Optimal Operation with Dynamic Partitioning Strategy for Centralized Shared Energy Storage Station with Integration of Large-scale Renewable Energy

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***Abstract*—As renewable energy continues to be integrated into the grid, energy storage has become a vital technique supporting power system development. To effectively promote the efficiency and economics of energy storage, centralized shared energy storage (SES) station with multiple energy storage batteries is developed to enable energy trading among a group of entities. In this paper, we propose the optimal operation with dynamic partitioning strategy for the centralized SES station, considering the day-ahead demands of large-scale renewable energy power plants. We implement a multi-entity cooperative optimization operation model based on Nash bargaining theory. This model is decomposed into two subproblems: the operation profit maximization problem with energy trading and the leasing payment bargaining problem. The distributed alternating direction multiplier method (ADMM) is employed to address the subproblems separately. Simulations reveal that the optimal operation with a dynamic partitioning strategy improves the tracking of planned output of renewable energy entities, enhances the actual utilization rate of energy storage, and increases the profits of each participating entity. The results confirm the practicality and effectiveness of the strategy.**

***Index Terms*—Shared energy storage (SES), dynamic partitioning strategy, optimal operation, Nash bargaining theory, actual utilization rate of energy storage.**

I. Introduction

ENERGY storage, as a fundamental technology, plays a pivotal role in the transformation of the modern power systems, holding immense importance in the seamless integration of energy sources, power networks, and electricity consumption. It actively promotes the transition to greener energy and the mitigation of extreme events, ensures energy security, advances high-quality energy development, and aligns with climate change objectives. Currently, energy storage facilities in diverse application scenarios are primarily constructed and invested by power generation companies, grid operators, and end-users worldwide. However, existing energy storage systems on the power source, grid, or user sides predominantly serve individual entities [1], [2], i.e., utilizing the energy storage in the individual distributed framework. The individual distributed framework is flexible enough to meet the customized needs of individual owners, which is also economically inefficient, particularly in the context of large-scale energy storage stations. The inefficiency arises from high-capital costs, maintenance expenses [3], and limited actual utilization [4]. In response, shared energy storage (SES) has emerged, combining energy storage technology with the sharing economy concept [5], [6]. Through flexible and well-planned operation strategies, SES provides auxiliary power services to both renewable energy power plants and the grid, thereby facilitating the integration of large-scale renewable energy sources into the grid while maximizing the economic benefits of energy storage devices.

The development of SES has garnered significant attention across various research fields, with three primary areas of interest, i.e., control, scheduling, and planning of SES. In terms of control, current methodologies primarily aim to enhance the stability of power systems integrated with renewable energy through SES, which includes providing primary frequency response [7], facilitating demand response [8], and mitigating thermal or voltage limit violations [9]. Furthermore, considerable efforts have been dedicated to economic scheduling to improve system efficiency and reduce operation costs through SES, benefiting both service providers and consumers. Typically, a sharing model of energy storage resources is rooted in non-cooperative or cooperative game theory [6], [10], [11]. In the sharing model, SES distinguishes between user rights and owner rights [10], [12], enabling different participants to access energy storage capacity through leasing agreements. Subsequently, the operation within the sharing model will be treated and solved as an op-

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timization problem to navigate trading prices and ensure equitable and secure energy transactions [13]-[15]. The SES planning emphasizes optimizing SES capacity allocation to enhance energy storage utilization and operational performance [16]. Most existing research works deal with the capacity allocation issues within local energy communities [17]-[19], while the primary studies in the above-mentioned research are focused on the energy trading of distributed energy storage systems. However, it is worth noting that energy trading involving large-scale centralized energy storage has not been thoroughly investigated. Furthermore, the capacity allocation strategy for centralized SES station with multiple energy storage batteries remains a complex and underexplored research area.

Large-scale centralized SES stations currently employ a fixed capacity allocation method [20]-[22], which poses challenges in meeting the dynamic energy storage needs of various entities across a spectrum of application scenarios. These scenarios encompass tasks such as mitigating fluctuations in renewable energy sources, peak shaving and valley filling, and capacity leasing, ultimately resulting in low energy storage utilization. To enhance the SES utilization and flexibility in catering to diverse entity demands, a promising solution involves partitioning the SES into different zones, each of which is tailored to specific application scenarios. The effectiveness of SES partitioning within local energy communities has been previously demonstrated [23]-[25]. In this paper, the methodology of SES partitioning is extended to large-scale centralized SES stations. The optimal operation that incorporates a dynamic partitioning strategy is proposed for the centralized SES station, considering the spatial and temporal characteristics of renewable energy entities, including concentrated integration of wind and PV power. This strategy divides the energy storage station into dynamic zones based on its physical structure and coordinates its operation accordingly. It takes into account the demand for renewable energy power plants leasing energy storage and the operational characteristics of energy storage, effectively allocating storage capacity, harnessing the regulating capabilities of energy storage, and enhancing the utilization and economic benefits. Furthermore, we discuss the collaboration and optimization of large-scale centralized SES stations with multiple renewable energy entities, achieving a win-win situation among different entities through bargaining and consensus. To summarize, the main contributions of this paper are as follows.

1) The optimal operation with a dynamic partitioning strategy is proposed for the centralized SES station to improve the utilization rates and economic benefits. The capacity of centralized SES stations is dynamically allocated and leased based on the standardized SES unit for renewable energy entities.

2) The Nash bargaining model is used to achieve cooperative bilateral energy trading in the renewable energy and SES entities with dynamic partitioning. The Nash bargaining problem is decomposed into an energy-trading subproblem and a leasing payment bargaining subproblem for energy trading and operation profits.

3) The simulation results demonstrate the effectiveness of the operation with a dynamic partitioning strategy, which improves the actual utilization rate and economic benefits in the tracking of planned output of renewable energy power plants and ultimately achieves a win-win situation for all involved entities.

The rest of this paper are organized as follows. Section II presents the dynamic partitioning strategy for SES. Section III presents the multi-entity operation Nash bargaining model. Section IV delineates the optimization operation solution for two subproblems based on the distributed alternating direction multiplier method (ADMM) algorithm. In Section V, case studies and results are performed to verify the effects of the strategy, particularly the efficiency and economy of SES. Finally, Section VI concludes this paper.

II. Dynamic Partitioning Strategy for SES

Large-scale energy storage stations consist of multiple energy storage battery units in parallel, forming an MW-level energy storage system. We refer to such an energy storage station as a large-scale centralized SES station. The dynamic partitioning strategy for SES proposed in this paper allocates the energy storage station into independently operated zones based on the demands of the participating entities. These entities may include wind and PV power plants, as illustrated in Fig. 1. These operated zones within SES can concurrently serve various applications, e.g., mitigating fluctuations in renewable energy, reducing peak load, filling valley load, and leasing capacity. The strategy maximizes the potential of energy storage capacity and power value, enhancing the overall utilization of energy storage stations.

A. Standardized SES Unit

To utilize the centralized SES station more flexibly, we adopt the dynamic partitioning strategy. Standardized SES units are composed of energy storage battery cabinets and power conversion systems (PCSs). They are organized based on the actual operation structure of the power station, forming standardized SES units with a capacity of 5 MW/10 MWh each, which are connected to the 35 kV busbars and possess the capability to receive and execute control commands independently. The dynamic partitioning strategy and standardized SES unit for centralized SES station are shown in Fig. 1. In the 5 MW/10 MWh standardized SES unit, there is one step-up transformer, eight battery cabinets (A1-1 to A1-8), and eight PCSs. The partitioning of energy storage units signifies a transition in which the minimum operation unit of energy storage shifts from the entire power station to individual SES units. This transition results in a reduction in the minimum operation power and capacity for large-scale energy storage stations. The strategy lays the foundation for the flexible operation of centralized SES stations and allows for effective reuse across multiple scenarios. The topology of the standardized SES unit is based on an actual project case at the State Grid Contemporary Amperex Technology Co. Limited (SG·CATL) GW-level energy storage station located in Fujian, China.

B. Dynamic Partitioning Strategy

When renewable energy power plants make use of centralized SES stations, the storage capacity becomes a critical factor in defining the range of energy storage allocated by these plants. Various output ranges directly influence the optimization possibilities for integrating renewable energy power plants. Employing a fixed partitioning strategy for SES presents several challenges, including limited flexibility and constrained regulation capabilities.

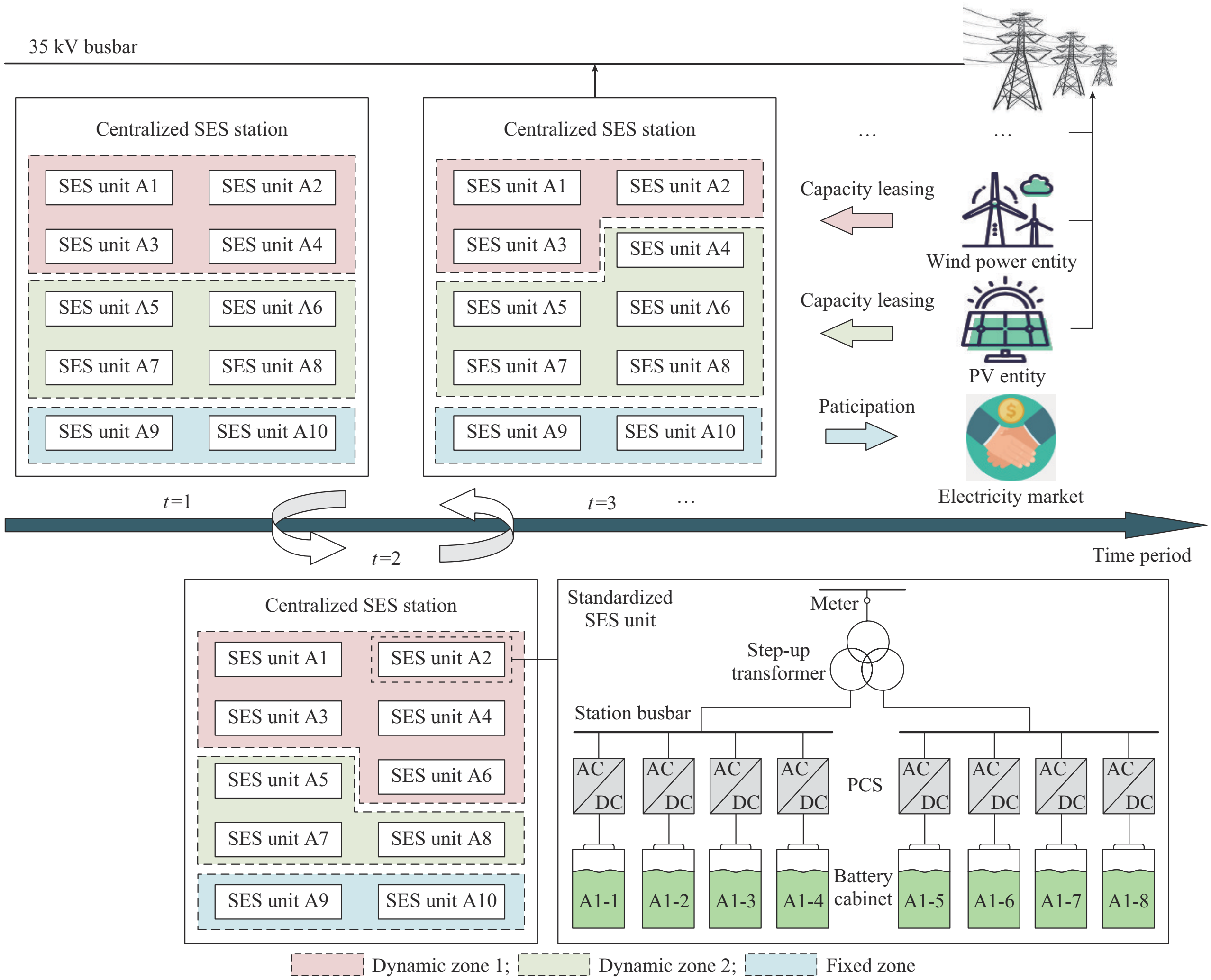

Fig. 1. Dynamic partitioning strategy and standardized SES unit for centralized SES station.

The dynamic partitioning strategy for the centralized SES station allows for hourly adjustments and is not limited to fixed users. The strategy empowers the centralized SES station to allocate its capacity more economically and efficiently. This, in turn, provides sufficient energy storage capacity for participating in the electricity market to generate profits and meet the demands of renewable energy entities. Moreover, renewable energy entities can lease energy storage capacity with greater flexibility. This enhanced flexibility unlocks the full potential of energy storage, mitigating the challenges associated with individually configuring energy storage capacity for renewable energy power plants. This strategy expands the range of applications for energy storage, reduces investment costs for renewable energy power plants, and directly boosts energy storage revenue.

The dynamic partitioning strategy for the centralized SES station is determined by the specific demands of renewable energy entities at the beginning of each day. In this process, the centralized SES station collects day-ahead demand data from these entities and then dynamically allocates the standardized SES units based on their anticipated capacity requirements. The quantities of day-ahead usage plan of standardized SES units for each entity are determined. The centralized SES station receives the predicted output curve and aligns it with the planned output curve during the next 24-hour scheduling period. The quantity of standardized SES units is dynamically adjusted, and capacities are allocated accordingly. Subsequently, each entity uses the allocated dynamic zones to optimize the charging and discharging scheduling of the SES throughout the day. Compared with the fixed partitioning strategy, this dynamic arrangement enhances the efficiency of energy storage utilization, allowing for a more rational and flexible distribution of the limited energy storage capacity.

There are M renewable energy entities, which include wind and PV power plants. In compliance with market policy guidelines [26], SES capacity participating in the spot market must be declared in advance to match the actual situation. Consequently, the allocated capacity in spot market is determined through the partitioning operation. The minimum operation unit of SES station is 5 MW/10 MWh, meaning that the power and capacity in the dynamic partitioning strategy for the centralized SES station are multiples of 5 MW and 10 MWh, respectively. The formulas for the dynamic partitioning strategy are provided as:

$$P_{need}^m(t) = P_F^m(t) - P_{Pd}^m(t) \tag{1}$$

$$P_{need}^m(t) = P_{need,c}^m(t) - P_{need,dis}^m(t) \tag{2}$$

$$E_{need}^m(t+1) = E_{need}^m(t) + \left(\eta_c P_{need,c}^m(t) - \frac{P_{need,dis}^m(t)}{\eta_{dis}}\right)\Delta t \tag{3}$$

$$E_{need}^m(t) \geq 0 \tag{4}$$

$$0 \leq P_{need,c}^m(t) \leq \alpha_{need}^m(t) P_E^m(t) \tag{5}$$

$$0 \leq P_{need,dis}^m(t) \leq \left(1 - \alpha_{need}^m(t)\right) P_E^m(t) \tag{6}$$

$$K^m(t) = \frac{E_{need}^m(t)}{\sum\limits_{m=1}^{M} E_{need}^m(t)} K_{\max} \tag{7}$$

$$\sum_{m=1}^{M} K^m(t) = K_{\max} \tag{8}$$

$$0 \leq K^m(t) \leq K_{\max} \tag{9}$$

where m is the number of renewable energy entities and also indicates the number of dynamic zones; t is the time period; M is the total number of renewable energy entities; $P_F^m(t)$ is the predicted output of renewable energy entity m; $P_{Pd}^m(t)$ is the planned output of renewable energy entity m; $P_{need}^m(t)$ and $E_{need}^m(t)$ are the day-ahead demand power and capacity of renewable energy entity m, respectively; $P_{need,c}^m(t)$ and $P_{need,dis}^m(t)$ are the demanded charging and discharging power of renewable energy entity m, respectively; $P_E^m(t)$ is the actual power output of renewable energy entity m; $\alpha_{need}^m(t)$ is a binary variable, which represents the charging and discharging status of demand power; $K^m(t)$ is the number of standardized SES units of renewable energy entity m; and $K_{\max}$ is the total number of standardized SES units in the centralized SES station.

$$E_{\max}^m(t) = E_{unit} K^m(t) \tag{10}$$

$$E_{\max} = \sum_{m=1}^{M} E_{\max}^m(t) + E_{\max}^{spot} \tag{11}$$

$$P_{c,dis}^m(t) = P_c^m(t) - P_{dis}^m(t) \tag{12}$$

$$\sum_{m=1}^{M} P_{c,dis}^{m,k}(t) = P_{c,dis}^m(t) \tag{13}$$

$$0 \leq P_c^m(t) \leq \alpha^m(t) P_{\max}^m(t) \tag{14}$$

$$0 \leq P_{dis}^m(t) \leq \left(1 - \alpha^m(t)\right) P_{\max}^m(t) \tag{15}$$

$$\sum_{m=1}^{M} P_{dis}^m(t) + P_{dis}^{spot}(t) \leq P_{\max} \tag{16}$$

$$\sum_{m=1}^{M} P_c^m(t) + P_c^{spot}(t) \leq P_{\max} \tag{17}$$

where $E_{\max}^m(t)$ is the allocated capacity of renewable energy entity m; $E_{\max}$ is the total rated capacity for centralized SES station; E_{unit} is the rated capacity of a standardized SES unit; $P_{c,dis}^m(t)$ is the total charging and discharging power of entity m; $P_c^m(t)$ and $P_{dis}^m(t)$ are the charging and discharging power requests of renewable energy entity m, respectively; $P_{c,dis}^{m,k}(t)$ is the discharging power of renewable energy entity m in standardized SES unit k; $P_c^{spot}(t)$ and $P_{dis}^{spot}(t)$ are the charging and discharging power of the SES entity; T, with a value of 24, is the number of operation periods; $P_{\max}^m(t)$ is the upper limit of the charging and discharging power of renewable energy entity m; $P_{\max}$ is the upper limit of the total charging and discharging power of the centralized SES station participating in the spot market; and $\alpha^m(t)$ is a binary variable, which represents the charging and discharging status of renewable energy entity m.

$$SoC^k(t+1) = SoC^k(t) + \frac{1}{E_{unit}}\left(\eta_c P_c^{m,k}(t) - \frac{P_{dis}^{m,k}(t)}{\eta_{dis}}\right)\Delta t \tag{18}$$

$$\underline{SoC}^k \leq SoC^k(t) \leq \overline{SoC}^k \tag{19}$$

$$SoC^k(1) = SoC^k(T) \tag{20}$$

where $SoC^k(t)$ is the state of charge (SoC) of standardized SES unit k; and $\underline{SoC}^k$ and $\overline{SoC}^k$ are the minimum and maximum SOC limits for standardized SES unit k, respectively. Formulas (5), (6), (14), and (15) decide the charging or discharging state of energy storage, where 1 represents charging state and 0 represents discharging state. Formula (20) presents an energy balance of standardized SES unit between scheduling cycles.

III. Multi-entity Operation Nash Bargaining Model

After the dynamic partitioning for SES has been completed, the multi-entity operation will be implemented with the Nash bargaining model. The multi-entity operation Nash bargaining model has three parts: the operation model of the renewable energy entity, the operation model of the SES entity, and the multi-entity Nash bargaining model. The dynamic partitioning strategy occurs one day in advance, based on the tracking of planned output demands. Renewable energy entities, comprising wind and PV power plants, are integrated into the grid. The centralized SES station leases energy storage capacity to renewable energy entities. The leased SES capacity is employed to smooth the power output fluctuations of wind and PV power plants, track their planned output curves, and compensate for the discrepancies between real-time dispatch output and their declared curve, reducing the deviation costs for wind and PV power plants. This ensures the accommodation of renewable energy, thereby increasing the trading volume for renewable energy entities. Simultaneously, the SES entity sets prices for the leased energy storage capacity [27]. Renewable energy entities sign capacity contracts with the centralized SES station, where they bargain and determine the leasing capacity and price. Reasonable prices for energy storage leasing can reduce investment costs for renewable energy entities and improve the utilization rate of energy storage.

The centralized SES station operates independently, providing charging and discharging services for renewable energy entities. When the demands of renewable energy entities are prioritized, the remaining capacity of the centralized SES station can flexibly participate in the spot market. The centralized SES stations participate in the spot market through a self-scheduling mechanism. If the SES does not partake in the spot market, the operational revenue of the station will be significantly reduced [28]. The remaining capacity of the centralized SES station can participate in the spot market as an independent entity, providing services, generating extra revenue, and ultimately achieving a win-win situation for all entities.

A. Renewable Energy Entity Operation

The capacity of the centralized SES station can track the planned output of renewable energy entities, and reduce the forecasting error of renewable energy entities, minimizing the curtailed power and improving the operation and dispatching flexibility of the power grid. The operation profit U_m for renewable energy entity m can be expressed as:

$$U_m = R_{sell}^m - \pi^{m,SES} - C_{om}^m - C_{sh}^m \tag{21}$$

where R_{sell}^m is the revenue from energy sales of renewable energy entity m; $\pi^{m,SES}$ is the leasing payment of SES for renewable energy entity m; C_{om}^m is the operation and maintenance (O&M) cost for renewable energy entity m; and C_{sh}^m is the penalty cost for renewable energy entity m deviated from the planned output. The revenue R_{sell}^m from the energy sales of renewable energy entities is defined as:

$$R_{sell}^m = \begin{cases} q_{sell} \sum_{t=1}^{T} \left(P_E^m(t) + P_{c,dis}^m(t) \right) \\ \qquad P_E^m(t) + P_{c,dis}^m(t) \le (1+\gamma) P_{Pd}^m(t) \\ q_{sell} \sum_{t=1}^{T} (1+\alpha) P_{Pd}^m(t) \\ \qquad P_E^m(t) + P_{c,dis}^m(t) > (1+\gamma) P_{Pd}^m(t) \end{cases} \tag{22}$$

where q_{sell} is the feed-in tariff for renewable energy; and γ is the allowable deviation range of the planned output. The O&M cost C_{om}^m of renewable energy entities is defined as:

$$C_{om}^m = k \sum_{t=1}^{T} P_E^m(t) \tag{23}$$

where k is the O&M cost of renewable energy generation. C_{sh}^m lies in compensating for the interference caused by real-time dispatch deviation of renewable energy entities from the planned output. According to relevant regulations in China, the reduction and exemption of the deviation power of the grid-connected renewable energy power plants at each moment are set at 5% of the declared power for the previous day, and the excess part is included in the deviation cost.

$$C_{sh}^m = z \sum_{t=1}^{T} Q_{sh}^m(t) \tag{24}$$

$$Q_{sh}^m = \max\left(\left| P_{sh}^m(t) \right| - \gamma P_{Pd}^m(t), 0 \right) \tag{25}$$

where Q_{sh}^m is the deviation power for grid-connected renewable energy entity m; $P_{sh}^m(t)$ is the power shortfall of renewable energy entity m; and z is the cost per deviation power unit.

The bilateral energy trading will be triggered when renewable energy entities lease the capacity from the SES entity to track the planned output on their needs. The leasing payment is calculated based on the charging and discharging of the SES per unit. Renewable energy entity m can bargain with the SES entity to finalize the terms of energy trading and determine the leasing payment amount. The leasing payment depends on the supply and demand relationship between the SES entity and renewable energy entities. The leasing payment $\pi^{m,SES}$ for energy trading between renewable energy and SES entities is defined as:

$$\pi^{m,SES} = q^m \sum_{t=1}^{T} P_{rent}^{m,SES}(t) \tag{26}$$

$$P_{rent}^{m,SES}(t) = P_c^m(t) + P_{dis}^m(t) \tag{27}$$

$$P_{rent}^{m,SES}(t) + P_{rent}^{SES,m}(t) = 0 \tag{28}$$

$$\pi^{m,SES} + \pi^{SES,m} = 0 \tag{29}$$

where q^m is the leasing payment of renewable energy entity m per unit; $P_{rent}^{m,SES}(t)$ and $P_{rent}^{SES,m}(t)$ are the amounts of energy trading between renewable energy entity m and the SES entity; and $\pi^{m,SES}$ and $\pi^{SES,m}$ are the leasing payments for energy trading between the renewable energy entity m and the SES entity.

B. SES Entity Operation

The operation profit for the SES entity U_{SES} is defined as:

$$U_{SES} = R_{spot} + R_{ca} - \sum_{m=1}^{M} \pi^{SES,m} - C_{om}^{SES} \tag{30}$$

where R_{spot} is the revenue of SES entity participating in the spot market; R_{ca} is the capacity tariff compensation of SES entity; and C_{om}^{SES} is the total O&M cost for the centralized SES station.

The revenue R_{spot} comes from the SES entity that participates in the spot market. The SES entity participates in the spot market by offering peak shaving and valley filling services based on price differences between peak and off-peak periods without submitting any bid price. As a price taker, the charging and discharging actions of the SES entity do not affect the market clearing prices. The SES entity can flexibly optimize its output shares for each period. It can profit from price variation by utilizing the remaining capacity of the SES for energy trading.

$$R_{spot} = \sum_{t=1}^{T} \lambda^{spot}(t) P_{c,dis}^{spot}(t) \tag{31}$$

$$P_{c,dis}^{spot}(t) = P_c^{spot}(t) - P_{dis}^{spot}(t) \tag{32}$$

where $\lambda^{spot}(t)$ is the clearing price of the spot market, and the locational marginal price (LMP) pricing mechanism is adopted; and $P_{c,dis}^{spot}(t)$ is the discharging power when SES entity participates in the spot market. According to the energy storage policy in provincial-level spot markets in China, R_{ca} is provided to energy storage participating in the spot market, while the capacity associated with leasing and other methods does not qualify for capacity tariff compensation.

$$R_{ca}=\tau E_{\max}^{spot} \tag{33}$$

where τ is the ration of capacity tariff compensation; and $E_{\max}^{spot}$ is the compensation capacity participating in the spot market. The O&M cost C_{om} of the SES entity is defined as:

$$C_{om}=\mu_{om}^{SES}\sum_{t=1}^{T}\sum_{m=1}^{M}P_{rent}^{m,SES}(t) \tag{34}$$

where μ_{om}^{SES} is the unit cost of O&M.

C. Nash Bargaining Model

The Nash bargaining model is introduced for optimizing the cooperative operation between renewable energy and SES entities. In this model, each entity is regarded as an independent and rational individual, and all participating entities strive to achieve consensus through bargaining. We seek an equilibrium strategy that maximizes the collective benefits of all participants to the fullest extent. Nash bargaining is a theory that belongs to cooperative games, providing a theoretical framework to elucidate the process of bargaining among multiple entities.

The Nash bargaining model is employed to analyze the collaboration between renewable energy and SES entities, which can fairly and reasonably determine both the leasing capacity and leasing price of the SES. The maximum Nash product solution represents the equilibrium outcome in the Nash bargaining game problem, and this solution can ensure that the cooperative participants achieve Pareto-optimal benefits. Each participating entity can reach its optimal decision through Nash bargaining. The formula for the Nash bargaining model is:

$$\begin{cases}\max \prod_{m=1}^{M}\left(U_m-U_m^0\right)\left(U_{SES}-U_{SES}^0\right)\\ \text{s.t. } U_m-U_m^0\geq 0\\ \qquad U_{SES}-U_{SES}^0\geq 0\\ \qquad (8)\text{-}(20),\ (27)\text{-}(29)\end{cases} \tag{35}$$

where U_m and U_{SES} are the profit functions for renewable energy bargaining entity m; and U_m^0 and U_{SES}^0 are the bargaining breakdown points referring to the profits of each bargaining entity before the cooperation, which represent the minimum acceptable profits that the entity refuses all agreements during the bargaining. The objective of Nash bargaining is to maximize the enhancement in benefits for all cooperation entities.

The Nash bargaining model is a non-convex and non-linear problem that is difficult to solve directly. The mean inequality is applied to decompose the bargaining model into two consecutive subproblems [28]. Specifically, the first subproblem S1 aims to maximize the operation profit problem of multi-entities with energy trading, and the second subproblem S2 focuses on determining the bilateral leasing payments for energy trading. The optimal solution to the original problem can be obtained by solving two subproblems sequentially. The decomposition of the Nash bargaining model proceeds as follows.

Each entity is willing to participate in energy trading and can strictly improve its performance in terms of upper total profit, i.e., $U_m-U_m^0\geq 0$, $U_{SES}-U_{SES}^0\geq 0$. All entities form a cohesive coalition, and the total profit for the coalition will increase due to energy trading.

For ease of calculation, we set two intermediate variables W_m and W_{SES} as:

$$W_m=U_m+\pi^{m,SES} \tag{36}$$

$$W_{SES}=U_{SES}+\sum_{m=1}^{M}\pi^{SES,m} \tag{37}$$

The energy trading of entities leads to an overall increase in coalition profit. The details of the proof for the subproblem decomposition can be found in Appendix A.

1) S1: multi-entity operation profit maximization problem

$$\max\left(\sum_{m=1}^{M}W_m+W_{SES}\right) \tag{38}$$

The planned output of renewable energy bargaining entity m at time t is defined as the sum of the actual renewable energy output, power shortfall, and energy storage charging and discharging power at time t.

$$\begin{cases}\text{s.t. } P_{Pd}^{m}(t)=P_{E}^{m}(t)+P_{c,dis}^{m}(t)+P_{sh}^{m}(t)\\ \qquad (8)\text{-}(20)\end{cases} \tag{39}$$

2) S2: leasing payment bargaining problem

$$\max\left(\sum_{m=1}^{M}\ln\left(W_m^*-\pi^{m,SES}-U_m^{0,*}\right)+\ln\left(W_{SES}^*-\sum_{m=1}^{M}\pi^{SES,m}-U_{SES}^{0,*}\right)\right) \tag{40}$$

$$\begin{cases}\text{s.t. } W_m^*-\pi^{m,SES}\geq U_m^{0,*}\\ \qquad W_{SES}^*+\sum_{m=1}^{M}\pi^{SES,m}\geq U_{SES}^{0,*}\\ \qquad (27)\text{-}(29),\ (36),\ (37)\end{cases} \tag{41}$$

where W_m^* and W_{SES}^* are the optimal solutions of S1; and $U_m^{0,*}$ and $U_{SES}^{0,*}$ are the breakdown points of optimal operation for renewable energy bargaining entity m and SES entity before the cooperative bargaining, respectively.

IV. Optimization Operation Solution

To protect the privacy of entities engaged in bargaining, this paper employs a distributed ADMM algorithm to solve the subproblems of maximizing profits of multi-entities and bargaining leasing payment for energy trading. The algorithm has strong convergence properties, simple form, and strong robustness, making it a common choice for solving optimization problems with separable variables. The detailed solution steps can be found in [29]. The solution process of distributed ADMM algorithm for the bargaining model is shown in Fig. 2 according to the two subproblems.

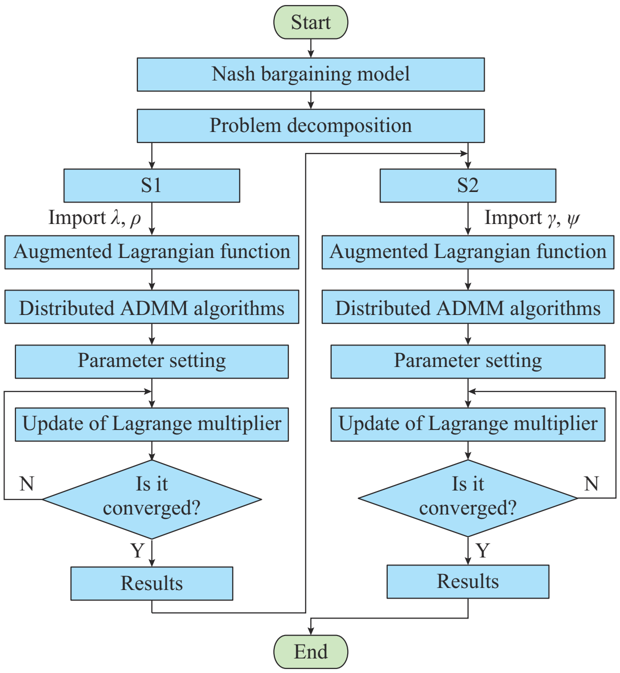

Fig. 2. Solution process of distributed ADMM algorithm.

To solve S1 for maximizing the profits of multiple entities, auxiliary variable $\hat{P}_{rent}^{m,SES}(t)$ is introduced, which represents the optimal energy expected to be leased from the SES entity by renewable energy entities at time t, the model of S1 is transformed into a double-coupling model.

$$\hat{P}_{rent}^{m,SES}(t) = P_{rent}^{m,SES}(t) \tag{42}$$

$$\hat{P}_{rent}^{m,SES}(t) + \hat{P}_{rent}^{SES,m}(t) = 0 \tag{43}$$

The multiple entities bargain and reach a consensus on energy trading. To convert the problem into a minimization problem, we construct the augmented Lagrangian function of S1 as:

$$L_1 = -\left(\sum_{m=1}^{M} U_m + U_{SES}\right) + \sum_{m=1}^{M}\sum_{t=1}^{T}\lambda^k(t)\left(\hat{P}_{rent}^{m,SES}(t) - P_{rent}^{m,SES}(t)\right) + \frac{\rho}{2}\sum_{m=1}^{M}\sum_{t=1}^{T}\left\| \hat{P}_{rent}^{m,SES}(t) - P_{rent}^{m,SES}(t)\right\|_2^2 \tag{44}$$

where $\lambda^k(t)$ is the Lagrange multipliers for renewable energy entities of S1; ρ is the penalty factor for S1; and k is the iteration number. By utilizing the distributed ADMM algorithm to solve the augmented Lagrangian function in the distribution framework, we can obtain:

1) Distributed optimization model for the renewable energy entity m

$$\min\left[-W_m + \sum_{m=1}^{M}\sum_{t=1}^{T}\lambda^k(t)\left(\hat{P}_{rent}^{m,SES}(t) - P_{rent}^{m,SES}(t)\right) + \frac{\rho}{2}\sum_{m=1}^{M}\sum_{t=1}^{T}\left\| \hat{P}_{rent}^{m,SES}(t) - P_{rent}^{m,SES}(t)\right\|_2^2\right] \tag{45}$$

2) Distributed optimization model for SES entity

$$\min\left[-U_{SES} + \sum_{m=1}^{M}\sum_{t=1}^{T}\lambda^k(t)\left(\hat{P}_{rent}^{m,SES}(t) - P_{rent}^{m,SES}(t)\right) + \frac{\rho}{2}\sum_{m=1}^{M}\sum_{t=1}^{T}\left\| \hat{P}_{rent}^{m,SES}(t) - P_{rent}^{m,SES}(t)\right\|_2^2\right] \tag{46}$$

Initialize the iteration number, set the parameters, and update the Lagrange multipliers:

$$\lambda^{k+1}(t) = \lambda^k(t) + \rho\left(\hat{P}_{rent}^{m,SES,k+1}(t) - P_{rent}^{m,SES,k+1}(t)\right) \tag{47}$$

Determine the convergence condition of the distributed ADMM algorithm:

$$\max\left(\sum_{t=1}^{T}\left\| \hat{P}_{rent}^{m,SES,k+1}(t) - P_{rent}^{m,SES,k}(t)\right\|_2^2\right) < \delta_1 \tag{48}$$

where δ_1 is the residual convergence precision for S1.

To solve S2 for bargaining the leasing payment, we introduce auxiliary variable $\hat{\pi}^{m,SES}(t)$ to represent the expected leasing payment for renewable energy entities.

$$\hat{\pi}^{m,SES}(t) = \pi^{m,SES}(t) \tag{49}$$

$$\hat{\pi}^{m,SES}(t) + \hat{\pi}^{SES,m}(t) = 0 \tag{50}$$

The augmented Lagrangian function for S2 can be constructed as:

$$L_2 = -\left(\sum_{m=1}^{M}\ln\left(W_m^* - \pi^{m,SES} - U_{wt,m}^{0,*}\right) + \ln\left(W_{SES}^* - \sum_{m=1}^{M}\pi^{SES,m} - U_{SES}^{0,*}\right)\right) + \sum_{m=1}^{M}\sum_{t=1}^{T}\gamma^k(t)\left(\hat{\pi}^{m,SES}(t) - \pi^{m,SES}(t)\right) + \frac{\psi}{2}\sum_{m=1}^{M}\sum_{t=1}^{T}\left\|\hat{\pi}^{m,SES}(t) - \pi^{m,SES}(t)\right\|_2^2 \tag{51}$$

where $\gamma^k(t)$ is the Lagrange multipliers for the renewable energy entities of S2; and ψ is the penalty factor for S2. Similar to S1, we can decompose the augmented Lagrangian function for S2 to obtain distributed optimization models for determining the leasing payment in energy trading and initialize the iteration number, set the parameters, and update the Lagrange multipliers:

$$\gamma^{k+1}(t) = \gamma^k(t) + \psi\left(\hat{\pi}^{m,SES,k+1}(t) - \pi^{m,SES,k+1}(t)\right) \tag{52}$$

$$\max\left(\sum_{t=1}^{T}\left\|\hat{\pi}^{m,SES,k+1}(t) - \hat{\pi}^{m,SES,k}(t)\right\|_2^2\right) < \delta_2 \tag{53}$$

where δ_2 is the residual convergence precision for S2.

Finally, we obtain the optimal leasing price $q^{m,*}$ for renewable energy entities. Additionally, the Pareto-optimal profits for multi-entities and the maximum profit for the coalition can be determined.

V. Case Studies and Results

A. Simulation Settings

In this subsection, we simulate the proposed optimal operation with a dynamic partitioning strategy for the centralized SES station. Detailed parameters of the standardized SES units are shown in Table I. Each standardized SES unit consists of one 35/0.4 kV step-up transformer, eight 0.63 MW/1.39 MWh battery cabinet systems, eight 630 kW PCSs, and corresponding combiner cabinets.

We examine three renewable energy entities, including two wind power plants of 150 MW and 100 MW and one PV power plant of 100 MW in northwest China.

TABLE I
DETAILED PARAMETER OF STANDARDIZED SES UNIT

Parameter	Value
Power of standardized SES unit (MW)	5
Capacity of standardized SES unit (MWh)	10
Ratio of step-up transformer (kV)	0.4/35
Rated capacity of step-up transformer (MVA)	5.5
Rated power of PCS (MW)	0.63
Rated power of battery cabinet (MW)	0.63
Rated capacity of battery cabinet (MWh)	1.395

To verify the effectiveness of the proposed strategy, we analyze the actual output and planned output of these renewable energy power plants on typical days. The equipment scale and cost of the centralized SES station as well as the feed-in tariff and O&M cost factor of renewable energy power plants are shown in Appendix B.

To validate the effectiveness of the optimal operation with a dynamic partitioning strategy for SES, our analysis explores three distinct scenarios.

Base scenario: entities do not cooperate with each other. Renewable energy entities are directly connected to the grid, and the SES entity operates independently.

Scenario 1: the optimal operation with a fixed partitioning strategy is involved for the centralized SES station. Here, renewable energy entities collaborate with the SES entity. The fixed capacity is determined based on the rated capacities of renewable energy entities.

Scenario 2: the optimal operation with a dynamic partitioning strategy is implemented for the centralized SES station. The strategy fosters collaboration between renewable energy entities and the SES entity.

B. Analysis of Optimization Operation Results

This paper presents an analysis of optimization operation results across the scenarios, as shown in Table II. In the Base scenario, the energy storage station operates independently, without any transactions between renewable energy entities and the SES entity. Scenario 1, as shown in Fig. 3, focuses on the tracking effect of wind and PV entities on planned output.

TABLE II
OPTIMIZATION OPERATION RESULTS

Entity	Results on Base scenario (kWh)				Results on Scenario 1 (fixed) (kWh)				Results on Scenario 2 (dynamic) (kWh)			
	Transaction	Curtailment	Penalty	Grid-connected	Transaction	Curtailment	Penalty	Grid-connected	Transaction	Curtailment	Penalty	Grid-connected
1		45.50	93.18	1979.50	144.81	0	26.42	2046.39	156.22	3.40	5.04	2074.34
2		87.78	25.32	1119.22	89.96	46.50	0	1167.90	114.50	12.43	2.80	1158.38
3		19.82	413.18	107249	59.49	0	14.31	458.04	70.99	1.99	7.24	470.72

Scenario 1 showcases the effectiveness of cooperative operations between renewable energy and the SES entities in reducing wind and PV curtailments as well as power deviation in renewable energy power plants. Nevertheless, some limitations persist. Wind power entity 1 faces power shortages during 10:00-14:00, wind power entity 2 experiences 46.5 kWh of wind curtailment, and PV entity 3 encounters power shortages as well. The results demonstrate that while fixed partitioning strategy in Scenario 1 largely aligns with the planned output, it falls short of fully harnessing the spatio-temporal adjustment capabilities of energy storage. Consequently, it leads to suboptimal energy storage utilization and high operational costs for both renewable energy and the SES entities.

Figure 4 illustrates the performance tracking of renewable energy entities in Scenario 2, where the dynamic partitioning strategy demonstrates a superior capability to align with the planned output compared with that of Scenario 1. The majority of renewable energy outputs fall within the allowable deviation range. In comparison to Scenario 1, Scenario 2 leads to a reduction of 21.38 kWh in the penalty amount for wind power entity 1, a decrease of 34.07 kWh in curtailment for wind power entity 2, and a reduction of 7.07 kWh in the penalty amount for PV entity 3. However, due to the influence of the dynamic partitioning strategy, there is a slight increase in curtailment for wind power entity 1 and PV entity 3 as well as an increase in the penalty amount for wind power entity 2. Nevertheless, when compared with Scenario 1, the overall grid-connected power increases by 31.11 kWh, the overall curtailment amount decreases by 38.32%, and the overall penalty amount decreases by 37.02%. The improvements result in significantly more overall profits.

Figure 5 presents a dynamic allocated capacity among various entities. The red line illustrates the dynamically allocated capacity in Scenario 2, with the cumulative dynamic capacity over time equaling the rated capacity of the entire centralized SES station. The green shaded area indicates the actual capacity utilized by different entities. In alignment with the typical configuration of large-scale energy storage stations, the minimum energy storage unit for operation is set to be 5 MW/10 MWh. When the renewable energy entities have zero demand, the dynamically allocated capacity leased by the renewable energy entity can be reduced to zero. Overall, the dynamic partitioning strategy for centralized SES station effectively matches the demands of the individual entity and validates the rationality of the strategy. The strategy establishes a theoretical foundation for multi-scenario applications of large-scale energy storage stations and provides valuable guidance to fully utilize the capacity and power of energy storage.

The total utilization rate of the centralized SES station is calculated as:

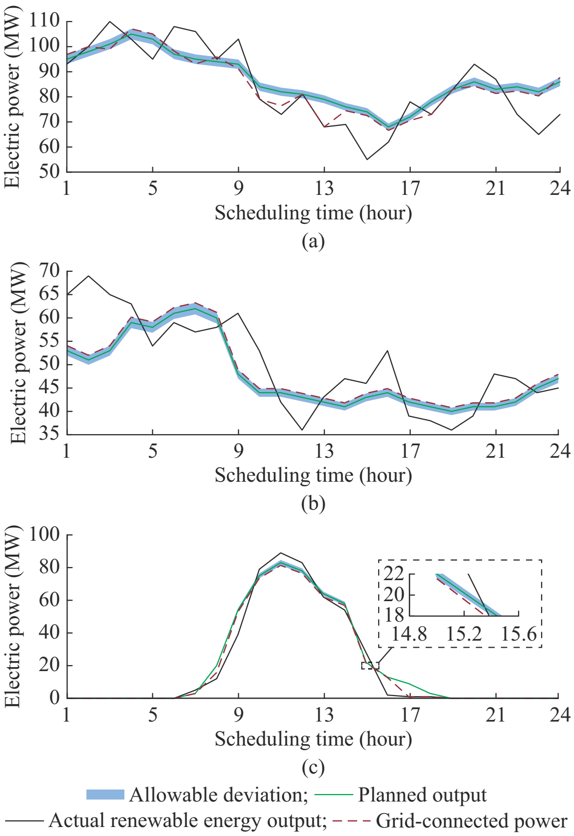

Fig. 3. Performance tracking of renewable energy entities in Scenario 1. (a) Wind power entity 1. (b) Wind power entity 2. (c) PV entity 3.

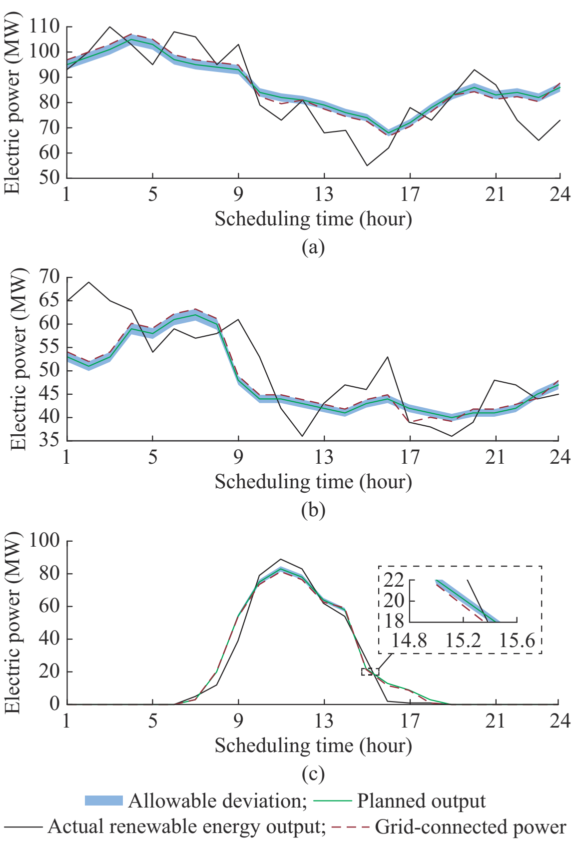

Fig. 4. Performance tracking of renewable energy entities in Scenario 2. (a) Wind power entity 1. (b) Wind power entity 2. (c) PV entity 3.

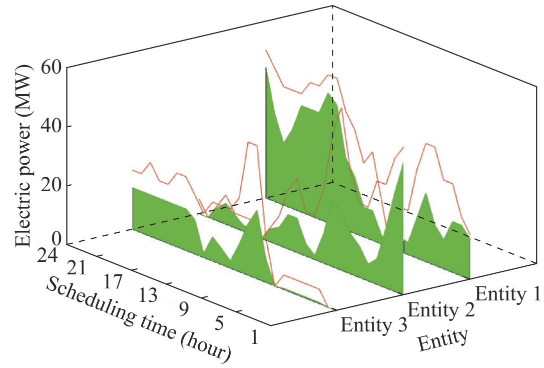

Fig. 5. Dynamic allocated capacity among various entities.

$$r_m = \frac{\sum_{t=1}^{T}\sum_{k=1}^{K^m} SoC^k \cdot E_{unit}}{\sum_{t=1}^{T} E_{\max}^m(t)} \times 100\% \tag{54}$$

$$r_{SES} = \frac{\sum_{t=1}^{T}\sum_{k=1}^{K_{\max}} SoC^k \cdot E_{unit} + SoC^{spot} \cdot E^{spot}}{\sum_{t=1}^{T} E_{\max}} \times 100\% \tag{55}$$

where r_m is the actual utilization rate of renewable energy entity m; r_{SES} is the actual utilization rate of the centralized SES station; and SoC^{spot} is the SoC of spot market capacity.

Table III presents a result of actual utilization rate between different entities and the entire centralized SES station within the contexts of Scenarios 1 and 2. Notably, the dynamic partitioning strategy for centralized SES station yields a substantial increase in the actual utilization of energy storage capacity across diverse entities. When compared with the fixed partitioning strategy, the actual utilization rates for entities 1, 2, and 3 increase by 30.83%, 10.53%, and 12.41%, respectively. Importantly, entities with higher energy storage demands experience proportionally higher utilization rates. For the overall centralized SES station, there is a noteworthy enhancement in the actual utilization rate, registering an impressive increase of around 20.91%.

TABLE III
RESULT OF ACTUAL UTILIZATION RATE

Entity	Actual utilization rate (%)	
	Scenario 1	Scenario 2
Wind power entity 1 (150 MW)	32.76	63.59
Wind power entity 2 (100 MW)	39.54	50.07
PV entity 3 (150 MW)	34.22	46.63
Entire centralized SES station	34.61	55.52

In Fig. 6, we visualize the dynamic energy trading among different entities in Scenarios 1 and 2 as a result of optimization operation. The implementation of the dynamic partitioning strategy has led to increased energy trading between renewable energy source entities and the SES entity, resulting in additional energy trades of 11.41 kWh, 22.53 kWh, and 11.09 kWh for entities 1, 2, and 3, respectively.

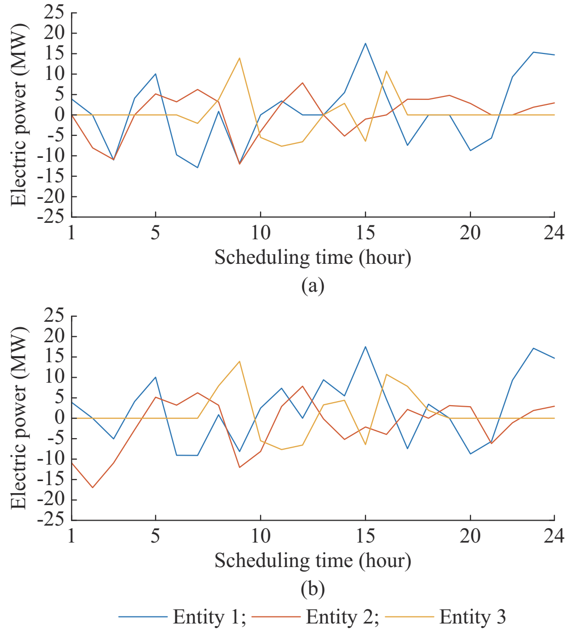

Fig. 6. Dynamic energy trading among different entities in Scenarios 1 and 2. (a) Scenario 1. (b) Scenario 2.

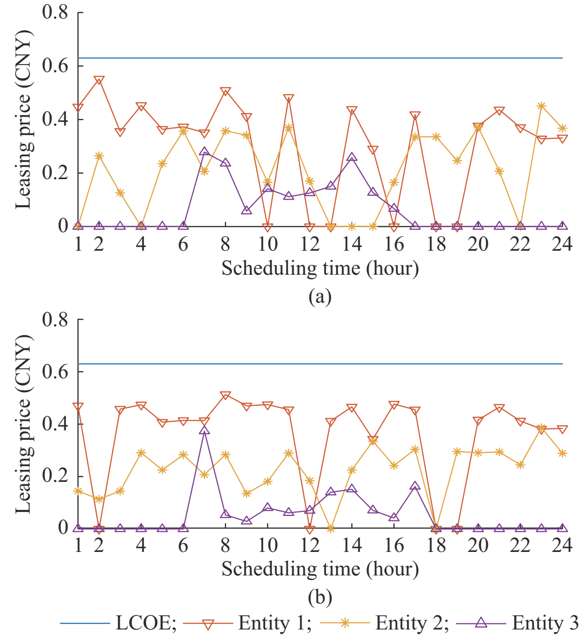

Fig. 7. Leasing payment of centralized SES station in Scenarios 1 and 2. (a) Scenario 1. (b) Scenario 2.

This increase in energy trading has also contributed to elevated electricity consumption by renewable energy entities, providing further validation of effectiveness of the dynamic partitioning strategy in improving energy storage utilization efficiency.

C. Economic Analysis of Operation

Figure 7 illustrates the leasing payment of centralized SES station in Scenarios 1 and 2. Notably, when renewable energy entities do not engage in leasing energy storage, leasing payments are non-existent, and their equivalent varies. However, the leasing payments are consistently below the levelized cost of electricity (LCOE) associated with large-scale lithium-ion battery energy storage stations [30].

In Scenario 1, the average leasing payments for the three renewable energy entities are CNY 0.30, CNY 0.21, and CNY 0.06, respectively. This suggests that accessing the SES through leasing is more cost-efficient than utilizing energy storage independently for renewable energy entities. Essentially, leasing the centralized SES station capacity proves to be a more economically efficient option compared with configuring energy storage independently. Through energy trading among various entities, the strategy can achieve lower leasing prices.

In Scenario 2, the average leasing prices for renewable energy entities 1, 2, and 3 are CNY 0.36, CNY 0.21, and CNY 0.07, respectively. A comparison reveals that the leasing prices in Scenario 2 are higher than those in Scenario 1. The increase in leasing prices results in increased leasing payments for renewable energy entities, consequently boosting the total profits of the coalition. The increased utilization of SES capacity mitigates the impact of higher leasing payments by reducing deviation penalty costs and curtailed power. As a result, it enhances the integration of renewable energy into the grid.

Table IV provides economic indexes of optimization operation. The profits encompass the revenue generated from renewable energy integration into the grid, leasing payments, and other costs such as operational and deviation costs. In Scenario 1, the collaboration among multiple entities through energy trading yields total revenues of CNY 31436.93, CNY 22879.6, and CNY 15704.04 for the three renewable energy entities 1, 2, and 3, respectively. Despite the leasing payment following cooperative operation, the effective tracking of the planned output reduces wind and PV curtailments and lowers deviation penalty costs, leading to a total cost decrease. Consequently, the profits of renewable energy entities 1, 2, and, 3 in Scenario 1 increase by approximately CNY 34522.35, CNY 34522.75, and CNY 34522.98, representing increments of 4.09%, 7.51%, and 32.19%, respectively, compared with the Base scenario. The total profit of SES entity amplifies by CNY 101621.07, indicating an increase of CNY 34523.01 compared with the non-cooperation scenario. The mutual collaboration among renewable energy entities enhances the overall operation efficiency, leading to improved profits for each entity while ensuring equitable distribution of cooperatively generated surplus.

In Scenario 2, the centralized SES station adopts a dynamic partitioning strategy, thereby enhancing the utilization of centralized SES station. The reasonable capacity partitioning better aligns with the planned output of renewable energy power plants, reducing wind and PV curtailments, increasing revenue, and trimming costs. The final results in Table IV reveal that the total profits of multiple entities employing the dynamic partitioning strategy increase by approximately CNY 10063.5 compared with the fixed partitioning strategy. Profits for entities 1, 2, and 3 as well as the centralized SES station increase by about 1.14%, 2.04%, 7.10%, and 9.90%, respectively. Compared with the Base scenario, the overall profits increase by approximately 12.06%. The adoption of the dynamic partitioning strategy by multiple entities further augments the economic benefits of the centralized SES station and enhances the profit of each entity. The strategy facilitates superior alignment with the planned output of renewable energy power plants.

TABLE IV
ECONOMIC INDEXES OF OPTIMIZATION OPERATION

Entity	Base Scenario				Scenario 1 (fixed)				Scenario 2 (dynamic)			
	Revenue (CNY)	Leasing payment (CNY)	Other cost (CNY)	Profit (CNY)	Revenue (CNY)	Leasing payment (CNY)	Other cost (CNY)	Profit (CNY)	Revenue (CNY)	Leasing payment (CNY)	Other cost (CNY)	Profit (CNY)
1	930365.0		85540	844825.0	961801.93	53044.80	29409.78	879347.35	974939.10	65104.81	20421.57	889412.72
2	526033.4		66206	459827.4	548913.00	21655.99	32905.86	494351.15	544437.12	22746.58	17274.85	504415.69
3	144613.0		37364	107249.0	160317.04	7749.41	10795.65	141771.98	164753.36	4664.46	8256.27	151832.63

VI. CONCLUSION

Due to operational and battery SoC constraints, the energy storage system has difficulty in achieving a maximum utilization rate. The key to improving energy storage utilization lies in a well-designed operational scheduling. For centralized energy storage systems, refined management that involves hierarchical, zonal, and clustered strategies has a significant impact on the overall efficiency of energy storage stations. Fully capitalizing on the multifunctionality of energy storage systems poses one of the future challenges in developing energy storage.

In this paper, we introduce a dynamic partitioning strategy for centralized SES stations. Our research findings highlight its suitability in operating and scheduling large-scale centralized SES stations, making it applicable across various scenarios and involving multiple entities through leasing arrangements. The practice of energy trading among multiple renewable energy entities effectively enhances the tracking of the planned output, improves the grid-connected power generation, and reduces overall deviation penalties and curtailed power. This strategy significantly elevates the actual utilization rate of energy storage facilities, resulting in an approximately 20.91% improvement compared with the fixed partitioning strategy. Furthermore, the collaboration between the centralized SES station and renewable energy entities reduces the usage costs of energy storage facilities, amplifies operational profits for each entity, shortens the recovery period for centralized SES stations, and ultimately creates a win-win situation for all involved entities.

APPENDIX A

The basic inequality has the following properties:

$$a_1 a_2 \dots a_m \le \left(\frac{a_1 + a_2 + \dots + a_m}{m}\right)^m \tag{A1}$$

With $a_m \ge 0$, according to the basic inequality, the objective function of the Nash bargaining model satisfies the following equation.

$$\prod_{m=1}^{M}\left(U_m - U_m^0\right)\left(U_{SES} - U_{SES}^0\right) \le \left[\frac{1}{m}\sum_{m=1}^{M}\left(U_m - U_m^0\right) + \left(U_{SES} - U_{SES}^0\right)\right]^m \tag{A2}$$

The formula is equivalent only if the following condition is met.

$$U_1 - U_1^0 = \dots = U_m - U_m^0 = U_{SES} - U_{SES}^0 \tag{A3}$$

Since $U_1^0 + U_2^0 + \dots + U_m^0 + U_{SES}^0$ is constant, maximizing $\prod_{m=1}^{M}\left(U_m - U_m^0\right)\left(U_{SES} - U_{SES}^0\right)$ is equivalent to maximizing $\sum_{m=1}^{M} U_m + U_{SES}$.

Due to $W_m = U_m + \pi^{m,SES}$, $W_{SES} = U_{SES} + \sum_{m=1}^{M} \pi^{SES,m}$, the following equality holds.

$$\max\left(\sum_{m=1}^{M} U_m + U_{SES}\right) = \max\left(\sum_{m=1}^{M} W_m + W_{SES}\right) \tag{A4}$$

APPENDIX B

TABLE BI
PARAMETERS OF OPERATION MODEL

Parameter	Value	Parameter	Value
$E_{\max}^{SES}$ (MWh)	200	q_{sell}^{wt} (CNY/kWh)	0.47
$P_{\max}^{SES}$ (MW)	100	k (CNY/kWh)	0.0008
τ^{SES} (CNY/kWh)	0.35	z (CNY/kW)	0.5
μ_{om}^{SES} (CNY/kW)	0.0018	q_{sell}^{pv} (CNY/kWh)	0.35
η_c	0.95	$K_{\max}$	20
η_{dis}	0.95	γ (%)	5

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