Real-time Energy Management for Net-zero Power Systems Based on Shared Energy Storage

Pengbo Du, Bonan Huang, Ziming Liu, *Student Member*, *IEEE*, Chao Yang, and Qiuye Sun, *Senior Member*, *IEEE*

Abstract—**Battery energy storage systems (BESSs) serve a crucial role in balancing energy fluctuations and reducing carbon emissions in net-zero power systems. However, the efficiency and cost performance have remained significant challenges, which hinders the widespread adoption and development of BESSs. To address these challenges, this paper proposes a real-time energy management scheme that considers the involvement of prosumers to support net-zero power systems. The scheme is based on two shared energy storage models, referred to as energy storage sale model and power line lease model. The energy storage sale model balances real-time power deviations by energy interaction with the goal of minimizing system costs while generating revenue for shared energy storage providers (ESPs). Additionally, power line lease model supports peer-to-peer (P2P) power trading among prosumers through the power lines laid by ESPs to connect each prosumer. This model allows ESP to earn profits from the use of power lines while balancing power deviations and better consuming renewable energy. Experimental results validate the effectiveness of the proposed scheme, ensuring stable power supply for net-zero power systems and providing benefits for both the ESP and prosumers.**

Index Terms—**Shared energy storage, energy storage provider (ESP), energy management, peer-to-peer (P2P) trading, net-zero power system.**

I. Introduction

In recent years, the clean and low-carbon transformation of the power systems has become an important development direction for energy and electricity [1]. The net-zero power system is a new type of power system constructed to ensure net-zero carbon emission. Carbon capture technology is one of the most critical net-zero technologies available, and is essential to achieving the goal of zero and negative carbon emissions [2]-[4]. In this context, the development and utilization of renewable energy sources (RESs) can reduce the environmental pollution and ecological damage caused by excessive reliance on fossil fuels, optimize the energy structure, and effectively alleviate global climate change and other environmental issues [5]. However, the instability and intermittency of the RES make it challenging to maintain a balance between electricity grid demand and supply, leading to fluctuations in frequency and voltage within the power systems [6].

The application of battery energy storage systems (BESSs) serve as an effective means to tackle the aforementioned challenges. They have gained extensive application in peak and frequency regulation within power systems. BESSs help mitigate fluctuations in RES generation and enhance the dependability of power delivery to electricity consumers [7]-[10]. On the energy supply side, RESs such as wind power and photovoltaic (PV) power have been experiencing rapid development. However, their output is intermittent, which leads to a mismatch between supply and demand [11]. The integration with energy storage not only enables the provision of continuous and reliable electricity to users but also mitigates the impact of distributed power on the stability of power systems [12]-[14]. Using demand-side energy storage configuration as an example, energy storage by storing electricity in low prices of grid and vice versa can save electricity expenses for users. Additionally, it helps reduce the load on the grid [15]-[17]. Previous research on user-side energy storage has typically focused on the "self-storage, self-use" mode, resulting in a significant amount of unused storage resources and exposing issues of investment waste, thereby failing to achieve the maximum effectiveness [18]. Some researchers have examined the case for energy storage sharing among users. In [19], multiple load users can share their invested BESSs mutually. In [20], numerous households can utilize an auction mechanism to share their BESSs with public facilities in community. However, [18]-[20] still necessitated that users bear the investment of BESSs. The excessive cost of investment imposes an economic burden on users, exacerbating issues such as resource idleness typically observed on the user side.

Over the past decade, the emergence of the sharing economy has provided a novel approach to improving the efficiency of resource use, which has been widely used in fields such as housing rental and transportation and has resulted in

Manuscript received: August 3, 2023; revised: November 2, 2023; accepted: December 30, 2023. Date of CrossCheck: December 30, 2023. Date of online publication: February 2, 2024.

This work was supported in part by the National Key Research and Development Program of China (No. 2018YFA0702200), the National Natural Science Foundation of China (No. 52377079), and the Liaoning Revitalization Talents Program (No. XLYC2007181).

P. Du, B. Huang (corresponding author), Z. Liu, and Q. Sun are with the School of Information Science and Engineering, Northeastern University, Shenyang 110004, China (e-mail: 2310254@stu.neu.edu.cn; huangbonan@ise.neu.edu.cn; liuzimingee@stumail.neu.edu.cn; sunqiuye@ise.neu.edu.cn).

C. Yang is with the Information and Communication Branch, State Grid Liaoning Electric Power Company Ltd., Shenyang 110004, China (e-mail: yangchaoneu@sina.com).

DOI: 10.35833/MPCE.2023.000535

significant economic gains [21]-[23]. Accordingly, the concept of "shared energy storage", which combines the sharing economy and energy storage, has been proposed to address the challenges of high investment costs and operational difficulties of energy storage operations [24], [25]. The shared model provides a clearer and more explicit investment framework to attract third-party capital investment and development. Energy storage providers (ESPs) offer energy storage services to users, which can be categorized into two types: capacity-based allocation and energy-based interaction. In [26], users can acquire capacity from shared energy storage facilities. This approach has the capability to decrease the average investment cost of energy storage, but due to the fundamental absence of practical energy exchange users, the attainment of optimal social energy remains unachievable. In [27], the ESP aggregated the BESS charging and discharging strategies of all users, and coordinated the optimal design of the capacity of shared energy storage based on the results of the aggregation with the objective of minimizing the total cost. Reference [28] modeled the interaction between the operator of facilities such as energy storage and the users as a two-level optimization problem, using apartment buildings equipped with energy storage and PV facilities as the study object. In this case, the distributed energy facilities such as energy storage are owned by a third party, and the users in the residential building can choose to purchase electricity from the facilities such as energy storage or from the grid to meet their daily electricity demands.

The development of the energy management strategy is another significant concern within the realm of energy sharing [29]. The energy management system is responsible for scheduling, managing, and planning the energy sharing systems, ensuring coordinated economic operation among its various modules [30]. It should be noted that the development of energy management strategy is closely associated with the proposal of energy sharing mechanism. However, [30] explored a rather limited pattern of energy storage sharing, focusing only on the service model wherein ESPs offer charging and discharging services to users under third-party investment and construction.

Recently, the coordination between prosumers and ESPs has led to better energy utilization. In [31], a new cooperative sharing framework was proposed in day-ahead (DA) stage, which consists of prosumers, an ESP, and an ESP agent. Reference [32] focused on how an energy sharing network can be formed among prosumers with the assistance of an ESP, which was considered as an energy management issue within a smart grid context. Reference [33] proposed a framework for peer-to-peer (P2P) energy sharing of buildings in a community to achieve sustainable development of building communities. However, the above studies did not consider the environmental pollution caused by CO_2 emissions in the energy sharing process. There is a lack of reasonable trading rules for energy sharing behaviors among prosumers through ESPs. Furthermore, the realization of P2P specific energy sharing among prosumers lacks the support of practical lines. Moreover, the aforementioned literature primarily focused on investigating energy sharing management strategies in the DA stage. However, in the real-time stage, electricity demands to be purchased from the grid at a high price, which not only increases system expenses but also indirectly contributes to carbon emissions. Hence, determining a rational energy sharing mechanism is a fundamental issue. And it is crucial to introduce a real-time energy management scheme for facilitating energy sharing in net-zero power systems. In real-time energy management, energy can be dynamically adapted to be generated and consumed in response to changes in demand, thereby better mitigating the challenges posed by energy fluctuations. In addition, the real-time energy management utilizes real-time information for intelligent deployment of energy demand and supply, which effectively reduces operating costs and improves utilization efficiency. Therefore, real-time energy management has become a research hotspot of energy section. Reference [34] proposed a real-time energy management method for electric vehicles that combines batteries and supercapacitors, which utilizes a Pontryagin's minimum principle strategy to save the cost of battery usage. Reference [35] proposed a real-time energy management scheme based on an adaptive approach, which reduces the operating cost of microgrids. Reference [36] proposed an optimal real-time energy management scheme based on optimal currents, which coordinates distributed renewable energy generation to reduce the energy demand of the distribution network. However, the real-time energy management for shared energy storage is imperfect, so it is a fundamental problem to develop a reasonable energy sharing mechanism.

Herein, we propose a new framework for net-zero power systems and give a real-time energy management scheme. The new framework consists of carbon capture power plants, thermal power units, wind turbines, ESP, prosumers, and demand responses (DRs). Carbon capture power plants are the result of decarbonizing traditional thermal power units, enabling highly carbonized thermal power units to achieve low-carbon emissions for the purpose of reducing carbon emissions from the system. An ESP charges and discharges as well as shares its lines under the management of the system operator. Prosumers equipped with shifting loads and PV balance their own demand and supply by participating in the framework, and the ESP deploys power lines for groups of prosumers to realize energy interactions among prosumers. DRs facilitate the provision of responsive services to address the demand requirements of the system. We focus on an energy management optimization problem during the real-time stage. The real-time energy management optimization takes into account both the energy storage sale model and the power line lease model of ESP, and in order to guarantee the net-zero nature of the system, the carbon capture power plant and wind turbine also provide the energy supply. Considering the cost of participants in the net-zero power system and the cost of P2P power trading among prosumers, the goal is to minimize the total cost of the system through energy management.

To this end, this paper aims to address the issue of real-time energy sharing management in the net-zero power system. The main contributions and organization of the paper are outlined as follows.

1) A novel real-time energy management scheme based on shared energy storage is developed for net-zero power systems. In the proposed scheme, a real-time energy management model is established, taking into account the cost of carbon capture power plants, operating costs of thermal power units, the load-shifting cost of DR, and the battery degradation cost of ESP. Furthermore, the cost of P2P power trading among prosumers is considered to address the issue of energy shortage after DA scheduling.

2) Two sharing models of ESP are proposed for the real-time stage, expanding energy sharing into the energy storage sale model and the power line lease model. The energy storage sale model involves the collaboration between ESP and carbon capture power plants to mitigate energy imbalances. The power line lease model aims to provide circuits for P2P transactions among prosumers. The combined effect of these sharing models enhances the consumption of renewable energy and increases the profitability of ESPs.

3) A P2P power trading approach based on game theory is proposed within a shared energy storage framework to address real-time partial supply shortages. Stepped lease fees are set up for lines constructed by ESP to be leased by exporting prosumers (EPs). Building upon the known power line lease fees, a game-based pricing strategy is employed between EPs and importing prosumers (IPs). This process enhances the utility for prosumers and promotes the consumption of renewable energy.

The rest of this paper is organized as follows. Section II presents the mathematical model that describes the main entities involved in the energy sharing framework for net-zero power systems. In Section III, a real-time optimization model of energy sharing for net-zero power systems is proposed. Numerous case studies are carried out in Section IV. Section V provides a summary of the main contributions of this paper.

II. Mathematical Modeling of Energy Sharing Framework for Net-zero Power Systems

The energy sharing framework for net-zero power systems is shown in Fig. 1, which includes the carbon capture power plant, wind turbines, ESP, load, prosumers, and DRs.

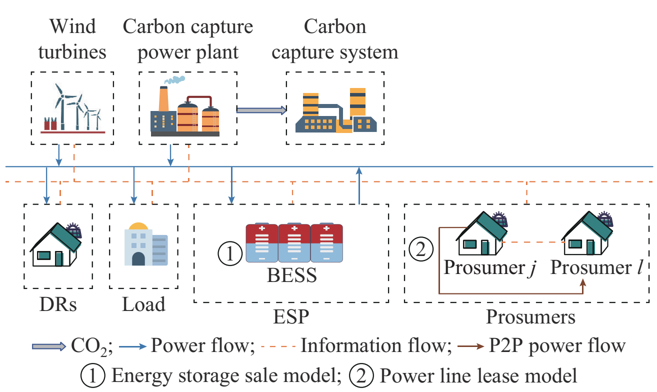

Fig. 1. Energy sharing framework for net-zero power system.

Carbon capture power plant is the low-carbon one that improve on traditional thermal power units; wind turbines act as power generators to provide electricity to the system load; ESP owns numerous BESSs; and electricity users exhibit various electricity attributes, including shiftable loads such as DRs, prosumers with rooftop PV, and others with conventional loads. Every participant is linked to a network, and the information network and the energy network have been adequately established to facilitate the smooth communication and the exchange of energy among all participants. The model for each participant is described below.

A. Modeling of Carbon Capture Power Plant

Carbon capture power plant is the result of low-carbon transformation of traditional thermal power units, enabling high-carbon power plants to achieve the objective of reducing system emissions. The total power output of carbon capture power plants includes two components: net output power and carbon capture energy consumption [37].

$$P_{Gi,t}=P_{GHi,t}+P_{Yi,t}+P_{Di} \tag{1}$$

where $P_{Gi,t}$ is the total power generated by the thermal power unit i; $P_{GHi,t}$ is the net output power of the thermal power unit i; P_{Di} is the fixed energy consumption of carbon capture; and $P_{Yi,t}$ is the operational energy consumption of carbon capture. The relationship between $P_{Yi,t}$ and the amount of CO_2 captured $E_{BCO_2,i,t}$ can be expressed as:

$$P_{Yi,t}=\sigma_i E_{BCO_2,i,t} \tag{2}$$

where σ_i is the energy consumption required per unit of CO_2 captured. The actual carbon emissions from the thermal power unit are as follows:

$$E_{Gi,t}=e_i P_{Gi,t} \tag{3}$$

where e_i is the carbon emission intensity of the thermal power unit i.

B. Modeling of DR

The system operator has the ability to flexibly adjust the electricity consumption schedule of DR loads [38]:

$$\sum_{t=1}^{T} P_{m,t}^{load} = \sum_{t=1}^{T} \overline{P}_{m,t}^{load} \tag{4}$$

$$P_{m,t}^{load,\min} \le P_{m,t}^{load} \le P_{m,t}^{load,\max} \tag{5}$$

where $P_{m,t}^{load}$ and $\overline{P}_{m,t}^{load}$ are the actual shiftable load and the expected shiftable load of DR m in time slot t, respectively; $P_{m,t}^{load,\min}$ and $P_{m,t}^{load,\max}$ are the minimum and maximum shiftable load limits, respectively; and T is the energy management period.

C. Modeling of ESP

In real-time energy management, in order to address the deviations that persist after the DA scheduling due to the uncertainty of renewable energy, as shown in Fig. 1, there are two different energy sharing models of ESP available for systems when it comes to shared energy storage. The first model is the energy storage sale model, where ESP under the coordination of system operators engages in charging and discharging operations in different time slots. This enables energy transfer within the system while increasing the revenue of ESP. The second model is the power line lease model, which involves sharing the energy storage lines directly without the involvement of batteries. This allows for energy sharing among prosumers by utilizing the shared energy storage infrastructure. Notice that these two different models work simultaneously in a net-zero power system, due to the fact that energy supply and demand do not match at every moment.

1) Energy Storage Sale Model

In the energy storage sale model, it is essential for system operators to establish energy management plans. Within these plans, the ESP undergoes regulated charging and discharging actions under the control of the system operator, for which the system operator provides compensation [39]:

$$E_{s,t}=E_{s,t-1}+\eta^{ch}P_{s,t}^{ch}-\frac{1}{\eta^{dis}}P_{s,t}^{dis} \tag{6}$$

$$0\le P_{s,t}^{ch}\le P_{s}^{ch,\max}U_{s,t} \tag{7}$$

$$0\le P_{s,t}^{dis}\le P_{s,t}^{dis,\max}(1-U_{s,t}) \tag{8}$$

$$E_{s}^{\min}\le E_{s,t}\le E_{s}^{\max} \tag{9}$$

$$E_{s,T}=E_{s,0} \tag{10}$$

where η^{ch} and η^{dis} are the charging and discharging efficiencies of the ESP, respectively; $P_{s,t}^{ch}$ and $P_{s,t}^{dis}$ are the charging and discharging power of the ESP in time slot t, respectively; $U_{s,t}$ is a binary variable representing the charging and discharging state of the BESS in time slot t; $P_{s,t}^{ch,\max}$ and $P_{s,t}^{dis,\max}$ are the maximum charging and discharging power of the ESP, respectively; $E_{s,t}$ is the capacity of the ESP in time slot t; $E_{s}^{\min}$ and $E_{s}^{\max}$ are the minimum and maximum residual capacities of the ESP, respectively; and $E_{s,0}$ and $E_{s,T}$ are the initial state and final state of the shared energy storage capacity, respectively.

2) Power Line Lease Model

Compared with the traditional transaction pricing mechanism, a stepped line lease fee pricing mechanism is used in order to ensure the reasonableness of the cost of leasing ESP for prosumers. The pricing mechanism divides the purchase intervals into multiple segments, and as the length of the leasing line increases, the purchase price of the corresponding distance interval increases:

$$\lambda_{D}^{P2P}=\begin{cases}\lambda D_{lj} & 0\le D_{lj}<d\\ \lambda(1+\alpha)(D_{lj}-d)+\lambda d & d\le D_{lj}<2d\\ \lambda(1+2\alpha)(D_{lj}-2d)+\lambda(2+\alpha)d & 2d\le D_{lj}<3d\\ \lambda(1+3\alpha)(D_{lj}-3d)+\lambda(3+3\alpha)d & 3d\le D_{lj}<4d\\ \lambda(1+4\alpha)(D_{lj}-4d)+\lambda(4+6\alpha)d & D_{lj}\ge 4d\end{cases} \tag{11}$$

where λ_{D}^{P2P} is the stepped line lease fee set by ESP for EPs; λ is the line lease price coefficient for decision-making of ESP, which is used to compensate for line losses incurred by ESP; d is the distance interval length; α is the price growth rate; and D_{lj} is the distance between prosumers in P2P transactions, which reflects the utilization level of P2P transactions between prosumers for the shared routes constructed by ESP.

D. Modeling of Prosumers

Prosumers play a crucial role in the power line lease model as entities capable of both generating and consuming electricity. In the energy sharing, we assume that prosumers during each time period can be classified into IPs and EPs based on their individual electricity situation.

The EP determines the line lease fee to be paid by the IP with whom it conducts a P2P transaction based on the length of the distance and credits it to the revenue function. As sellers of electricity in P2P transactions, the EPs want to maximize their financial benefits. The profit of EPs U_{EP} consists of the electricity sold, the electricity price, and the line lease fee:

$$U_{EP}=\sum_{t=1}^{T_a}(\varphi_t p_{j,t}-\lambda_{D}^{P2P}p_{j,t}) \tag{12}$$

where $\sum_{t=1}^{T_a}\varphi_t p_{j,t}$ is the income of P2P power trading; T_a is the period in which the P2P transaction among prosumers occurs; φ_t is the ultimate matched price for P2P power trading in time slot t; and $p_{j,t}$ is the discharging power of the EP.

In P2P transactions among prosumers, the IP aims to purchase electricity at a lower price. Moreover, the IP also expects the seller to provide electricity in a timely manner to meet its own power consumption demands. Therefore, the electricity purchasing behavior of IP is influenced by both the price and the reputation of the EP. To better describe the electricity purchasing demands of prosumers, an utility function U_{IP} is established for the IP:

$$U_{IP}=q_1\sum_{t=1}^{T_a}\varphi_t p_{l,t}-q_2 R_j-q_3\sum_{t=1}^{T_a}k_{l,t}\ln(1+p_{l,t}) \tag{13}$$

where $p_{l,t}$ is the charging power of the IP; R_j is the reputation value of the EP who provides electricity to the IP, and a higher reputation value indicates a higher quality of charging service provided by the EP; q_1 and q_2 are the preference coefficients of the IP for charging costs and the reputation value of the EP, respectively; q_3 is the coefficient of the utility received by the pronsumer for carrying out the consumption of electrical energy; and $k_{l,t}\ln(1+p_{l,t})$ is the utility that IP achieves through consuming energy $p_{l,t}$. The IP determines the values of q_1 and q_2 based on their own preferences, and they satisfy the condition $q_1+q_2+q_3=1$.

III. Real-time Optimization Model of Energy Sharing for Net-zero Power Systems

A. Description of Proposed Real-time Energy Management Scheme

We present an overview of a two-stage decision-making process involving the net-zero power system. Due to the involvement of fewer entities in the decision-making process in the DA stage, and the absence of participants such as shared energy storage, our research focuses on energy sharing management strategies in the real-time stage. The scheduling process of the DA stage is not elaborated in detail. The decision-making process for real-time energy management is based on careful consideration of system structure and energy sharing models. The corresponding flowchart of the optimization problem modeling is illustrated in Fig. 2.

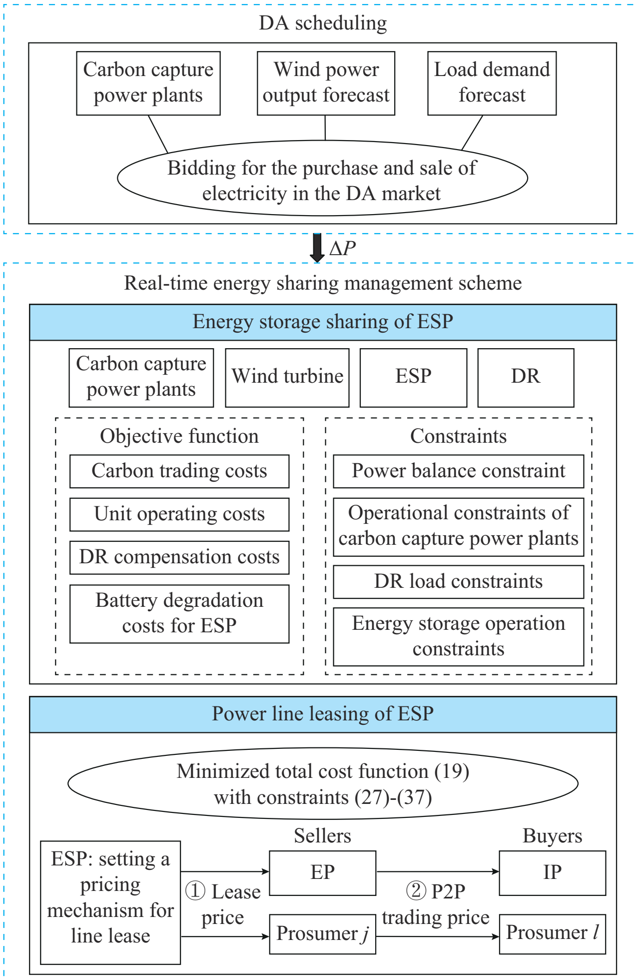

Fig. 2. Flowchart of optimization problem modeling.

1) DA optimization. The net-zero system considers the economic costs of individual participants in the case of load demand forecast and wind power output forecast. The purpose of the DA scheduling plan is to provide a baseline for the startup and shutdown condition of the units and an output reference of the following day [40].

A one-hour time interval is used, with a one-day cycle, to formulate a 24-hour scheduling plan for the following day based on short-term forecast of load and wind power. The objective function C_1 consists of startup and shutdown costs, carbon trading costs, and thermal unit operating cost:

$$\min C_1 = \min(C_K + C_P + C_H) \tag{14}$$

$$P_{W,t} + \sum_{i=1}^{n} u_{i,t} P_{GHi,t} = P_{el,t} \tag{15}$$

$$u_{i,t} P_{Gi}^{\min} \le P_{Gi,t} \le u_{i,t} P_{Gi}^{\max} \tag{16}$$

$$-R_{Di} \le P_{Gi,t} - P_{Gi,t-1} \le R_{Ui} \tag{17}$$

where C_K is the startup and shutdown cost of thermal power units; C_P is the cost of purchasing carbon emission trading rights; C_H is the operating cost of thermal power units; $P_{Gi}^{\min}$ and $P_{Gi}^{\max}$ are the minimum and maximum output power of thermal power unit i, respectively; R_{Di} and R_{Ui} are the down ramp rate (hourly) and up ramp rate (hourly) of thermal power unit i, respectively; $P_{W,t}$ is the planned wind power output in the energy management; $u_{i,t}$ is the startup and shutdown status of thermal power unit i; n is the number of units; and $P_{el,t}$ is the amount of electricity used by the load in time slot t. The output climbing speed constraint, thermal unit startup and shutdown time constraints, and spinning reserve constraints of the thermal power unit are detailed in [41].

For the purpose of assessing the stability of the distribution network, the power fluctuation of the distribution network (energy deviation after DA scheduling due to wind power output forecast deviation) ΔP is defined as:

$$\Delta P = \left| \left(P_{W,t} + \sum_{i=1}^{n} u_{i,t} P_{GHi,t} \right) - P_{el,t} \right| \le \varepsilon \tag{18}$$

where ε is the threshold of fluctuation. When the deviation between the generation side and the load side is significant denoted by $\left| P_t^{flu} \right| > \varepsilon$, the system operator will perform further real-time stages of energy management to maintain the balance of energy supply and demand.

2) Real-time optimization. The scheduling results in DA stage can promote the energy utilization efficiency of the proposed framework by minimizing the total energy cost, based on which the bidding power for the next 24 hours is declared to the electricity market. After the transaction settlement in DA phase is optimized, in order to improve the efficiency of energy utilization, the benefits of ESP are increased, and the carbon emissions during the real-time stage are reduced. A real-time energy management scheme based on shared energy storage is proposed to ensure the balance of energy supply and demand of the system and net-zero carbon emissions, considering the existence of wind power output forecast deviations. The scheme is based on energy sharing management realized in two different sharing models of ESP.

B. Overall Objective Function

The purpose of the system operator during the real-time stage is to provide a unit output plan, which is based on ultra-short-term forecast of wind power and load in 15-min periods. Considering unit operating costs, carbon trading costs, load shifting costs for DR, battery degradation costs for ESP, and P2P power trading costs for ESP lines, the overall objective function can be established as:

$$\min C = \min C_{ESSM} + \min C_{P2P} \tag{19}$$

where C_{ESSM} is the total system cost under the energy storage sale model; and C_{P2P} is the cost of P2P power trading under the power line lease model.

In the real-time stage of energy management, the consideration of unit startup and shutdown is omitted. Instead, the focus lies solely on operating costs, carbon trading costs, load transfer costs associated with DR, and battery degradation costs associated with ESP.

Given that the startup and shutdown schedule of thermal power units has been determined in DA stage, the relevant constraints are not considered. However, since the time scale changes from 1 hour to 15 min, the climbing constraints and spinning reserve constraints for thermal power units are modified. The mathematical formulation for this can be expressed as:

$$C_{ESSM} = C_H + C_P + C_m(\boldsymbol{P}_m^{load}) + C_s(\boldsymbol{P}_s^{ch}, \boldsymbol{P}_s^{dis}) \tag{20}$$

where $C_m(\cdot)$ is the cost of compensation for DRs; $\boldsymbol{P}_m^{load} := [P_{m,1}^{load}, P_{m,2}^{load}, ..., P_{m,T}^{load}]$; $C_s(\cdot)$ is the cost of charging and discharging of ESP; $\boldsymbol{P}_s^{ch} := [P_{s,1}^{ch}, P_{s,2}^{ch}, ..., P_{s,T}^{ch}]$; and $\boldsymbol{P}_s^{dis} := [P_{s,1}^{dis}, P_{s,2}^{dis}, ..., P_{s,T}^{dis}]$

However, carbon trading occurs when there is a variance between carbon emissions and carbon emission allowances.

C_P can be expressed as:

$$C_P = \gamma\left(E_a - \sum_{i=1}^{n}\sum_{t=1}^{T}\theta_b P_{Gi,t}\right) \tag{21}$$

where γ is the carbon trading price; E_a is the amount of CO_2 emitted by the thermal power unit i operating in time slot t; and θ_b is the carbon allowance coefficient. C_P consists of two parts: the first one represents the amount of CO_2 produced by the thermal power unit i operating in time slot t, and the second one is the amount of CO_2 captured by the carbon capture device.

C_K can be expressed as [41]:

$$C_K = \sum_{i=1}^{n}\tau_i\sum_{t=1}^{24}[u_{i,t}(1-u_{i,t-1}) + u_{i,t-1}(1-u_{i,t})] \tag{22}$$

where τ_i is the unit startup and shutdown cost of thermal power unit i.

C_H can be expressed as:

$$C_H = \sum_{t=1}^{T}\sum_{i=1}^{n}(a_i P_{Gi,t}^2 + b_i P_{Gi,t} + c_i) \tag{23}$$

where a_i, b_i, and c_i are the operating cost coefficients of thermal power unit i.

$C_s(\boldsymbol{P}_s^{ch}, \boldsymbol{P}_s^{dis})$ can be expressed as:

$$C_s(\boldsymbol{P}_s^{ch}, \boldsymbol{P}_s^{dis}) = \rho_s\sum_{t=1}^{T}(P_{s,t}^{ch}\eta^{ch} + P_{s,t}^{dis}/\eta^{dis}) \tag{24}$$

where ρ_s is the degradation parameter of the BESS for ESP, and $\rho_s > 0$.

However, the alteration of electricity schedules inevitably affects user comfort. Therefore, the system operator needs to provide appropriate compensation. $C_m(\boldsymbol{P}_m^{load})$ can be expressed as:

$$C_m(\boldsymbol{P}_m^{load}) = \beta_m\sum_{t=1}^{T}\left|P_{m,t}^{load} - \overline{P}_{m,t}^{load}\right| \tag{25}$$

where β_m is the unit scheduling cost of load for DR, which reflects the adverse impact on the deviation of shiftable load for DR m.

In order to conclude transactions among prosumers, we design a P2P power trading scheme among prosumers, which normalizes the trading behavior of prosumers. It is assumed that in the real-time energy management stage, the value of power deviation after the energy storage sale model of ESP can be compensated by the P2P trading volume of all prosumers, and the overall system will not generate additional energy demand. The P2P power trading among prosumers is facilitated through shared energy storage infrastructure, and therefore, prosumers should allocate a certain power lease fee to the ESP. However, this cost is influenced by the distance among the prosumers engaged in transactions and the length of power lines connected to the shared energy storage infrastructure, as well as the power of P2P transactions in which the prosumers participate in. Prosumers aim to minimize the frequency of P2P transactions as much as possible in order to reduce their costs and maximize their own utility.

$$C_{P2P} = \sum_{j\in K}\sum_{t=1}^{T}\lambda_D^{P2P}\left|P_{lj,t}^{P2P}\right| \tag{26}$$

where K is the set of EPs; and $P_{lj,t}^{P2P}$ is the power of P2P final transactions among prosumers.

C. Constraints

1) Power System Constraints

The main constraints of the power system include power balance constraints, thermal power unit output constraints, thermal power unit ramp constraints, spinning reserve constraints, and wind power output constraints.

$$\sum_{i=1}^{n}P_{GHi,t} + P_{W,t} - \left(P_{el,t} + \sum_{m=1}^{M}P_{m,t}^{load} + P_{s,t}^{ch} - P_{s,t}^{dis} + P_{lj,t}^{P2P}\right) = 0 \tag{27}$$

where M is the number of DRs.

Notice that (16) and (17) represent the constraints of the DA schedule, while the climbing and spinning reserve constraints in the real-time stage are as follows:

$$-\frac{R_{Di}}{4} \le P_{Gi,t} - P_{Gi,t-1} \le \frac{R_{Ui}}{4} \tag{28}$$

$$\begin{cases}\sum_{i=1}^{n}\min\left[\frac{R_{Ui}}{4}, u_{i,t}P_{GJi}^{\max} - P_{GHi,t}\right] \ge \mu_{11}P_{el,t} + \mu_{22}P_{wcp}\\ \sum_{i=1}^{n}\min\left[\frac{R_{Di}}{4}, P_{GHi,t} - u_{i,t}P_{GJi}^{\min}\right] \ge \mu_{11}P_{el,t} + \mu_{22}P_{wcp}\end{cases} \tag{29}$$

where μ_{11} and μ_{22} are the reserve capacity factors set for load and wind power uncertainty, respectively; $P_{GJi}^{\max}$ and $P_{GJi}^{\min}$ are the maximum and minimum net output power of thermal power unit i, respectively; and P_{wcp} is the installed capacity of the wind farm.

The upper and lower bounds of wind power are:

$$0 \le P_{W,t} \le P_{F,t} \tag{30}$$

where $P_{F,t}$ is the predicted wind power.

2) Prosumer Constraints

The amount of electricity sold by the EP j is described as:

$$p_{req} \le p_{j,t} \le p_j^{\max} \quad \forall t \in T_a \tag{31}$$

where p_{req} and $p_j^{\max}$ are the minimum and maximum power to support P2P transactions, respectively.

The battery capacity constraints for the EP are:

$$\begin{cases}B_{j,lim} \le B_{j,t} = B_{j,t-1} - p_{j,t}/\eta_j \le B_{j,\max} \quad \forall t \in T_a\\ B_{j,1} = B_{j,0}\end{cases} \tag{32}$$

where $B_{j,lim}$ is the limit value of battery capacity; $B_{j,t}$ is the the battery capacity of the EP's own energy storage; $B_{j,\max}$ is the limit value of battery capacity; η_j is the charging/discharging efficiency of the battery of EP; and $B_{j,1} = B_{j,0}$ indicates that the capacity of the battery at $t=1$ is equal to the initial capacity value at $t=0$, which implies that there is no discharging behavior between $t=0$ and $t=1$.

EP as the seller of the trading price should have a reasonable price range:

$$\varphi_t^{\mathrm{l}} \le \varphi_t \le \varphi_t^{\mathrm{u}} \quad \forall t \in T_a \tag{33}$$

where φ_t^{l} is the price of the previous charging of the EP; and φ_t^{u} is the trading price of the real-time market.

$$\sum_{t=1}^{T_a} p_{l,t} = \gamma_l B_l^{\max} - B_l^0 \tag{34}$$

where $B_l^{\max}$ is the maximum battery capacity of the IP; B_l^0 is the initial capacity of the IP; and γ_l is charging ratio coefficient of the IP.

$$\begin{cases} 0 \le p_{l,t} \le p_l^{\max} & \forall t \in T_a \\ p_{l,t} = 0 & \forall t \notin T_a \end{cases} \tag{35}$$

$$\sum_{j \in K} p_{j,t} = \sum_{l \in L} p_{l,t} \quad \forall t \in T_a \tag{36}$$

where $p_l^{\max}$ is the limit value for purchased power; and L is the set of IPs .

D. Solution

We use the YALMIP to build a mathematical model of energy management and use the CPLEX to solve optimization functions in MATLAB, which is an ideal tool for solving mixed-integer linear programming.

In addition, given the solution to the problem of P2P power trading strategies for prosumers, we formulate the optimal power pricing strategy as a multi-objective optimization problem. The objective of this optimization is to maximize the benefits for both parties involved in power trading, encompassing economic gains and utility. The economic benefits are determined by the trading price, traded electricity, and the cost of selling electricity, which contribute to the economic benefits of IP and EP. Additionally, the utility aspect is reflected by the comprehensive reputation value of EP. To establish the pricing mechanism, we propose a multi-objective optimization function as [42]:

$$\begin{cases} \max U_{EP} = \sum_{t=1}^{T_a} (\varphi_t p_{j,t} - \lambda_D^{P2P} p_{j,t}) \\ \min U_{IP} = q_1 \sum_{t=1}^{T_a} \varphi_t p_{l,t} - q_2 R_j - q_3 \sum_{t=1}^{T_a} k_{l,t} \ln(1 + p_{l,t}) \end{cases} \tag{37}$$

IV. Case Study

A. Experiment Environment

The performance of designed energy sharing framework for the net-zero power system is confirmed on a laptop with an Intel Core CPU i7-9750H. We carry out the emulation cases on energy sharing systems with three prosumers and an ESP. Simulation parameters are provided in Table I.

Figure 3 shows the wind power forcast output for real-time stages, and the load forecast result, dividing the 24 hours into a sequence of 96 periods with each period scheduled for 15 min. The PV power generation and PV energy consumption of the prosumers are shown in Fig. 4 and Fig. 5, respectively, where p1 to p3 represent prosumer 1 to prosumer 3, respectively.

TABLE I
Simulation Parameters

Parameter	Value
Initial state of charge (SOC) of BESS	0.2
The minimum and maximum SOCs of BESS	0.2, 0.9
Length of interval in stepped line lease fee pricing mechanism	50 km
Carbon trading price	12 $/t
Price growth rate	25%
Charging/discharging efficiency of BESS	98%
Carbon capture efficiency	80%
Fixed energy consumption	5 MWh
Rated charging/discharging power of ESP	40 MW
Degradation factor for ESP	1.43 $/MW
Carbon emission allowance factor	0.7

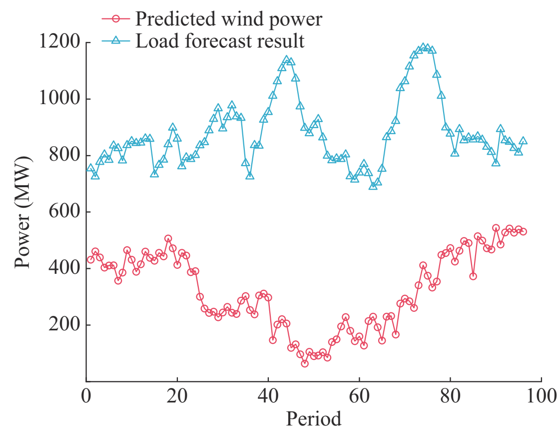

Fig. 3. Predicted wind power output and load forecast result.

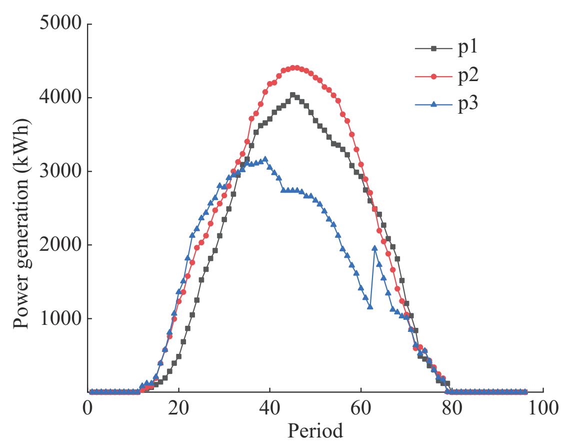

Fig. 4. PV power generation of prosumers.

B. Results and Discussions

The energy sharing results of ESP under different energy sharing models in different time slots are given in Fig. 6 and Fig. 7, respectively. The SOC variation of the BESS is given in Fig. 8. The findings indicate that, with the objective of minimizing the economic cost of system energy management, the ESP operates with different sharing modes in different time slots, and both modes can coexist at the same time scale.

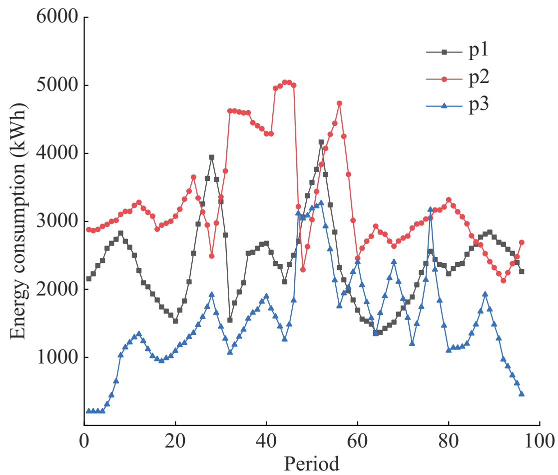

Fig. 5. Energy consumption of prosumers.

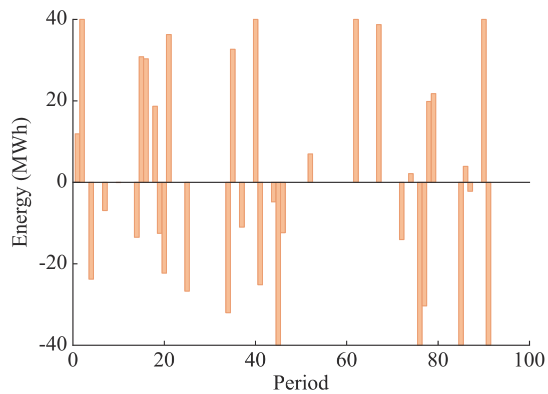

Fig. 6. Energy sharing results under energy storage sale model of ESP.

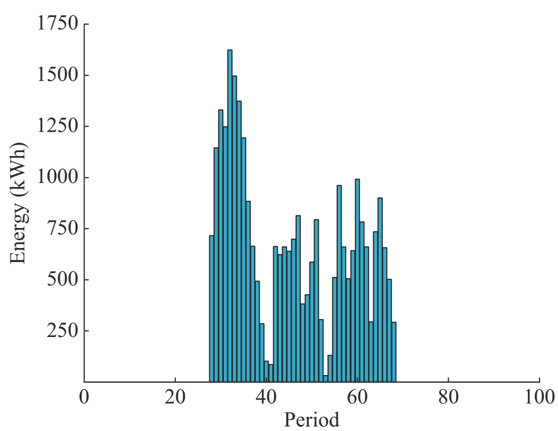

Fig. 7. Energy sharing results under power line lease model of ESP.

From the period when the ESP is under energy storage sale model, it can be observed that the power balance requirement of the system is satisfied due to the participation of energy storage devices in the regulation. This is demonstrated by the fact that: during periods with low-load demand or high wind power generation such as periods of 4-16, the BESS is charged, while during periods with high-load demand such as periods of 40-48 and 72-76, the BESS is discharged to replace some of the output of carbon capture units and meet the load demand. When ESP shares its power lines, it can be observed from Fig. 7 that since the prosumer is a customer equipped with rooftop PV systems, the PV generation facilities cannot produce electricity during the periods of 01:00-06:00 and 19:00-24:00, and the sharing activity cannot be implemented. So P2P transactions among prosumers primarily occur during the period of 08:00-18:00.

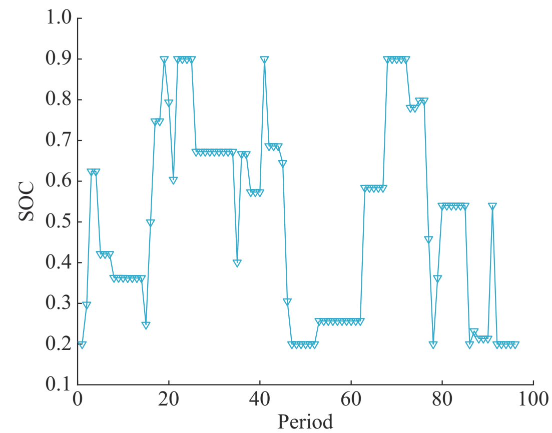

Fig. 8. SOC variation of BESS in different time slots.

Figure 9 shows the net output of thermal power units and the energy consumption of carbon capture units. Due to the presence of the solvent storage tank in the carbon capture power plant, the energy consumption of carbon capture units can be adjusted by regulating the solvent inventory. Specifically, during peak-load periods, the energy consumption of carbon capture units is reduced, while during off-peak-load periods, it is increased. This can facilitate wind power integration and improve the flexibility of the system.

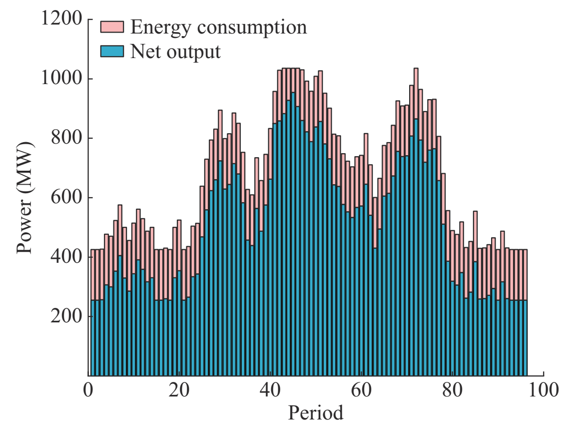

Fig. 9. Net output of thermal power units and energy consumption of carbon capture units.

Table II presents the system optimization results in different scenarios. Scenario 1 considers DRs and the installation of carbon capture power plants without shared energy storage devices. While Scenario 2 is built on Scenario 1 by integrating shared energy storage devices, resulting in a total cost reduction of \$4328. The shared energy storage devices discharge during peak-load periods, and the surplus electricity is utilized by the carbon capture units, leading to a significant reduction of 46.6% in system carbon emissions. The inclusion of shared energy storage devices also decreases the wind curtailment rate and improves wind power integration. ESP can profit from the charging and discharging activities as well as the leasing process, making it a profitable venture for ESP.

With known energy sharing results under power line lease model of ESP, Table III presents the real-time trading strategies between prosumers. Taking the energy sharing during the time period of 07:00-07:15 as an example, as shown in Fig. 7, there is a P2P trading between p1 and p3. The transaction volume between them is 716 kWh. Based on known volumes, the trading prices and volumes for both p1 and p3 at each 1-min time scale are shown in Table III. It can be observed that in time slots with higher trading power, the game-based electricity price is lower, while in time slots with lower power trading, the game-based electricity price is higher. Furthermore, P2P trading price of p1 and p3 is always smaller than the electricity price in the real-time market, which is determined by the objective functions of the EP and IP. This greatly enhances the motivation of prosumers to participate in the shared energy storage framework, and improves the consumption of RESs. The profits of p1, p2, and p3 are \$3375, \$2940, and \$4616, respectively.

TABLE II
SYSTEM OPTIMIZATION RESULTS IN DIFFERENT SCENARIOS

Scenario	Total cost (\$)	Carbon emission (t)	Carbon trading cost (\$)	P2P power trading cost (\$)	Wind power consumption rate (%)	ESP profit (\$)
1	247476	1067	–124678		89.2	0
2	243148	571	–131904	262	98.1	59375

TABLE III
REAL-TIME TRADING STRATEGIES BETWEEN PROSUMERS

Time slot	Power (kWh)	Price (\$/kWh)	Time slot	Power (kWh)	Price (\$/kWh)
1	60	0.11	9	71	0.08
2	67	0.09	10	72	0.08
3	9	0.26	11	12	0.25
4	68	0.09	12	72	0.08
5	47	0.16	13	71	0.08
6	7	0.28	14	36	0.17
7	21	0.21	15	60	0.11
8	41	0.15			

V. CONCLUSION

This paper highlights the significance of BESSs in achieving stable power supply and reducing carbon emissions in net-zero power systems. A real-time energy management scheme is proposed in this study, which incorporates the participation of prosumers to support net-zero power systems. The scheme introduces two shared energy storage models: the energy storage sale model and the power line lease model. The energy storage sale model, combined with a carbon capture power plant, effectively balances real-time power deviations while minimizing costs. The sale of energy storage in BESSs generates revenue for ESP. The power line lease model facilitates P2P power trading among prosumers, utilizing power lines laid by ESP to connect each prosumer. This model allows ESP to earn profits from power line usage while ensuring power balance and maximizing the consumption of RESs. Experimental results demonstrate the effectiveness of the proposed scheme, which ensures stable power supply in net-zero power systems.

For future work, the traditional centralized information management model should be avoided due to the large number of user groups involved in shared energy storage transactions. Adopting this model would exacerbate the potential single point of failure, vulnerability to malicious attacks, and untrustworthiness of the central server. This will lead to the leakage of private data of each user, making it difficult to implement shared energy storage transactions reliably and securely.

REFERENCES

[1] X. Xiao, J. Yin, L. Chen *et al.*, “Evolutionary game-theoretic modeling of massive distributed renewable energy deployment towards low-carbon distribution networks,” *Journal of Modern Power Systems and Clean Energy*, vol. 11, no. 5, pp. 1519-1528, Sept. 2023.

[2] X. Li, R. Zhang, L. Bai *et al.*, “Stochastic low-carbon scheduling with carbon capture power plants and coupon-based demand response,” *Applied Energy*, vol. 210, pp. 1219-1228, Jan. 2018.

[3] X. Guo, S. Lou, Y. Wu *et al.*, “Low-carbon operation of combined heat and power integrated plants based on solar-assisted carbon capture,” *Journal of Modern Power Systems and Clean Energy*, vol. 10, no. 5, pp. 1138-1151, Sept. 2022.

[4] H. Xi, M. Zhu, K. Y. Lee *et al.*, “Multi-timescale and control-perceptive scheduling approach for flexible operation of power plant-carbon capture system,” *Fuel*, vol. 331, p. 125695, Jan. 2023.

[5] Z. Liu, B. Huang, X. Hu *et al.*, “Blockchain-based renewable energy trading using information entropy theory,” *IEEE Transactions on Network Science and Engineering*. doi: 10.1109/TNSE.2023.3238110.

[6] Q. Wang, X. Zhang, C. Yi *et al.*, “A novel shared energy storage planning method considering the correlation of renewable uncertainties on the supply side,” *IEEE Transactions on Sustainable Energy*, vol. 13, no. 4, pp. 2051-2063, Oct. 2022.

[7] A. Bharatee, P. K. Ray, and A. Ghosh, “A power management scheme for grid-connected PV integrated with hybrid energy storage system,” *Journal of Modern Power Systems and Clean Energy*, vol. 10, no. 4, pp. 954-963, Jul. 2022.

[8] B. Huang, S. Zheng, R. Wang *et al.*, “Distributed optimal control of DC microgrid considering balance of charge state,” *IEEE Transactions on Energy Conversion*, vol. 37, no. 3, pp. 2162-2174, Sept. 2022.

[9] T. Ha, Y. Xue, K. Lin *et al.*, “Optimal operation of energy hub based micro-energy network with integration of renewables and energy storages,” *Journal of Modern Power Systems and Clean Energy*, vol. 10, no. 1, pp. 100-108, Jan. 2022.

[10] X. Cai, X. Nan, B. Gao *et al.*, “Distributed event-triggered secondary control of microgrids with quantization communication,” *IEEE Transactions on Power Systems*, vol. 38, no. 5, pp. 4572-4581, Sept. 2023.

[11] J. Ding, K. Xie, B. Hu *et al.*, “Mixed aleatory-epistemic uncertainty modeling of wind power forecast errors in operation reliability evaluation of power systems,” *Journal of Modern Power Systems and Clean Energy*. vol. 10. no. 5. pp. 1174-1183, Sept. 2022.

[12] W. Wang, B. Yuan, Q. Sun *et al.*, “Application of energy storage in integrated energy systems – a solution to fluctuation and uncertainty of renewable energy,” *Journal of Energy Storage*, vol. 52, p. 104812,

Aug. 2022.
[13] Z. Guo, W. Wei, L. Chen *et al*., "Impact of energy storage on renewable energy utilization: a geometric description," *IEEE Transactions on Sustainable Energy*, vol. 12, no. 2, pp. 874-885, Apr. 2021.
[14] B. Wang, X. Wang, Z. Zhu *et al*., "Siting and sizing of energy storage for renewable generation utilization with multi-stage dispatch under uncertainty: a tri-level model and decomposition approach," *Applied Energy*, vol. 344, p. 121286, Aug. 2023.
[15] K. Bradbury, L. Pratson, and D. Patiño-Echeverri, "Economic viability of energy storage systems based on price arbitrage potential in real-time U.S. electricity markets," *Applied Energy*, vol. 114, pp. 512-519, Feb. 2014.
[16] P. Harsha and M. Dahleh, "Optimal management and sizing of energy storage under dynamic pricing for the efficient integration of renewable energy," *IEEE Transactions on Power Systems*, vol. 30, no. 3, pp. 1164-1181, May 2015.
[17] A. J. Sangster, "Massive energy storage systems enable secure electricity supply from renewables," *Journal of Modern Power Systems and Clean Energy*, vol. 4, no. 4, pp. 659-667, Oct. 2016.
[18] S. Lai, J. Qiu, and Y. Tao, "Individualized pricing of energy storage sharing based on discount sensitivity," *IEEE Transactions on Industrial Informatics*, vol. 18, no. 7, pp. 4642-4653, Jul. 2022.
[19] Y. Shi, B. Xu, D. Wang *et al*., "Using battery storage for peak shaving and frequency regulation: joint optimization for superlinear gains," *IEEE Transactions on Power Systems*, vol. 33, no. 3, pp. 2882-2894, May 2018.
[20] W. Tushar, B. Chai, C. Yuen *et al*., "Energy storage sharing in smart grid: a modified auction-based approach," *IEEE Transactions on Smart Grid*, vol. 7, no. 3, pp. 1462-1475, May 2016.
[21] J. Liu, N. Zhang, C. Kang *et al*., "Decision-making models for the participants in cloud energy storage," *IEEE Transactions on Smart Grid*, vol. 9, no. 6, pp. 5512-5521, Nov. 2018.
[22] K. Rahbar, C. C. Chai, and R. Zhang, "Energy cooperation optimization in microgrids with renewable energy integration," *IEEE Transactions on Smart Grid*, vol. 9, no. 2, pp. 1482-1493, Mar. 2018.
[23] C. Zhang, J. Wu, Y. Zhou *et al*., "Peer-to-peer energy trading in a microgrid," *Applied Energy*, vol. 220, pp. 1-12, Jun. 2018.
[24] R. Dai, R. Esmaeilbeigi, and H. Charkhgard, "The utilization of shared energy storage in energy systems: a comprehensive review," *IEEE Transactions on Smart Grid*, vol. 12, no. 4, pp. 3163-3174, Jul. 2021.
[25] P. Chakraborty, E. Baeyens, K. Poolla *et al*., "Sharing storage in a smart grid: a coalitional game approach," *IEEE Transactions on Smart Grid*, vol. 10, no. 4, pp. 4379-4390, Jul. 2019.
[26] J. Jo and J. Park, "Demand-side management with shared energy storage system in smart grid," *IEEE Transactions on Smart Grid*, vol. 11, no. 5, pp. 4466-4476, Sept. 2020.
[27] J. Liu, N. Zhang, C. Kang *et al*., "Cloud energy storage for residential and small commercial consumers: a business case study," *Applied Energy*, vol. 188, pp. 226-236, Feb. 2017.
[28] A. Fleischhacker, H. Auer, G. Lettner *et al*., "Sharing solar PV and energy storage in apartment buildings: resource allocation and pricing," *IEEE Transactions on Smart Grid*, vol. 10, no. 4, pp. 3963-3973, Jul. 2019.
[29] S. Li, J. Zhu, Z. Chen *et al*., "Double-layer energy management system based on energy sharing cloud for virtual residential microgrid," *Applied Energy*, vol. 282, p. 116089, Jan. 2021.
[30] J. Pascual, J. Barricarte, P. Sanchis *et al*., "Energy management strategy for a renewable-based residential microgrid with generation and demand forecasting," *Applied Energy*, vol. 158, pp. 12-25, Nov. 2015.
[31] X. He, J. Xiao, S. Cui *et al*., "A new cooperation framework with a fair clearing scheme for energy storage sharing," *IEEE Transactions on Industrial Informatics*, vol. 18, no. 9, pp. 5893-5904, Sept. 2022.
[32] N. Liu, M. Cheng, X. Yu *et al*., "Energy-sharing provider for PV prosumer clusters: a hybrid approach using stochastic programming and stackelberg game," *IEEE Transactions on Industrial Electronics*, vol. 65, no. 8, pp. 6740-6750, Aug. 2018.
[33] S. Cui, Y. Wang, Y. Shi *et al*., "A new and fair peer-to-peer energy sharing framework for energy buildings," *IEEE Transactions on Smart Grid*, vol. 11, no. 5, pp. 3817-3826, Sept. 2020.
[34] B. H. Nguyen, R. German, J. P. F. Trovao *et al*., "Real-time energy management of battery/supercapacitor electric vehicles based on an adaptation of Pontryagin's minimum principle," *IEEE Transactions on Vehicular Technology*, vol. 68, no. 1, pp. 203-212, Jan. 2019.
[35] J. G. Robertson, G. P. Harrison, and A. R. Wallace, "OPF techniques for real-time active management of distribution networks," *IEEE Transactions on Power Systems*, vol. 32, no. 5, pp. 3529-3537, Sept. 2017.
[36] S. Zeinal-Kheiri, A. M. Shotorbani, A. Khardenavis *et al*., "An adaptive real-time energy management system for a renewable energy-based microgrid," *IET Renewable Power Generation*, vol. 15, no. 13, pp. 2918-2930, Oct. 2021.
[37] Z. Ji, C. Kang, Q. Chen *et al*., "Low-carbon power system dispatch incorporating carbon capture power plants," *IEEE Transactions on Power Systems*, vol. 28, no. 4, pp. 4615-4623, Nov. 2013.
[38] C. Li, Y. Xu, X. Yu *et al*., "Risk-averse energy trading in multienergy microgrids: a two-stage stochastic game approach," *IEEE Transactions on Industrial Informatics*, vol. 13, no. 5, pp. 2620-2630, Oct. 2017.
[39] S. Cui, Y. Wang, X. Liu *et al*., "Economic storage sharing framework: asymmetric bargaining-based energy cooperation," *IEEE Transactions on Industrial Informatics*, vol. 17, no. 11, pp. 7489-7500, Nov. 2021.
[40] B. Huang, Y. Li, F. Zhan *et al*., "A distributed robust economic dispatch strategy for integrated energy system considering cyber-attacks," *IEEE Transactions on Industrial Informatics*, vol. 18, no. 2, pp. 880-890, Feb. 2022.
[41] Q. Tan, S. Mei, Q. Ye *et al*., "Optimization model of a combined wind-PV-thermal dispatching system under carbon emissions trading in China," *Journal of Cleaner Production*, vol. 225, pp. 391-404, Jul. 2019.
[42] Z. Liu, Y. Xu, C. Zhang *et al*., "A blockchain-based trustworthy collaborative power trading scheme for 5G-enabled social internet of vehicles," *Digital Communications and Networks*, vol. 8, no. 6, pp. 976-983, Dec. 2022.

Pengbo Du received the B.S. degree in new energy science and engineering from Hohai University, Nanjing, China, in 2021. She is currently pursuing the Ph.D. degree in School of Information Science and Engineering, Northeastern University, Shenyang, China. Her main research interests include renewable energy trading, game theory, energy storage, and blockhain.

Bonan Huang received the B.S. degree in electronic information engineering from Tianjin University, Tianjin, China, in 2005, and the M.A.Sc. and Ph.D. degrees in control theory and control engineering from Northeastern University, Shenyang, China, in 2008 and 2014, respectively. He is currently an Associate Professor with the School of Information Science and Engineering, Northeastern University. His main research interests include collaborative control and operation optimization of Energy Internet and multienergy systems, and cyber-physical security analysis of smart energy systems.

Ziming Liu received the B.S. degree in electrical engineering and automation from Shenyang Institute of Engineering, Shenyang, China, in 2017. He is currently pursuing the Ph.D. degree in School of Information Science and Engineering, Northeastern University, Shenyang, China. His main research interests include information entropy theory, electricity market, renewable energy generation, and blockchain.

Chao Yang received the Ph.D. degree in computer applications technology from Dalian Maritime University, Dalian, China, in 2016. He is currently an Engineer with the Information and Communication Branch, State Grid Liaoning Electric Power Company Ltd., Shenyang, China. His main research interests include smart grid informatization, Internet of Things, and artificial intelligence.

Qiuye Sun received the Ph.D. degree in control theory and control engineering from Northeastern University, Shenyang, China, in 2007, where he has been a Full Professor and the Ph.D. Supervisor since 2014. His current research interests mainly include modeling and optimal operation of Energy Internet, complementary optimization of multienergy system, and network control of distributed generation systems.