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Research article

Trading strategies of energy storage participation in day-ahead joint market based on Stackelberg game

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ABSTRACT

The goal of "carbon peak, carbon neutral" and the increasing expansion of new energy have helped to advance the development of energy storage. However, since the operating cost of energy storage is high, carbon emission trading and power market trading have emerged, effectively improving the efficiency. In this paper, a trading strategy and bidding framework of energy storage participation in the day-ahead joint market are studied. A market bidding model has been established in a framework based on the Stackelberg game. Finally, the "Day-Ahead and Intra-Day and Carbon Emission Trading (CET)" market clearing model has been constructed. It has been simplified to solve the equivalent mixed-integer linear programming (MILP) problem with equilibrium constraints through the use of the Karush–Kuhn–Tucker (KKT) optimality criterion and duality principle. The proposed model is validated through improved examples to obtain thermal unit output cuts of up to 32.2% during load trough periods, and up to 16.75% increase in clearing prices during peak load periods. The storage life is extended and the storage output variation is minimized.

1. Introduction

The pursuit of "Carbon peak, Carbon neutrality" is a significant decision China took on the course of its social and economic growth. Amongst many other industries, the electric power industry is the main driving force behind the national "dual carbon" goal [1,2], and China's electric power industry aims to build a new power system with new energy at its foundation. In recent years, with structural adjustments in the power industry, China's electricity regulatory system has been undergoing much reform [3]. Adjustments to the electricity price mechanism and price level have been increasing, and direct transactions between users and power producers have achieved certain results. However, at present, there is no effective market competition mechanism, and the concept of the market is still in its exploratory stage. Thus, the establishment of an effective market competition mechanism still needs to be studied [4].

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Energy storage technology, with its advantages of fast response speed and good management flexibility, has been extensively utilized in power grids, covering all aspects of power systems such as power generation, transmission, supply, distribution, and use [5,6]. The application of energy storage technology reduces the frequency of the power grid, flattens the load curve, and improves the reliability and stability of the power grid. Sun et al. [7] built the temperature control load model and composite energy storage model architecture, improve the hierarchical control method of composite energy storage; Using the state of energy (SOE) function, Xiang et al. [8] presented a unique approach for the optimal sizing of energy storage systems (ESS) in active distribution networks; The goal of Hedayat et al. [9] was to address the issue of optimal ESS planning, which includes determining the optimal bus location, power rating, and energy capacity in distribution networks. Zhang et al. [10] established the ESS planning and their merits and drawbacks. In Ref. [11], the influence of intelligent charging and discharging strategies on supporting new energy consumption and reducing power fluctuations was discussed at length. A strategy model of time-sharing charging and a battery charging and discharging strategy were also proposed. In Ref. [12], a two-stage optimization model is established on the basis of the operation principle of energy storage, where the objective function was to minimize the total cost. The aims were achieved, with the model having optimal capacity allocation and operating cost. Peng et al. [13] constructed a two-stage optimization model based on a hybrid ESS, where the objective function was to minimize the cost of energy consumption. Tian et al. [14] studied the polymerization methods and existing problems of energy storage devices and renewable energy. In the microgrid, the polymerization of energy storage and renewable energy can complement each other and achieve a win–win effect. Wang et al. [15] established a multi-objective optimization model aimed at the lowest system operating cost, the highest reliability, and maximum wind power efficiency. The optimization objectives of the mixed-integer nonlinear optimization problem created by Ahmad et al. [16] are the average voltage deviation, average power loss, and overall operating and planning cost of the ESS.

Furthermore, it is pointed out in Refs. [17,18] that the rapid development of the energy storage industry in the United States was due to its relatively mature market mechanism. The recommendations made by Das et al. [19] covered matters such as relevant requirements or procedures, suitable ESS selection, intelligent ESS charging and discharging, ESS installation and operation, ESS sizing, and power quality concerns. In Ref. [20], in order to address the problem of optimal ESS planning in distribution networks, it proposed an optimal ESS planning including optimal bus location, power rating, and energy capacity determination in the distribution networks. The business model of the energy storage industry mainly dealt with the auxiliary service market, such as the frequency modulation (FM) energy storage project of Chicago SGEM 20 MW/10 MWh [21]. The construction of a 100 MW/129 MWh Li-Cell ESS in Australia in 2017 was studied, which established a power regulation market, and there were plans to expand it to 150 MW/194 MWh by 2020. In Ref. [22], state of charge (SOC) was applied to the problem of continuous disturbance, and an adaptive primary frequency control strategy is proposed that takes into account the constraints of energy storage battery capacity and FM power; the purpose of this was to achieve the goal of frequency control while ensuring a certain proportion of SOC. Under the constraint of peak load regulation of a power system, El-Zonkoly and Amany [23] studied the energy–time–space conversion characteristics of an ESS, and propose an efficient consumption strategy of a power system based on them. Lunz et al. [24] put the energy storage as a dispatchable load, which plays an important role in optimizing energy production, grid redundancy, and grid economic benefits. Iversen et al. [25] discussed the peak–valley problem whilst considering electricity price. The work proposes that an ESS can store electricity in low-electricity-price periods and discharge it in high-electricity-price periods, which can reduce the peak and valley filling to reduce the charging cost. In order to move the load demand from peak to valley in a microgrid, Zhou et al. [26] suggested an EV-coordinated charging scheduling strategy.

Thus, from the above existing energy storage, it is simple and easy to implement, and can effectively cut peaks and fill valleys. Nevertheless, the aforementioned study works consider the application of energy storage only for configuration, scheduling control operation, optimization-model-solving algorithms and do not consider the participation of energy storage in the optimization of trading strategies in the power market, not to mention the link between CET and energy storage.

The following are this paper's primary contributions in response to the aforementioned problems:

(1) The paper analyzes and builds the bidding model structure of the energy storage participation in day-ahead joint power market to improve energy storage participation during power system operation;
(2) In order to take into account the benefits and risks of bidding, the load uncertainty is characterized using the Latin hypercube sampling approach, and the master–slave game bidding model of the energy storage participating in the day-ahead joint electricity market is established under typical scenarios.
(3) The paper constructs a day-ahead joint market clearing model under the energy storage bidding strategy, and establishes corresponding objective functions and constraints for day-ahead markets, intra-day markets, and carbon emission trading (CET) markets. The model is converted into an equivalent mixed-integer linear programming (MILP) problem by applying the duality principle and the Karush–Kuhn–Tucker (KKT) optimization criteria.

The content of this paper is organized as follows: Section 1 analyzes the framework of the electricity market bidding model. Section 2 establishes the master–slave game bidding model of the energy storage participating in the day-ahead joint power market. In Section 3, the "Day-Ahead and Intra-Day and CET" market clearing model is established according to Section 2. In Section 4, the overall bidding situation and profit of the recent joint market are analyzed with examples to prove the effectiveness and feasibility of the proposed method. Finally, Section 5 concludes this paper.

2. Energy storage participates in the Stackelberg game bidding model architecture of the day-ahead joint power market

In the electricity market, there are intra-day markets, day-ahead markets, and CET markets. Intra-day and day-ahead markets have the largest share of the spot market: the day-ahead market aggregates the quotes of all participants from the previous day of the trading day and matches them to clear them, which can help to accurately calculate the output status of each hour of the next day's trading, while the day-ahead market can adjust for output changes in more detail. However, the day-ahead market and CET market are interrelated and influence each other due to the typical thermal power units' actions, and there is a transmission effect in terms of price [27]. The frame diagram of the interaction between the day-ahead market and CET market is illustrated in Fig. 1.

This section adopts the method of "power generation side quoted quantity, load side quoted quantity does not quote" to study the day-ahead joint market bidding strategy. As independent subjects participating in joint power market trading, energy storage and traditional units need to be submitted to the trading center in advance of the quotation and quantity of the next day in the energy market [28], as well as the size and price of the frequency modulation capacity (FMC) and frequency modulation mileage (FMM) in the FM market. Users only need to submit the electricity demand for different periods of time. Based on the electricity demand of each user and information related to the quantity and price of each participant in the quotation, the trading center predicts the load deviation of the next day's electricity market [29]. The carbon emission cost of conventional units is calculated to minimize the power purchase cost and balance cost. The power purchase plan for the next day is formulated [30], and the benefit of energy storage is defined by the bid quantity and clearing price feedback from the joint market. Therefore, energy storage power stations need to adopt strategic quotation. Energy storage ought to be able to engage in a variety of transactions and develop the best bid strategy, in order to maximize the benefits of the energy storage power plant itself, for there is a correlation between electricity energy transactions and FM service transactions. In Fig. 2, a model flow chart is given which shows the optimal bidding strategy of the energy storage participating in the joint market.

Since energy storage and conventional power generation companies obtain electricity in different ways, energy storage is used to purchase electricity from the power market, and the cost is determined by the real-time electricity market price; therefore, its quotation adopts a strategic bidding strategy to meet the demand and obtain purchasing power. Traditional units need to consume fuel when producing electricity, and so the cost has a certain relationship with the output [31]. Without taking the CET market into account, the quotation shows a step-up curve related to the output. For the specific quotation curve, please refer to Fig. 3.

The quotation $b_{g,t,k}$ of section k of the conventional unit g in the time period t, calculated as eq. (1):

$$b_{g,t,k} = a_g\left(p_{g,t,k}\right)^2 + b_g p_{g,t,k} + c_g \tag{1}$$

where a_g, b_g, and c_g are the fuel cost factors of the conventional unit g. $p_{g,t,k}$ is the output of the conventional unit g in the k section of the period t (eq. (2)):

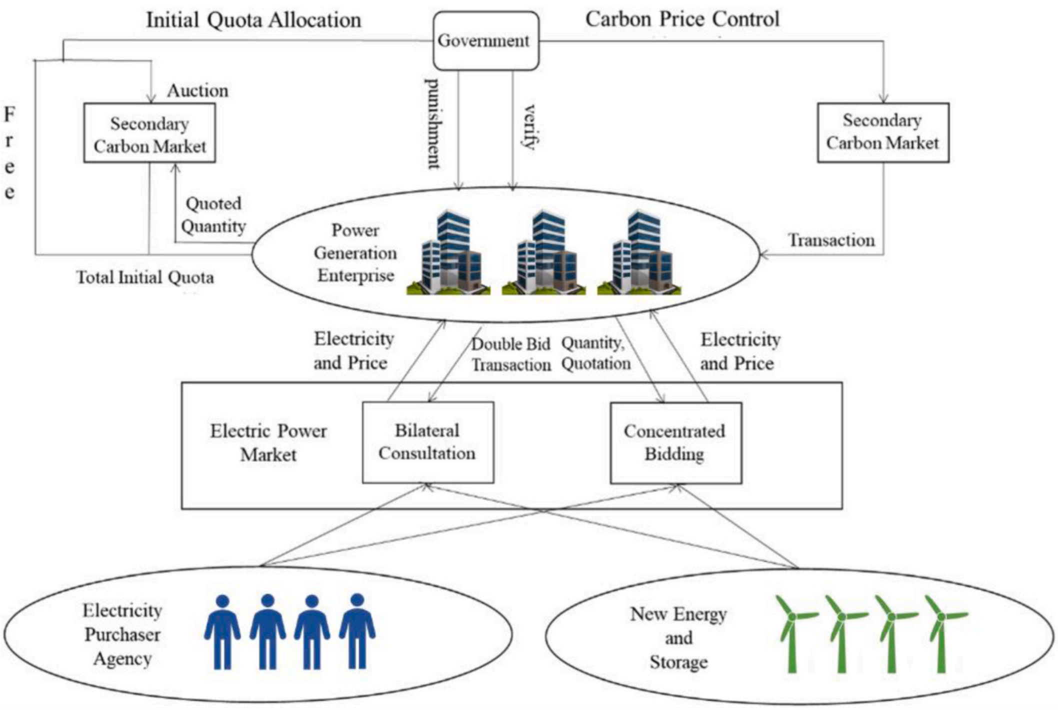

Fig. 1. The frame diagram of the interaction between the day-ahead market and CET market.

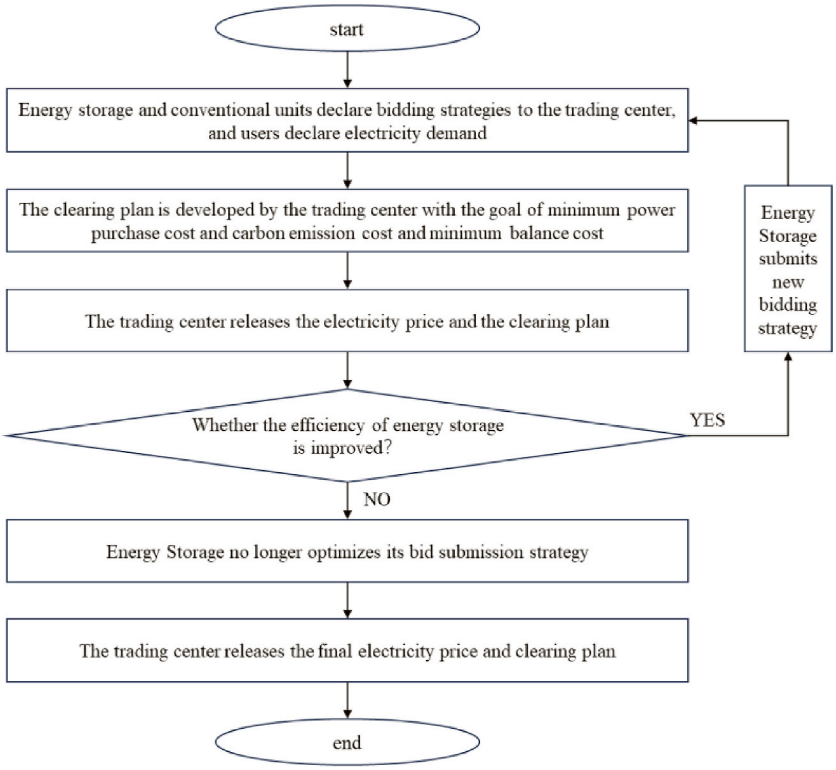

Fig. 2. Model flow chart showing the optimal bidding strategy of the energy storage participating in the day-ahead joint market.

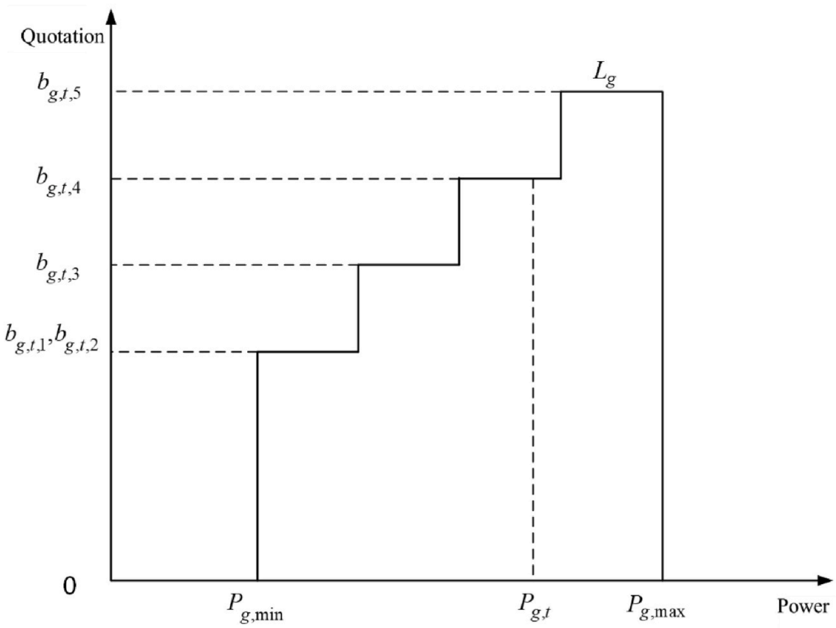

Fig. 3. The quotation curve for conventional units.

$$p_{g,t,k} = \begin{cases} P_{g,\min} + L_g & k = 1, 2 \\ P_{g,\min} + 2L_g & k = 3 \\ P_{g,\min} + 3L_g & k = 4 \\ P_{g,\min} + 4L_g & k = 5 \end{cases} \tag{2}$$

where $P_{g,\min}$ is the minimum output of the conventional unit g. L_g is the output interval quoted by the conventional unit g segment (eq. (3)):

$$L_g = \frac{P_{g,\max} - P_{g,\min}}{4} \tag{3}$$

where $P_{g,\max}$ is the maximum output of the conventional unit g.

In the CET market, when the carbon emissions generated by the conventional unit g exceed the free quota, the conventional unit needs to pay the carbon emission cost corresponding to the excess amount. Therefore, the operation of the CET market will affect the power generation cost of the conventional unit. The conventional unit calculates the carbon emission cost by predicting the power generation situation and then estimating the carbon emission, so as to adjust its quotation. After considering the CET market, the quotation of segment k of the conventional unit g in the period t is calculated as eq. (4):

$$b_{g,t,k} = a_g \left(p_{g,t,k}\right)^2 + b_g p_{g,t,k} + c_g + \frac{\left(24\beta_g P_{g,\max} - \eta E_{q,g}\right) p_{re}}{24 P_{g,\max}} \tag{4}$$

Among them, p_{re} is the cost of each ton of greenhouse gas emissions, which is set at 25 CNY/t, β_g is the greenhouse gas emissions corresponding to the production of the unit power of the thermal power plant, η is the free greenhouse gas emission quota given to the carbon market for the power generator, and $E_{q,g}$ is the carbon emission quota obtained via the conventional unit g.

When energy storage participates in power spot market transactions, the Stackelberg game bidding model can be used to solve the trading and regulating behavior of energy storage in the short-term market. In the Stackelberg game, the bidding model of energy storage, and the day-ahead joint market, energy storage is the leader and the day-ahead joint market is the follower. Energy storage is utilized to create trading strategies as a leader in order to maximize its own revenue and create bidding tactics in order to effectively steer the joint market for the coming day [32]. As the recipient of bidding strategies, the day-ahead joint market seeks to minimize the cost of purchasing electricity by optimizing operation strategies and carbon emission and achieving the lowest balance cost. The day-ahead energy market, auxiliary service market, and CET market joint clearing, as well as the intra-day balance market clearing under the centralized bidding trading mode, are all included in the day-ahead joint market clearing strategy. The Stackelberg game relationship between energy storage and the day-ahead combined power market is represented in Fig. 4.

3. Energy storage participates in the day-ahead joint market Stackelberg game bidding model

The day-ahead energy, day-ahead ancillary services, and intra-day balancing markets provide for the majority of ESS's overall revenue. In order to take into account the benefits and risks of bidding and ensure that energy storage can rationally participate in market transactions, this chapter adopts the Latin hypercube sampling method to describe the peril of trying to maximize energy storage revenues due to the uncertainty of competitors' bids through scenario e; Additionally, it employs scenario q to describe the load uncertainty in the intra-day balance market and selects typical scenarios by using the backward scene reduction technique.

(1) Objective function

The energy storage bidding model aims to maximize energy storage revenue, which involves five parts of the energy storage objective function: energy storage involvement in the day-ahead energy market income, day-ahead auxiliary service market FMC income, FMM income, intra-day balance market FMC income, and the operating costs incurred in energy storage both charged and discharged and in providing FM services. The objective function is determined as eq. (5):

$$\max F = F^{engry} + F^{regulation} + F^{rt} - F^{\cos t} \tag{5}$$

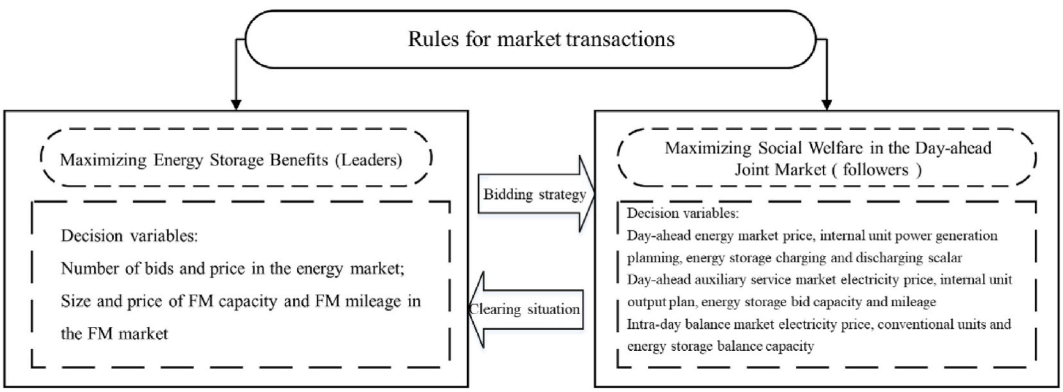

Fig. 4. Game model architecture of energy storage and day-ahead joint electricity market.

where F^{engry} is the day-ahead energy market return; $F^{regulation}$ is the FMC income and FMM income of the day-ahead auxiliary service market; F^{rt} is the FMC income of the intra-day balance market; and $F^{\cos t}$ is the energy storage device's operational costs (eq. (6), (7), (8), (9)).

$$F^{engry} = \sum_{e=1}^{E} \varphi_e \sum_{t=1}^{T} \sum_{s=1}^{S} \gamma_{t,e} \left(p_{s,t,e}^{\mathrm{dis}} - p_{s,t,e}^{\mathrm{ch}} \right) \tag{6}$$

$$F^{regulation} = \sum_{e=1}^{E} \varphi_e \sum_{t=1}^{T} \sum_{s=1}^{S} \gamma_{t,e}^{\mathrm{as}} \left(r_{s,t,e}^{\mathrm{up}} + r_{s,t,e}^{\mathrm{dn}} \right) + \gamma_{t,e}^{\mathrm{as,m}} \left(m_{s,t,e}^{\mathrm{up}} + m_{s,t,e}^{\mathrm{dn}} \right) \tag{7}$$

$$\begin{aligned} F^{rt} = \sum_{e=1}^{E} \varphi_e \sum_{q=1}^{Q} \varphi_q \sum_{t=1}^{T} \gamma_{t,q,e}^{\mathrm{rt}} \Bigg[& \sum_{s=1}^{S} u_{s,t,e}^{\mathrm{dis}} \left(r_{s,t,q,e}^{\mathrm{dn,rt}} - r_{s,t,q,e}^{\mathrm{up,rt}} \right) + \sum_{s=1}^{S} u_{s,t,e}^{\mathrm{ch}} \left(r_{s,t,q,e}^{\mathrm{up,rt}} - r_{s,t,q,e}^{\mathrm{dn,rt}} \right) \\ & + \sum_{s=1}^{S} \left(1 - u_{s,t,e}^{\mathrm{dis}} - u_{s,t,e}^{\mathrm{ch}} \right) \left(r_{s,t,q,e}^{\mathrm{dn,rt}} + r_{s,t,q,e}^{\mathrm{up,rt}} \right) \Bigg] \end{aligned} \tag{8}$$

$$F^{\cos t} = \sum_{e=1}^{E} \varphi_e \sum_{q=1}^{Q} \varphi_q \sum_{s=1}^{S} \sum_{t=1}^{T} C_M \left(p_{s,t,e}^{ch} + p_{s,t,e}^{dis} + r_{s,t,e}^{up} + r_{s,t,e}^{dn} + r_{s,t,q,e}^{up,rt} + r_{s,t,q,e}^{dn,rt} \right) \tag{9}$$

where S represents energy storage power stations' number; φ_e represents the probability of scenario e occurring; E is the quantity of occurrences of scenario e; φ_q is the probability of scenario q occurring; Q is the quantity of times that scenario q occurs; and T represents the number of scheduling cycles. In scenario e, the price settlement is occurred at t on the day-ahead market. Furthermore, $\gamma_{t,e}$ represents the energy settlement price; $\gamma_{t,e}^{\mathrm{as}}$ represents the FMC settlement price; and $\gamma_{t,e}^{\mathrm{as,m}}$ represents the FMM settlement price. In scenario e and q, the price settlement is occurred at t on the intra-day market; $\gamma_{t,q,e}^{\mathrm{rt}}$ represents the FMC settlement price; and the output of energy storage in each market the day before is determined via market clearing. Moreover, $u_{s,t,e}^{\mathrm{ch}}$ and $u_{s,t,e}^{\mathrm{dis}}$ represent the energy storage s's charging and discharging states at time t; $p_{s,t,e}^{\mathrm{ch}}$ and $p_{s,t,e}^{\mathrm{dis}}$ represent the outputs for the corresponding energy power; $r_{s,t,e}^{\mathrm{up}}$ and $r_{s,t,e}^{\mathrm{dn}}$ are the outputs for the FMC; $m_{s,t,e}^{\mathrm{dn}}$ is the output for the FMM; $r_{s,t,q,e}^{\mathrm{up,rt}}$ and $r_{s,t,q,e}^{\mathrm{dn,rt}}$ are the outputs for the FMC of the energy storage, which is calculated via the intra-day market clearing, and C_M is cost of the operation and maintenance for the battery energy storage.

(2) Constraint conditions

The constraint conditions include six categories, namely, operation state constraint (eq. (10)), declared price constraint (eq. (11)), energy storage charge state constraint (eq. (12), (13), (14)), upper and lower FMC constraints of energy storage declaration (eq. (15), (16), (17), (18)), upper and lower FMM constraints of energy storage declaration (eq. (19), (20)), and bidding constraint (eq. (21), (22), (23), (24), (25), (26)).

1) Operation state constraint:

$$u_{s,t}^{dis} u_{s,t}^{ch} = 0 \tag{10}$$

2) Declared price constraint:

$$0 \le b_{s,t,e}^{ch}, b_{s,t,e}^{dis}, b_{s,t,e}^{as,up}, b_{s,t,e}^{as,dn}, b_{s,t,e}^{as,m,up}, b_{s,t,e}^{as,m,dn} \tag{11}$$

where $b_{s,t,e}^{ch}$, $b_{s,t,e}^{dis}$, $b_{s,t,e}^{as,up}$, $b_{s,t,e}^{as,dn}$, $b_{s,t,e}^{as,m,up}$, and $b_{s,t,e}^{as,m,dn}$ reflect the charging and discharging quotes of s under scenario e at the time of t, as well as the up and down FMCs and mileage quotation.

3) Energy storage charge state constraint

$$Soc_{s,t} = Soc_{s,t-1} + \eta_s p_{s,t}^{ch} \Delta t - p_{s,t}^{dis} \Delta t \big/ \eta_s \tag{12}$$

$$Soc_{s,t} + r_{s,t,e}^{up} \eta_s \Delta t \le Soc_{s,\max} \tag{13}$$

$$Soc_{s,t} + r_{s,t,e}^{dn} \Delta t \big/ \eta_s \ge 0 \tag{14}$$

where $Soc_{s,t}$ is the state of charge for s at the time of t; $Soc_{s,\max}$ is the maximum state of charge for s; η_s is the charge and discharge efficiency of s; and Δt refers to a scheduling cycle. The value is 1 h.

4) Upper and lower FMC constraints of energy storage declaration

$$0 \le R_{s,t,e}^{up} \le R_{s,\max}^{up} \tag{15}$$

$$0 \le R_{s,t,e}^{dn} \le R_{s,\max}^{dn} \tag{16}$$

$$0 \le P_{s,t,e}^{dis} + R_{s,t,e}^{up} \le u_{s,t}^{dis} P_{s,\max}^{dis} \tag{17}$$

$$0 \le P_{s,t,e}^{ch} + R_{s,t,e}^{dn} \le u_{s,t}^{ch} P_{s,\max}^{ch} \tag{18}$$

The energy storage bidding model is used to determine capacity declarations in each market, where $P_{s,t,e}^{ch}$ and $P_{s,t,e}^{dis}$ are the energy supplement and release of energy storage; $R_{s,t,e}^{up}$ and $R_{s,t,e}^{dn}$ are its FMCs; $R_{s,\max}^{up}$ and $R_{s,\max}^{dn}$ represent the maximum up and down FMCs of s; and $P_{s,\max}^{ch}$ and $P_{s,\max}^{dis}$ represent the maximum power of charging and discharging for s.

5) Upper and lower FMM constraints of energy storage declaration

$$R_{s,t,e}^{up} \le M_{s,t,e}^{up} \le V_s R_{s,t,e}^{up} \tag{19}$$

$$R_{s,t,e}^{dn} \le M_{s,t,e}^{dn} \le V_s R_{s,t,e}^{dn} \tag{20}$$

The energy storage bidding model determines the mileage declaration for energy storages in the FM market, where the mileage $M_{s,t,e}^{up}$ and $M_{s,t,e}^{dn}$ can be calculated from the FMC, and the range is between the FMC, the product of the FMC, and the FMM multiplier V_s.

6) Bidding constraint

$$p_i(p_{si}) = k_{ei}(d_i p_{si} + z_i) \tag{21}$$

$$p_i(r_{rsi}) = k_{ri}(\alpha_i r_{rsi} + \beta_i) \tag{22}$$

$$p_i(m_{smi}) = k_{mi}(\xi_i m_{smi} + \sigma_i) \tag{23}$$

$$k_{ei\ \min} \le k_{ei} \le k_{ei\ \max} \tag{24}$$

$$k_{ri\ \min} \le k_{ri} \le k_{ri\ \max} \tag{25}$$

$$k_{\text{mimin}} \le k_{mi} \le k_{\text{mi max}} \tag{26}$$

In the formulae, p_{si} represents the charge or discharge quantity of the energy storage, where its price can be determined by d_i, z_i, and the price factor k_{ei}, and its expression is similar to the primary function; r_{rsi} represents the up–down FMC of energy storage s, where the price of which can be determined by α_i, β_i, and the price factor k_{ri}; and m_{smi} represents the up–down FMM of energy storage s, where the price of which can be determined by ξ_i, σ_i, and the price factor k_{mi}.

4. Day-ahead, intra-day, and CET market clearing model

The day-ahead joint market clearing model, that is, the day-ahead, intra-day, and CET market clearing model, calculates the carbon emission cost of the generator set according to the CET market. When the carbon emissions of the unit exceed the free quota allocated by the unit, it must be used to pay an additional carbon emission cost [33]. Therefore, the carbon quota of each power generation enterprise needs to first be determined. Before carbon credits can be allocated to each power generation company, their total carbon emissions must be calculated. The sum of greenhouse gases emitted by each power generation company when it does not participate in the CET market is taken as the reference value, and on this basis, the corresponding emission reduction coefficient is further considered, calculated as eq. (27):

$$Q = (1 - \alpha)E^b \tag{27}$$

where Q is the total amount of carbon emission quota that can be allocated to all conventional units in a day; E^b is the sum of greenhouse gases emitted by conventional units when they do not participate in the CET market; and α is the emission reduction factor.

At present, the carbon quota allocation of power generation enterprises is mainly based on historical data regarding carbon emissions and generation performance. Among them, the carbon quota allocation $E_{q,g}$ of the conventional unit g according to generation performance is as follows (eq. (28)):

$$E_{q,g} = G \sum_{t=1}^{96} p_{g,t} \tag{28}$$

where G is the quantity of greenhouse gases released by conventional units that produce 1 MW h electricity per unit time, which can be given as eq. (29):

$$G = \frac{Q}{\sum_{i=1}^{N_1} \sum_{t=1}^{96} p_{g,t}} \tag{29}$$

In eq. (29), $p_{g,t}$ is the output of unit g during t, and N1 indicates the total quantity of units.

Meanwhile, $E_{q,g}$ assigned to the conventional unit g based on historical carbon emission data is as follows (eq. (30)):

$$E_{q,g} = \frac{E_i^b}{E^b} Q \tag{30}$$

where E_i^b is the carbon emission of unit i when it does not participate in the CET market.

(1) Day-ahead market

It is mainly composed of two parts, namely, the day-ahead energy market and the day-ahead auxiliary service market [34]. The day-ahead market aims to minimize the cost of purchasing electricity to maximize social welfare, and its objective function is given as eq. (31):

$$\begin{aligned} \min \sum_{e=1}^{E} \varphi_e \Bigg\{ & \sum_{s=1}^{S} \left(b_{s,t,e}^{\text{dis}} p_{s,t,e}^{\text{dis}} - b_{s,t,e}^{\text{ch}} p_{s,t,e}^{\text{ch}} \right) + \sum_{g=1}^{G} b_{g,t,e} p_{g,t,e} + \\ & \sum_{s=1}^{S} \left[b_{s,t,e}^{\text{as}} \left(r_{s,t,e}^{\text{up}} + r_{s,t,e}^{\text{dn}} \right) + b_{s,t,e}^{\text{ss,m}} \left(m_{s,t,e}^{\text{up}} + m_{s,t,e}^{\text{dn}} \right) \right] + \\ & \sum_{g=1}^{G} b_{g,t,e}^{\text{as}} \left(r_{g,t,e}^{\text{up}} + r_{g,t,e}^{\text{dn}} \right) + \sum_{g=1}^{G} b_{g,t,e}^{\text{s,m}} \left(m_{g,t,e}^{\text{up}} + m_{g,t,e}^{\text{dn}} \right) \Bigg\} \end{aligned} \tag{31}$$

In the formula, G is the total quantity of conventional units, and the thermoelectricity devices submit the quotations of each market to the trading center, which are, respectively, energy quotation $b_{g,t,e}$, FMC quotation $b_{g,t,e}^{\text{as}}$, and FMM quotation. The optimal prices of each market are determined via the energy storage bidding model, and include energy price $b_{s,t,e}$, FMC price $b_{s,t,e}^{\text{as}}$, and FMM price $b_{s,t,e}^{\text{ss,m}}$, respectively. According to the day-ahead market clearing model, the output of thermoelectricity devices in each market can be determined, where $p_{g,t,e}$ is the energy output, $r_{g,t,e}^{\text{up}}$ and $r_{g,t,e}^{\text{dn}}$ are the FMC outputs, and $m_{g,t,e}^{\text{up}}$ and $m_{g,t,e}^{\text{up}}$ are the FMM outputs.

The following constraints need to be taken into account when the day-ahead market is in operation:

1) Energy market power balance constraint

$$\sum_{s=1}^{S} \left(p_{s,t,e}^{\text{dis}} - p_{s,t,e}^{\text{ch}} \right) + \sum_{g=1}^{G} p_{g,t,e} + p_{\text{w},t} - p_{\text{L},t} = 0 \tag{32}$$

In eq. (32), $p_{\text{w},t}$ and $p_{\text{L},t}$ represent the system's wind power output value and the load value at the time t respectively.

2) Conventional unit power constraint

$$r_{g,t,e}^{\text{dn}} + P_{g\ \text{min}} \le p_{g,t,e} \le P_{g\ \text{max}} - r_{g,t,e}^{\text{up}} \tag{33}$$

In eq. (33), $p_{g,t,e}$ denotes the output value of g at the time of t, and $P_{g\ \text{min}}$ and $P_{g\ \text{max}}$ denotes the minimum and maximum power outputs of g.

3) Power flow safety constraint

$$p_{l,\text{min}} \le p_{l,t} \le p_{l,\text{max}} \tag{34}$$

In eq. (34), $p_{l,t}$ is the power flow of line l at the time of t, and $p_{l,\text{min}}$ and $p_{l,\text{max}}$ are the minimum and maximum transmission capacities of the line.

4)System FMC balance constraints

$$R_{sys,t}^{up} - \sum_{s=1}^{S} r_{s,t,e}^{up} - \sum_{g=1}^{G} r_{g,t,e}^{up} = 0 \tag{35}$$

$$R_{sys,t}^{dn} - \sum_{s=1}^{S} r_{s,t,e}^{dn} - \sum_{g=1}^{G} r_{g,t,e}^{dn} = 0 \tag{36}$$

Where $R_{sys,t}^{up}$ and $R_{sys,t}^{dn}$ are given to show the up and down FMC requirements at the time of t (eq. (35), (36)).

5) System FMM balance constraints

$$M_{sys,t}^{up} - \sum_{s=1}^{S} m_{s,t,e}^{up} - \sum_{g=1}^{G} m_{g,t,e}^{up} = 0 \tag{37}$$

$$M_{sys,t}^{dn} - \sum_{s=1}^{S} m_{s,t,e}^{dn} - \sum_{g=1}^{G} m_{g,t,e}^{dn} = 0 \tag{38}$$

where $M_{sys,t}^{up}$ and $M_{sys,t}^{dn}$ are the up and down FMM requirements at the time of t (eq. (38)).

6)Constraints on the amount of winning bids

$$0 \le p_{g,t,e}^{up} \tag{39}$$

$$0 \le p_{g,t,e}^{dn} \tag{40}$$

$$0 \le p_{g,t,e} + p_{g,t,e}^{up} \le P_g \tag{41}$$

$$0 \le p_{g,t,e} - p_{g,t,e}^{dn} \tag{42}$$

$$0 \le p_{s,t,e}^{ch} + p_{s,t,e}^{dn} \le P_{s,t}^{ch} \tag{43}$$

$$0 \le p_{s,t,e}^{dis} + p_{s,t,e}^{up} \le P_{s,t}^{dis} \tag{44}$$

$$0 \le p_{s,t,e}^{up} \le P_{s,t}^{up} \tag{45}$$

$$0 \le p_{s,t,e}^{dn} \le P_{s,t}^{dn} \tag{46}$$

Constraints on the amount of winning bids is jointly represented by the above inequality (eq. (39), (40), (41), (42), (43), (44), (45), (46)).

In addition, conventional units are also subject to other restrictions such as climbing restrictions, FMC declaration restrictions, and FMM restrictions. Since the declaration constraints of FMC and FMM are the same as those of energy, there is no need to go into detail about them.

(2) Intra-day balance market

In the intra-day balance market, the output change in wind power generation is taken as the trigger factor, the difference between the predicted output of wind power generation and the actual value is used as the system net load deviation, and the existing auxiliary service market indicators such as FMC and FMM are used to adjust the system net load deviation [35], so as to establish a balanced power network.

The purpose of the revenue generated by FMM is to incentivize resources with different degrees of FM performance to participate in the FM market, and the settlement of FMM revenue is carried out ahead of the day [36]; therefore, there is no need to make repeated payments in the intra-day market. For the purpose of solving above problems, an intra-day balanced market algorithm based on day-ahead scheduling is proposed by constructing an objective function designed to minimize costs of the social imbalance caused by net load deviations in the intra-day balance market (eq. (47)):

$$\begin{aligned} \min \sum_{e=1}^{E} \varphi_e \sum_{q=1}^{Q} \varphi_q \Bigg\{ \delta_t \Bigg[\sum_{s=1}^{S} u_{s,t,e}^{\mathrm{dis}} \left(r_{s,t,q,e}^{\mathrm{dn,rt}} - r_{s,t,q,e}^{\mathrm{up,rt}} \right) + \\ \sum_{s=1}^{S} u_{s,t,e}^{\mathrm{ch}} \left(r_{s,t,q,e}^{\mathrm{up,rt}} - r_{s,t,q,e}^{\mathrm{dn,rt}} \right) + \sum_{s=1}^{S} \left(1 - u_{s,t,e}^{\mathrm{dis}} - u_{s,t,e}^{\mathrm{ch}} \right) \left(r_{s,t,q,e}^{\mathrm{dn,rt}} + r_{s,t,q,e}^{\mathrm{up,rt}} \right) \\ + \frac{p_{g,t,e} - p_{g,t-1,e}}{\left| p_{g,t,e} - p_{g,t-1,e} \right|} \sum_{g=1}^{G} \left(r_{g,t,q,e}^{\mathrm{up,rt}} - r_{g,t,q,e}^{\mathrm{dn,rt}} \right) \Bigg] + \varphi b_t \left(d_{t,q}^{\mathrm{w}} + d_{t,q}^{\mathrm{load}} \right) \Bigg\} \end{aligned} \tag{47}$$

In the intra-day market, it is essential to not only consider the scenario e where the bidder's bid is uncertain, but also the scenario q where the net load deviation is uncertain. According to the abandoned air volume and reduced load at the time of t under these two scenarios, the FMC $r^{\mathrm{up,rt}}_{s,t,q,e}$ and $r^{\mathrm{dn,rt}}_{s,t,q,e}$ of energy storage and thermoelectricity devices are invoked to balance markets. The intra-day market needs to calculate the unbalanced cost through the real-time electricity price $r^{\mathrm{dn,rt}}_{s,t,q,e}$ and the abandoned wind price b_t. In order to ensure that FM resources can preferentially participate in balancing intraday deviations, the value can be increased.

During the operation of the intra-day market, the following constraints must also be considered.

(1) Deviation balance constraint

$$\sum_{s=1}^{S} r^{up,rt}_{s,t,q,e} + \sum_{g=1}^{G} r^{up,rt}_{g,t,q,e} + d_{Lj,t} = L^{up}_{t,q} \tag{48}$$

$$\sum_{s=1}^{S} r^{dn,rt}_{s,t,q,e} + \sum_{g=1}^{G} r^{dn,rt}_{g,t,q,e} + p^{loss}_{wi,t} = L^{dn}_{t,q} \tag{49}$$

In eq. (48) and eq. (49), $L^{up}_{t,q}$ and $L^{dn}_{t,q}$ represent the net load deviation value under scenario q at the time of t.

(2) Abandoned wind constraint

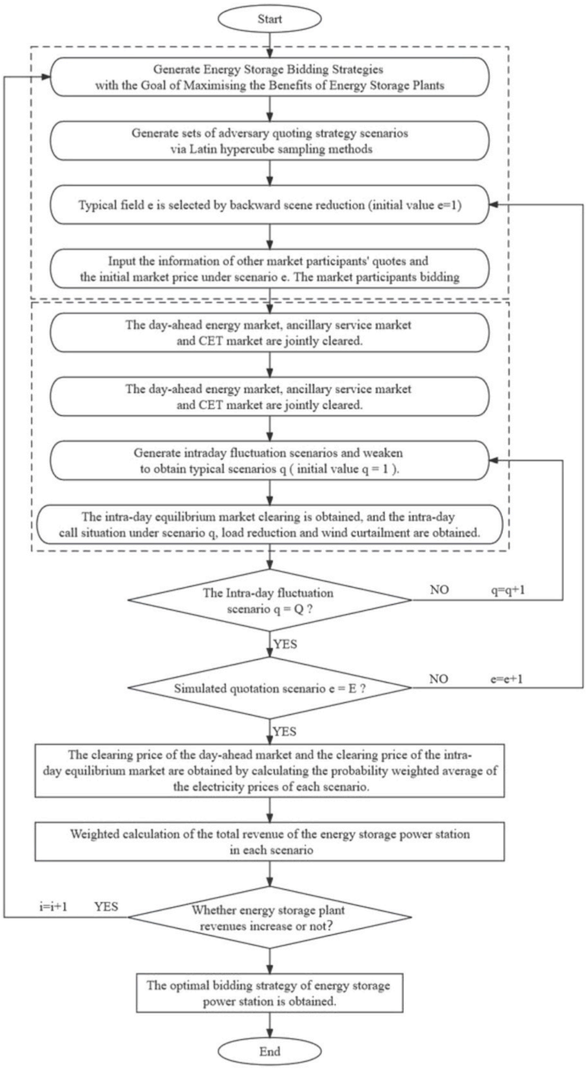

Fig. 5. Solution flow chart.

$$p_{wi,t}^{loss} = P_{wi,t}^{0} - p_{wi,t} \quad (50)$$

$$0 \leq p_{wi,t}^{loss} \leq P_{wi,t}^{0} \quad (51)$$

In eq. (50) and eq. (51), $P_{wi,t}^{0}$ denotes the predicted output of the wind farm at the time of t.

3) Load reduction constraints

$$d_{Lj,t} = P_{Lj,t}^{0} - p_{Lj,t} \quad (52)$$

$$0 \leq d_{Lj,t} \leq P_{Lj,t}^{0} \quad (53)$$

In eq. (52) and eq. (53), $P_{Lj,t}^{0}$ denotes the predicted load size at the time of t.

In addition, in the intra-day market constraints, there are also FMC auction constraints and FMM auction constraints of traditional thermal power and energy storage, and these two constraints must be within the range of the bid.

(3) CET market

The CET market aims to minimize the cost of carbon emissions that each conventional unit needs to pay, i.e. (eq. (54)):

$$\min \sum_{i=1}^{G} \left(\sum_{t=1}^{96} E_{g,t} - \eta E_{q,g} \right) p_{re} \quad (54)$$

where $E_{g,t}$ is the carbon emissions of the conventional unit g during the period t, as follows (eq. (55)):

$$E_{g,t} = \beta_g p_{g,t} \quad (55)$$

Its constraint conditions are the same as the current market power balance constraint, conventional unit power constraint, and power flow safety constraint, which will not be detailed here.

5. Case analysis

In the constructed day-ahead electricity market master–slave game bidding model, the upper energy storage bidding model takes the energy storage bidding strategy as the decision variable. The energy storage bidding strategy is introduced into the day-ahead, intra-day, and CET market clearing model as a known quantity to determine the clearing situation and clearing price of each market. The clearing price obtained from the lower model and the scalar in each energy storage market are introduced into the upper model to calculate the energy storage income. The KKT optimization condition is used to convert the lower model into the higher model's constraint condition. In this way, the two-layer model can be converted into a single-layer model, and the problem can be simplified to solve the mathematical programming problem (MPEC) with equilibrium constraints. Through the use of the duality principle, the nonlinear expression is simplified. Therefore, the model is transformed into an equivalent MILP problem. The CPLEX in the MATLAB is used to solve the problem, and the flow chart is shown in Fig. 5.

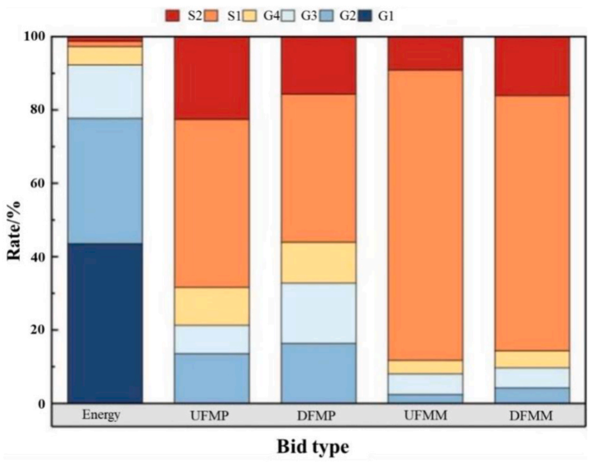

Fig. 6. The overall winning bid situation of the day-ahead joint market.

5.1. Input data and scenario setting

This section is based on the improved IEEE 30-bus system. The circuit diagram of the IEEE 30 standard test system is shown in Fig. A1. The system includes two energy storage power stations and six conventional units. The conventional unit parameter settings are shown in Table A1, the energy storage power station parameter settings are shown in Table A2, the system FMM multiplier is shown in Table A3, and the conventional unit FM market quotation is shown in Table A4. Fig. A2 shows the prediction curve of the daily load and wind power output of the system, while the System FM demand capacity is shown in Fig. A3. The wind power generation system provides electricity to the market at the price of 0.15 CNY/kW•h. Without taking into account the self-discharge of the energy storage, the operating cost is 0.03882 CNY/kW•h.

5.2. Results and discussion

(1) The overall bid-winning situation and the market main body income of the day-ahead joint market

The overall bidding results of the power system are compared in the two markets of energy and frequency regulation. The profits of each market are compared. The results are shown in Fig. 6 and Table 1.

As shown in Fig. 6, the output of conventional units in the energy market accounts for about 97 % of the total output, while the share of the energy storage output is small. In the energy market, the universality and typicality of conventional unit power supply are fully reflected. In the FM market, the proportion of conventional units has declined, while the proportion of energy storage in the market has significantly increased. Specifically in the frequency regulation capacity market, the output of energy storage accounts for about 62 %, and the output in the frequency regulation mileage market accounts for about 87 %. Since the ESS has the advantages of fast response, high precision, and flexible charging and discharging, it has become a high-performance FM resource. It requires conventional units and energy storage to jointly undertake FM tasks.

In Table 1, the total income of S1 from the day-ahead joint market is CNY 74591.07, whereby the energy market income accounts for 10.27 %, and the FM market income accounts for 89.73 %. The total income of S2 from the day-ahead joint market is CNY 29571.68, whereby the energy market income accounts for 11.75 % and the FM market income accounts for 88.25 %. Evidently, the income of energy storage from the FM market is much greater than that in the energy market. Therefore, energy storage participation in the FM service could bring more significant economic benefits.

(2) Day-ahead joint bidding in various markets

Fig. 7, Fig. 8, and Fig. 9 show the winning bids of each unit in the electricity market and the FM market, respectively.

As can be seen from Fig. 7, the conventional units bear most of the electricity demand, and the units G1 and G2 generate electricity at all times, and are almost full during the peak hours of electricity consumption. This is because G1 and G2 have a low price and give priority to power generation, followed by G3 with a low price to make up the power, and G4 only generates electricity in the peak period of electricity consumption to meet the load demand. Energy storage's engagement in energy markets is not high, and charging in the low-load period does not only bring about new energy generation but also makes up for the energy loss in the charge and discharge process. If the discharge is carried out in the period of a high-load trough, the profit can be calculated from markets.

Figs. 8 and 9 show winning bids of the FMC market and FMM market. From figures, energy storage is the main task of FM, and in the FMM market, energy storage makes up a larger percentage. Since the FMM multiple of energy storage devices is higher than that of traditional devices, under the same FMC, energy storage can provide more FMM, so that it is preferentially utilized in the FM market.

(3) Energy storage power station bidding strategy

Fig. 10 shows the optimal bidding strategy of the energy storage power station in the energy and FM market, and Fig. 11 shows the bidding situation of the energy storage in the energy and FM market.

As can be seen from Fig. 10, there are distinctions in the bidding strategies in different markets. Moreover, the bidding strategies in different states of the same market are also different. Energy storage S1 and S2 offer the same price in the FM market, but the price in the energy market is different, and it depends on the energy storage integrated with the operating characteristics; other market players

Table 1
Income of each market.

Market Player	Energy Gain/CNY	FMC Income/CNY	FMM Income/CNY	Carbon Emission Cost/CNY	Total/CNY
G1	648098.9564	0	0	17285.6670	630813.2893
G2	491069.8345	17850.73	655.6022	13561.8177	496014.349
G3	206351.0786	16003.7815	1293.1858	5779.8692	217868.1768
G4	86135.4445	14631.2397	877.01383	1988.3446	99655.3534
G5	0	0	0	0	0
G6	0	0	0	0	0
S1	7658.9397	53364.8955	13567.2353	0	74591.0706
S2	3474.8065	23701.2121	2395.6619	0	29571.6805

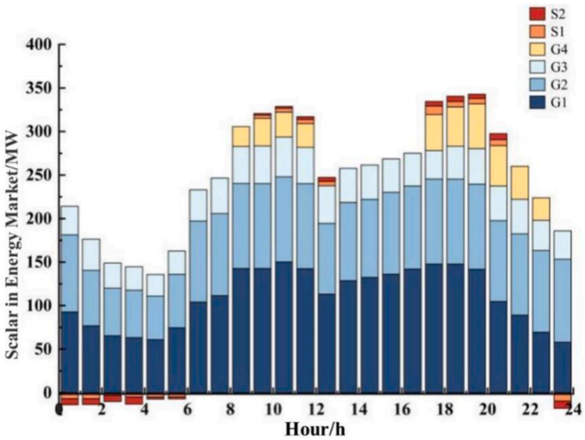

Fig. 7. Energy market bidding situation.

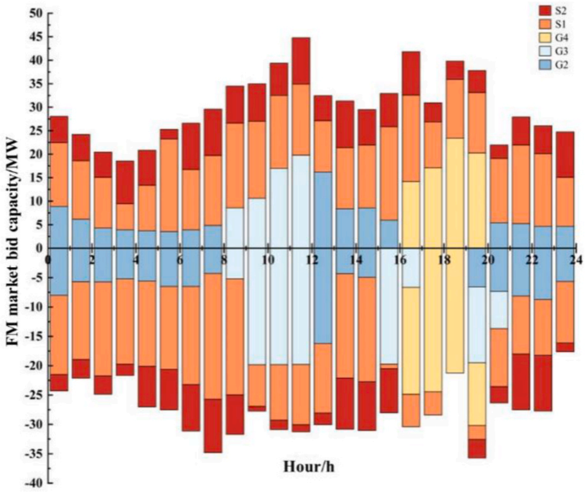

Fig. 8. The winning bid of FMC.

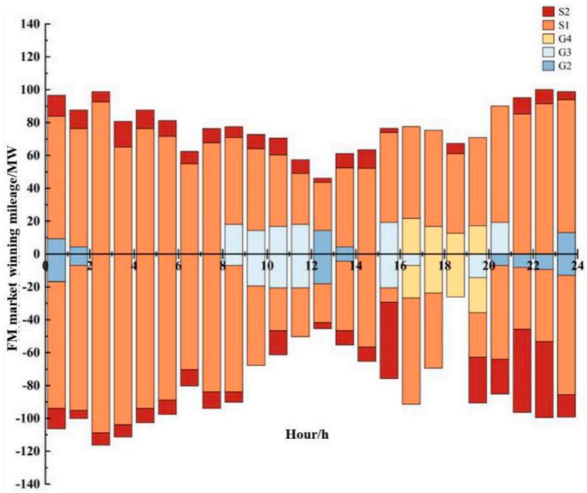

Fig. 9. The winning bid of FMM.

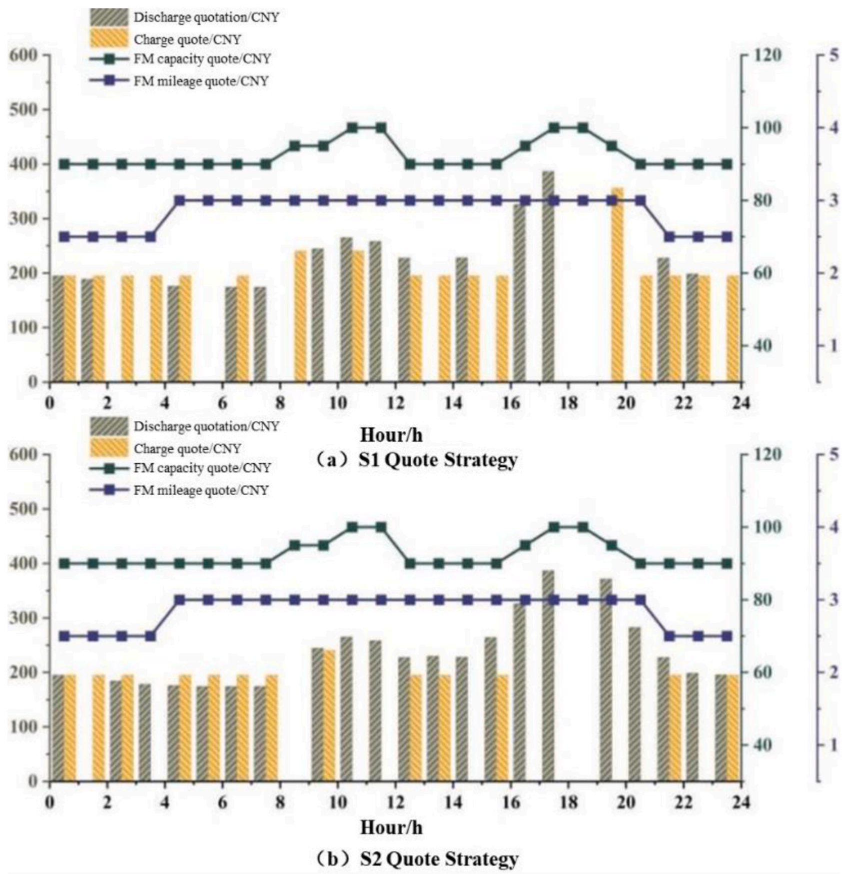

Fig. 10. Optimal bidding strategy for energy storage power station.

also offer strategic prices to maximize benefits. Although the bidding strategies of S1 and S2 are the same in the FM market, it can be known from the bidding situation for energy storage in the electricity and FM market in Fig. 11 that the bidding results of the two ESSs are different in FM markets. S1 undertakes more FM tasks than S2 and plays a more obvious role, which is because the FM performance and parameter settings of the energy storage devices are different. Furthermore, the installation locations in the system are different. Therefore, it should be the focus of future research to select the energy storage equipment with the most appropriate parameters and rationally arrange the installation position of ESS to obtain the best FM effect.

(4) The day-ahead joint market clearing price

As can be seen from Fig. 12 of the clearing price in the energy market, the clearing price in the energy market has an identical trend as the load. It also shows a change in trend from low at night to high in the day. The market clearing price of energy can map the market supply and demand relationship, because the quotation of conventional units refers to its power generation cost, and the power generation cost is positively correlated with the output power; therefore, the trend of electricity price is basically proportional to the trend of electricity load. When the system is in the peak hours of electricity consumption, such as at 18:00 and 19:00, the conventional unit will declare a higher market price, resulting in a more extreme peak in the energy market clearing price at 18:00 and 19:00.

As can be seen from Fig. 13 of the clearing price in the FM market, the clearing price of the FMC shows a similar trend to the demand capacity in the FM market. The settlement price of FMM is different from the quotation of each unit at 15:00, and at time t, the conventional FMM of individual scenes fails to win the bid, and the energy storage undertakes all of the FM tasks, as well as the comprehensive electricity price obtained after calculations under various scenarios.

(5) Analysis of the influence of CET market on clearing results

Fig. 14 shows a comparison of the clearing prices when the CET market is considered in the ESS and when it is not.

The clearing price is compared when the CET market is considered in the system and when it is not. As can be seen from Fig. 14, the clearing price remains roughly the same before and after the CET market runs, but it shows a significant increase over the whole period compared with the clearing price when the CET market is not considered. In addition, the increase is more significant in the peak hours

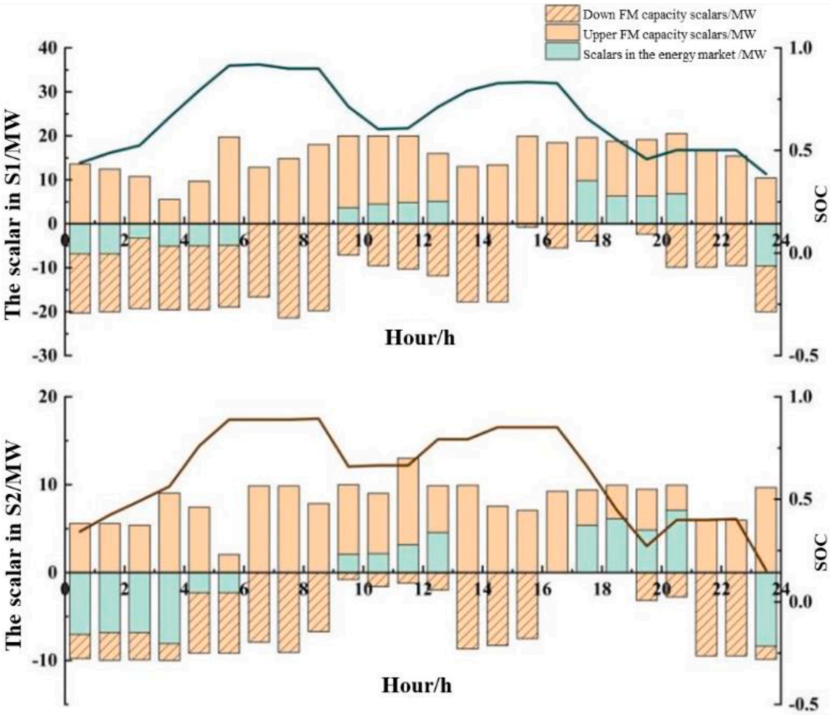

Fig. 11. Bid-winning situation of energy storage power station joint market.

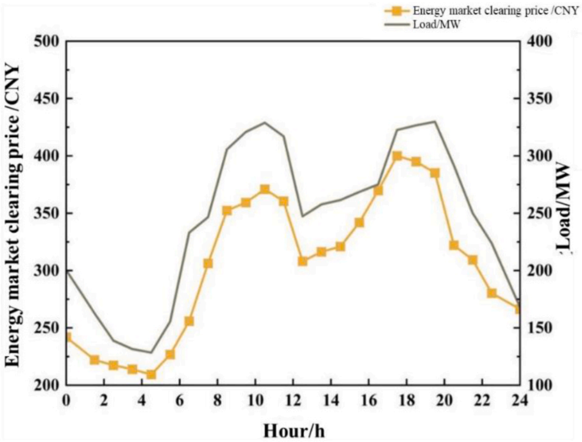

Fig. 12. Energy market clearing price.

of electricity consumption, with the highest being 22.04%. This is because after taking into account the carbon emission cost, the power generation cost of conventional units increases; thus, the quotation also increases accordingly, resulting in an increase in the clearing price.

To further measure the impact of the CET market on the clearing results, the following three scenarios are constructed:

Scenario 1: does not consider the CET market.

Scenario 2: considers the CET market and allocates carbon allowances according to historical carbon emission data.

Scenario 3: considers the CET market and allocates a carbon quota according to the power generation performance.

A comparison of the outputs of the conventional unit G1 under three scenarios is shown in Fig. 15.

Fig. 15 compares the outputs of conventional thermal power unit G1 under different carbon quota allocation schemes. In Fig. 15, the high carbon emission intensity coefficient of thermal power units. In order to reduce costs of carbon emission when the CET market is considered, the output of the conventional thermal power unit G1 in the load off-peak period will be greatly reduced compared with a situation that does not take the CET market into account. In Scenario 3, the carbon quota allocation based on the power generation

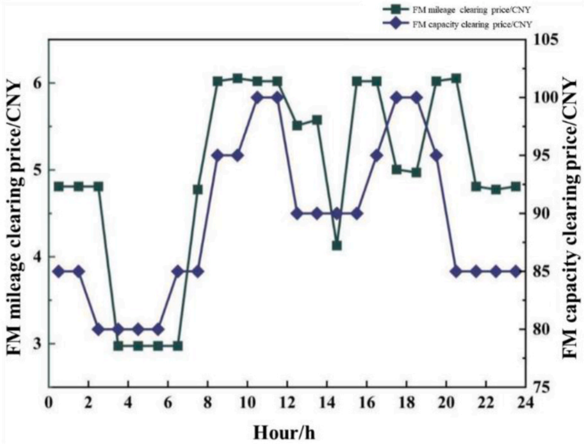

Fig. 13. FM market clearing price.

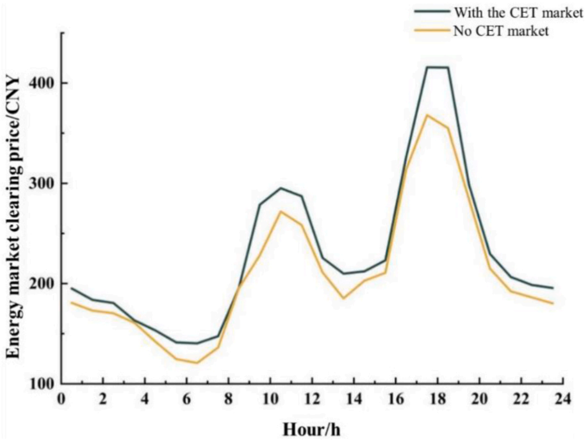

Fig. 14. Comparison of energy market clearing prices.

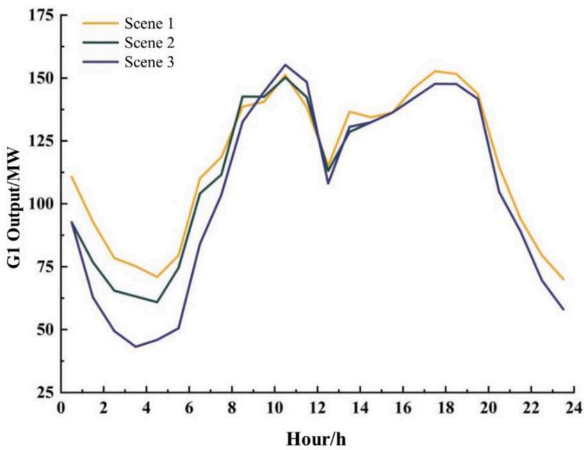

Fig. 15. Comparison of G1 outputs of conventional unit.

performance is lower than that in Scenario 2 due to the low power generation performance of G1 in the load off-peak period; furthermore, the carbon quota allocation is reduced, and its output is further reduced by up to 32.2% compared with Scenario 2.

Fig. 16 compares the outputs of energy storage station S1 under different carbon quota allocation schemes. In the figure, the running space in Scenario 2 and Scenario 3 is compressed compared with that in Scenario 1, and the phenomenon in Scenario 3 is more obvious than that in Scenario 2. As can be seen from Fig. 15, after taking the CET market into consideration, the output of conventional thermal power units is affected: it decreases in the low-load period and increases in the peak load period. Therefore, the net load difference in the system is reduced, which further affects the output. In summary, considering the operation of the CET market, the life of energy storage can be extended and the output variation in energy storage can be reduced.

A comparison of day-ahead energy market clearing prices under the three scenarios is shown in Fig. 17.

Fig. 17 compares the outputs of the day-ahead energy market clearing price under different carbon quota allocation schemes. In the figure, the clearing price trend of the energy market under the three scenarios is still roughly the same. The clearing prices of Scenario 2 and Scenario 3 show a significant increase over the whole time period compared with that of Scenario 1, and the clearing price of Scenario 3 shows a larger increase than that of Scenario 2, which is more obvious in the peak load period, with a maximum increase of 16.75%. When assigning carbon quotas based on generation performance, the carbon emission cost of conventional thermal power units is higher than that of historical data regarding carbon emission units, as they cannot obtain sufficient quotas. As a result, the quotation of all conventional thermal power units is higher.

6. Conclusion

1) In the energy market, energy storage can realize its own economic value by "transferring" energy, and can effectively improve the operation economy of the unit. Because the ESS has a fast response speed and high accuracy, it can be flexibly charged and discharged; therefore, it will be preferentially called upon by the FM market and obtain considerable FM benefits.
2) The game bidding model of the energy storage participating in the day-ahead joint market proposed in this paper fully considers the bidding information of all parties, historical information, and all of the advantages, and realizes the strategic bidding of energy storage power stations in the day-ahead joint market to maximize benefits. Due to the different parameter settings and FM performances of energy storage equipment, as well as the different installation positions in the system, the quoting strategies of energy storage in different markets are different, and therefore the bidding situations in the market are also different.
3) If we consider that the CET market will increase the clearing price of the day-ahead energy market, when carbon quotas are allocated according to generation performance, the output of thermal power units will be greatly reduced, and the day-ahead market clearing price of energy will increase.

This paper has constructed a day-ahead joint market bidding model for energy storage participation based on game theory. Because the FM performance of an energy storage power station is related to the parameter setting of the ESS, under the same adjustment goal and adjustment strategy, different parameter settings will have different FM performances and adjustment effects related to the energy storage power station. Considering that the CET market increases the clearing price of the day-ahead energy market, when the carbon quota is allocated according to the generation performance, the output of the thermal power units will be greatly reduced, and the clearing price will be further increased. However, more work is required to study this further. In future research, we will add sensitivity analysis to trading strategies and game models to further study energy storage in markets.

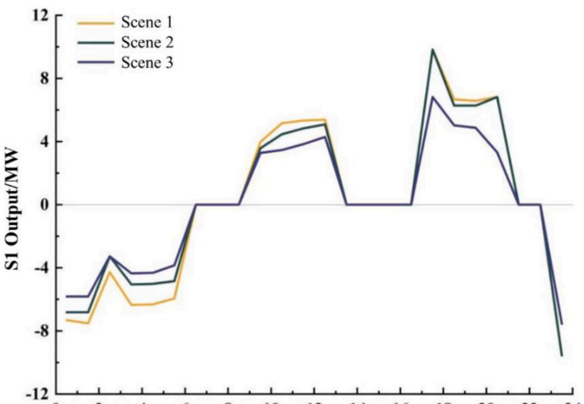

Fig. 16. Comparison of S1 outputs of energy storage.

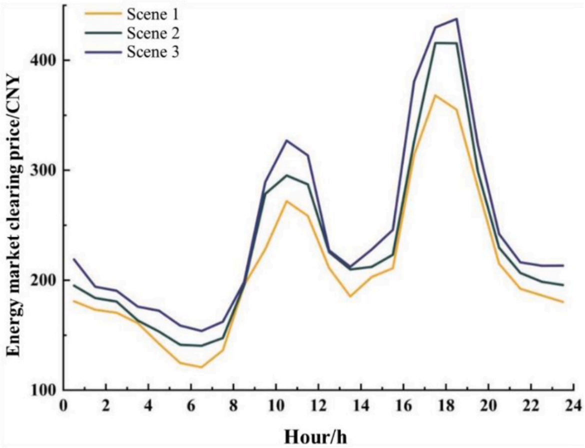

Fig. 17. Comparison of energy market clearing prices.

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Data availability statement

All data used in this research has been included in the paper.

CRediT authorship contribution statement

Bowen Zhou: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Ziyu Zhao:** Writing – original draft, Software, Methodology, Conceptualization. **Yichen Jiang:** Writing – review & editing, Validation, Software. **Guangdi Li:** Validation, Formal analysis. **Peng Gu:** Formal analysis. **Liaoyi Ning:** Supervision. **Zhenyu Wang:** Visualization, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Input data and scenario setting

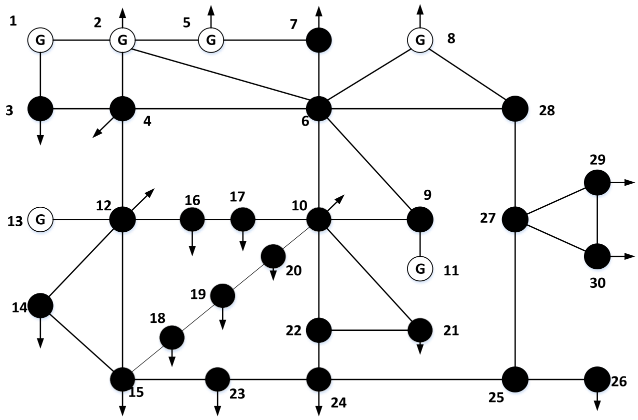

Fig. A1. IEEE 30 standard test system circuit diagram.

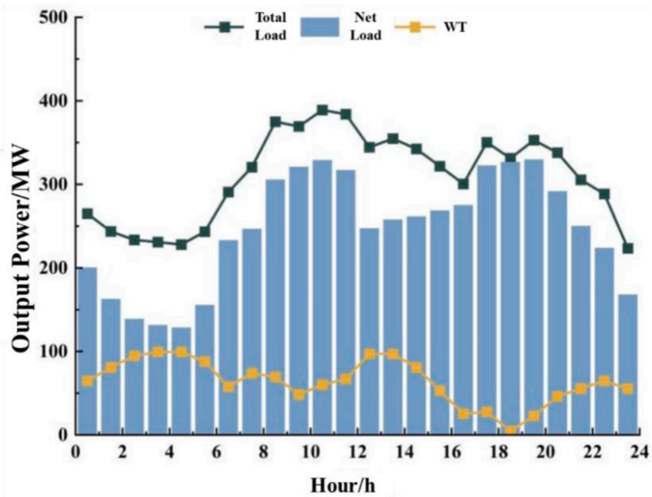

Fig. A2. Daily load and wind power output prediction curves.

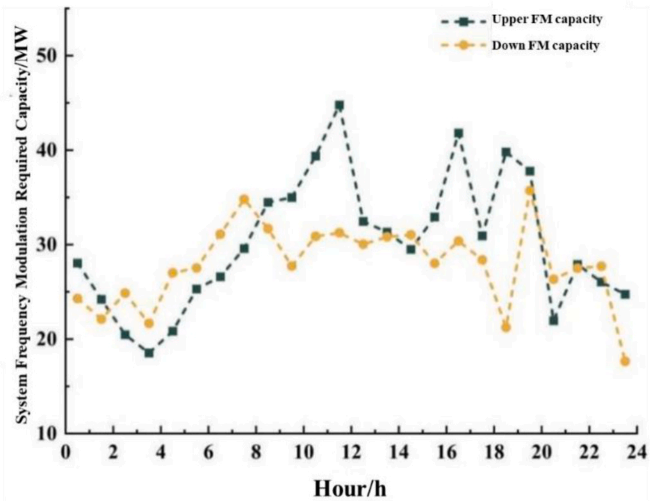

Fig. A3. System FM demand capacity.

Table A1
Conventional unit parameter settings.

Type	Unit	$P_{g\ max}$ /MW	$P_{g\ min}$ /MW	a/(CNY/ MW^2)	b/(CNY/MW)	c/CNY	$R_{g\ max}$/MW	V_g	Access Position
Base Load Units	G1	157	45	0.09	151.64	2433.99	25	6	1
	G2	100	35	0.11	147.53	2628.17	40	6	2
	G3	60	15	0.19	104.98	1949.99	20	6	5
Peaking Units	G4	80	20	0.16	134.80	2849.56	25	6	8
	G5	40	10	0.53	150.80	2292.85	10	6	11
	G6	40	10	0.76	142.70	2192.70	10	6	13

Note: a, b, and c are the cost characteristic parameters of the thermal power units; $R_{g\ max}$ is the maximum FMC of the thermal power units; and V_g is the thermal power unit FMM multiplier.

Table A2
Energy storage parameter settings.

Unit	Maximum Capacity /(MW•h)	$P^{ch}_{s,max}$ /MW	$P^{dis}_{s,max}$ /MW	η_{ESS}/%	$R_{s\ max}$ /MW	V_s	Access Position
S1	60	20	20	0.9	20	12	18
S2	40	10	10	0.9	10	10	24

Table A3
System FMM multiplier.

t/h	V_{sys}	t/h	V_{sys}	t/h	V_{sys}
1 : 00	3.87	9 : 00	2.53	17 : 00	2.34
2 : 00	4.05	10 : 00	2.24	18 : 00	2.43
3 : 00	4.74	11 : 00	1.87	19 : 00	1.52
4 : 00	4.77	12 : 00	1.41	20 : 00	2.19
5 : 00	3.97	13 : 00	1.46	21 : 00	3.63
6 : 00	3.38	14 : 00	1.87	22 : 00	3.45
7 : 00	2.47	15 : 00	2.12	23 : 00	3.71
8 : 00	2.64	16 : 00	2.49	24 : 00	3.67

Note: V_{sys} denotes the system FMM multiplier.

Table A4
Conventional unit frequency regulation market quotation.

Unit	G1	G2	G3	G4	G5	G6	S1	S2
FMC quotation/(CNY/MW)	110	100	80	70	65	60	95	95
FMM quotation /(CNY/MW)	4.5	5.8	6	5	4.5	4.3	3	3

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