Low-carbon Dispatching for Virtual Power Plant with Aggregated Distributed Energy Storage Considering Spatiotemporal Distribution of Cleanness Value

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***Abstract*—The scale of distributed energy resources is increasing, but imperfect business models and value transmission mechanisms lead to low utilization ratio and poor responsiveness. To address this issue, the concept of cleanness value of distributed energy storage (DES) is proposed, and the spatiotemporal distribution mechanism is discussed from the perspectives of electrical energy and cleanness. Based on this, an evaluation system for the environmental benefits of DES is constructed to balance the interests between the aggregator and the power system operator. Then, an optimal low-carbon dispatching for a virtual power plant (VPP) with aggregated DES is constructed, wherein energy value and cleanness value are both considered. To achieve the goal, a green attribute labeling method is used to establish a correlation constraint between the nodal carbon potential of the distribution network (DN) and DES behavior, but as a cost, it brings multiple nonlinear relationships. Subsequently, a solution method based on the convex envelope (CE) linear reconstruction method is proposed for the multivariate nonlinear programming problem, thereby improving solution efficiency and feasibility. Finally, the simulation verification based on the IEEE 33-bus DN is conducted. The simulation results show that the multidimensional value recognition of DES motivates the willingness of resource users to respond. Meanwhile, resolving the impact of DES on the nodal carbon potential can effectively alleviate overcompensation of the cleanness value.**

***Index Terms*—Distributed energy storage, virtual power plant (VPP), spatiotemporal distribution, low-carbon dispatching.**

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I. Introduction

In recent years, the aggregation capacity of distributed energy resources has increasingly contributed to the flexibility construction of new power systems, while the gradual improvement of electricity market mechanisms has allowed more end-users to participate in market operations [1], [2]. However, due to the diverse aggregation forms, uneven response quality, and differentiated interest demands, a reasonable business model meeting the personalized requirements of end-users is difficult [3], [4].

The virtual power plant (VPP) has emerged to meet these requirements, providing a new solution for the aggregation and operation of distributed energy resources [5], [6]. As coordinators, VPPs play two roles in meeting these requirements.

1) From a commercial perspective, the distributed energy resources aggregated by VPPs are usually small in scale and dispersed in location, making it difficult for these resources to obtain access to the electricity market when operating independently. VPPs can build a cooperative game platform for end-users to jointly arbitrage in the electricity market and collaborate with each other [7].

2) From an operational perspective, the VPP and distributed energy resources rely on the Internet of Things and have real-time communication capabilities [8]. After receiving dispatching instructions issued by the power system operator, the VPP can decompose control instructions into different resource objects based on optimization dispatching decision-making, prompting each resource to achieve the same control target and complete the response, thereby playing collaborative roles [6].

Among the numerous distributed energy resources aggregated by VPPs, distributed energy storage (DES) has strong advantages due to their fast regulation ability and stable control characteristics. However, due to the high investment cost and large response wear-cost, DESs present few response times in the absence of a perfect business model [9]-[11]. The basic profit models for energy storage are peak-valley electricity price arbitrage, which involves "charging energy during low-price period and discharging energy during high-price period" to achieve energy price arbitrage. However, energy storage not only has energy value, but can also has capacity value as power generation units [12], [13]. It is incorporated into the capacity market mechanism as a special market entity, thus better recovering investment costs. Of course, energy storage can also participate in market operations through business models such as frequency regulation and fast ramp. Varieties leverage its flexibility value and thereby improve market-oriented benefits.

However, the existing problem is that DES does not have market access qualifications due to its small capacity, dispersed location, and diverse entities. Cost recovery can only be achieved through the energy price arbitrage model mentioned above; however, factors such as limited and uncertain peak-valley price gap in an insufficient market, and the reverse peak characteristic of renewable energy have lowered the profit margin of DES. Still harder, based on the estimated investment cost of DES, the arbitrage can be obtained until the peak-valley price difference needs to be than a margin value [14], [15]. That is to say, the existing business model for DES is still incomplete and cannot sustainably motivate the willingness of market participation, nor support the reasonable avoidance of market risks. Therefore, as one of the research motivations, this paper attempts to further explore the multidimensional value of DES, expanding the value of DES from energy value, capacity value, and regulation value to cleanness value. Enriching the pricing mechanism of DES is the motivation of this paper, and the given solution is conducting coupling management between DES operation and clean attributes of green power, thus maximizing the utilization of green power in the temporal and spatial dimensions.

DES is chosen as the research object in this paper for many reasons. ① DES can provide the transfer of energy in tempral dimension, providing infrastructure for the consumption and storage of renewable energy [16]. ② DES access location is flexible and can provide green power support at different distribution network (DN) nodes, thereby meeting the personalized requirements of end-users [17]. ③ There is a lack of the business model and value evaluation system suitable for DES, and relying solely on current arbitrage of the energy market cannot fully increase the willingness of resource users and meet cost recovery [18]. ④ DES has a certain cleanness value and can change the nodal carbon potential of DN through the storage, transfer, and utilization of green power, thereby supporting the low-carbon operation of the power supply network [19].

Researchers have conducted in-depth research on DES operation optimization in recent years. For dispatching decision-making, fully considering the regulating capabilities of DES can effectively improve the operation characteristics of VPP, thereby improving the overall operation efficiency and economy [20], [21]. DES can achieve centralized cooperative dispatching through aggregation. To achieve the independent optimization and iterative coordination of DES, [22] adopts the cross-mixing method of centralized control and distributed control to model the operation of DES and gives full attention to the economic value of DES. Aiming to address the poor DES economy in the single operation mode, [23] proposes a two-layer dynamic game optimization approach for shared DESs under multiple application scenarios considering economic benefits. With the optimization goal of minimizing cost-benefit, the optimal capacity and operation strategy of the DES in VPP are obtained through the collaborative optimization of the two-layer model. Furthermore, based on the above studies, [24] constructs a three-stage dispatching model of VPP with generalized energy storage and adjusts the dispatching plan of energy storage time by time at each stage to better stabilize the uncertainty of renewable output.

Meanwhile, to address the carbon emissions of the VPP, the low-carbon economic dispatching can effectively balance the economy and cleanness [25], [26]. To improve the reliability of the multiload power supply and ensure the low-carbon economic operation of VPPs, [27] constructs a multiload aggregation model aiming to maximize profit and a VPP supply-demand matching model aiming to minimize carbon emissions. In addition, to verify the low-carbon economic value of energy storage at a multi-time scale, [28] combines a carbon emission assessment system with a carbon trading mechanism and proposes an economic optimization dispatching approach for microgrids.

The above analysis shows that in existing studies on energy storage dispatching approaches, economic optimization still remains a priority. The charging and discharging behavior of energy storage is determined to address energy management. Although some studies have considered low-carbon operation supported by energy storage, the primary research focus is still the allocation problem of energy storage oriented to renewable consumption and carbon reduction. The above studies neglect the cleanness value created by energy storage itself for the storage, transfer, and utilization of green power, which in turn affects the integrity and effectiveness of energy storage business models.

In accordance with analysis, the energy storage itself is not a clean resource, but has good regulation performance. Meanwhile, the renewable energy has poor regulation ability due to its randomness and intermittent feature, but it has cleanness value. For this reason, the coupling management between DES operation and clean attributes of green power can tap into the low-carbon feature of DES, which facilitates the DES as a new type of allocation resources from the perspective of cleanness value.

Aiming at it, this paper has made three main efforts.

1) The cleanness value concept of DES is proposed, and the spatiotemporal distribution mechanism is identified, thereby creating an evaluation system of cleanness value to improve the business model of DES. Moreover, after introducing environmental benefits, in order to balance the interests of power system operators and aggregators in the new business model, a comprehensive evaluation indicator is proposed.

2) A coupling management decision-making model of DES operation and green power for VPP is proposed, considering both energy value and cleanness value. The influence of charging and discharging green power of DES on the nodal carbon potential of DN is discussed. Then, the contribu-

tion of individual DES behavior to overall low-carbon dispatching can be finely calculated, which allows system operators to achieve low-carbon goals at lower environmental costs.

3) To resolve the multiple nonlinear relationships involved in the green attribute labeling of DES in this paper, a solution method based on the convex envelope (CE) linear reconstruction method is introduced. Notably, the fractional nonlinear relationship is converted into a product nonlinear relationship, and nonlinear processing is then conducted.

The remaining of this paper are organized as follows. In Section II, the spatiotemporal characteristics of DES are introduced, and the evaluation system is created. In Section III, the optimal low-carbon dispatching scheme of VPP is depicted. In Section IV, the simulation verification and result analysis are conducted. Finally, a conclusion is provided.

II. Spatiotemporal Characteristics of DES and Evaluation System

A. Spatiotemporal Distribution of Cleanness Values for DES

As mentioned above, DES can play a multidimensional energy management role in system operation through its charging and discharging behavior [29]. As shown in Fig. 1, DES has the spatiotemporal characteristics from the perspective of electrical energy. Firstly, DES can change the load curve of end-users through energy consumption, storage, and release, thus achieving the energy transfers in the temporal dimension. This helps the DES users obtain arbitrage based on the peak-valley price. Secondly, DES can be deployed in different DN nodes to change the power flow state in DN; however, the end-users still face different electricity price due to the network congestion. Under this, the optimal dispatching scheme considering spatial characteristic can help the end-users achieve the efficient cost, and meanwhile, it can guide the investment to and upgrading of DN.

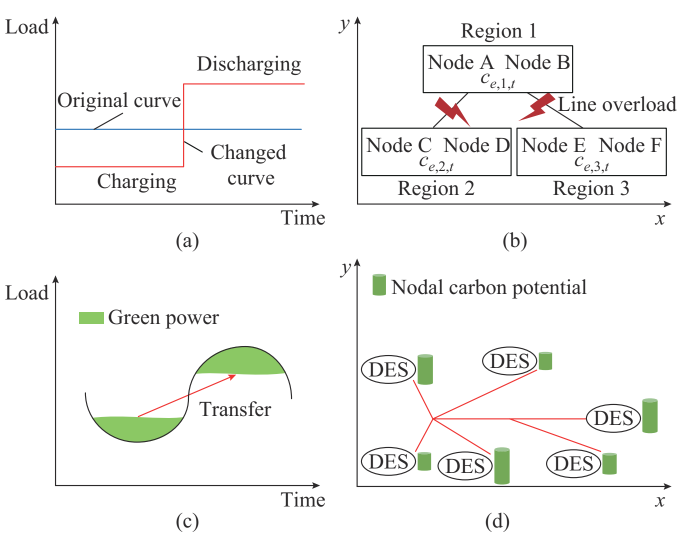

Fig. 1. Spatiotemporal distribution characteristics of DES cleanness values. (a) Temporal distribution characteristics from perspective of electrical energy. (b) Spatial distribution characteristics from perspective of electrical energy. (c) Temporal distribution characteristics from perspective of cleanness. (d) Spatial distribution characteristics from perspective of cleanness.

From the perspective of cleanness, green attributes cannot be extracted from electrical energy at the physical level, because the power generated by various types of generation units exhibits similar energy values. However, different types of power generation units have additional attributes such as the cleanness value of renewable energy. For example, the environmental premium accounting of the green electricity market in China is a key measure to recognize the cleanness value, thus to support the development of renewable energy. DES, as a type of special electricity consumers, is unique because the green power it consumes does not immediately eliminate its clean properties, but can be stored to unleash its cleanness value in other temporal and spatial points. Therefore, the coupling management of green power attribute and DES behavior will bring great benefits to the power system and DES users.

The characteristics of cleanness value are reflected in two dimensions as well. In the temporal dimension, the charging and discharging behavior of DES has green attributes, and the utilization of green power in the DES considering the system carbon emission factors (or carbon prices) will induce differentiated carbon emissions. In the spatial dimension, the green power of DES changes the green proportion of DN nodes, thus affecting the nodal carbon potential of DN and providing differentiated power supply services for end-users in different geographical locations, as shown in Fig. 1(d). Based on this, the optimal dispatching of DES considering nodal carbon potential will further enhance the low-carbon operation goals of the system.

Therefore, the cleanness value of DES can be defined as the low-carbon benefits generated by the spatiotemporal green power transfer conducted by DES. Therefore, the cleanness value of DES herein refers to the carbon reduction benefits obtained by coupling DES operation with the clean attributes of green power for management, and is not related to the carbon emissions of DES itself. Herein, the green power transfer of DES does not need additional physical measurement and tracing; instead, it can be achieved through the charging and discharging behavior of DES and labeling green power to complete attribute identification. This behavior will not change the network constraints of power flow or the operation state of the power system, and it provides an accounting basis for the cleanness value of DES.

In summary, the spatiotemporal characteristics and the multidimensional value of DES could be evaluated from the perspectives of electrical energy and cleanness. From the perspective of electrical energy, the temporal dimension value of DES can be characterized by the time-of-use (TOU) electricity price, which can guide end-users to charge at a low-level TOU electricity price and discharge at a high-level TOU electricity price to reduce operating costs. The spatial dimension value can be characterized by the nodal price of DN, which is the electricity price generated by the differentiated supply and demand of different physical nodes at the same time due to physical congestions of DN. When power flow congestion is present in DN, DES can use the nodal price as a price signal to implement optimal dispatching and allocate resources in spatial distribution.

From the perspective of cleanness, the coupling operations of the electricity–carbon market have become a new trend. To accommodate this change, some developed electricity markets are gradually promoting the temporal constraints on green attributes, such as the newly added available period constraints in the green certificate and the nodal carbon potential calculation of the 15 min running cycle in the Pennsylvania–New Jersey–Maryland (PJM) market [30]. This indicates that in the future carbon market, carbon price fluctuations will become more frequent, while the settlement cycle will become smaller, promoting precise and timely coupling between the electricity market and the carbon market.

Therefore, the green power of DES may bring differentiated environmental benefits between the situations with and without considering the spatiotemporal characteristics of cleanness value.

Based on this advanced assumption, the cleanness value of DES in temporal dimension can be characterized by time-varying carbon prices, wherein a day is divided into 24 periods, and the emission reduction unit benefits differ in each period. Moreover, the DES deployed in different locations has different levels of green power supply, such as different carbon potentials. Therefore, the discharging green power in different spatial locations will have differentiated cleanness values, which affects the energy consumption decisions of end-users and the overall environmental benefits. Therefore, the cleanness value of DES in spatial dimension can be characterized by the nodal carbon price of DN, which is calculated based on the above TOU carbon price and nodal carbon potential of DN, as shown in Table I.

TABLE I
CHARACTERIZATION INDEXES OF SPATIOTEMPORAL VALUE OF DES

Perspective	Index	Expression form
Electrical energy	TOU electricity price	Energy value in the temporal dimension
	Nodal electricity price	Energy value in the spatial dimension
Cleanness	TOU carbon price	Cleanness value in the temporal dimension
	Nodal carbon price of DN	Cleanness value in the spatial dimension

Notably, the nodal carbon potential of DN is a relatively novel concept. Herein, it refers to the nodal carbon potential of DN with deployment of DES. The discharging green power of DES will inevitably lead to an increase in the green proportion of the DN node, thereby reducing the nodal carbon potential.

To better account for the contribution of individual DES user on the overall low carbon dispatching, the influence mechanism is analyzed. Without considering the changes in nodal carbon potential, the environmental benefits of DES are calculated uniformly based on the nodal carbon potential of transmission system. This will induce two problems: ① there is no targeted incentive for the behavior of individual DES users; and ② it can lead to overcompensation of DES environmental benefits. To address it, the nodal carbon potential change brought by the discharging green power of DES need to be quantified.

The following method is adopted to calculate the nodal carbon potential of DN.

1) Total carbon emission calculation of each supplying region without congestion: regional carbon emissions can be calculated based on the unified nodal carbon potential and nodal electric load of each region. The nodal carbon emissions at time t of region i are given as:

$$D_{i,t} = P_{i,t}^{\text{load}} e_{s,t} \Delta t \tag{1}$$

where $e_{s,t}$ is the initial nodal carbon potential at time t of each region; $P_{i,t}^{\text{load}}$ is the electric load at time t of region i; and Δt is the time interval.

2) Impact of DES on nodal carbon potential of DN: when charging green power of DES, the nodal carbon potential of DN is the same as that of the transmission system. When discharging green power of DES, the green proportion in the power supplying area increases, thus changing the nodal carbon potential of DN. The changes in the nodal carbon potential of DN and the updated nodal carbon potential of DN are depicted as:

$$\begin{cases} D_{i,t}^{\text{gre}} = P_{i,t}^{\text{gre}} e_{i,t} \Delta t \\ \Delta e_{i,t+1} = \dfrac{D_{i,t}^{\text{gre}}}{P_{i,t-1}^{\text{load}}} \\ e_{i,t+1} = e_{s,t+1} - \Delta e_{i,t+1} \end{cases} \tag{2}$$

where $D_{i,t}^{\text{gre}}$ is the CO_2 emission reduction at time t of region i; $P_{i,t}^{\text{gre}}$ is the charging green power of DES at time t of region i; $e_{i,t}$ is the nodal carbon potential at time t of region i; and $\Delta e_{i,t+1}$ is the nodal carbon potential change at time $t+1$ of region i.

Using (1) and (2), the differentiated nodal carbon price of each region can be calculated as:

$$\begin{cases} c_{\text{car},i,t} = c_{\text{car},s,t} e_{i,t} \\ e_{i,1} = e_{s,1} \end{cases} \tag{3}$$

where $c_{\text{car},i,t}$ is the nodal carbon price at time t of region i; and $c_{\text{car},s,t}$ is the initial TOU carbon price at time t of region i.

B. Evaluation System of Environmental Benefits

To improve the business model and pricing system for DES, an evaluation system for the envieonmental benefits of DES in different scenarios is proposed in this paper. As discussed previously, the cleanness value of DES is reflected in the emission reduction effect created by the spatiotemporal green power transfer. The environmental benefits and contribution value can be evaluated based on the Shapley value method. The cleanness value can be obtained by calculating the operation cost difference between the situations with and without considering DES environment benefit, and the environment benefit change can be obtained by calculating the operation cost difference between the situations with and without considering the impact of discharging green power of DES on nodal carbon potential. For this reason, the application scenarios are preset as follows.

Scenario 1: the objective function of the low-carbon dispatching scheme considers both energy cost and environmental benefits. Energy cost refers to the energy interaction between the VPP and the power grid, which is primarily affected by factors such as the TOU electricity price and nodal electricity price. Environmental benefits refer to carbon reduction revenue by discharging green power of DES, and are primarily affected by the time-varying carbon price and nodal carbon potential.

Scenario 2: the impact of discharging green power of DES on nodal carbon potential is further examined. The differentiated nodal carbon potential induces different nodal carbon prices of DN. Therefore, the environmental benefits consider the spatial distribution characteristics of DES.

Scenario 3: this is the benchmark case. Only the energy cost caused by energy interaction is considered, and the environmental benefits of DES are not considered.

In accordance with the theory of contribution value, the difference of the objective function value in different scenarios will be identified to be the evaluation results of environmental benefits of DES. The details are given as:

$$\begin{cases} f_{obj}(1)=\min \sum_{i=1}^{n}\sum_{t=1}^{24}\left(c_{e,i,t}^{\text{buy}}P_{e,i,t}^{\text{buy}}-c_{e,i,t}^{\text{sell}}P_{e,i,t}^{\text{sell}}-c_{\text{car},i,t}P_{\text{ess},i,t}^{\text{dis}}\right) \\ f_{obj}(2)=\min \sum_{i=1}^{n}\sum_{t=1}^{24}\left(c_{e,i,t}^{\text{buy,am}}P_{e,i,t}^{\text{buy,am}}-c_{e,i,t}^{\text{sell,am}}P_{e,i,t}^{\text{sell,am}}-c_{\text{car},i,t}^{\text{am}}P_{\text{ess},i,t}^{\text{dis,am}}\right) \\ f_{obj}(3)=\min \sum_{i=1}^{n}\sum_{t=1}^{24}\left(c_{e,i,t}^{\text{buy}}P_{e,i,t}^{\text{buy}}-c_{e,i,t}^{\text{sell}}P_{e,i,t}^{\text{sell}}\right) \\ f_{lcr}=f_{obj}(3)-f_{obj}(1) \text{ or } f_{lcr}=f_{obj}(3)-f_{obj}(2) \end{cases} \tag{4}$$

where $f_{obj}(1)$, $f_{obj}(2)$, and $f_{obj}(3)$ are the overall operation costs in scenarios 1, 2, and 3, respectively; f_{lcr} is the difference in operation costs; $c_{e,i,t}^{\text{buy}}$ and $c_{e,i,t}^{\text{sell}}$ are the purchasing and selling electricity prices at time t in region i, respectively; $P_{e,i,t}^{\text{buy}}$ and $P_{e,i,t}^{\text{sell}}$ are the purchasing and selling electricity at time t in region i, respectively; $P_{\text{ess},i,t}^{\text{dis}}$ is the discharging green power of DES at time t in region i; and the superscript "am" indicates the modified parameter.

However, it is obvious that the introduction of evaluation on environmental benefits increases the revenue of DES end-users, but the operation cost of the power system increases as well. Certainly, this is the reasonable cost for energy transition and environmental governance. However, an incentive compatible business model should balance the interests of all parties. Therefore, an evaluation system for the environmental benefits proposed in this paper gives attention to both VPP aggregators and power system operators. That is, from the perspective of VPP aggregators, the more environmental benefits there are, the better. From the perspective of power system operators, the lower environmental cost is, the better. To balance and weight their interests, low carbon rule (LCR), a comprehensive evaluation indicators is proposed as follows. Equation (5) concerns the revenue evaluation index of VPP aggregators LCR. Equation (6) concerns the cost evaluation index of the power system operators.

$$LCR=\frac{\gamma_1 f_{lcr}}{f_{obj}(3)}+\frac{\gamma_2(\lambda-f_{lcr})}{\lambda} \tag{5}$$

$$\gamma_1+\gamma_2=1 \tag{6}$$

where λ is the expected value of the environmental compensation cost that the power system operator is willing to bear; and γ_1 and γ_2 are the weights of the VPP aggregator and the power system, respectively.

The larger the value of comprehensive evaluation indicator LCR is, the greater the benefits that VPP operators can obtain, and the lower the operation costs of the power system operators, which better aligns with the interests of all members. In addition, to improve the willingness of the VPP in the electricity market, the weight parameter of VPP aggregators could be given a higher value.

III. Low-carbon Dispatching Scheme of VPP

A. Objective Function

The objective function of decision-making problem is minimizing the operation prices of VPP, including the purchasing electricity prices, selling electricity prices, and environmental benefits. This objective function is expressed as follows:

$$\min \sum_{i=1}^{5}\sum_{t=1}^{24}\left(c_{e,i,t}^{\text{buy}}P_{e,i,t}^{\text{buy}}-c_{e,i,t}^{\text{sell}}P_{e,i,t}^{\text{sell}}-c_{\text{car},i,t}P_{i,t}^{\text{gre}}\right) \tag{7}$$

$$c_{\text{car},i,t}=p_{\text{car},t}\eta_{\text{car}} \tag{8}$$

where $p_{\text{car},t}$ is the carbon price at time t in the carbon market; and η_{car} is the coefficient of carbon emission per MWh coal-fired power generation, which is 0.892 t/MWh. The current fluctuation range of the carbon market price is approximately 40-60 ¥/t, so the carbon price is calculated as 35.68-53.52 ¥/MWh.

B. Constraints

1) Physical Constraints of VPP

In order to ensure the safe and stable operation of DNs, it is necessary to set upper and lower limits of purchasing and selling electricity of DES. On the one hand, purchasing electricity is used for the charging of DES and meeting load demands, so the upper limit of purchasing electricity in each region should be set as the sum of the load at each time slot in that region and the remaining capacity of DES. On the other hand, selling electricity comes from the discharging of DES, so the upper limit of selling electricity in each region should be set to the state of charge (SOC) capacity of DES at each time slot in that region. Meanwhile, the purchasing and selling electricity in each region cannot be conducted at the same time, and the specific constraints are given as:

$$\begin{cases} P_{e,i,t,\min}^{\text{buy}}\le P_{e,i,t}^{\text{buy}}\le P_{e,i,t,\max}^{\text{buy}} \\ P_{e,i,t,\min}^{\text{sell}}\le P_{e,i,t}^{\text{sell}}\le P_{e,i,t,\max}^{\text{sell}} \end{cases} \tag{9}$$

$$\begin{cases} P_{e,i,t,\max}^{\text{buy}}=P_{i,t}^{\text{load}}+(1-SOC_{\text{ess},i,t})E_{\text{ess},c} \\ P_{e,i,t,\max}^{\text{sell}}=SOC_{\text{ess},i,t}E_{\text{ess},c} \end{cases} \tag{10}$$

$$P_{e,i,t}^{\text{buy}}P_{e,i,t}^{\text{sell}}=0 \tag{11}$$

where $E_{ess,c}$ is the rated capacity of DES; $P_{e,i,t,\min}^{\text{buy}}$ and $P_{e,i,t,\min}^{\text{sell}}$ are the lower limits of purchasing and selling electricity at time t in region i, respectively, which are both 0 in this paper; $SOC_{\text{ess},i,t}$ is the SOC of hybrid electrical energy of DES at time t in region i; and $P^{\text{buy}}_{e,i,t,\max}$ and $P^{\text{sell}}_{e,i,t,\max}$ are the upper limits of purchasing and selling electricity at time t in region i, respectively.

In addition, the energy interaction between different regions should consider the preset congestion, where the power flow transfer factor would be 0. Therefore, the operation of each region is both independent and collaborative. Region is independent indicates that the same regional DES shares the supplying proportion of green power, and the discharging green power only affects the nodal carbon potential of the region. Region is collaborative indicates the aggregated effort of each region to achieve the overall electric demand of the whole DN.

$$P^{\text{buy}}_{e,i,t} \geq P^{\text{cha}}_{\text{ess},i,t} \tag{12}$$

$$P^{\text{dis}}_{e,i,t} \geq P^{\text{sell}}_{e,i,t} \tag{13}$$

$$\sum_{t=1}^{24} P^{\text{load}}_{t} = \sum_{i=1}^{5}\sum_{t=1}^{24}\left(P^{\text{buy}}_{e,i,t} - P^{\text{sell}}_{e,i,t} + P^{\text{dis}}_{\text{ess},i,t} - P^{\text{cha}}_{\text{ess},i,t}\right) \tag{14}$$

where P^{load}_{t} is the overall electric load of the DN at time t; and $P^{\text{cha}}_{\text{ess},i,t}$ and $P^{\text{dis}}_{\text{ess},i,t}$ are the charging and discharging power of DES at time t in region i, respectively.

2) Physical Constraints of DES

The physical constraints of DES primarily characterize the charging and discharging behaviors of DES, including the upper and lower limits of DES power conversion system (PCS), the uniqueness constraint of charging and discharging, and the SOC constraint in each period, as shown below:

$$E_{\text{ess},i,t} = E_{\text{ess},i,t-1} + \left(P^{\text{cha}}_{\text{ess},i,t} - P^{\text{dis}}_{\text{ess},i,t}\right)\Delta t \tag{15}$$

$$E_{\text{ess},i,\min} \leq E_{\text{ess},i,t} \leq E_{\text{ess},i,\max} \tag{16}$$

$$P^{\text{cha}}_{\text{ess},i,t,\min} \leq P^{\text{cha}}_{\text{ess},i,t} \leq P^{\text{cha}}_{\text{ess},i,t,\max} \tag{17}$$

$$P^{\text{dis}}_{\text{ess},i,t,\min} \leq P^{\text{dis}}_{\text{ess},i,t} \leq P^{\text{dis}}_{\text{ess},i,t,\max} \tag{18}$$

$$P^{\text{cha}}_{\text{ess},i,t} P^{\text{dis}}_{\text{ess},i,t} = 0 \tag{19}$$

$$E_{\text{ess},i,1} = E_{\text{ess},i,25} \tag{20}$$

$$SOC_{\text{ess},i,t} = \frac{E_{\text{ess},i,t}}{E_{\text{ess},i,\max}} \times 100\% \tag{21}$$

where $P^{\text{dis}}_{\text{ess},i,t,\min}$ and $P^{\text{dis}}_{\text{ess},i,t,\max}$ are the lower and upper limits for discharging green power of DES at time t in region i, respectively; $E_{\text{ess},i,t}$ is the electricity capacity of DES at time t in region i; and $E_{\text{ess},i,\min}$ and $E_{\text{ess},i,\max}$ are the lower and upper limits of the electricity capacity of DES in region i, respectively.

3) Green Attribute Labeling for DES

Physical constraints of DES only constrain the overall behavior of DES. However, as described in Section II, to truly reflect the spatiotemporal distribution characteristics of the cleanness value of DES, the green power of DES must be labeled.

The basic idea is that the charging green power of DES is only temporarily stored in the DES and is not consumed, so the green attribute does not disappear. If the environmental benefit is calculated according to the carbon price at the current time slot, it cannot fully reflect the correlation between the cleanness value and physical power flow.

The technology of green attribute labeling is conducive to tracing the spatiotemporal green power transfer, which can be used for accounting for and providing more accurate feedback on environmental benefits.

The labeled green power does not have actual physical meaning, only recording the proportion of green power in DES. Therefore, the SOC of green power is introduced to characterize it based on the overall SOC. To facilitate understanding, the overall SOC of DES is referred to as integrated SOC, and the SOC of green power in the DES is referred to as green SOC. These are expressed as follows:

$$E^{\text{gre}}_{\text{ess},i,t} = E^{\text{gre}}_{\text{ess},i,t-1} + \left(P^{\text{gre,cha}}_{\text{ess},i,t} - P^{\text{gre,dis}}_{\text{ess},i,t}\right)\Delta t \tag{22}$$

$$E^{\text{gre}}_{\text{ess},i,t} \leq E_{\text{ess},i,t} \tag{23}$$

$$P^{\text{gre,cha}}_{\text{ess},i,t} = \mu_{i,t} P^{\text{cha}}_{\text{ess},i,t} \tag{24}$$

$$P^{\text{gre,dis}}_{\text{ess},i,t} = \frac{SOC^{\text{gre}}_{\text{ess},i,t-1}}{SOC_{\text{ess},i,t-1}} P^{\text{dis}}_{\text{ess},i,t} \tag{25}$$

$$SOC^{\text{gre}}_{\text{ess},i,t} = \frac{E^{\text{gre}}_{\text{ess},i,t}}{E_{\text{ess},i,\max}} \times 100\% \tag{26}$$

where $\mu_{i,t}$ is the proportion of green power at time t in region i (ranging from 0 to 1) injected from the transmission grid; $P^{\text{gre,cha}}_{\text{ess},i,t}$ and $P^{\text{gre,dis}}_{\text{ess},i,t}$ are the charging and discharging green power of DES at time t in region i, respectively; $SOC^{\text{gre}}_{\text{ess},i,t}$ is the DES green SOC in DES at time t in region i; and $E^{\text{gre}}_{\text{ess},i,t}$ is the green power capacity of DES at time t in region i.

C. Linearization Processing

Unfortunately, the green attribute labeling for DES converts the original simple programming problem of charging and discharging of DES into a complex multivariate mixed-integer nonlinear programming (MINLP) problem.

The discharging green power of DES is the optimization variable of the low-carbon dispatching decision-making model. However, as shown in (25), the discharging green power of DES in each region is calculated based on the integrated SOC, green SOC, and overall discharging green power. A nonlinear fractional expression $X=a/c$ is formed, where a represents the green SOC, and c represents the integrated SOC, and they are real number variables. It is found that Gurobi 11.0 (Win64) solver has difficulty in solving fractional nonlinear constraint directly [31]. Therefore, the CE linear reconstruction method is introduced to linearize the multiplicative nonlinear constraints by introducing auxiliary variables, and the multiplicative expression is replaced by a linear variable to form a CE linear constraint, where the nonlinear constraints of fractional expressions ($X=a/c$) are converted to those of multiplicative expressions ($X=ab$). The specific conversion method is shown in (27) and (28).

$$\begin{cases} b = \dfrac{1}{c} \\ c_{\min} \leq c \leq c_{\max} \\ \dfrac{1}{c_{\max}} \leq b \leq \dfrac{1}{c_{\min}} \end{cases} \tag{27}$$

$$\begin{cases} b_{\min} \le b \le b_{\max} \\ b_{\min} = \dfrac{1}{c_{\max}} \\ b_{\max} = \dfrac{1}{c_{\min}} \end{cases} \tag{28}$$

$$\begin{cases} a_{\min} \le a \le a_{\max} \\ b_{\min} \le b \le b_{\max} \\ ab_{\min} - a_{\min} b_{\min} \le X - a_{\min} b \\ ab_{\max} - a_{\max} b_{\max} \le X - a_{\max} b \\ X - a_{\min} b \le ab_{\max} - a_{\min} b_{\max} \\ X - a_{\max} b \le ab_{\min} - a_{\max} b_{\min} \end{cases} \tag{29}$$

This model is implemented on MATLAB R2021b, the specific model is built by the Yalmip toolkit, and the solver is built by Gurobi 11.0 (Win64). The computer has an 3.20 GHz AMD Ryzen 7 5800H with Radeon Graphics, and 16 GB memory.

IV. Simulation Verification and Result Analysis

A. Simulation Conditions and Hypothesis

The benchmark of IEEE 33-bus DN is chosen as the research architecture. The DN is assumed to be divided into 5 regions due to preset congestion, where the identification of power flow congestion is given in [32], [33], which will not be elaborated here. And each of the 5 regions is deployed with a DES (may be consisted of a few small-scale DESs), where the PCS capacity is 1 MW, and the rated capacity is 1 MWh. Regardless of distributed generation units and other controllable loads, the power supply of each region can only be met by the transmission grid through the point of common coupling (PCC). The entire installed DES in 5 regions is aggregated into a VPP, and simulation scenario construction of VPP structure is shown in Fig. 2. In addition, to emphasize the research focus, the following hypotheses are made in this paper.

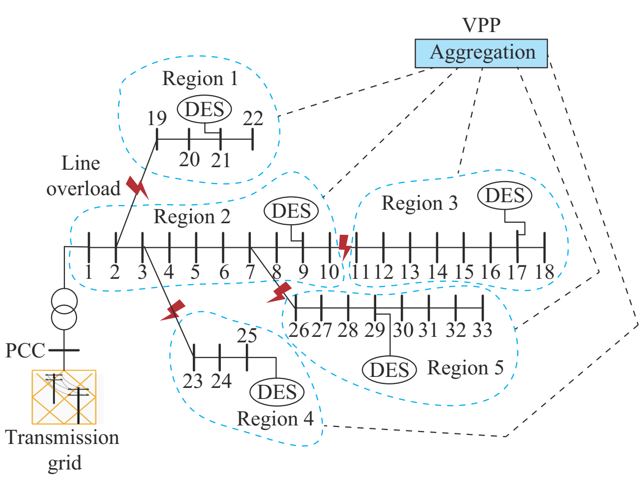

Fig. 2. Simulation scenario construction of VPP.

Hypothesis 1: the electric load of 5 regions can be met by purchasing electricity from transmission grid and the discharging green power of DES, and the assumed electric load of DN is shown in Fig. 3. In addition, even in the same DN area, the TOU electricity prices differ among the 5 regions due to preset congestion, and the electricity bill settlement is charged based on the assumed nodal prices of DN. The assumed nodal TOU electricity prices of 5 regions are derived from European Transmission Network Operators, as shown in Fig. 4.

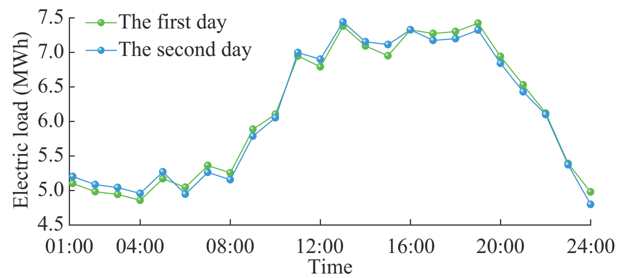

Fig. 3. Assumed electric load of DN.

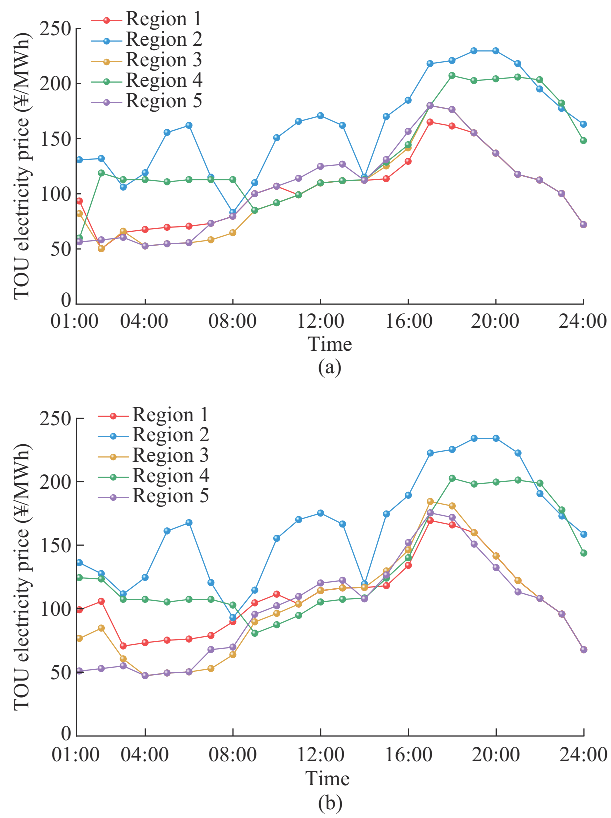

Fig. 4. Assumed nodal TOU electricity prices of 5 regions. (a) TOU electricity prices of 5 regions on the first day. (b) TOU electricity prices of 5 regions on the second day.

Hypothesis 2: the green power proportion of the transmission grid is assumed to be known, that is, the green component in the energy exchange between the PCC and DN can be accounted for. Meanwhile, the carbon price also fluctuates based on the fluctuation of the green proportion of the transmission grid. The higher the green proportion of the transmission grid, the lower the carbon price, and vice versa. The proportional coefficient of green power is reasonably valued, as shown in Fig. 5, and the initial TOU carbon price is assumed, as shown in Fig. 6.

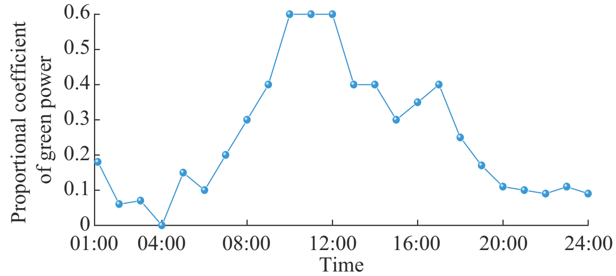

Fig. 5. Proportional coefficient of green power in transmission grid.

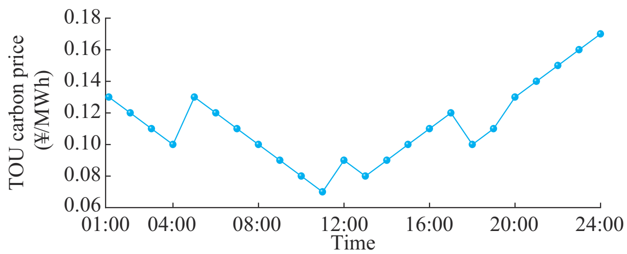

Fig. 6. Initial TOU carbon price.

Without considering the effect of the discharging green power of DES on the nodal carbon potential, the initial nodal carbon potential of DN should be consistent and fluctuate over time, as shown in Fig. 7, where the assumed values are obtained in accordance with [34].

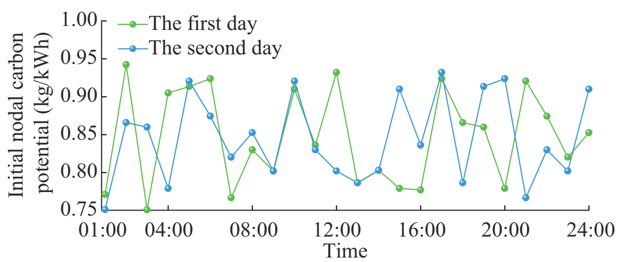

Fig. 7. Initial nodal carbon potential.

In this paper, the simulation verification is conducted in three scenarios discussed in Section II-B to verify the cleanness value of DES and explore the impact of the nodal carbon potential of DN on low-carbon dispatching decision-making.

B. Analysis of Simulation Results

Table II shows the simulation results of operation cost of VPP, and Table III shows the comparison of consumption of green power in three scenarios. Table IV shows the *LCR* in scenario 1 and scenario 2, which are obtained in accordance with (4) and (5), respectively.

TABLE II
VPP OPERATION COST COMPARISON OF DIFFERENT SCENARIOS

Scenario	Total cost (¥)	Total purchasing electricity price (¥)	Total selling electricity price (¥)	Environmental benefit (¥)
Scenario 1	13055	15039	1025	959
Scenario 2	13564	14874	670	637
Scenario 3	14121	14715	594	0

TABLE III
COMPARISON OF GREEN POWER CONSUMPTION OF DIFFERENT SCENARIOS

Scenario	Green power (MW)					
	Region 1	Region 2	Region 3	Region 4	Region 5	Total
Scenario 1	2.7200	1.2689	2.6200	1.6432	2.3580	10.6101
Scenario 2	1.1350	0.4239	1.5197	1.2382	1.8347	6.1515
Scenario 3	0.1100	0.8200	0.1149	0.5940	0.0980	1.7369

TABLE IV
INTERESTS EQUILIBRIUM ANALYSIS OF PROPOSED BUSINESS MODEL

Scenario	*LCR* (%)		
	VPP aggregators	Power system operator	Environmental benefit indicator
Scenario 1	7.55	28.90	13.96
Scenario 2	3.94	62.08	21.60

As shown in Tables II-IV, from the perspective of VPP aggregators, the cleanness values of DES not only effectively reduce the total operation costs of VPPs, but also improve the actual consumptions of green power. The total operation costs in three scenarios in Table II are substituted into formula $f_{lcr}/f_{obj}(3)$, and it can be observed that compared with scenario 3, the total operation costs in scenario 1 and scenario 2 are reduced by 7.55% and 3.94%, respectively, and the actual consumptions of green power are increased by 8.87 MWh and 4.41 MWh. Compared with scenario 1, scenario 2 further considers the influence of the charging and discharging green power of DES on the nodal carbon potential of DN, which results in higher total operation cost. However, when the operation costs in three scenarios are substituted into (30), it can be observed that the environmental benefit compensation in scenario 2 can be reduced by 47.8% for the power system operator.

From the perspective of power system operators, the expected value of the environmental compensation cost is set to be ¥1500 herein. The weight parameters γ_1 and γ_2 for *LCR* calculation are set to be 0.7 and 0.3, respectively. The operation costs in three scenarios in Table II are substituted into (4), and the weight parameters γ_1 and γ_2 are substituted into (5) for calculation, obtaining the *LCR* in scenarios 1 and 2 of 13.96% and 21.6%, respectively. Above all, scenario 1 has higher environmental benefits from the perspective of VPP aggregators alone, but scenario 2 has higher environmental benefits from integrated perspectives of VPP aggregators and power system operators.

$$\frac{(f_{obj}(3)-f_{obj}(1))-(f_{obj}(3)-f_{obj}(2))}{f_{obj}(3)-f_{obj}(1)} \tag{30}$$

Tables V and VI show the charging and discharging times of DES of 5 regions in three scenarios. The responsiveness of DES in responding to dispatching instructions when considering the cleanness value of DES is significantly higher than that of energy-only dispatching strategies. The charging and discharging times in scenario 1 are 44 and 50, respectively, while the charging and discharging times in scenario

2 are 41 and 47, respectively, all of which are far greater than those in scenario 3. The impact of the nodal carbon potential of DN is further analyzed by comparing the optimization results of scenario 1 and scenario 2. In scenario 2, the discharging green power of DES changes the nodal carbon potential of DN, thus reducing the nodal carbon price. Therefore, the charging and discharging times in scenario 2 decreases by 3 times from the above optimization results, the green power consumption decreases by 4.46 MWh, the green power consumption benefit decreases by ¥322, and the overall operation costs increases by 3.75%.

TABLE V
CHARGING TIMES OF DES OF 5 REGIONS IN THREE SCENARIOS

Scenario	Charging times					
	Region 1	Region 2	Region 3	Region 4	Region 5	Total
Scenario 1	9	7	10	8	10	44
Scenario 2	9	4	11	7	10	41
Scenario 3	1	4	2	2	2	11

TABLE VI
DISCHARGING TIMES OF DES OF 5 REGIONS IN THREE SCENARIOS

Scenario	Discharging times					
	Region 1	Region 2	Region 3	Region 4	Region 5	Total
Scenario 1	11	9	10	8	12	50
Scenario 2	11	8	10	7	11	47
Scenario 3	2	4	4	3	3	16

However, as the operation costs of the VPP decrease, the environmental compensation cost of power system increases. Table III demonstrates that in scenario 2, the environmental compensation cost supported by the power system operator is reduced by 33.18% and the environmental benefits increase by 7.64% compared with those in scenario 1. By considering the impact of discharging green power of DES on the nodal carbon potential, the operation strategy of VPP can be effectively modified, allowing both VPP aggregators and power systems to achieve global optimization.

Figures 8 and 9 show the nodal carbon potential changes in scenarios 1 and 2, respectively. As the primary focus of this subsection is on revealing the impact mechanism of nodal carbon potential changes of DN on DES behavior decision-making, the figures primarily compare the nodal carbon potential changes of DN from 01:00 to 07:00. Figures 8 and 9 show that the trends of nodal carbon potential changes of DN in 5 regions are consistent between 02:00 and 06:00, indicating that the charging and discharging behavior of DES in each region is consistent from 01:00 to 05:00 and unaffected by the nodal carbon potential changes of DN. At 07:00, the nodal carbon potential of DN in 5 regions changes in scenario 1. However, in scenario 2, the nodal carbon potential of DN in region 2 remains unchanged. This indicates that the DES in region 2 has not discharged at 06:00, which is due to the carbon price reduction in region 2 at 06:00. The nodal carbon potential changes of DN can change the charging and discharging decisions of DES.

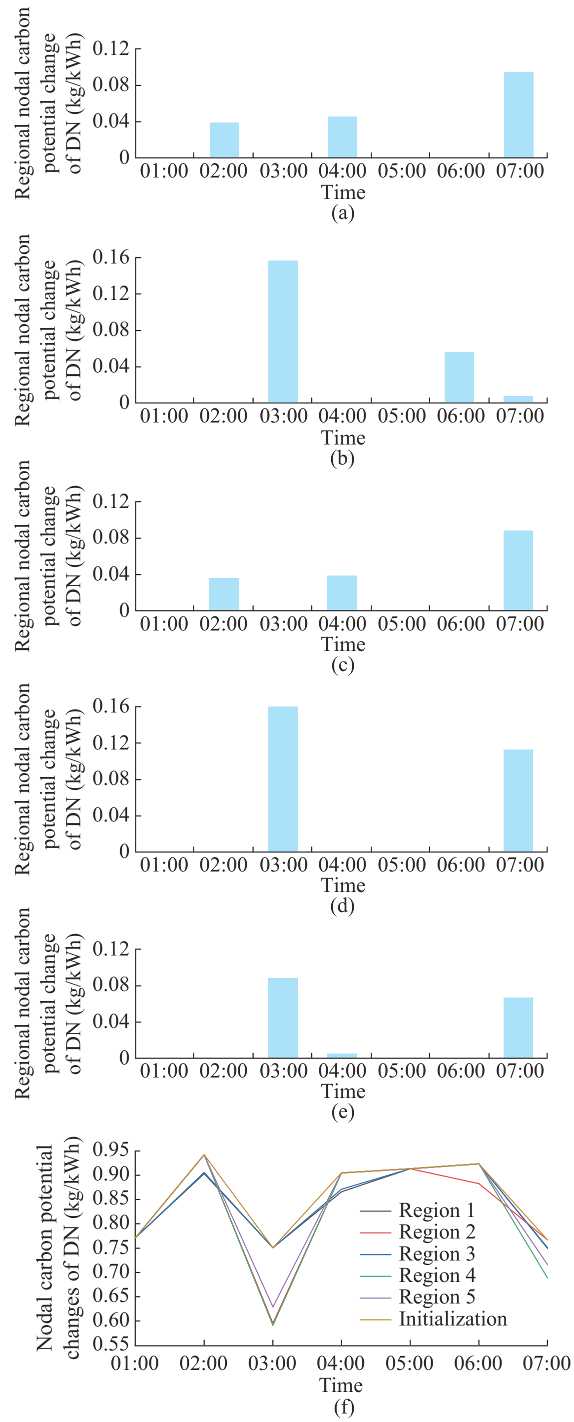

Fig. 8. Nodal carbon potential changes in scenario 1. (a) Nodal carbon potential changes in region 1. (b) Nodal carbon potential changes in region 2. (c) Nodal carbon potential changes in region 3. (d) Nodal carbon potential changes in region 4. (e) Nodal carbon potential changes in region 5. (f) Nodal carbon potential of DN.

C. Analysis of Dispatching Results

Figures 10 and 11 show the optimized dispatching results with transmission system of the 5 regions in scenarios 2 and 3, respectively. Figures 12 and 13 show the integrated SOC and green SOC of DES in scenarios 2 and 3, respectively.

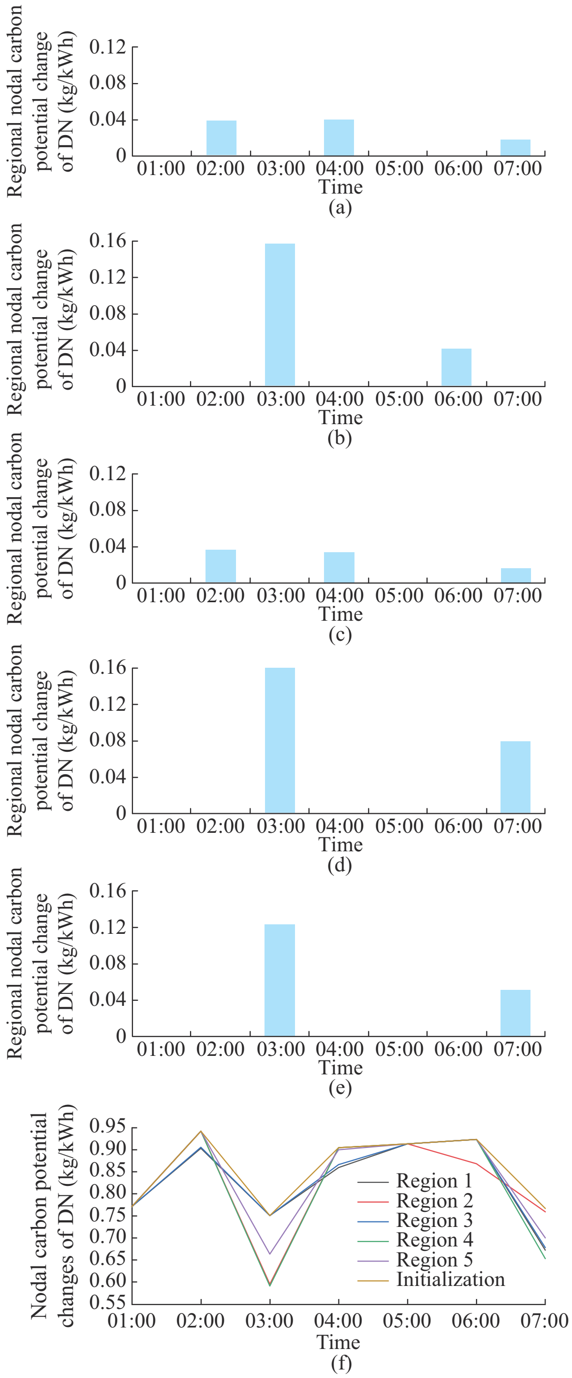

Fig. 9. Nodal carbon potential and changes in scenario 2. (a) Nodal carbon potential changes in region 1. (b) Regional nodal carbon potential changes in region 2. (c) Regional nodal carbon potential changes in region 3. (d) Regional nodal carbon potential changes in region 4. (e) Regional nodal carbon potential changes in region 5. (f) Regional nodal carbon potential of DN.

As shown in Fig. 10, the charging and discharging behavior of DES is no longer simple high-charging or low-discharging behavior but is instead more frequent under the coupling incentive of energy and cleanness values. Figures 12 and 13 demonstrate that although the DES in scenario 2 tends to charge at low electricity prices and carbon prices and discharge at high electricity prices and carbon prices, to better discharge green power for arbitrage, the DES of each region conducts periodic charging and discharging behavior throughout almost the entire dispatching cycle.

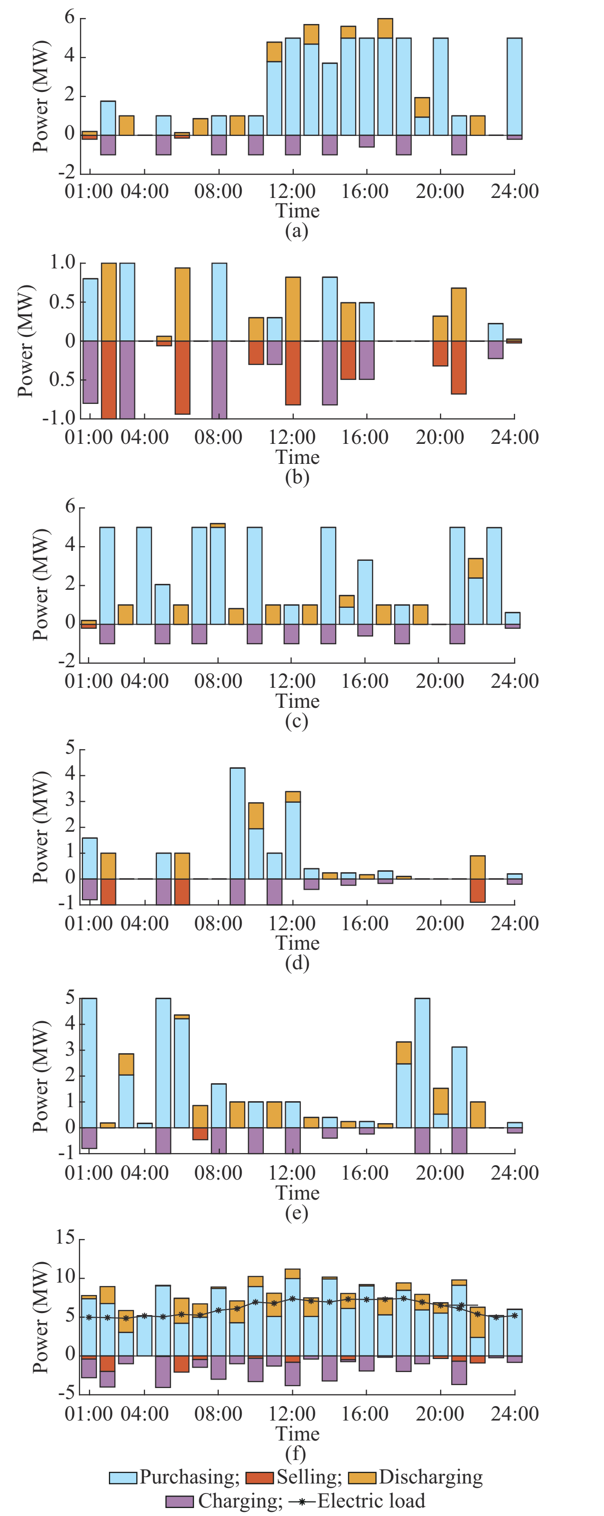

Fig. 10. Optimized dispatching power in scenario 2. (a) Region 1. (b) Region 2. (c) Region 3. (d) Region 4. (e) Region 5. (f) Entire system.

In addition, due to the high TOU electricity prices at noon and in the afternoon, the DES exhibits no action from 11:00 to 16:00 in scenario 3 with the exception of region 2. However, the proportion coefficients of the charging green power of DES at noon and in the afternoon are relatively high, and the DES can discharge more green power during this period to gain profits and reduce the overall operation costs of VPP. Therefore, with the exception of region 2, the DES is continuously charged and discharged from 11:00 to 16:00 in scenario 2.

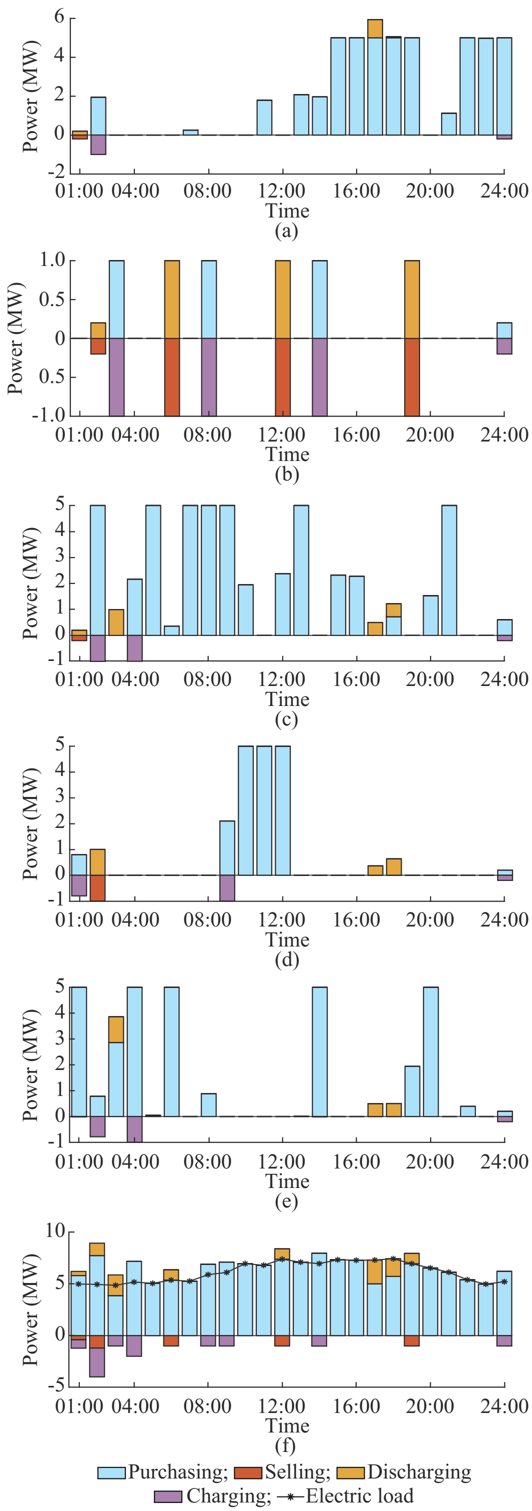

Fig. 11. Optimized dispatching power in scenario 3. (a) Region 1. (b) Region 2. (c) Region 3. (d) Region 4. (e) Region 5. (f) Entire system.

As shown in Fig. 12, the charging and discharging periods of DESs vary in different regions. Among these, DESs in regions 2 and 4 tend to charge during the day, then discharge at night, storing power for a long time from 15:00 to 20:00, rather than discharging power immediately like DESs in other regions.

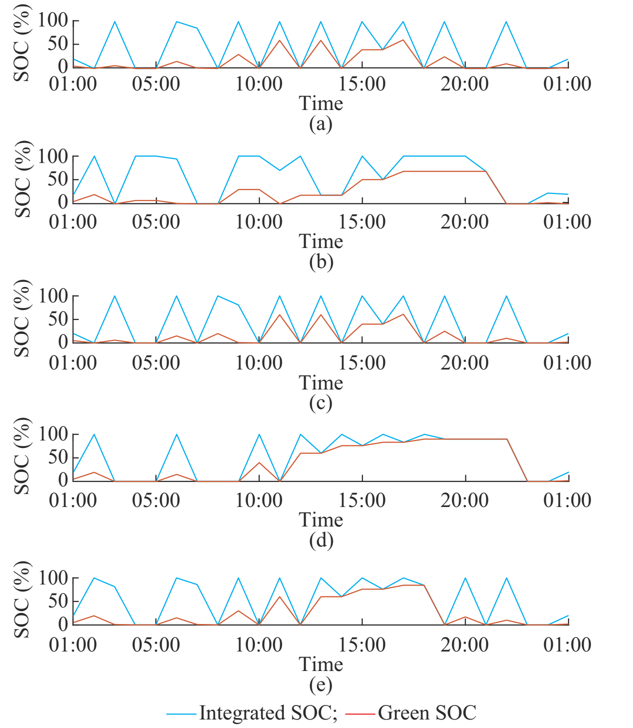

Fig. 12. Integrated SOC and green SOC of DES in scenario 2. (a) Region 1. (b) Region 2. (c) Region 3. (d) Region 4. (e) Region 5.

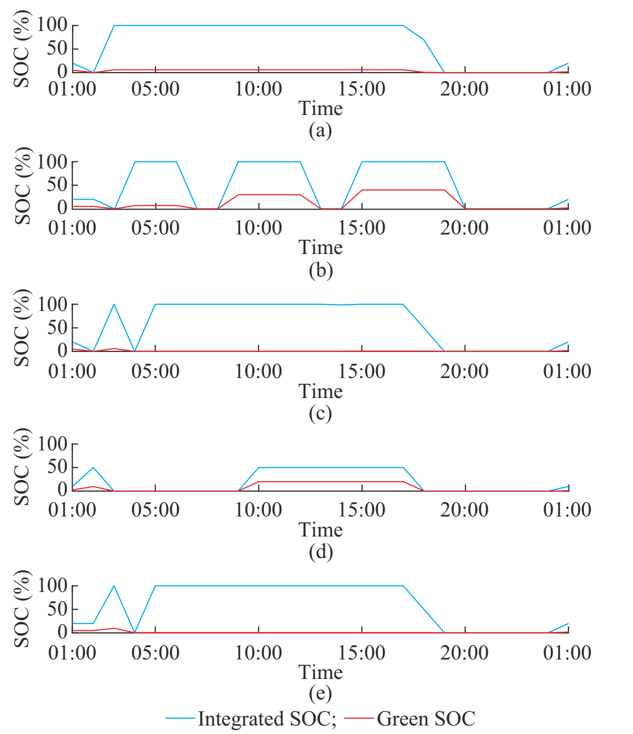

Fig. 13. Integrated SOC and green SOC of DES in scenario 3. (a) Region 1. (b) Region 2. (c) Region 3. (d) Region 4. (e) Region 5.

This is due to the significant TOU electricity price differences between daytime and nighttime in regions 2 and 4. In addition, the charging and discharging behaviors in regions 2 and 4 are less active than those in other regions, which is due to the high electricity price and large difference between peak and valley electricity prices. Figures 12 and 13 show that when the cleanness value of the DES is not considered, the DESs in regions 2 and 4 charge only at low electricity prices in the early morning hours and discharge at high electricity prices. When considering the cleanness value of DESs, DESs in regions 1 and 3 charge during the day, ensuring DES charging power at low electricity prices or the arbitrage in carbon market.

V. Conclusion

Considering the spatiotemporal characteristics of the cleanness value of DES and the time-varying nodal carbon potential, an evaluation system for the environmental benefits of DES is proposed and a low-carbon dispatching scheme of VPP is constructed in this paper. Numerical simulation results in three scenarios yield the following conclusions.

1) The accurate evaluation and reasonable pricing of the cleanness value of DESs will improve the business model, thereby increasing the responsive and investment willingness of end-users. The simulation results show that willingness is improved by 83.6% in scenario 1 and 41.6% in scenario 2.

2) The proposed low-carbon dispatching scheme for VPP aggregated DESs can fully leverage their spatiotemporal characteristics. This scheme can improve the utilization efficiency of DES to support the economic operation of the power system. It can also improve the economic benefits of resource users and accelerate the recovery of investment costs. The simulation results show that the benefits are improved by 7.55% in scenario 1 and 3.94% in scenario 2.

3) Green attribute labeling can identify the green attributes of DES while facilitating the refinement and improvement of nodal carbon potential analysis of DN, thereby addressing the overcompensation of the cleanness value. The simulation results show that the economic benefit allocation is reduced by 47.8% in scenario 2 compared with scenario 1.

The limitation of this paper lies in the insufficient hypotheses. However, the coupling operation of electricity and carbon markets are anticipated, and the current research status on nodal carbon prices and time-varying carbon prices are analyzed. The study and verification conducted on these hypotheses have previous research foundations [34].

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