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Optimal Scheduling Strategy of Regional Power System Dominated by Renewable Energy Considering Physical and Virtual Shared Energy Storage

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Abstract: In view of the current situation of the global energy crisis and environmental pollution, the energy industry transition and environmental governance are urgently needed. To deal with the problem above, the construction of a power system dominated by renewable energy (PSDRE) with wind turbine (WT), photovoltaic (PV), biomass power (BP), and other clean, low-carbon, renewable energy sources as the principal part has become a consensus all over the world. However, the random and uncertain power output of renewable energy will not only put pressure on the power system but also lead to the unreasonable and insufficient usage of renewable energy. In this context, the energy storage (ES) effects of flexible resources, such as physical energy storage of batteries and demand response (DR), are analyzed first. Next, a modeling method for the operational characteristics of physical and virtual shared energy storage (PVSES) in regional PSDRE (RPSDRE) is proposed. Finally, an optimal scheduling strategy for RPSDRE that considers PVSES is proposed to achieve coordination of WT, PV, PVSES, and other flexible resources. The case study on RPSDRE in Lankao county, Kaifeng city, Henan province of China verifies the effectiveness and practicability of the proposed strategy.

Keywords: regional power system dominated by renewable energy (RPSDRE); physical and virtual shared energy storage (PVSES); flexible resource; coordinated operation; optimal scheduling strategy

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Citation: Chai, Z.; Liu, J.; Zhang, Y.; Chen, Y.; Zhang, K.; Liu, C.; Yang, M.; Yin, S.; Qiu, W.; Lin, Z.; et al. Optimal Scheduling Strategy of Regional Power System Dominated by Renewable Energy Considering Physical and Virtual Shared Energy Storage. *Energies* **2023**, *16*, 2506. https://doi.org/10.3390/en16052506

Academic Editor: Surender Reddy Salkuti

Received: 4 February 2023
Revised: 28 February 2023
Accepted: 3 March 2023
Published: 6 March 2023

1. Introduction

1.1. The Background of the Global Energy Industry Revolution and the Demand for ES

With the global energy system transition and decarbonization development, there are many renewable energy power generations such as wind power, photovoltaic, and biomass power undergoing rapid development [1]. The demand for large-scale grid connection of renewable energy and peak shaving, valley filling, voltage control, and frequency regulation of power systems has increased rapidly [2,3]. In this context, the ES has advantages in low-cost, swift-response, and high-energy density power charging and discharging, which will play an indispensable role and be an essential choice for the development of the power industry. As a kind of flexible resource combining the capability of power discharging and charging, the ES has become a significant research object during the construction of RPSDREs [4,5]. Currently, the operation modes of ES devices are mainly divided into the decentralized allocation mode and shared mode. In [6–10], the two-stage scheduling optimization model for the adoption of distributed batteries, and the optimal coordinated operational model of renewable energy resources accompanied by distributed batteries, are constructed. An optimal energy management method considering distributed ES along with renewable energy resources, the optimal dispatching strategy of solar-powered electric bus network considering onboard ES, and the distributionally robust optimization model of the system with uncertain WT and PV considering optimal battery ES system capacity and power rating are proposed.

1.2. Research Status of Optimal Scheduling Considering ES

The current research mainly focuses on optimal scheduling considering ES with a decentralized allocation mode, while the scheduling strategies considering ES shared with a whole power system are rarely studied. However, compared to the decentralized allocation mode that follows renewable energy generation, the shared mode of ES is more advantageous in terms of operational security, economy, and comprehensive performance [11–13]. From the perspective of construction, operation, and maintenance, when involved in the economic comparison between the SES mode and the "renewable energy with ES" decentralized configuration mode, the advantages of SES are mainly reflected in the obvious scheduling cost decrease through centralized construction and management. However, the current research is lacking a method to achieve the operational characteristics modeling of SES which can comprehensively consider the physical energy storage (PES) and the virtual energy storage characteristics of DR [14]. Due to the flexible up and down adjustment ability, load-side power will become a kind of controllable resource, which is equivalent to the energy time-shifting effect of ES [15,16]. However, the energy storage potential of DR is usually ignored in current research [17,18], which will make the existing scheduling strategies unable to give full consideration to the coordinated and complementary operation of diverse and heterogeneous flexible resources such as WT, PV, BP, and PVSES in RPSDREs. Thus, it is of great significance to research the optimal scheduling method considering the PVSES of RPSDREs for the coordination between the source-side renewable power generation and the load-side power load of RPSDREs, the consumption of renewable energy, and the improvement of the system's economy, flexibility, and stability.

1.2.1. Overview of Optimal Scheduling and Planning of ES in Power Systems

It has been widely studied that the participation of ES can bring benefits for the optimal scheduling of power systems, and some scheduling and planning strategies of ES in various power systems have been enthusiastically studied in the existing researches. Aiming at the energy management and efficiency improvement of the seaport industry, the operation and planning strategies considering energy storage centralized in a smart grid is proposed in [19], and the cost saving as the scale of energy storage is enlarged is estimated. Similarly, it was summarized in [20] that energy storage systems have the benefits as the main technological and operational tools for peak shaving, efficiency promotion, economy improvement, low carbon emissions, and renewable utilization of ports and terminals. Furthermore, a sizing and operational approach considering shared energy storage for the involved stakeholders is proposed in [21] to achieve cost savings, a reduction in renewable energy, and peak shaving. Based on the model construction of cloud energy storage, the optimal scheduling of regional electric heating integrated energy is analyzed in [22] and win-win results have been achieved through the interaction between users and aggregators supported by the cloud energy storage. The business model of shared energy storage is clarified in [23] and the core idea of shared energy storage is to release the ownership and the use right of energy storage so as to obtain additional benefits and shorten the cost recovery period. In [24], the evaluation indices of the SES market for the privacy protection of data sharers are analyzed to improve the computation flexibility and utilization of node resources in the shared energy storage markets.

It can be observed that the optimal scheduling and planning of physical ES in power systems have been fully studied from the perspective of different commercial modes and abundant application scenarios. The benefits of energy storage for the improvement of the system's economy, operational efficiency, and stability have been verified widely. However, there are few pieces of research considering the optimal operation for the utilization of systems' virtual energy storage resources, which is not constrained by operational conditions limitations such as site layout, equipment performance, and physical circumstances. As a mechanism supported by the contracted flexible regulation of loads, the demand response has become a kind of practical resource to realize the dynamic balance of power systems more independently. Due to the equivalence between the flexible adjustment of load and the energy time-shift effect of energy storage, the demand response can be constructed as a type of virtual energy storage to achieve further optimization of power systems.

In [25], an integrated demand response model is expanded from the traditional model to achieve a more comprehensive optimization of system operation. In [26], the demand response program is applied in the planning and operational strategy to improve the recoverability of distribution systems. In [27], a demand response considering the flexible use of electric vehicles is proposed and the simulation results show the consideration of demand response in dispatching can reduce the curtailment of renewable energy and increase the environmental benefits, economy, and stability. A concrete demand response modeling of air conditioning is proposed in [28] to make use of the operational flexibility of the air conditioning load. At present, the optimal scheduling of centralized demand response has accumulated a lot of research results. However, due to the lack of a shared mechanism, the existing research results are not available for the flexible adjustment of load dispersedly allocating at each node of the power network. Thus, based on the shared modes of energy storage, the virtual shared energy storage model is constructed in this paper to achieve the utilization of demand response in power systems.

1.2.2. Overview of Optimal Scheduling Considering the Carbon Trading Mechanisms

With the rapid development of the social economy, the global energy demand is increasing constantly. Furthermore, with the uninterrupted decrease of traditional energy reserves, the pressure on the shortage of energy is becoming larger and larger. At the same time, the burning of coal, oil, natural gas, and other fossil fuels will release a large number of pollution gases, such as carbon dioxide, sulfur dioxide, and nitrogen dioxide, which will aggravate the greenhouse effect and promote global warming, leading to increasingly serious environmental problems. In this context, it has become important to explore low-carbon scheduling in power systems, and the carbon trading mechanism has been recognized as an effective approach to improving the system operational economy and low-carbon environmental protection. The carbon trading mechanism is introduced to the scheduling of virtual power plants, community electric–gas integrated energy systems, and power–heat–gas integrated energy systems in [29–31]. Furthermore, it has been verified that participation in carbon trading has the effect of economic promotion and carbon emission reduction. However, the fixed carbon price or penalty-based carbon price is the main method to achieve carbon trading, and the user's enthusiasm for carbon emission decrease may not be stimulated fully in the current carbon trading mechanism. Correspondingly, the reward policy for a reduction in carbon emissions is promulgated to achieve deep carbon emission administrative control. Thus, the carbon trading mechanism considering a reward and penalty ladder carbon price (RPLCP) is introduced in the scheduling strategy in this paper to obtain the optimal low-carbon results.

1.3. Research Background, Significance, and Task Summary

In summary, there has been much research on the scheduling of physical shared energy storage and carbon trading mechanisms, the strengths of which include the improvement of the operational economy, carbon emission reduction, and flexibility. However, there is still room for further improvement, which can include the following aspects. (1) The virtual energy storage characteristics of demand response cannot be considered in the existing scheduling method, which may weaken the system's operational performance. The construction of equivalent energy storage effects for demand response still needs to be studied in depth. (2) Most of the existing demand response is not available for the sharing mechanism, which will impose limitations on the scenarios for the application of demand response. It is of great significance to introduce shared energy storage into the system's scheduling to achieve the potential release of flexible adjustment ability from both the physical and virtual energy storage resources. (3) Few existing scheduling strategies for carbon emission reduction can consider the reward and penalty of carbon emission intensity at the same time. With the aggravation of air pollution, a carbon trading mechanism to activate willingness for carbon emission reduction should be studied in depth.

Therefore, given the shortcoming of the existing research, an optimal scheduling strategy for a regional power system dominated by renewable energy considering physical and virtual shared energy storage under the carbon trading mechanism with reward and penalty ladder carbon price is proposed in this paper. The contributions of this paper can be summarized as follows: the model of operational characteristics for physical ES represented by batteries and virtual ES represented by DR in the RPSDRE is first built, and then an optimal scheduling strategy for RPSDREs considering PVSES and a carbon trading mechanism is constructed based on the proposed shared ES model, aiming at the minimization of the RPSDRE operational cost. The proposed model is used to fully mobilize the coordinated and complementary enthusiasm for flexible resources in RPSDREs to enhance the independent and economic operational capability of RPSDREs, and explores new ideas for the effective renewable energy consumption of power systems and the achievement of an economic, clean, and low-carbon power supply.

The rest of this paper is organized as follows. Based on the analysis of operational performance, the operational model of physical and virtual shared energy storage is constructed in Section 2. The carbon trading mechanism considering the reward and penalty ladder carbon price is analyzed in Section 3. The optimal scheduling strategy of RPSDREs considering PVSES under a RPLCP is clarified in Section 4. The effectiveness of the proposed strategy is verified by an RPSDRE in Lankao county of China in Section 5, and the main results of the paper are summarized in Section 6.

2. Operational Characteristics Modeling of PVSES

The integrated operation mode of ES makes shared energy storage (SES) more advantageous than decentralized energy storage [32–34]. Firstly, SES is more secure in its innovative operation mode. The centralized procurement, construction, operation, and management mode of SES confers its distinct advantages in the aspects of ES power plant equipment procurement standards, construction management level, professional operation, and maintenance guarantee, and is a benefit to the promotion of the secure and stable operation of ES stations. Secondly, the SES is more economic due to its flexible responsiveness. The ES facility operation and management efficiency can be improved, and the construction, operation, and maintenance cost can be reduced effectively through the centralized construction, scheduling, and management of SES. Thirdly, SES has better performance in operation due to its participation in the global optimization of RPSDREs. The unified scheduling and professional management mode of energy storage systems (SES) enables the operation and maintenance department to dynamically allocate ES resources according to provincial and local renewable energy consumption. This approach benefits ES utilization improvement, grid operation service, and ancillary service revenue increase. Thus, based on characteristics analysis, the operational model of PVSES is constructed here to effectively coordinate the multiple flexible resources in RPSDREs.

2.1. Operational Characteristics Modeling of Physical SES (PSES)

The existing PES devices are mainly divided into five categories, that is, mechanical ES, electrical ES, electrochemical ES, thermal ES, and chemical ES. The electrochemical-based battery ES is a common form of the PES in current power system development. The operational characteristics of PSES considering battery ES in RPSDREs are constructed as follows.

A. The constraint of PSES charging and discharging power

The upper and lower power limit constraints of PSES charging and discharging are expressed below.

$$\begin{cases} 0 \leq P_{j,t}^{\mathrm{rec}} \leq u_{j,t}^{\mathrm{rec}} P_{j}^{\mathrm{recmax}} \\ 0 \leq P_{j,t}^{\mathrm{red}} \leq u_{j,t}^{\mathrm{red}} P_{j}^{\mathrm{redmax}} \end{cases} \tag{1}$$

where $P_{j,t}^{\mathrm{rec}}$, and $P_{j,t}^{\mathrm{red}}$ are the charging and discharging power of PSES j at the tth scheduling period, respectively; $u_{j,t}^{\mathrm{rec}}$ and $u_{j,t}^{\mathrm{red}}$, respectively, represent the charging and discharging state variable of PSES j at the tth scheduling period, and $u_{j,t}^{\mathrm{rec}}/u_{j,t}^{\mathrm{red}}$ = 0, 1 mean that the PSES is in or not in the state of charge/discharge, respectively; P_{j}^{recmax} and P_{j}^{redmax} are the maximum charging and discharging power of PSES j, respectively.

B. The constraint of PSES charging and discharging status

The operational status constraint of PSES charging and discharging is expressed below.

$$u_{j,t}^{\mathrm{rec}} + u_{j,t}^{\mathrm{red}} \leq 1 \tag{2}$$

C. The constraint of PSES electricity storage

The upper and lower storage capacity constraint of PSES is as follows.

$$E_{j}^{\mathrm{rsmin}} \leq E_{j,t}^{\mathrm{ress}} \leq E_{j}^{\mathrm{rsmax}} \tag{3}$$

where $E_{j,t}^{\mathrm{ress}}$ is the storage capacity of PSES j at the tth scheduling period; E_{j}^{rsmin} and E_{j}^{rsmax} are the minimum and maximum storage capacity of PSES j, respectively.

D. Dynamic balance constraint of PSES electricity storage

The dynamic change characteristics model for the electricity storage of PSES is as follows.

$$E_{j,t}^{\mathrm{ress}} = \left(1 - n_{j}^{\mathrm{rloss}}\right) E_{j,t-1}^{\mathrm{ress}} + \eta_{j}^{\mathrm{rec}} P_{j,t}^{\mathrm{rec}} - \frac{P_{j,t}^{\mathrm{red}}}{\eta_{j}^{\mathrm{red}}} \tag{4}$$

where $E_{j,t-1}^{\mathrm{ress}}$ is the storage capacity of PSES j at the $(t-1)$th scheduling period; n_{j}^{rloss}, η_{j}^{rec} and η_{j}^{red} are the self-discharging coefficient, and charging and discharging efficiency of PSES j, respectively.

E. Consistency constraint of stored energy state of charge

The PSES energy constraints at the initial and last moment of the scheduling cycle is constructed below.

$$E_{j,0}^{\mathrm{ress}} = E_{j,T}^{\mathrm{ress}} \tag{5}$$

where $E_{j,0}^{\mathrm{ress}}$ and $E_{j,T}^{\mathrm{ress}}$ are the electricity storage of PSES j at the beginning and end of schedule, respectively; T corresponds to the scheduling cycle.

2.2. Operational Characteristics Modeling of Virtual SES (VSES)

DR is a means of regulation applied on the load demand side, and both the consumption of renewable energy and the independent and reliable operational ability of the RPSDRE will be improved through the integration of the flexible and dispatchable power resources of the load side. The equivalence of the energy-shifting effect between DR and PES can be achieved by the adjustment of the load curve. Thus, the VSES model considering DR is proposed in this manuscript, which is used to promote the flexibility of RPSDRE scheduling. The model of VSES considering price-based and incentive DR is as follows.

A. Priced-based DR

The electricity price is an important influencing factor that can affect the users' electricity consumption behaviors. The variation of the spot price in actual operation will impel the users to change their electricity consumption behaviors in actual operation. Thus, the users can be guided to adjust their electricity consumption behaviors through the flexible adjustment of electricity prices and then the time-shifting of energy and the flexible allocation of controllable loads can be achieved. The association between the change in electricity price and the change in users' electricity consumption is established by the elasticity coefficient matrix of price-based DR. The characteristic of price-based DR considering electricity price signal guidance is expressed below.

$$\begin{bmatrix} \Delta P_{1,k}^{\mathrm{pve}} / P_{1,k}^{\mathrm{pve}} \\ \Delta P_{2,k}^{\mathrm{pve}} / P_{2,k}^{\mathrm{pve}} \\ \vdots \\ \Delta P_{T,k}^{\mathrm{pve}} / P_{T,k}^{\mathrm{pve}} \end{bmatrix} = r^{\mathrm{pve}} \begin{bmatrix} \Delta c_{1}^{\mathrm{pve}} / c_{1}^{\mathrm{pve}} \\ \Delta c_{2}^{\mathrm{pve}} / c_{2}^{\mathrm{pve}} \\ \vdots \\ \Delta c_{T}^{\mathrm{pve}} / c_{T}^{\mathrm{pve}} \end{bmatrix} \tag{6}$$

where $P_{1,k}^{\mathrm{pve}}, P_{2,k}^{\mathrm{pve}}, \ldots, P_{T,k}^{\mathrm{pve}}$ are the load power of price-based DR k at the scheduling period 1, 2, ..., T, respectively; $\Delta P_{1,k}^{\mathrm{pve}}, \Delta P_{2,k}^{\mathrm{pve}}, \ldots, \Delta P_{T,k}^{\mathrm{pve}}$ are the load power variations of price-based DR k at the scheduling periods 1, 2, ..., T, respectively; $c_{1}^{\mathrm{pve}}, c_{2}^{\mathrm{pve}}, \ldots, c_{T}^{\mathrm{pve}}$ are the electricity prices at the scheduling periods 1, 2, ..., T, respectively; $\Delta c_{1}^{\mathrm{pve}}, \Delta c_{2}^{\mathrm{pve}}, \ldots, \Delta c_{T}^{\mathrm{pve}}$ are the electricity price variations at the scheduling periods 1, 2, ..., T, respectively; r^{pve} is the elasticity coefficient matrix of electricity price and load power, which is expressed as

$$r^{\mathrm{pve}} = \begin{bmatrix} r_{1,1}^{\mathrm{pve}} & r_{1,2}^{\mathrm{pve}} & \cdots & r_{1,T}^{\mathrm{pve}} \\ r_{2,1}^{\mathrm{pve}} & r_{2,2}^{\mathrm{pve}} & \cdots & r_{2,T}^{\mathrm{pve}} \\ \vdots & \vdots & & \vdots \\ r_{T,1}^{\mathrm{pve}} & r_{T,2}^{\mathrm{pve}} & \cdots & r_{T,T}^{\mathrm{pve}} \end{bmatrix} \tag{7}$$

where $r_{u,v}^{\mathrm{pve}}$ ($u = v$, u = 1, 2, ..., T, v = 1, 2, ..., T) and $r_{u,v}^{\mathrm{pve}}$ ($u \neq v$, u = 1, 2, ..., T, v = 1, 2, ..., T) are the self-elastic coefficient and mutual elastic coefficient, respectively.

On the basis of the above electricity price–users' power consumption DR model, the load power of price-based DR can be expressed as

$$P_{k,t}^{\mathrm{pve}} = P_{k,t}^{\mathrm{pve0}}\left[1 + r^{\mathrm{pve}}\left(c_{t}^{\mathrm{pve}} - c_{t}^{\mathrm{pve0}}\right) / c_{t}^{\mathrm{pve0}}\right] \tag{8}$$

where $P_{k,t}^{\mathrm{pve0}}$ and $P_{k,t}^{\mathrm{pve}}$ are the load power before and after the response of price-based DR k at the scheduling period t, respectively; c_{t}^{pve0} and c_{t}^{pve} are the electricity price before and after the response of price-based DR k at the scheduling period t, respectively.

B. Incentive DR

The peak load shedding of incentive DR will be achieved through the signing of a DR contract, which is mainly equivalent to the discharge effect of ES. The incentive DR contract mainly stipulates the execution period and contracted capacity of DR, which is expressed as

$$0 \leq P_{k,t}^{\mathrm{mve}} \leq P_{k}^{\mathrm{msig}}, \forall t \in \left[T^{\mathrm{mstart}}, T^{\mathrm{mend}}\right] \tag{9}$$

$$P_{k,t}^{\mathrm{mve}} = 0, \forall t \notin \left[T^{\mathrm{mstart}}, T^{\mathrm{mend}}\right] \tag{10}$$

where T^{mstart} and T^{mend} are the start and end time of incentive DR, respectively; P_{k}^{msig} and $P_{k,t}^{\mathrm{mve}}$ are the contracted capacity and DR power at the scheduling time t of incentive DR, respectively.

With the comprehensive consideration of price-based and incentive DR, the VSES of the RPSDRE is established as

$$\begin{cases} P_{k,t}^{\mathrm{vec}} = \left| P_{k,t}^{\mathrm{pve}} \right|, P_{k,t}^{\mathrm{pve}} < 0 \\ P_{k,t}^{\mathrm{ved}} = P_{k,t}^{\mathrm{pve}} + P_{k,t}^{\mathrm{mve}}, P_{k,t}^{\mathrm{pve}} > 0 \end{cases} \tag{11}$$

where $P_{k,t}^{\mathrm{vec}}$ and $P_{k,t}^{\mathrm{ved}}$ are the charge and discharge power of VSES k at the scheduling time t in the RPSDRE.

3. Carbon Trading Mechanism Considering the Reward and Penalty Ladder Carbon Price (RPLCP)

With the development of the energy industry revolution, carbon emission control has become a serious and urgent problem to be solved. As one of the main sources of carbon emission, the economic and low-carbon scheduling of power systems has been of concern and widely studied. For the purpose of carbon emission governance, the carbon trading mechanism is proposed to make carbon emission rights a kind of commodity which can be traded freely and to promote the reduction of carbon emissions.

3.1. Carbon Emission Trading Mode

At present, there are two kinds of carbon trading modes in the carbon trading market: total carbon emission trading mode (TCETM) and carbon emission intensity trading mode (CEITM). The TCETM means that the system's quota of total carbon emission is allocated by the government or regulatory authorities and the initial quota is allocated according to the capacity of each unit. When the system's total carbon emission exceeds the allocated limit, carbon emission rights will be purchased for the excess. Without the limits of total carbon emission, the CEITM focuses on the carbon emission control of units of carbon emissions above the baseline settings of carbon emissions. The TCETM is mainly used in developed countries and the CEITM is mainly adopted by developing countries to consider both carbon emission and economic development.

According to the CEITM, the carbon emission quota of the RPSDRE can be expressed as:

$$Z_g^{\mathrm{b}} = \lambda^{\mathrm{cb}} P_{g,t} \tag{12}$$

where Z_g^{b} is the carbon emission quota of unit g; $P_{g,t}$ is the power output of unit g at the scheduling time t of RPSDRE; λ^{cb} is the baseline of carbon emission intensity.

The carbon emission trading generated from the difference between carbon emission quota and operational carbon emission is as follows.

$$Z_g^{\mathrm{c}} = \lambda^{\mathrm{ce}} P_{g,t} \tag{13}$$

$$\Delta Z = Z_g^{\mathrm{c}} - Z_g^{\mathrm{b}} \tag{14}$$

where Z_g^{c} is the carbon emission of unit g; λ^{ce} is the carbon emission per unit power generation; ΔZ is the difference between the carbon emission and its quota.

3.2. CETIM Considering Reward and Penalty Ladder Carbon Price (RPLCP)

Based on the calculation of the carbon emission difference, the carbon emission cost (or profit) is as follows.

$$f^{\mathrm{carb}} = \sum_{t=1}^{T} \sum_{g=1}^{N^{\mathrm{G}}} \lambda_{g,t}^{\mathrm{carb}} |\Delta Z| \tag{15}$$

where f^{carb} is the cost or profit of carbon emission trading; $\lambda_{g,t}^{\mathrm{carb}}$ is the carbon price of unit g at the scheduling time t; N^{G} is the number of power generation in the RPSDRE.

Carbon trading based on the fixed carbon price has been widely studied in the existing research. To motivate the enthusiasm for the carbon emission reduction of power systems, the CETIM considering the RPLCP is analyzed in this paper, that is, the higher the excess of carbon emissions, the higher the carbon price; conversely, the greater the reduction in carbon emissions, the higher the reward. The calculation method is expressed as follows and the RPSDRE is shown in Figure 1.

$$\lambda_{g,t}^{\text{carb}} = \begin{cases} y[1+(\kappa-1)\omega x], (\kappa-1)x < \Delta Z \le \kappa x, \kappa = 1,2,\ldots \\ -y[1+(\varpi-1)\omega x], -\varpi x < \Delta Z \le -(\varpi-1)x, \varpi = 1,2,\ldots \end{cases} \tag{16}$$

where x is the interval increase of carbon emission difference; y is the baseline of carbon price; ω is the percentage increase in carbon price; N^{G} is the amount of power generation in the RPSDRE; κ and ϖ are the number of segments in the reward and penalty carbon prices, respectively.

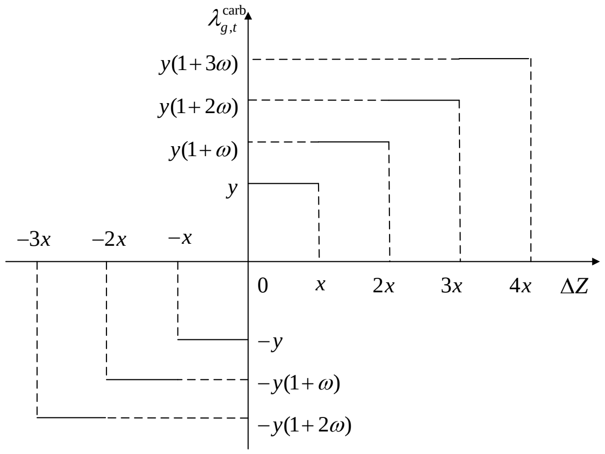


Figure 1. Sketch map of RPLCP.

4. Optimal Scheduling Model for RPSDRE Considering Battery PSES and DR VSES

Based on the operational characteristics modeling of battery PSES and DR VSES and carbon trading mechanisms, the proposed optimal scheduling model aiming at the optimal economy of the RPSDRE is as follows.

4.1. Objective Function of Optimal Scheduling Model for RPSDRE Considering Battery PSES and DR VSES

During the actual operation, the cost of the RPSDRE is mainly incurred by the power purchase from the superior power grid in actual operation, meanwhile, the invocation of ES devices charging and discharging will incur the corresponding operational cost due to the consideration of PVSES effects in the RPSDRE. Thus, the constructed objective function of the optimal scheduling model for the RPSDRE considering the cost of power purchase from the superior power grid, the PSES charging and discharging, and the VSES charging and discharging is shown as

$$\begin{gathered} F = \min\left(f^{\text{pur}} + f^{\text{ress}} + f^{\text{vess}} + f^{\text{carb}}\right) \\ f^{\text{pur}} = \sum_{t=1}^{T} \sum_{i=1}^{N^{\text{line}}} \left(\lambda_{i,t}^{\text{pur}} P_{i,t}^{\text{pur}} \Delta t\right) \\ f^{\text{ress}} = \sum_{t=1}^{T} \sum_{j=1}^{N^{\text{ress}}} \left(\lambda_{i,t}^{\text{rec}} P_{j,t}^{\text{rec}} \Delta t + \lambda_{i,t}^{\text{red}} P_{j,t}^{\text{red}} \Delta t\right) \\ f^{\text{vess}} = \sum_{t=1}^{T} \sum_{k=1}^{N^{\text{vess}}} \left(\lambda_{i,t}^{\text{vec}} P_{k,t}^{\text{vec}} \Delta t + \lambda_{i,t}^{\text{ved}} P_{k,t}^{\text{ved}} \Delta t\right) \end{gathered} \tag{17}$$

where F is the operational cost of the RPSDRE; f^{pur}, f^{ress}, and f^{vess} are the costs of power purchases from the superior power grid, PSES charging and discharging, and VSES charging and discharging, respectively; $P_{i,t}^{\text{pur}}$ is the power of line i in the RPSDRE which can purchase power from the superior grid at the scheduling period t; $\lambda_{i,t}^{\text{pur}}$, $\lambda_{j,t}^{\text{rec}}$, $\lambda_{j,t}^{\text{red}}$, $\lambda_{k,t}^{\text{vec}}$, and $\lambda_{k,t}^{\text{ved}}$ are the unit prices of the power purchase from line i, the charging of PSES j, the discharging of PSES j, the charging of VSES k, and the discharging of VSES k, respectively; N^{line}, N^{ress}, and N^{vess} are the number of power purchase lines from the superior power grid, PSES, and VSES in RPSDRE, respectively; Δt is the scheduling interval.

4.2. Constraints of Optimal Scheduling Model for RPSDRE Considering Battery PSES and DR VSES

The RPSDRE incorporates WT, PV, and BP as power generation resources on the source side, and utilizes battery PSES and DR VSES as SES resources on the energy storage side. In addition to the PVSES operational models mentioned above, the model also takes into account power balance constraints, renewable energy output constraints, system power purchase constraints from the superior grid, and network power flow constraints. The specific constraint model is presented below.

A. Power balance constraints

The power balance constraint that reflects the joint coordination of multiple flexible resources in the RPSDRE is shown as

$$\begin{aligned} &\sum_{m=1}^{N^{\text{wind}}} P_{m,t}^{\text{wind}} + \sum_{n=1}^{N^{\text{sun}}} P_{n,t}^{\text{sun}} + \sum_{p=1}^{N^{\text{bio}}} P_{p,t}^{\text{bio}} + \sum_{i=1}^{N^{\text{line}}} P_{i,t}^{\text{pur}} \\ &+ \sum_{j=1}^{N^{\text{ress}}} P_{j,t}^{\text{rec}} + \sum_{k=1}^{N^{\text{vess}}} P_{k,t}^{\text{vec}} = \sum_{s=1}^{N^{\text{load}}} P_{s,t}^{\text{load}} + \sum_{j=1}^{N^{\text{ress}}} P_{j,t}^{\text{red}} + \sum_{k=1}^{N^{\text{vess}}} P_{k,t}^{\text{ved}} \end{aligned} \tag{18}$$

where $P_{m,t}^{\text{wind}}$, $P_{n,t}^{\text{sun}}$, $P_{p,t}^{\text{bio}}$, and $P_{s,t}^{\text{load}}$ are the power of WT m, PV n, BP p, and system's load s in the RPSDRE at the scheduling period t, respectively; N^{load}, N^{wind}, N^{sun}, and N^{bio} are the number of the system's load nodes, WT, PV, and BP in the RPSDRE, respectively.

B. Charge and discharge power constraints of VSES

The constraints on the upper and lower limits of VSES charge and discharge power are shown as

$$\begin{cases} 0 \le P_{k,t}^{\text{vec}} \le u_{k,t}^{\text{vec}} \sigma_k^{\text{vecmax}} P_{k,t}^{L} \\ 0 \le P_{k,t}^{\text{ved}} \le u_{k,t}^{\text{ved}} \sigma_k^{\text{vedmax}} P_{k,t}^{L} \end{cases} \tag{19}$$

where σ_k^{vecmax} and σ_k^{vedmax}, respectively, represent the maximum charge and discharge proportion of DR VSES; $P_{k,t}^{L}$ is the load forecast power of DR VSES k; $u_{k,t}^{\text{vec}}$ and $u_{k,t}^{\text{ved}}$, respectively, represent the charging and discharging state variable of VSES k at the tth scheduling period, and $u_{k,t}^{\text{vec}}/u_{k,t}^{\text{ved}} = 0, 1$ mean that the VSES k is in or not in the state of charge/discharge, respectively. The constraints that $u_{k,t}^{\text{vec}}$ and $u_{k,t}^{\text{ved}}$ should satisfy are as follows.

$$u_{k,t}^{\text{vec}} + u_{k,t}^{\text{ved}} \le 1 \tag{20}$$

C. Renewable energy power output constraints

The output of renewable energy is limited by the power output constraints below.

$$P_{\min}^{\text{s}} \le P_{n,t}^{\text{sun}} \le P_{\max}^{\text{s}} \tag{21}$$

$$P_{\min}^{\text{w}} \le P_{m,t}^{\text{wind}} \le P_{\max}^{\text{w}} \tag{22}$$

$$P_{\min}^{\text{b}} \le P_{p,t}^{\text{bio}} \le P_{\max}^{\text{b}} \tag{23}$$

where $P_{\min}^{\text{s}}$ and $P_{\max}^{\text{s}}$ are the upper and lower limits of PV power output, respectively; $P_{\min}^{\text{w}}$ and $P_{\max}^{\text{w}}$ are the upper and lower limits of WT power output, respectively; and $P_{\min}^{\text{b}}$ and $P_{\max}^{\text{b}}$ are the upper and lower limits of BP power output, respectively.

D. Network power flow constraints

Considering the existence of maximum power transmission limits in the RPSDRE, the network power flow constraints based on the DC power flow model are expressed as

$$P_{a,b,t}^{\text{line}} = \sum_{\varphi \in \psi} \left(\frac{X_{a,\varphi} - X_{b,\varphi}}{X_{a,b}} \right) P_{\varphi,t} - \sum_{\mu \in L} \left(\frac{X_{a,\mu} - X_{b,\mu}}{X_{a,b}} \right) D_{\mu,t} \tag{24}$$

$$-P_{a,b}^{\max} \leq P_{a,b,t}^{\text{line}} \leq P_{a,b}^{\max} \tag{25}$$

where $P_{a,b,t}^{\text{line}}$ is the transmission power between node a and node b in RPSDRE at the tth scheduling period; $P_{a,b}^{\max}$ is the maximum transmission power between node a and node b; ψ and L are the node sets of power source and load in the RPSDRE, respectively; $X_{a,\varphi}$, $X_{b,\varphi}$, $X_{a,\mu}$, $X_{b,\mu}$, and $X_{a,b}$ are the impedance of the node between a and φ, the node between b and φ, the node between a and μ, the node between b and μ, and the node between a and b, respectively; $P_{\varphi,t}$ and $D_{\mu,t}$ are the power of electricity source node φ and load node μ at the tth scheduling period, respectively.

4.3. Algorithm Flow of Optimal Scheduling for RPSDRE Considering PVSES

The proposed optimal scheduling model belongs to the mixed integer linear programming problem (MILP), which can be effectively solved by some mature commercial solvers such as Gurobi and Cplex in the actual operation. Thus, based on the software platform in Matlab 2020a and the compilation environment from Yalmip R20190425, the constructed optimal scheduling for the RPSDRE considering PVSES is solved by Gurobi 9.5. Correspondingly, the flowchart of the proposed optimal scheduling strategy is shown in Figure 2.

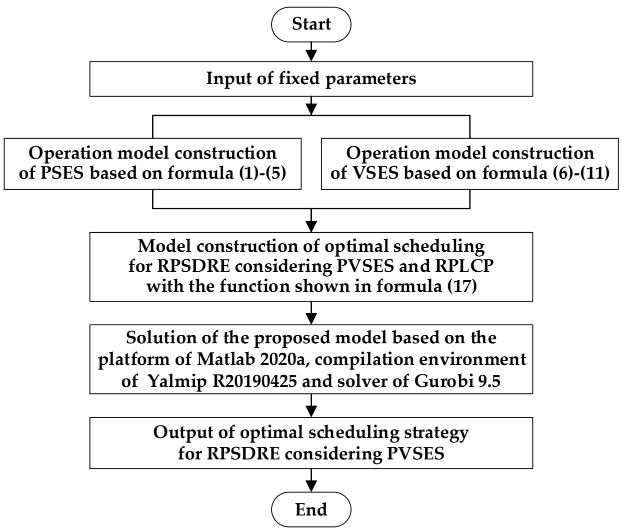


Figure 2. Flowchart of optimal scheduling for the RPSDRE considering PVSES.

5. Results and Discussion

5.1. Introduction of the Lankao RPSDRE

Based on the actual operational data of renewable energy output, existing line construction, and load characteristics in Lankao county, Kaifeng city, in the Henan province of China, the proposed model is performed on the RPSDRE with two wind farms, two PV stations, and two BP stations, whose network topology is shown in Figure 3. It can be observed from Figure 3 that there are three lines in this system to transport power in the superior power grid, which correspond to nodes 12, 21, and 24. The interaction between the RPSDRE and the superior power grid can provide a certain guarantee of stable supply for the system's load, but the operational economy may not be promised. Thus, the ES configuration can be considered to assist in the improvement of the operational economy. As shown in Figure 1, the ES is allocated at nodes 1, 2, and 7 on the power grid topology of the RPSDRE considering battery PES. Furthermore, the parameters of related devices in the Lankao RPSDRE are shown in the following Tables 1–3.

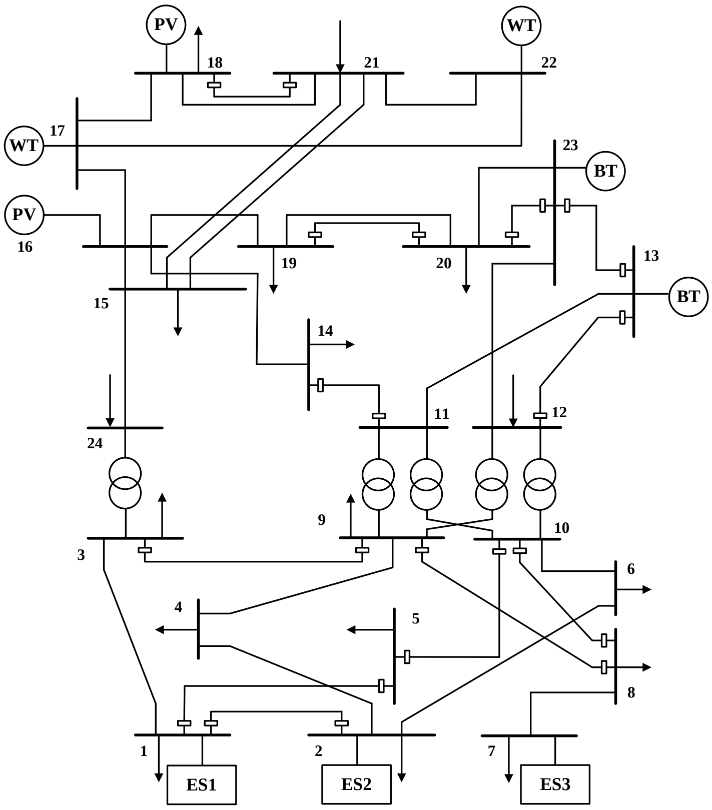


Figure 3. Network topology of the RPSDRE in Lankao county, Henan province, China.

Table 1. Parameters of battery PSES.

ES	Node	P_j^{recmax} (MW)	P_j^{redmax} (MW)	E_j^{rsmin} (MWh)	E_j^{rsmax} (MWh)	n_j^{rloss}	η_j^{rec} (%)	η_j^{red} (%)
ES 1	1	20	20	25	300	0.01	0.93	0.93
ES 2	2	50	50	25	400	0.03	0.97	0.97
ES 3	7	30	30	25	200	0.02	0.95	0.95

Table 2. Parameters of DR VSES.

Parameters	T^{mstart}	T^{mend}	σ^{vecmax}	σ^{vedmax}	P^{msig} (MW)
Parameters of DR	69	84	0.3	0.3	20

Table 3. Parameters of operational cost unit price.

Scheduling Period	λ_t^{pur} (CNY/MWh)	λ_t^{rec} (CNY/MWh)	λ_t^{red} (CNY/MWh)	λ_t^{vec} (CNY/MWh)	λ_t^{ved} (CNY/MWh)
1–28 and 93–96	41	10	10	30	30
29–40 and 57–68 and 85–92	100	10	10	30	30
41–56 and 69–84	164	10	10	30	30

5.2. Analysis of Lankao RPSDRE

5.2.1. Analysis of Optimal Scheduling for RPSDRE in Different ES Operation Modes

The optimal scheduling results of the RPSDRE in different ES operation modes is shown in Table 4. It can be seen from Table 4 that the power system has a greater reliance on the power purchase from a superior power grid to meet the system's power balance when not considering the participation of ES, which further leads to the highest operating cost. On the other hand, it is because the charge and discharge effect of ES is a benefit for the improvements of mismatch between the renewable energy power output and load power, the dependency of the RPSDRE on the superior power grid will be reduced in the optimal scheduling considering ES. Correspondingly, compared with the scheduling without any ES consideration, the operational cost of the RPSDRE respectively decreased by 51.56%, 18.46%, and 35.86% in the optimal scheduling that considered both PSES and VSES, considered PSES only, and considered VSES only. Furthermore, the most economic scheduling results can be obtained in the mode in which both PSES and VSES are considered. It can be seen that although the invocation of ES will increase the system's operational cost, the system's total operation can be decreased correspondingly when considering the dispatchable participation of ES due to the greater reduction effect of power purchase from the superior power grid of SES in the RPSDRE. Namely, the participation of SES in the RPSDRE will promote the overall operational economy and is conducive to the self-balancing operation of the economy.

Table 4. Optimal scheduling results of RPSDRE in different ES operation modes.

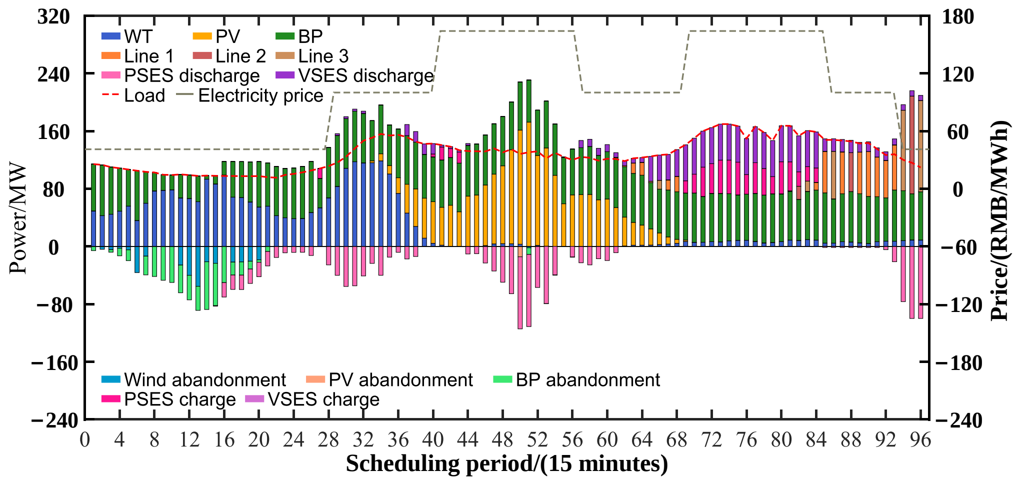
ES Operation Mode	F (CNY)	f^{pur} (CNY)	f^{ress} (CNY)	f^{vess} (CNY)
PSES and VSES joint-participation	137,912	79,653	21,033	37,226
only PSES participation	259,770	234,547	25,223	0
only VSES participation	195,799	157,155	0	38,644
without PSES and VSES participation	327,622	327,622	0	0

In addition, the optimal scheduling of flexible resources within the RPSDRE in different ES operation modes is shown in Figure 4. From the overall view of Figure 4, it is evident that the charging and discharging behavior of SES is closely coordinated with the curves of renewable energy power output, load power, as well as peak and valley electricity prices. For example, both PSES and VSES discharged to support the system's load supply and avoid an operational cost increase by purchasing power during the peak period of electricity price during the scheduling periods 69–84 when the electricity price and load are both at the peak, and renewable energy output is at its lowest. During scheduling periods 44–60, which correspond to the peak period of renewable energy output and the off-peak period of the system's load, there is surplus renewable energy power output that cannot be fully utilized. At this time, the SES is charged to mitigate power abandonment of WT, PV, and BP, and to prepare for the subsequent peak periods of load. Furthermore, by comparing the charging and discharging behaviors of VPSES between the system that only considers the participation of VSES in Figure 4c and the system that does not consider any VPSES in Figure 4d, it is evident that during scheduling periods 64–84, when the system load is at its peak and there is a shortage of wind and PV power output, the discharge behavior of the virtual energy storage system is employed to decrease the amount of power purchased from the superior power grid. This reduces the transmission pressure on the system, decreases the reliance of the RPSDRE on the superior power grid, lowers the operating costs of the system, and provides effective support for the independent, economic, and reliable operation of the system.

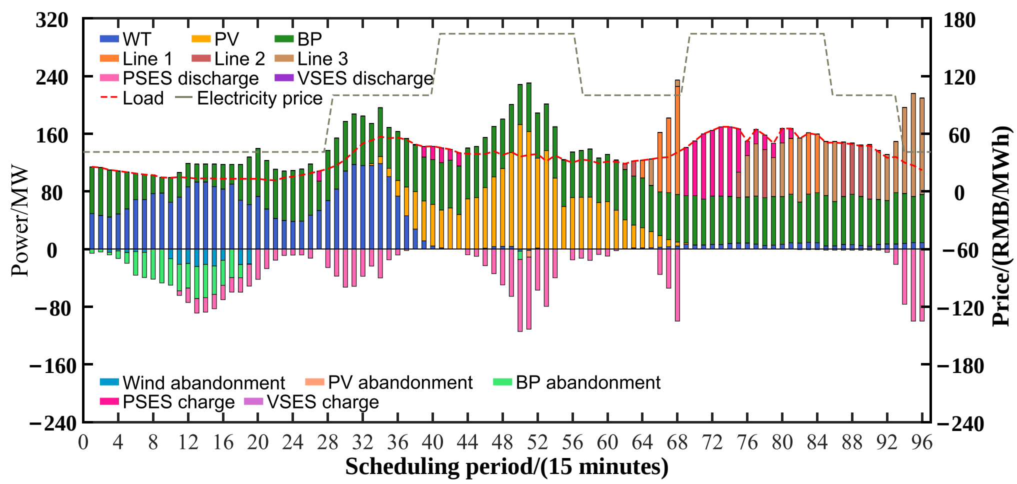
It can also be seen from the comparison of the power purchased from the superior power grid during the periods 64–84 that, compared with the optimal dispatching without considering any ES in Figure 4d, the power purchased from the superior power grid by the system is more decentralized when only considering VSES in Figure 4c, and the use of a single transmission line is less concentrated. This is because the VSES model can reflect the equivalent ES effect of distributed DR, and the load distributed at each node of the system topology can participate in the DR, Thus, it can reduce the power purchase from the superior power grid, coordinate the power transmission distribution, and effectively avoid the congestion caused by the limited power transmission capacity of a single line.

Furthermore, it can be observed that, compared with the optimal dispatching results of the system that does not consider any VPSES in Figure 4d, the system that only considers the participation of PSES in Figure 4b can make use of the charging of PSES to reduce the wind and PV abandonment of the system during the periods 8–36 when the system load is low and the wind power is at the peak, and during the periods 44–56 when the system load is low and the PV is at the peak. During periods 69–80 when the system load is at the peak and both wind power and PV output are in short supply, PSES will discharge to reduce the system's power purchase from the superior grid, which reflects the "peak cutting and valley shaving" effect of physical battery energy storage. In addition, since the constraint that the energy of battery energy storage throughout the day remains unchanged is considered in the optimal scheduling for battery energy storage, it can be observed from Figure 4b that the PSES is charged at periods 92–96 by purchasing power from the superior grid, which not only provides preparation for the next day's energy storage and discharge but also reflects the coordination of the proposed strategy on the charging and discharging efficiency and self-discharge characteristics of PSES.

In summary, the RPSDRE considering PVSES can achieve the promotion of both the operational economy and the utilization rate of renewable energy power generation through the effective coordination of ES charge and discharge.

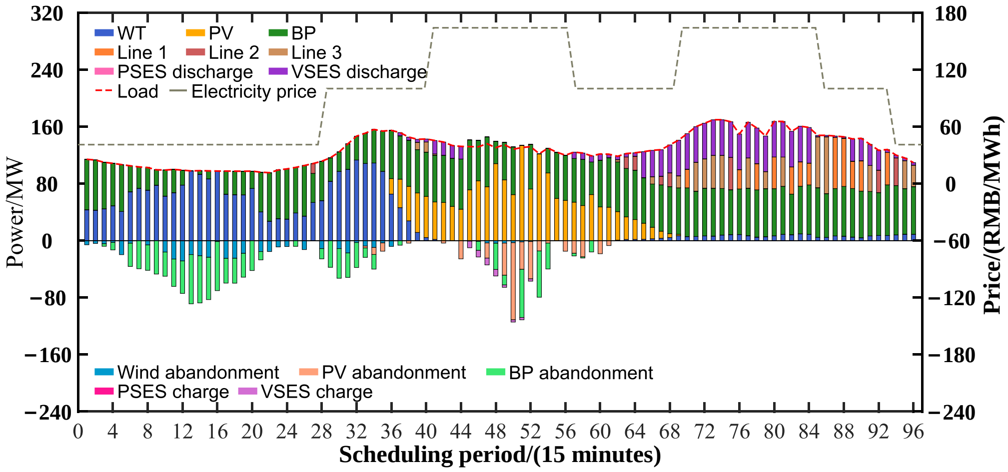


(**a**)

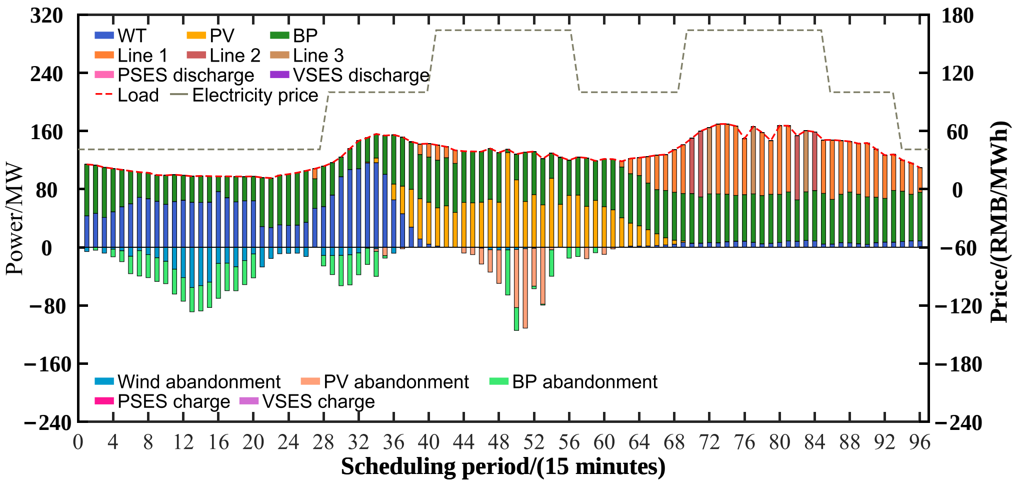


(**b**)

Figure 4. *Cont.*



(**c**)



(**d**)

Figure 4. Optimal scheduling of flexible resources within the RPSDRE in different ES operation modes: (**a**) PSES and VSES joint participation; (**b**) only PSES participation; (**c**) only VSES participation; and (**d**) without PSES and VSES participation.

5.2.2. Sensitivity Analysis of Optimal Scheduling for RPSDRE Considering the Degradation of Battery PSES

In this section, sensitivity analyses are conducted to clarify the impact of battery degradation of PSES on the scheduling results of the RPSDRE. The degradation of battery energy storage is reflected by the change of the self-discharging coefficient and the charging and discharging efficiency of PSES, which are represented as the parameters n_j^{rloss}, $\eta_j^{\mathrm{rec}}/\eta_j^{\mathrm{red}}$ in Formula (4), respectively. The operational performance of the RPSDRE with the change of n_j^{rloss} and $\eta_j^{\mathrm{rec}}/\eta_j^{\mathrm{red}}$ is shown in Figure 5.

It can be observed from Figure 5a–c that the operational cost of the PRSDRE and the power purchase from the superior grid increase with the increase in the self-discharging coefficient and the decrease in the charging/discharging efficiency, which means that the degradation of battery PSES will affect the system's operational economy directly with the decrease in charging and discharging adjustment flexibility and the increased dependence on power purchase from the superior power grid. It can also be observed from Figure 5b,d that there is a maximum point of PSES cost and CETIM profit with the increase in the self-discharging coefficient. This is because, with the deepening of battery degradation, more power is needed to achieve the storage of electricity, which will lead to the increase in PSES costs generated from the charging behavior and the initial increase in power consumption from the renewable energy power output. However, with the constant increase in PSES costs, the utilization of PSES will produce a higher economic cost than the power purchase. To achieve the most economic scheduling, the invocation of battery PSES will be reduced and the CETIM profit will be reduced accordingly.

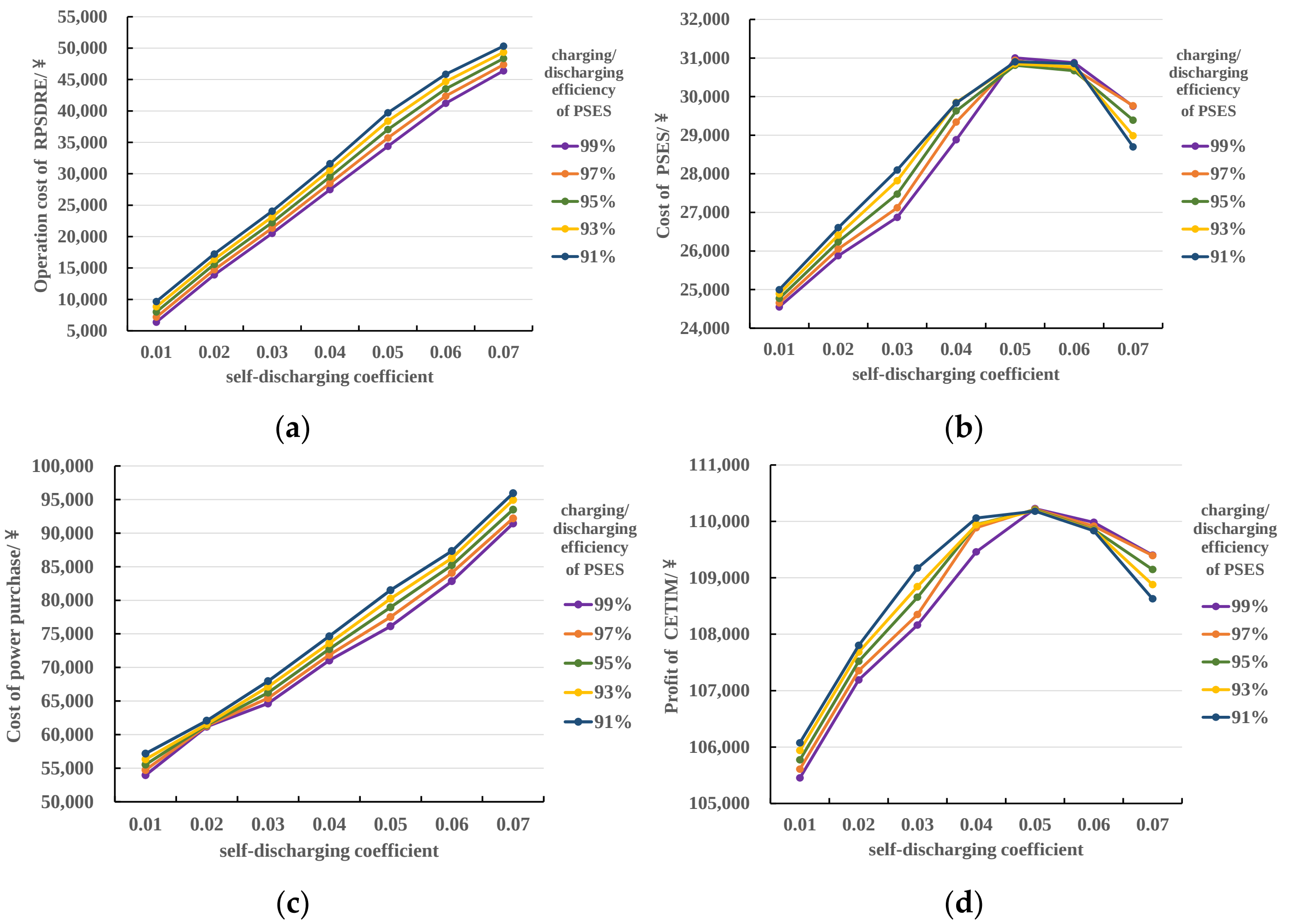


Figure 5. Optimal scheduling results of the RPSDRE considering the degradation of battery PSES: (**a**) operational cost of the RPSDRE; (**b**) cost of PSES; (**c**) cost of power purchase from the superior grid; and (**d**) profit of CETIM.

Furthermore, it can be seen from Figure 5 that the optimal scheduling is more sensitive to the change in the self-discharging coefficient than the charging/discharging efficiency of battery PSES. Correspondingly, more attention should be paid to the self-discharging coefficient monitoring of battery PSES in the actual optimization to keep the flexible operational performance of battery PSES.

5.2.3. Comparison among Four Kinds of Optimal Scheduling Strategies for RPSDRE

In this section, four kinds of existing optimal scheduling strategies for the RPSDRE considering PVSES and different carbon trading mechanisms are compared with their optimization results, which can be seen in Table 5. The definition and source of each model are as follows.

- M-RPLCP: M-PRLCP refers to the proposed scheduling strategy with the objective function considering the CETIM with the RPLCP;
- M-FCP: M-FCP refers to the scheduling strategy with the objective function considering the CETIM with a fixed carbon price [29];

- M-PLCP: M-PCP refers to the scheduling strategy with the objective function considering the CETIM with a penalty ladder carbon price [30];
- M-NON: M-NON refers to the scheduling strategy without considering the objective function of the CETIM [35].

As shown in Table 5, the proposed optimal scheduling strategy of RPSDRE considering the CETIM with the RPLCP has the lowest total operational cost of CNY 21,353.12, the lowest carbon emission of −1946.96 t, and the highest consumption rate of renewable energy of 97.42%, which means the proposed strategy can obtain the most comprehensive performance of scheduling optimization among the four methods. Meanwhile, it can also be observed that no matter which kind of carbon trading price is used, the introduction of carbon trading can achieve the promotion of the economy, the reduction in carbon emissions, and the consumption of renewable energy when compared with the scheduling strategy not considering the carbon trading mechanism. Furthermore, the motivational impact of the carbon trading mechanism on the flexible adjustment of PVSES is reflected in the operational cost increase of PVSES compared with the strategy M-NON. To sum up, the consideration of the carbon trading mechanism in the scheduling of the RPSDRE improves the system's comprehensive operational performance, including economy, carbon emission restriction, and the potential simulation of flexible adjustment from PVSES.

Table 5. Optimal scheduling results of RPSDRE with different carbon trading mechanisms.

Scheduling Strategies for RPSDRE	F (CNY)	f^{pur} (CNY)	f^{ress} (CNY)	f^{vess} (CNY)	Carbon Emission (t)	Renewable Energy Consumption Rate (%)
M-RPLCP	21,353.12	65,426.07	27,120.49	37,154.86	−1946.96	97.42
M-FCP	57,421.07	65,509.94	26,541.11	36,926.62	−1933.96	96.77
M-PLCP	38,069.91	65,426.07	26,487.63	37,154.86	−1936.14	96.88
M-NON	128,326.44	64,808.09	26,049.40	37,468.94	−1913.72	95.77

6. Conclusions

Aiming at the accommodation between the rapid increase of renewable energy capacity and the effective utilization level in the current development of power systems, the method to guarantee the coordination and complementarity of multiple flexible resources in RPSDREs is proposed in this paper, and an optimal scheduling strategy for SES considering battery PSES and DR VSES is constructed. An actual case study conducted in Lankao county, China, demonstrates that the proposed model effectively utilizes PVSES and several other flexible resources in RPSDRE to achieve coordinated and complementary system operation, ultimately enabling adaptive and economic scheduling. According to the results of the study, the more concrete conclusions are summarised below.

The utilization of SES in the optimal scheduling of the RPSDRE can achieve the improvement of the system's economy, and the invocation of PVSES can produce the highest profit for the system operation. This can be observed from the simulation results which show that the scheduling considering PVSES, considering PSES only, and considering VSES only can, respectively, reduce the total operational cost by 51.56%, 18.46%, and 35.86% compared with scheduling without considering any SES.

The simulation result of the coordination between the charge and discharge behavior of PSES and the accommodation of renewable energy, load characteristics, and change of electricity price reveals the "peak cutting and valley shaving" effect of PSES, which can help the further optimization of the RPSDRE operation.

The decentralized optimization results of the power purchase mean the utilization of equivalent ES effect from distributed DR has the advantages to optimize the power transmission distribution and avoid the blockage problem of unreasonable power purchase through single line transmission, which will also promote the flexibility and economy of the system's operation.

According to the comparison of related research in the case study, the proposed optimal scheduling strategy considering the CETIM with RPLCP has more comprehensive optimization ability than other related studies, whether from the operational economy, from the carbon emission reduction, or from the accommodation of renewable energy.

The sensitivity analysis of optimal scheduling for the RPSDRE considering different input parameters of battery PSES reflects the impact of battery degradation on the optimization results for the RPSDRE. Namely, the degradation of battery PSES will weaken the operational economy, carbon emission control, and operational flexibility and the self-discharging coefficient is a key element that can be monitored to keep the comprehensive performance of the system operation, which can serve as a reference for RPSDRE scheduling.

Furthermore, there are still some elements that have not been considered in this paper, which may need further research in future studies. The two main prospects of the proposed scheduling strategy for RPSDREs are described below.

1. The steady-state optimal scheduling strategy on the hour-level time scale is proposed in this paper and the frequency restoration reserves, frequency containment reserves, and inertial response of battery energy storage systems on the time scale of minutes or seconds have yet to be analyzed, which will be studied in further researches.
2. With the upgrading of renewable energy utilization technology, the types and installed capacity of renewable energy power generation are changing rapidly, and waste-to-energy has become an avenue to achieve the disposal of waste and the production of electric energy. Thus, the coordination of waste-to-energy and energy storage could be analyzed in future research.

Author Contributions: Conceptualization, Z.C., Y.C., Z.L. and K.Z.; methodology, Y.C., C.L., L.Y. and W.Q.; software, J.L., Y.C. and C.L.; validation, Y.C., Y.Z. and W.Q.; investigation, S.Y.; resources, S.Y., M.Y. and K.Z.; data curation, Y.C.; writing—original draft preparation, Z.C., Y.C. and W.Q.; writing—review and editing, Y.C., K.Z., W.Q. and C.L.; visualization, Y.C.; supervision, J.L. and Y.Z.; project administration, Z.C., J.L. and S.Y.; funding acquisition, Z.C. and S.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Science and Technology Project of State Grid Henan Electric Power Co., Ltd. (SGHAYJ00NNJS2200047).

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

A. Abbreviations

PSDRE	power system dominated by renewable energy
RPSDRE	regional PSDRE
WT	wind turbine
PV	photovoltaic
BP	biomass power
DR	demand response
ES	energy storage
SES	shared energy storage
PSES	physical SES
VSES	virtual SES
PVSES	physical and virtual SES
RPLCP	reward and penalty ladder carbon price
TCETM	total carbon emission trading mode
CEITM	carbon emission intensity trading mode

B. Decision Variables

$P_{j,t}^{\mathrm{rec}}/P_{j,t}^{\mathrm{red}}$	charging and discharging power of PSES j at period t
$u_{j,t}^{\mathrm{rec}}/u_{j,t}^{\mathrm{red}}$	charging and discharging states of PSES j at period t
$E_{j,t}^{\mathrm{ress}}/E_{j,t-1}^{\mathrm{ress}}$	storage capacity of PSES j at period t/t-1
$P_{t,k}^{\mathrm{pve}}/\Delta P_{t,k}^{\mathrm{pve}}$	load power and its variation of price-based DR k at period t

$c_{t,k}^{\mathrm{pve}}/\Delta c_{t,k}^{\mathrm{pve}}$	electricity price and its variation of price-based DR k at period t
$P_{k,t}^{\mathrm{pve}}$	load power after the response of price-based DR k at period t
c_t^{pve}	electricity price after the response of price-based DR k at period t
$P_{k,t}^{\mathrm{mve}}$	response power of incentive DR k at period t
$P_{j,t}^{\mathrm{vec}}/P_{j,t}^{\mathrm{ved}}$	charging and discharging power of VSES j at period t
$P_{m,t}^{\mathrm{wind}}/P_{n,t}^{\mathrm{sun}}/P_{p,t}^{\mathrm{bio}}/P_{s,t}^{\mathrm{load}}$	power of WT m/PV n/BP p/system's load s in RPSDRE at period t
$u_{k,t}^{\mathrm{vec}}/u_{k,t}^{\mathrm{ved}}$	charging and discharging states of VSES k at period t
$P_{a,b,t}^{\mathrm{line}}$	transmission power between node a and node b in RPSDRE at period t
$P_{\varphi,t}/D_{\mu,t}$	power of electricity source node φ and load node μ at period t

C. Input Parameters

$P_j^{\mathrm{recmax}}/P_j^{\mathrm{redmax}}$	maximum charging and discharging power of PSES j
$E_j^{\mathrm{rsmin}}/E_j^{\mathrm{rsmax}}$	minimum and maximum storage capacity of PSES j
$n_j^{\mathrm{rloss}}/\eta_j^{\mathrm{rec}}/\eta_j^{\mathrm{red}}$	self-discharging coefficient, and charging and discharging efficiency of PSES j
$E_{j,0}^{\mathrm{ress}}/E_{j,T}^{\mathrm{ress}}$	storage electricity of PSES j at the beginning/end of the scheduling period
$r_{u,v}^{\mathrm{pve}}$ $(u = v, u = 1, 2, \ldots, T, v = 1, 2, \ldots, T)$	self-elastic coefficient
$r_{u,v}^{\mathrm{pve}}$ $(u \neq v, u = 1, 2, \ldots, T, v = 1, 2, \ldots, T)$	mutual-elastic coefficient
$P_{k,t}^{\mathrm{pve0}}$	load power before the response of price-based DR k at period t
c_t^{pve0}	electricity price before the response of price-based DR k at period t
$T^{\mathrm{mstart}}/T^{\mathrm{mend}}$	start/end time of incentive DR
P_k^{msig}	contracted capacity of incentive DR k
$\lambda_{i,t}^{\mathrm{pur}}$	unit price of the power purchase from line i at period t
$\lambda_{j,t}^{\mathrm{rec}}/\lambda_{j,t}^{\mathrm{red}}$	unit price of charging/discharging of PSES j at period t
$\lambda_{k,t}^{\mathrm{vec}}/\lambda_{k,t}^{\mathrm{ved}}$	unit price of charging/discharging of VSES k at period t
$N^{\mathrm{line}}/N^{\mathrm{ress}}/N^{\mathrm{vess}}$	number of power purchase lines from the superior power grid/PSES/VSES in RPSDRE
$N^{\mathrm{load}}/N^{\mathrm{wind}}/N^{\mathrm{sun}}/N^{\mathrm{bio}}$	number of system's load nodes/WT/PV/BP in RPSDRE
$\sigma_k^{\mathrm{vecmax}}/\sigma_k^{\mathrm{vedmax}}$	maximum charge and discharge proportion of DR VSES
$P_{k,t}^{L}$	load forecast power of DR VSES k at period t
$P_{\min}^{\mathrm{s}}/P_{\max}^{\mathrm{s}}$	upper and lower limits of PV power output
$P_{\min}^{\mathrm{w}}/P_{\max}^{\mathrm{w}}$	upper and lower limits of WT power output
$P_{\min}^{\mathrm{b}}/P_{\max}^{\mathrm{b}}$	upper and lower limits of BP power output
$P_{a,b}^{\max}$	maximum transmission power between node a and node b
$X_{a,\varphi}/X_{b,\varphi}/X_{a,\mu}/X_{b,\mu}$	impedance of node between a and φ/ node between b and φ/ node between a and μ/ node between b and μ/ node between a and b
λ^{cb}	baseline of carbon emission intensity
λ^{ce}	unit carbon emission
κ/ϖ	number of segments in reward/penalty carbon price
ω	percentage increase in the carbon price

D. Indices and Sets

r^{pve}	elasticity coefficient matrix of electricity price and load power
Δt	scheduling interval
ψ/L	node sets of power source and load in RPSDRE
T	numbers of scheduling periods

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