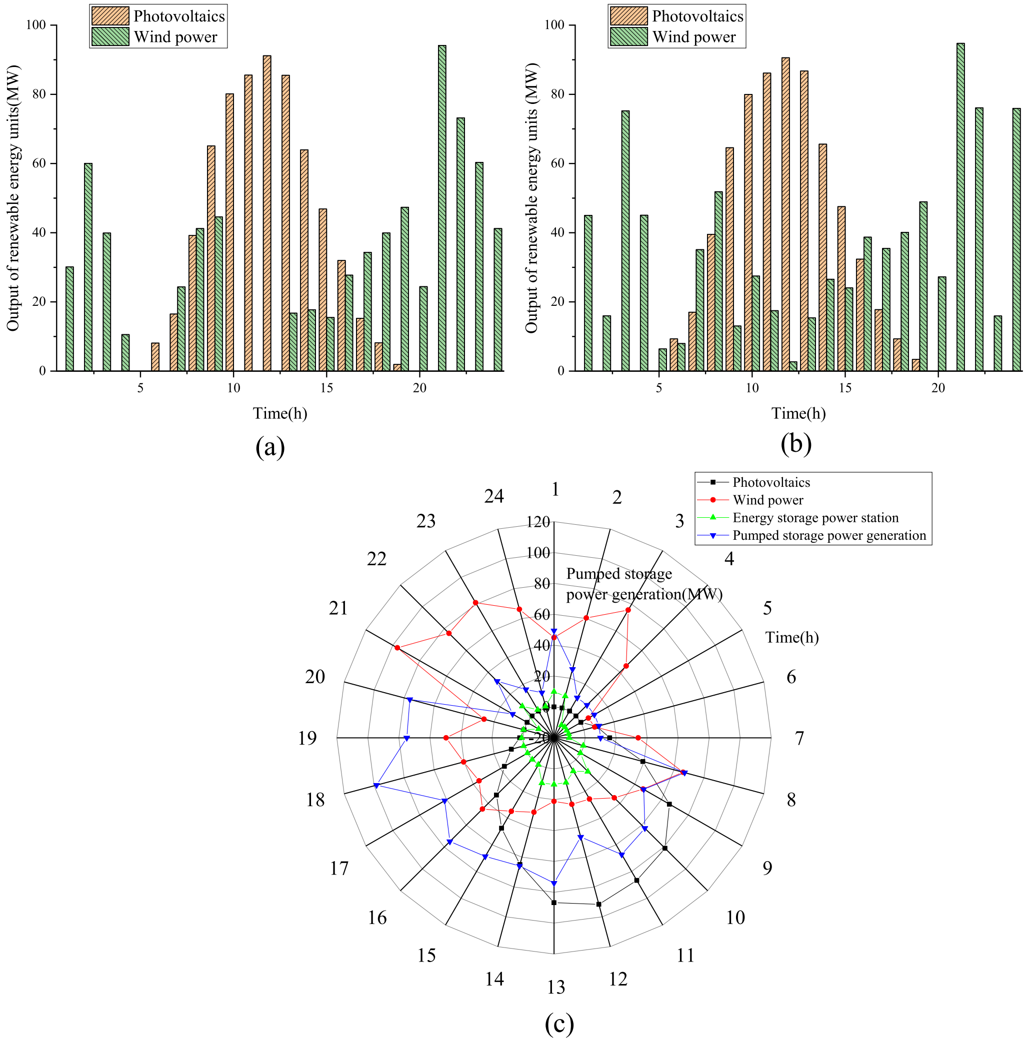


Fig. 4. Day-ahead predicted power.



(a)

(b)

(c)

Fig. 5. Arrangement of generator unit outputs under different scenarios (a) Generator unit output arrangement under scenario 1; (b) Generator unit output arrangement under scenario 2; (c) Generator unit output arrangement under scenario 3.

diametrically opposite to those of the PV power generation system. These findings bear significant implications for EPS operation and scheduling, offering valuable insights for devising system operation strategies. They serve as essential references for optimizing resource utilization and enhancing the operational efficiency of EPS.

4.2. *Effect of optimized scheduling model on individual generator units*

(1) Impact of the optimized scheduling model on individual generator units in various scenarios

Fig. 5 illustrates the effects of the optimized scheduling model on the output organization of different power generation systems across various scenarios.

In scenario 1, as depicted in Fig. 5, wind power generation and PV power generation exhibit distinct temporal patterns. Wind energy generation gradually increases throughout the recording period, starting from a low level and reaching a stable state. Conversely, PV power generation initially peaks, experiences fluctuations, and maintains relative stability thereafter. In scenario 2, wind power generation follows a similar upward trajectory, gradually increasing and stabilizing over time, albeit with intermittent zero-power periods. PV power generation also shows a similar pattern, with occasional zero-power intervals but maintaining overall stability. In scenario 3, both wind power generation and PV power generation exhibit fluctuating trends across the majority of the period. Despite fluctuations, the overall trend for both energy sources is upward, indicating a growing role of renewable energy generation in the energy production landscape. Overall, the gradual increase in both wind power generation and PV power generation aligns with the evolving trend of renewable energy development, underscored by technological advancements and increasing adoption of renewable energy sources.

The integration of demand-side response, pumped storage power generation, and energy storage power stations within the EPS framework yields noteworthy observations. While wind power generation experiences a gradual increase in consumption, the influence on the PV power generation system remains inconspicuous. Notably, a standalone energy storage power station exhibits limited sensitivity to renewable energy power generation systems and fails to fulfill its potential. However, with the incorporation of a pumped storage power generation system, energy storage power stations exhibit heightened activity. Evaluation criteria for this study encompass the evolving trends in renewable energy generation across scenarios, system stability, and the efficacy of energy storage power stations. These findings hold significant implications for guiding EPS operation scheduling and planning, offering theoretical underpinnings and practical directives for optimizing energy resource utilization, enhancing system stability and economic efficiency. Furthermore, the results serve as a crucial reference for fostering sustainable development in EPS and energy transformation initiatives, fostering the adoption of clean energy and the advancement of smart grid infrastructure toward sustainable energy use and environmental conservation.

(2) Comparative analysis of power generation costs across scenarios post-optimization

Fig. 6 illustrates the comparative analysis of power generation costs across three scenarios subsequent to the optimization of the dispatch model.

Fig. 6 illustrates the fluctuation in total power generation costs across different scenarios, showcasing a range from a minimum of €33,447.97 to a maximum of €34,920.16. This observation underscores the substantial impact that varying energy combinations and configurations can exert on overall power generation expenses. The introduction of non-storage renewable energy generation systems is associated with an increase in total power generation costs. Conversely, the incorporation of battery energy storage power stations and pumped storage power stations leads to a reduction in the system's power generation costs. Notably, the addition of a pumped storage power station results in a significant decrease in both total cost and unit cost of power generation, thereby optimizing the

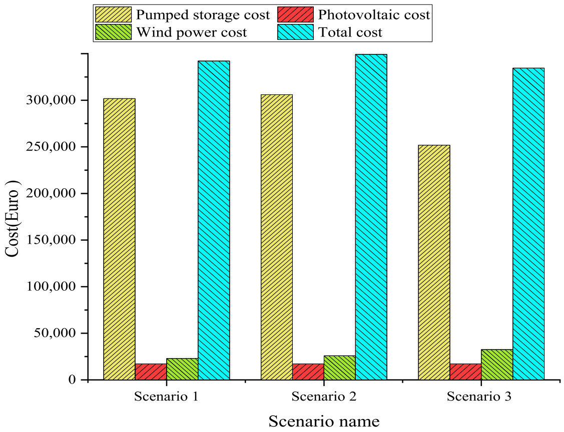


Fig. 6. Electricity generation costs for three scenarios.

overall power generation cost of the system.

5. Discussion

In this study, a cost-optimal scheduling model based on VPP is proposed to construct an optimized VPP development system within the market environment and promote VPP advancement. Unlike existing VPP models and methods, the proposed model comprehensively integrates the demand response model of multiple energy sources and price basis, along with the load constraints of each subsystem. By formulating the problem as a mixed integer linear optimization problem and utilizing a CPLEX solver, the optimal scheduling results for each generating unit are realized. The VPP-based cost-optimal scheduling model achieved remarkable results in increasing the proportion of renewable energy consumption and reducing the overall system power generation cost. Firstly, the integration of pumped storage power stations into the renewable energy generation system minimized total system costs and notably increased the proportion of renewable energy consumed. Pumped storage power stations offer efficient energy conversion and storage capacity, enabling flexible adjustment between energy supply and demand. This enhances system stability, scheduling performance, and reduces operating costs. Secondly, the study emphasizes the significance of concentrated PV power generation and discusses its impact on system stability and overall power generation cost through optimal scheduling and rational allocation of energy storage systems. Concentrated PV power generation provides a reliable base power supply and stable generation characteristics, aiding in balancing renewable energy source fluctuations, thereby enhancing system reliability and stability. Lastly, the study underscores the critical role of maximizing energy storage equipment utilization. By fully utilizing energy storage equipment, the study emphasizes better management of load and energy fluctuations, improving system efficiency and reliability. Consequently, the cost-optimal scheduling model proposed in this study comprehensively considers these factors and has been empirically validated, offering a viable solution to bolster the proportion of renewable energy consumption while concurrently curbing overall power generation costs. The findings of this investigation resonate with the pressing imperatives of the ongoing energy transition and underscore the significant potential of VPPs in realizing sustainable energy usage objectives. By integrating pumped storage power stations, concentrated PV power generation, and other technical innovations, the proposed model not only achieves notable reductions in system operating costs but also furnishes practical strategies for the sustainable evolution of forthcoming power systems. This research outcome holds considerable significance within the academic domain and furnishes invaluable insights for policymakers and stakeholders in the energy industry. It facilitates the advancement of clean energy utilization and smart grid infrastructure, thus contributing to the realization of sustainable energy utilization goals and environmental conservation efforts.

6. Conclusion

This study integrates a VPP with a novel power system and presents an optimized scheduling model based on PBDR within the VPP framework. The objective is to mitigate the impact of renewable energy fluctuations on the grid and enhance the overall utilization of renewable energy sources. Experimental findings indicate that the incorporation of a pumped storage power station substantially heightens the activity level of energy storage facilities, resulting in a marked reduction in the overall generation costs of the entire new power system. This underscores the pivotal role of pumped storage power stations in optimized scheduling, effectively trimming system operational costs through their inherent flexibility and efficiency. Concurrently, there is a significant uptick in the proportion of renewable energy consumption within the new power system, highlighting the practical application potential of VPP theory within this context. This study offers robust evidence supporting the attainment of low-cost and efficient EPS operation. Moreover, the adoption of the optimized scheduling model facilitates the widespread adoption of clean energy, fosters sustainable development in the renewable energy sector, and provides technological and strategic underpinnings for realizing carbon neutrality objectives and addressing climate change challenges.

While yielding significant findings, this study also reveals certain limitations that warrant further refinement. Firstly, the proposed optimization scheduling model exhibits prolonged solving times, hampering its efficiency and real-world applicability. Future research endeavors should thus prioritize enhancing the computational efficiency of the model through algorithmic optimizations. Secondly, the study's treatment of uncertainties is limited, failing to comprehensively address diverse uncertainty factors from external environments, energy supply, and demand sides. Future investigations could explore robust modeling and handling methods for multi-source uncertainties to bolster the model's resilience and versatility. Additionally, the current research predominantly focuses on optimizing the scale of complementary energy storage and reducing generation costs, with scant attention to specific operational strategies and control mechanisms for ESSs. Subsequent research efforts can delve into these aspects to achieve optimal ESS operation. Lastly, the study confines its optimization scheduling analysis to a single scenario, thus limiting its adaptability to various operational contexts. Future explorations could extend to optimization scheduling across multiple scenarios, catering to the diverse operational requirements of power systems under different conditions. In summary, future research directions encompass optimizing solving algorithms, enhancing modeling and handling of multi-source uncertainties, exploring operational strategies and control mechanisms for ESSs, and addressing optimization scheduling across multiple scenarios. These efforts aim to further enrich and broaden the scope and applications of this study.

Data availability

All data generated or analysed during this study are included in this published article [and its supplementary information files].

CRediT authorship contribution statement

Beibei Guo: Writing – review & editing, Writing – original draft, Visualization, Methodology, Funding acquisition, Data curation, Conceptualization. **Fenglin Li:** Writing – review & editing, Visualization, Supervision, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Jie Yang:** Writing – review & editing, Writing – original draft, Validation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Wei Yang:** Writing – original draft, Visualization, Validation, Software, Formal analysis, Data curation, Conceptualization. **Boyang Sun:** Writing – review & editing, Visualization, Resources, Project administration, Data curation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:Jie Yang reports financial support was provided by Key Scientifc and Technological Problems in Henan Province. If there are other authors, they 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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e31748.

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