Auxiliary Service Dynamic Compensation Mechanism Design for Incentivizing Market Participants to Provide Flexibility in China

Yibo Wang, Yifan Wang, Chuang Liu, Yuan Fang, Guowei Cai, and Weichun Ge

***Abstract*— Because of the rapid growth of new energy and the accompanying considerable uncertainty in the power market, the demand for flexibility in a power system has risen sharply. In the meantime, the market structure of auxiliary services has changed, resulting in market participants (MPs) benefiting less than expected from providing flexible services. To encourage MPs to provide flexibility, this study proposes a dynamic design framework for an auxiliary service compensation mechanism. To evaluate the proposed framework, a case study is conducted, examining a peak-shaving service in Liaoning province in northeast China. First, the operational status and limitations of the typical product, the peak-shaving service, in China's flexibility auxiliary services market are analyzed. Then, taking into consideration the time value of the flexible products provided by the MPs, a dynamic mechanism for hierarchical compensation of flexibility auxiliary service costs is proposed, and a mathematical model aimed at optimizing the MPs' comprehensive income is constructed. The results show that, compared with the existing traditional mechanism, the proposed method can effectively guarantee fair remuneration for the flexibility provider, while easing the tense supply-demand relationship in the flexibility market.**

***Index Terms*—Power system flexibility, auxiliary services market, peak shaving auxiliary service, differentiated operation scenario, dynamic hierarchical compensation mechanism.**

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I. INTRODUCTION

A. Motivation

The world is undergoing comprehensive energy reform to deal with a series of social and environmental challenges, such as environmental pollution and the greenhouse effect caused by the increase in fossil energy consumption. As the core of energy transformation, a sustainable low-carbon energy system based on new energy has become an important strategic choice for global energy development. In recent years, the installed capacity and power generation of new energy have increased rapidly [1], [2]. According to the International Renewable Energy Agency (IRENA), at the end of 2021, the total installed capacity of global renewable energy reached 3064 GW, including 849 GW of photovoltaic and 825 GW of wind power, accounting for 28% and 27% of global renewable energy, respectively. Statistical data released by the National Energy Administration of China in early 2022 indicate that the total installed capacity of wind power, photovoltaic, and hydropower in China ranked first in the world. The installed capacity of renewable energy has reached 1063 GW, accounting for 44.8% of the total capacity of power generation, and has gradually replaced traditional petrochemical energy [3].

The rapid development of new energy has alleviated the problems of energy shortage, environmental pollution, and climate change to a certain extent. However, a high proportion of new energy connected to the power system will impact its operation and planning [4]. To reduce the impact of the uncertainty and fluctuation of new energy on the security and economy of the power grid, sufficient response and regulation capacity of the power system, i.e., sufficient flexibility, is needed. At present, research on incentivizing flexibility in the power system primarily focuses on two aspects: 1) mining the flexibility resources from multiple angles to enable regulation of the power grid [5]–[8]; and 2) properly incentivizing and compensating flexible resources by improving the market mechanism continuously [9], [10].

B. Literature Review

Much research has been carried out on the flexibility of energy systems with high proportions of new energy and corresponding auxiliary service products and mechanisms have been put forward. Among the existing flexible products, a notable representative is the flexible ramping product (FRP), which is an auxiliary service transaction product proposed by the California independent system operator (CAISO) and the midcontinent independent system operator (MISO) in the United States. The central power grid of the United States is used to study the application of FRP from the aspects of system operation efficiency, reliability, and economy [11]. An analysis of using flexible products to improve the flexibility of the system is presented in [12], and it is reported that designing effective flexible products or incentive mechanisms can encourage market members to provide flexibility.

Whether establishing a flexible market or introducing flexible products, a robust market system is essential. However, there are great differences among the power market maturities in different countries. In China, the market is imperfect and is still in the reform stage, so it is difficult to establish a flexible market or introduce flexible products in the short term. Thus, the problems faced by China are different from those faced by the mature power markets in Europe and the United States. Therefore, it is necessary to establish a power market mechanism to improve system flexibility while taking into account China's national conditions. China's coal-based energy structure means that coal-fired power plants are the main source of power, and coal-fired generating units will need to undertake more flexible regulation tasks in the foreseeable future [13], [14]. References [15]–[17] show that the flexibility of China's power system at this stage mainly depends on coal-fired generating units, but the flexibility potential of those units has not been fully tapped. On the other hand, an effective market mechanism helps to encourage flexible resources to provide flexibility services [18], coordinate the interests of renewable energy and thermal power generation through price signals, and improve the utilization rate of renewable energy. In [19], the power generation right transaction (PGRT) between hydropower and thermal power in Sichuan province, the PGRT between wind power and thermal power in northeast China, the northeast peak shaving auxiliary service transaction, and the PGRT between renewable energy units and self-provided generating units in northwest Gansu province, are used as examples to help explore how to handle the consumption problem of renewable energy through market means.

Most of the aforementioned literature focuses on improving the new energy consumption capacity through the flexible transformation of thermal power units or the increase of flexible regulation resources. However, the issue of providing effective compensation for the flexibility value offered by market participants is often overlooked, making it challenging to incentivize the provision of flexibility. Based on the actual market construction situation in China, introducing a new flexibility auxiliary service compensation mechanism into the existing market system framework to achieve fair and reasonable income distribution will effectively incentivize market participants (MPs) to provide flexibility. An effective mechanism will promote reasonable competition and value discovery of various resources, and help to meet the needs of system flexibility and promote the construction of China's power market.

C. Contribution

To overcome the inability to fully utilize flexible resources in the power market, we aim to solve the following problems in this study:

1) How to coordinate the relationship between new energy and traditional flexible regulation power sources to make them complement each other, i.e., how to determine an effective development model between flexibility service providers and acquirers to promote reasonable competition and value discovery of various resources.

2) How to accurately identify the value of flexibility services provided by participants in the continuously evolving power system.

3) How to establish a compensation mechanism suitable for different scenarios and diverse needs to provide sufficient incentive signals for the long-term improvement of flexibility.

In this study, a dynamic design framework is proposed for the auxiliary service compensation mechanism. Based on the analysis of the current flexible auxiliary service compensation mechanism in China, a specific dynamic hierarchical compensation mechanism is then proposed, and its functions and effects are analyzed through examples. The main contributions of this paper are:

1) A dynamic view is put forward of the design of the auxiliary service compensation mechanism. In the context of the current global energy crisis and environmental challenges, power system development is in a low-carbon and clean direction. Therefore, in the long run, the power system is always in the process of development, and its power structure, load characteristics, and operating scenarios are constantly evolving. Thus, the demand scenario of the power system for flexibility is also changing over time, and it is not advisable to only consider the mechanism design from a static perspective. Changes should be viewed from a dialectical perspective. Therefore, considering dynamic changes in the flexibility auxiliary service compensation mechanism makes it better adapted to the actual scenario.

2) A dynamic hierarchical compensation mechanism and its mathematical model are established to effectively tap flexible resources in the power system. Thermal power provides a guarantee for the consumption of new energy, and the resulting external cost recovery will inevitably affect MPs' willingness to participate in a flexible market. To ensure the recovery of the thermal power external cost and realize the efficient utilization of flexible resources in the power system, by increasing the design of the compensation mechanism, the redistribution of the MPs' interests is completed by using market-oriented means. Flexible resources in the

power system are tapped to improve its flexibility with a high proportion of new energy.

3) Taking the northeast region of China as an example, an empirical study is conducted using actual operational data. For countries like China that are undergoing or are about to undergo electricity marketization reform, then because of a lack of awareness of market reform, the participants may initially lack a desire for participating in electricity market transactions. This problem is solved by adjusting the coefficients in the dynamic compensation mechanism of flexibility auxiliary services. This encourages MPs to actively participate. It is also beneficial for helping small- and medium-sized enterprises gradually adapt.

II. Materials

A. Case and Scene Description

Liaoning province (38°43'–43°26'N, 118°53'–125° 46'E), located in the southern part of northeast China, has a temperate monsoon climate. With a land area of approximately 148 000 km^2, it accounts for about 1.5% of China's total land area. The region is abundant in renewable energy and coal resources, and its power system relies mainly on thermal, wind, and photovoltaic power generation. The annual heating period spans five months, from November to March. Depending on whether it is a heating or non-heating period, the seasonality of wind power can be divided into four categories, as shown in Table I.

TABLE I
HEATING PERIOD AND WIND SPEED CATEGORY

Period	Heating		Non-heating	
Wind speed	Normal	Strong	Light	Strong
Month	Jan., Feb., Dec.	Mar., Nov.	Jun., Jul., Aug., Sep.	Apr., May, Oct.

According to the 14th Five-Year Plan for Energy Development in Liaoning Province, the proportion of non-fossil energy in the total energy consumption of the province will reach 13.7% by the end of 2025. Non-fossil energy will become the main power supply, accounting for more than 50%, and the proportion of non-fossil energy power generation will increase to about 47%. All coal-fired units will meet ultra-low emission standards, and the proportion of clean utilization of coal will reach about 45%. However, although Liaoning Province is rich in wind and solar energy resources, and the proportion of wind power and photovoltaic power in the power structure is increasing, the proportion of flexible resources, such as hydropower, gas-fired generating units, and other adjustable power stations, is relatively small. Thus, Liaoning's power system urgently needs to optimize the auxiliary service market mechanism to encourage MPs to provide flexibility.

Considering the heating period and non-heating period, and the characteristics of wind energy resources, data with a daily sampling interval of 15 minutes (96 points per day) are randomly selected from the above four categories as cases, and the selected actual load curve, new energy prediction curve and new energy actual output curve are shown in Fig. 1 and Table II. The parameters of the 72 thermal power plants (TPUs) in the selected statistical period are shown in Table III.

TABLE II
DATA SHEET OF MAXIMUM AND MINIMUM VALUES OF LOAD AND NEW ENERGY

Sampling data	Load		New energy	
	Maximum value (MW)	Minimum value (MW)	Maximum value (MW)	Minimum value (MW)
Non-heating period	23 273	19 308	3676.6	1513.6
	24 230	19 223	3557.9	1703.1
Heating period	26 720	23 096	4749.7	1142.5
	27 295	22 643	5431.4	511.1

TABLE III
THE TECHNICAL PARAMETERS OF TPUS

Unit No.	Maximum output (MW)	Minimum output (MW)	Climbing size (MW/min)
1–4	350	70	3.5
5, 60	300	70	4
6–7	350	60	3.5
8, 61	135	60	1.5
9–10	330	80	4
11, 12, 58	350	120	3.5
13, 14	320	120	3.2
15, 16	600	90	6
17, 18	600	170	6
19, 63	350	105	3.7
20, 21	350	130	3.5
22–27	300	100	3
28, 29	350	100	6
30–33, 40, 41, 46, 47	600	180	6
34, 35	270	150	3
36, 37	350	135	3.5
38, 39	300	90	5
42–45	300	120	3
48, 49	220	88	2.2
50	150	95	3
51	180	90	2
52, 53	330	120	3.5
54, 55	350	150	3.5
56, 57	330	95	3
59, 70–72	150	60	2
62, 63	200	85	2
64, 65	90	48	2
66	120	72	3
67	135	72	3
68	350	295	3.5
69	330	295	3.5

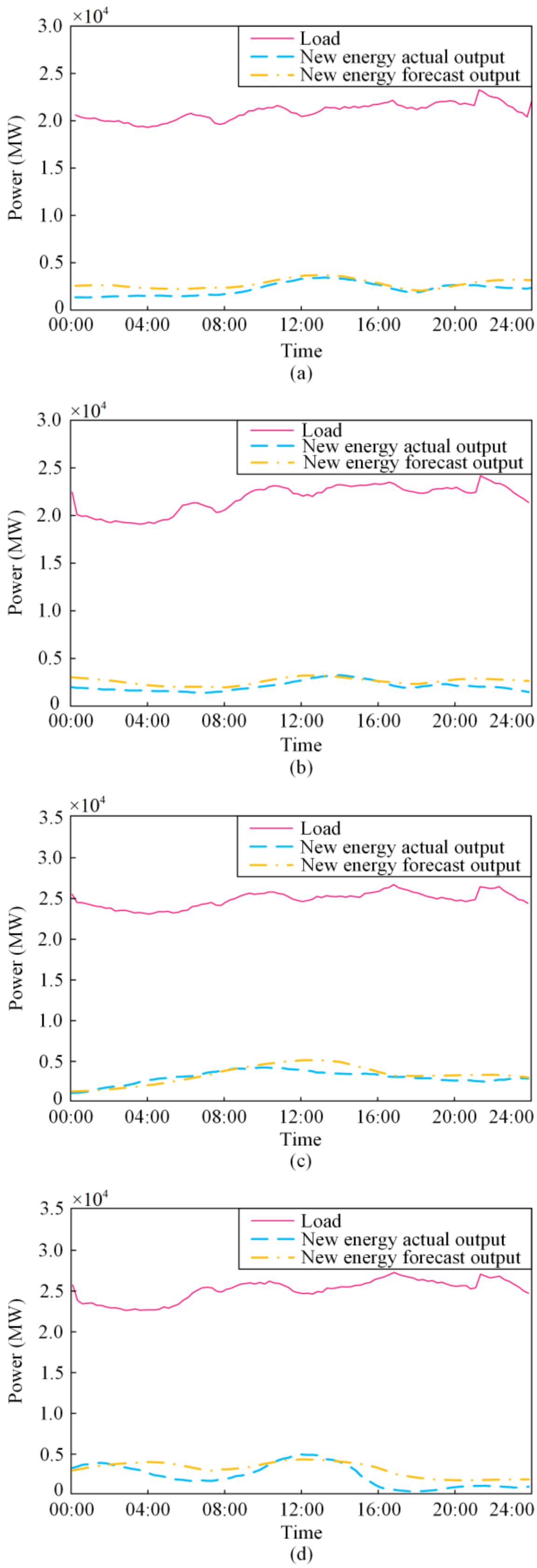

Fig. 1. Daily load and new energy output curve in Liaoning province. (a) Non-heating period sampling day 1. (b) Non-heating period sampling day 2. (c) Heating period sampling day 3. (d) Heating period sampling day 4.

B. Current Peak Shaving Auxiliary Service Market in China

As one of the means for improving the flexibility of the power system, a variety of service products, e.g., peak shaving service, frequency modulation service, automatic generation control, reactive power regulation, standby, and black start, are included in the flexibility auxiliary services. To facilitate analysis, the peak shaving auxiliary service product is selected as an example in this study, and the design and application of the electric auxiliary service market in northeast China, which is the earliest and most typical representative in China, is introduced. The peak shaving auxiliary service is divided into basic compulsory peak shaving auxiliary service (BC-PSA) and paid peak shaving auxiliary service (P-PSA). The peak shaving of real-time deep, interruptible load, electric energy storage, thermal power shutdown standby, thermal power emergency startup, shutdown, and cross provincial, etc. are included in P-PSA. The deep peak shaving transaction is analyzed in this section as an example to illustrate its operation process and mechanism.

The operation rules for the northeast electric power auxiliary service market, issued by the China National Energy Administration (CNEA), have been strictly implemented in northeast China to carry out peak shaving auxiliary service transactions. Synchronous transfer is carried out according to the actual transaction conditions. In addition, the MPs follow the dispatching instructions issued by the power grid and participate in the auxiliary service market, to ensure the stability of power supply and heating. The market operation process includes day-ahead bidding, intra-day dispatch, clean up by day, and settling accounts by month.

In view of the ‘ladder-type’ quotation method and price mechanism, the floating quotation, according to the corresponding quotation range, needs to be completed by power generation enterprises. The specific stage and upper-lower limits of quotation are shown in Table IV. During intra-day dispatch, considering the actual power grid operational conditions, the principle of ‘deploy on-demand, deploy in order’ is adopted to select the best transfer according to the bidding conditions before the day. The actual power regulation results are cleaned up daily, and the total revenue and expenditure of all participants in the deep peak shaving market are calculated. The compensation fee from peak load regulation is calculated according to the paid peak load regulation electricity and the clearing price in the stage, and is settled synchronously with the electricity charge of the current month.

TABLE IV
QUOTATION RULES OF TPUS

Time interval	Quotation stage	Type of thermal power plant	Load rate of thermal power plant	Lower quotation limit (yuan/kWh)	Quotation ceiling (yuan/kWh)
Non-heating period	Phase I	Pure condensing thermal power unit	40%< LR⩽50%	0.0	0.4
		Thermo-electric unit	40%<LR⩽48%		
	Phase II	All thermal power units	LR⩽40%	0.4	1.0
Heating period	Phase I	Pure condensing thermal power unit	40%<LR⩽48%	0.0	0.4
		Thermo-electric unit	40%<LR⩽50%		
	Phase II	All thermal power units	LR⩽40%	0.4	1.0

C. Cost Sharing Mechanism for Peak Shaving Auxiliary Services in Northeast Grid

Reasonable distribution of the interests of all MPs is of long-term and profound significance to the construction of the auxiliary service market. For the peak shaving fee acquirer, the compensation fee obtained from peak shaving is calculated according to the paid peak shaving electricity and the clearing price in the stage. The cost sharing of MPs for peak shaving auxiliary services is divided into four types: TPUs that fail to meet the paid peak shaving benchmark, wind farms, photovoltaic power plants, and nuclear power plants that cannot undertake peak shaving. Their cost sharing is calculated as follows:

$$F = \frac{Q^*}{(\sum Q^*_{\text{D-}i} + \sum Q^*_{\text{W-}i} + \sum Q^*_{\text{S-}i} + \sum Q^*_{\text{N-}i})} \times I \quad (1)$$

$$Q^*_{\text{D-}i} = \sum_{i=1}^{3} (Q_{\text{D-}i} \times k_i) \quad (2)$$

$$Q^*_{\text{W-}i} = Q_{\text{W-}i} \times d \times p \times z \quad (3)$$

$$Q^*_{\text{S-}i} = Q_{\text{S-}i} \times d \times p \times z \quad (4)$$

where I is the total amount of peak shaving compensation; while $\sum Q^*_{\text{D-}i}$, $\sum Q^*_{\text{W-}i}$, $\sum Q^*_{\text{S-}i}$, and $\sum Q^*_{\text{N-}i}$ are the respective corrected total generating capacities of all TPUs, wind turbines, photovoltaic power stations, and nuclear power units participating in the allocation in the region; Q^* is the corrected power generation, while different types of power plants have different correction methods; $Q_{\text{D}-i}$ is the actual generating capacity of the i-stage TPU, while k_i is the correction factor, and $k_i = 1$, $k_i = 1.5$ and $k_i = 2.0$ with TPU load rates of [0–70%], [70%–80%] and [80%–100%] respectively; $Q_{\text{W}-i}$ and $Q_{\text{S}-i}$ are the actual power generation of wind turbines and photovoltaic arrays, respectively, while d, z, p, and q are the correction factors of wind power and photovoltaic power stations, and their values are shown in Table V.

TABLE V
CORRECTION FACTOR CLASSIFICATION

Correction factor	Value	Wind farm, photovoltaic power station
d	1	Non-heating period
	2	Heating period
z	0.5	Unsubsidized wind farms and photovoltaic power stations
	0.8	Nationally recognized wind power concession projects
	1	Other wind farms and photovoltaic power stations
p/*q*	1	The utilization hours of wind farm/photovoltaic power station in the previous year are greater than or equal to the hours of indemnificatory acquisition in the previous year
	0.9-0.1*n*	Less than 200 *n* hours of protective acquisition in the previous year, *n*⩾1
	0	*N*⩾9

The corresponding allocation will be different if the number of units in a nuclear power plant is different. For a number greater than or equal to 2, the apportionment amount is calculated as:

$$Q^*_{\text{N-}i} = Q_{\text{N-}i} \times d \quad (5)$$

For a number less than 2 (more than 77% of the electricity will be shared), the apportionment amount is calculated as:

$$Q^*_{\text{N-}i} = (Q_{\text{N-}i} - Q^{\text{U}}_{\text{N-}i} \times 77\%) \times d \quad (6)$$

where $Q_{\text{N-}i}$ and $Q^{\text{U}}_{\text{N-}i}$ and the actual and rated generating capacities of the nuclear power unit, respectively, while $d = 2$ for a heating period and $d = 1$ for a non-heating period.

The peak shaving recipient apportions the peak shaving auxiliary service fee according to its revised power generation ratio. The apportionment cap referred to in this study is a way to prevent high peak shaving auxiliary service costs. Its essence is to achieve effective guidance through a "prevention" approach, thereby improving the rationality of the apportionment mechanism. As shown in (7), the apportionment cap is not a cut-off based on the theoretical apportionment amount, but rather a calculation method to protect the interests of the peak shaving recipient. Therefore, when the cost to be shared by the MPs in the statistical cycle is greater than the apportionment cap, the payment will be made according to the apportionment cap.

Compared to directly using the theoretical apportionment amount, setting the apportionment cap can fully consider the price-bearing capacity of the peak shaving participants and the economic incentive role of the peak shaving providers. While using market-oriented means to guide MPs to reasonably participate in peak shaving and gain profits, setting an appropriate apportionment cap adds a layer of protection to the interests of the peak shaving recipients by avoiding high peak shaving costs, given as:

$$F_m^{\lim} = Q_m \times \rho_e \times \zeta \tag{7}$$

where $F_m^{\lim}$ is the apportionment cap of payment for MPs; ρ_e is the environmental protection benchmark price of MPs and ζ is the calculation coefficient in different conditions.

When some MPs pay up to the apportionment cap, it results in a shortage of peak shaving allocation costs. Such shortages will be allocated by other MPs that do not reach the apportionment cap of payment in proportion. The allocation formula is given in (8). As the payment expenses of all MPs reach the apportionment cap, such deficiency will be offset by those TPUs whose load rate is lower than the paid peak shaving benchmark. The offset formula is shown in (9).

$$F_{Q\text{-}m} = (Q_m^* - Q^*) \times F_Q \tag{8}$$

$$F_{X\text{-}m} = (F_m - F) \times F_Q \tag{9}$$

where $F_{Q\text{-}m}$ refers to the deficiency of deep adjustment expenses to be borne by MPs whose apportionment expenses are lower than the apportionment cap; F_Q is the total shortage of deep adjustment expenses; and $F_{X\text{-}m}$ is the shortfall cost of the peak shaving provider; Q_m^* is the corrected power generation of the power generation enterprise, while Q^* is the total corrected power generation capacity of that enterprise whose apportionment cost is lower than the apportionment cap; F_m is the deep regulation fee obtained by the peak regulation provider; and F is the total amount of deep adjustment fees in its region.

D. Limitation Analysis

In recent years, the flexibility transformation scale and adjustment capacity of TPUs in northeast China have increased, and the market supply and demand structure has been changing constantly. For instance, from 2018 to 2020, the flexible regulation capacities of thermal power in Liaoning province were 2.1 GW, 3 GW and 4.9 GW, respectively. However, compared with the increasing flexible adjustment capability of TPUs, the flexibility service income of thermal power enterprises has decreased. The comparison of flexibility service benefits of some thermal power enterprises in Liaoning province from 2018 to 2020 is shown in Fig. 2, while Fig. 3 is the schematic diagram of flexibility service benefits of thermal power under the current mechanism within a certain sampling day. It can be seen from Fig. 3 that the actual income of thermal power is lower than expected at most times, and the thermal power plants cannot obtain the due compensation, i.e., although the flexible regulation ability of thermal power is improved, its willingness to participate in flexible regulation is gradually declining, which leads to the current situation that the flexibility service income of thermal power enterprises is decreasing year by year.

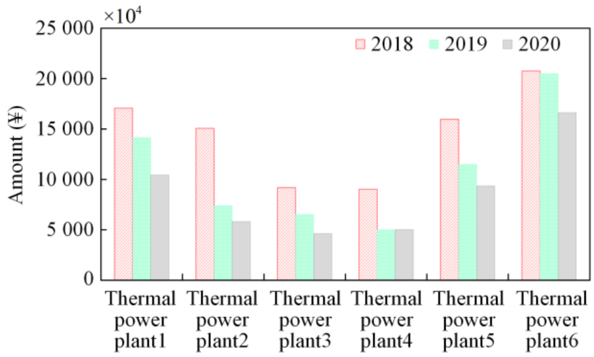

Fig. 2. Annual flexibility service benefits comparison of TPUs.

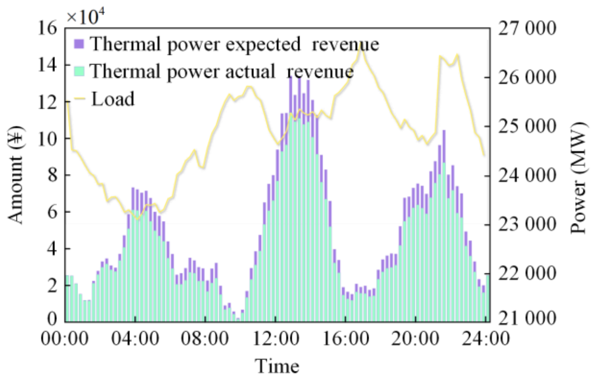

Fig. 3. Flexibility service benefits of TPU in a certain day under the static mechanism.

Effective benefit sharing and adaptive market mechanisms are essential to fully leverage the value of flexible resources [20]. The existing compensation and sharing rules make it difficult to protect the interests of thermal power enterprises, and reduce their willingness to participate in flexibility regulation. The theoretical flexibility auxiliary service apportionment costs and their apportionment caps for wind farms, photovoltaic plants and nuclear plants within a sampling day in Liaoning Province are shown in Fig. 4. It can be seen that, because of the constraint of payment caps, the new energy plants did not bear the flexibility auxiliary service fees that should be borne, and the flexibility value provided by thermal power was not reasonably compensated.

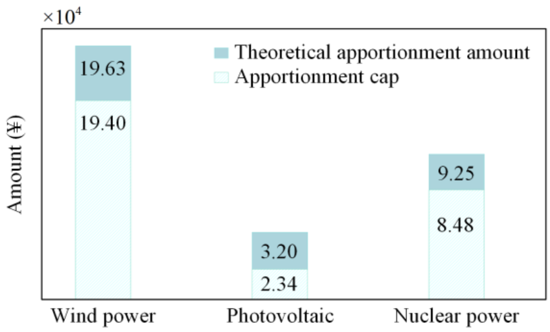

Fig. 4. Clean energy apportionment cap and its theoretical apportionment amount.

The correction coefficient corresponding to the unit's revised power generation in the current apportionment cap is fixed in the time dimension. However, this 'fixed value' restricts its ability to adapt to structural changes in the market at different times, such as seasonal variations, heating periods, and the presence of large-scale wind power generation, leading to a decrease in the willingness for peak shaving in coal-fired power plants. The most straightforward approach to handling the apportionment coefficient is to directly adjust it. After a period of policy implementation, issues may arise concerning the inefficiency or misallocation of resources, whereas direct increases or decreases of the apportionment cap can be implemented to effectively regulate resource allocation. However, formulating the coefficient based on experience does not ensure 'technology neutrality' or take into account the fairness of participation of various MPs. Additionally, it is difficult to guarantee the applicability of the directly adjusted coefficient in different periods. In the case of the continuous increase in the proportion of new energy in China, scenario transformation is rapid, and it is difficult to formulate a suitable coefficient for each emerging scenario. In other words, choosing direct adjustment means choosing continuous adjustment. Frequent intervention will weaken the ability of the market mechanism to automatically adjust to economic problems, while it is also not conducive to the transformation of China from a planned economy system to a socialist market economy system. Furthermore, directly adjusting the apportionment cap may still lack sufficient economic incentive to effectively stimulate the active peak shaving of thermal power generation in certain scenarios.

In summary, the existing market allocation mechanism for peak shaving auxiliary services has limited ability to cope with market structural changes or to provide benefit distribution and risk sharing among participants. The upper limit of the allocation cost of the demand side may be unable to adapt to the high proportion of new energy. Thus, the actual flexible adjustment income of thermal power is lower than expected, and the ability of thermal power to provide flexible regulation services is reduced. Furthermore, the guiding role of the market mechanism has been weakened, which is not conducive to the consumption of clean energy in the future [21], [22]. To solve these problems, this study proposes a hierarchical compensation mechanism to incentivize market members to participate in flexibility auxiliary services, one which can effectively reflect the dynamic value of flexibility services and activate the auxiliary services market.

III. Methodology

A. Framework

As power systems around the world transform, power system flexibility has become a global priority. Effectively assessing the value of the flexible resources offered by the participants and ensuring fair remuneration for the flexible services provided by various power system assets are crucial steps toward increasing flexibility. This has become an important research topic. Numerous strategies, approaches, and instruments can be readily applied and adapted to power systems. Energy policy, legal frameworks, regulatory mechanisms, and market rules are powerful means of addressing the above challenges. However, with the existing mechanism, there are constant values on some time scales, such as the benchmark load rate in the rotating reserve market, the paid peak shaving benchmark in the peak shaving market, and the price ceiling or floor price in the power market. The formulation of the constant values has the advantage of simple operation in the market clearing and settlement process. Nevertheless, the operating environment of power systems is by no means static, while power systems are always in the process of development, and the power structures, load characteristics, and system characteristics are always evolving. Thus, given the real value of flexible resources in different circumstances it is often difficult to truly reflect this by adopting a constant value. Therefore, the existing mechanism for evaluating flexible resources does not optimize the fairness and efficiency of market operation, nor provide sufficient incentive signals for the improvement of power system flexibility.

In the construction of the market-oriented environment of China's power system, if the flexibility value of market members can be identified and quantified differently according to different working conditions and scenarios to make corresponding compensation settlement more reasonable, and make the individual flexibility value and the flexibility operation target of the system converge, the willingness of market members for flexible resource supply can be fundamentally stimulated. This can ultimately facilitate the flexible operation of a power system with a high proportion of new energy. Indeed, all power system assets, including intermittent renewable energy, can provide flexibility services if enabled by proper policy, markets, and regulatory frameworks. Considering that the mining and analysis of the "particularity of differentiated scenarios" are key, a dynamic mechanism design framework for different scenarios, shown in Fig. 5, is proposed in this study.

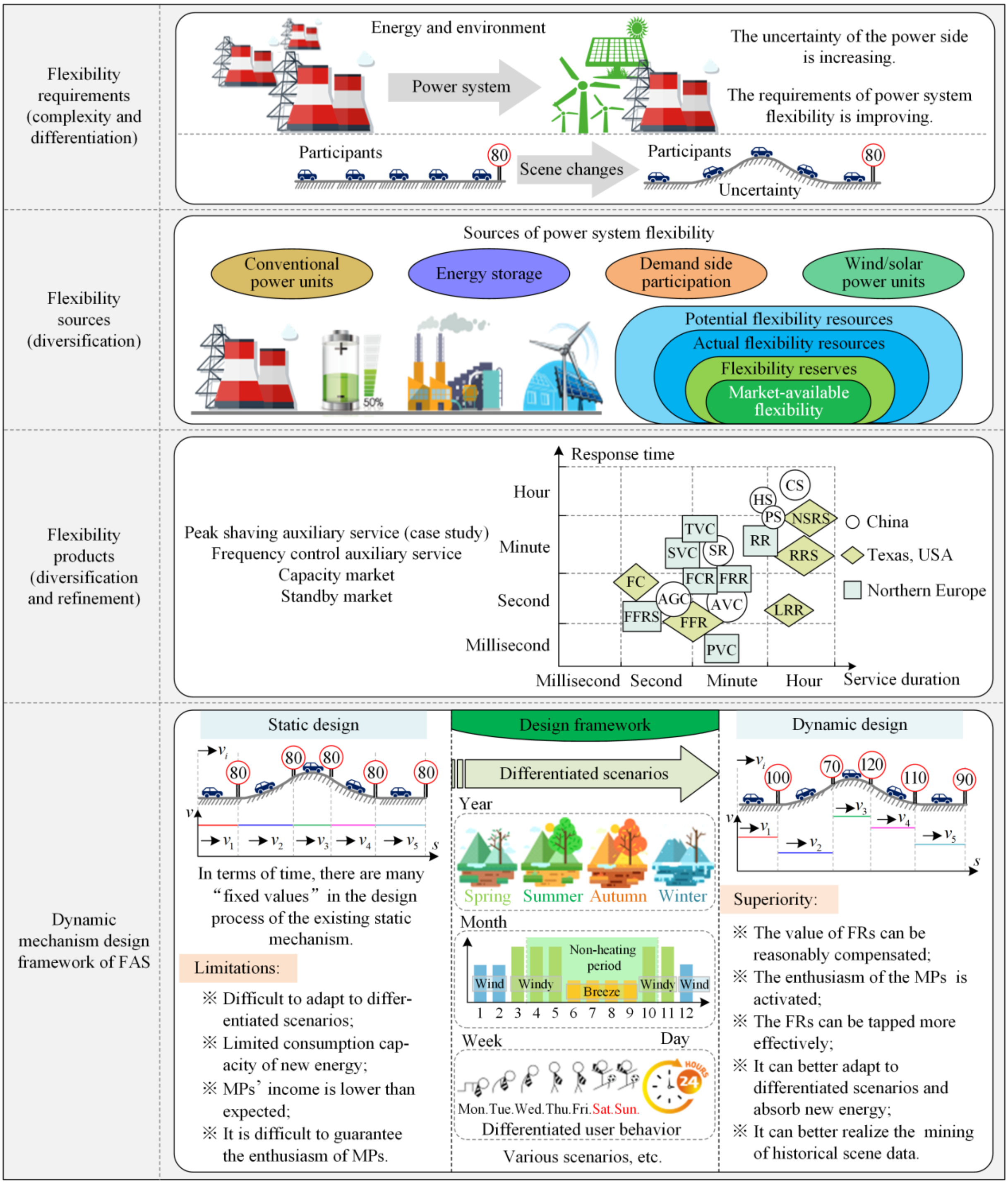

Fig. 5. Dynamic mechanism design framework of FAS.

Figure 5 is divided into four parts to introduce the proposed flexibility auxiliary services dynamic mechanism design framework considering the three aspects of flexibility in requirements, resources, and products. The first part describes the current energy development trend of China's power system wherein demand is rising for new energy absorption capacity and flexibility space. There are many uncertainties in the process of power system operation and planning. These bring challenges to MPs. The second part describes the multi-flexibility resources in the power system, as well as potential and actual flexibility resources, flexibility in reserves, and that available in the market. It can be seen that the potential of large-scale flexible resources in the power system has not been fully exploited. It is necessary to allocate a variety of flexible resources from a higher level of planning and mechanism to fundamentally solve the problem of mismatch between new energy development and power system flexibility adjustment capability. The third part introduces the transaction varieties of auxiliary services in China and compares the duration and response time of auxiliary service products in Northern Europe, Texas in the United States, and China. There are few types of auxiliary service products in China at present, so the auxiliary service standardization system should be gradually improved to meet the flexibility requirements of the system in different periods. The fourth part compares and analyzes the differences between static and dynamic mechanisms, and fully considers the needs and adaptability of different mechanisms for seasonal differences, heating and non-heating periods, strong and light wind periods. The 'constant value' in the traditional static mechanism design process is given a dynamic concept, which can accurately measure the flexibility value provided by the MPs on different time scales. It can also encourage MPs to actively provide flexible services and maximize the system's flexibility potential. Thus, to a certain extent, it overcomes the main defect of the traditional static mechanism design, since that does not appropriately reflect the value of flexible resources in response to changes in market structure. Moving forward, updating system flexibility policies to match the pace of technological development can help to accelerate the transformation of China's power system, while promoting cleaner, more reliable, flexible, and affordable energy development.

B. Framework

1) Pareto Equilibrium in the Design of Auxiliary Service Market

The core idea of the Pareto equilibrium resource allocation strategy is to use compensation and allocation to benefit at least one participant, without damaging the interests of any MP. By adjusting the MPs' interests, we can strategically allocate resources to optimize the system [23]. The compensation mechanism based on Pareto equilibrium can be explained with the help of a utility possibility curve, as shown in Fig. 6.

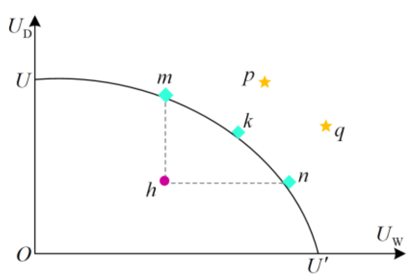

Fig. 6. Utility possibility curve.

In Fig. 6, D and W are the flexibility auxiliary services (FAS) provider and recipient, respectively. The different interest combinations from various allocations of established resources are obtained, while the combination of possible and impossible benefits is divided by the curve. The points in the curve and the lower left area of the curve can be reached, e.g., *m*, *k*, *n*, *h* points, while the points in the upper right area of the curve cannot, e.g., *p* and *q* points. The curve *UU*' represents the set of all possible maximum benefit combinations of the FAS provider and the receiver, i.e., reaching the Pareto optimal state. At the bottom left of the curve, the benefits of both parties do not reach the Pareto optimal state, and at least one participant's benefits can be increased by adjusting the allocation mechanism.

2) Hierarchical Compensation Mechanism for FAS

The compensation mechanism for flexibility auxiliary services exploits the potential of system flexibility by adjusting the benefit distribution of MPs. Considering that the current common auxiliary service fee is counted in a 15-min period, the dynamic allocation upper limit parameter is set at the same period so that it is possible to use this parameter to guide the market operation to the highest efficiency point, i.e., to achieve the Pareto optimal state. Then, three compensation stages are established based on the difference between the actual allocation amount, the current allocation upper limit, and the dynamic allocation upper limit, as shown in Table VI.

TABLE VI
GRADING COMPENSATION

Grade	Classification conditions	Compensation amount
1	Static apportionment cap > Theoretical apportionment amount > Dynamic apportionment cap	Difference between the theoretical apportionment amount and the dynamic apportionment cap
2	Dynamic apportionment cap > Theoretical apportionment amount > Static apportionment cap	Difference between the theoretical apportionment amount and the static apportionment cap
3	Theoretical apportionment amount > Dynamic apportionment cap > Static apportionment cap	Difference between the dynamic apportionment cap and the static apportionment cap

A hierarchical compensation mechanism can effectively alleviate the shortage of flexibility auxiliary service fees and ensure market operational efficiency and comprehensive income of participants. Raising or lowering the allocation upper limit during load peak valley periods is a poor strategy for adapting to different scenarios, such as different loads or power structures [24], [25]. Therefore, a flexibility auxiliary services compensation mechanism based on the Pareto optimality principle is proposed, in which the upper limit of flexibility service cost allocation is determined based on actual power generation. According to the Pareto optimality principle, the dynamic allocation upper limit is formed by adjusting the coefficient factor each time, and the compensation amount is determined in the form of difference. The mechanism is beneficial to the profit sharing of MPs, in addition to being able to stimulate a decentralized decision of the MPs, consistent with the expectations of the designers of the entire market mechanism as well as adapting to changes in future scenarios [26], [27]. The compensation mechanism proposed in this study requires a 15-min clearing period for daily statistics, and the auxiliary service fee is settled together with the electricity charge of the current month.

The mechanism proposed stipulates the cost-sharing arrangement for flexible ancillary services between the buyers and sellers. The expenses related to these services are settled and calculated in 15-min clearing intervals daily. Additionally, the auxiliary service cost is consolidated with the monthly electricity bill for convenient settlement. The market transaction flowchart is shown in Fig. 7. As seen, on the bidding day $(T-1)$, the dispatch control center completes the information release before 9:30, while MPs complete the transaction declaration before 10:00. At 10:30, the dispatch control center calculates the auxiliary service cost apportionment cap of the buyer in the previous period in real time, followed by completing the market pre-clearance in combination with the auxiliary service compensation and apportionment calculation method. On the running day (T), the market is cleared in real time within a 15-min period to form an intraday power generation plan. Every hour, the dispatch control center publicizes the transaction situation and apportionment results of the previous hour to each MP within the dispatching jurisdiction. In each dispatching cycle, the flexibility auxiliary services of thermal power units are called in real time and the actual electricity consumption is counted. After the end of the operational day $(T+)$, the dispatch control center releases the final transaction results of the previous day's flexibility auxiliary service transaction at 1:00 on the second day $(T+1)$. After each month $(T+n)$, the technical support system re-evaluates the revenue and expenditure data provided by each power plant. The monthly information regarding the auxiliary service market for the previous month is announced before the fifth working day so that the market is fair, open, and transparent.

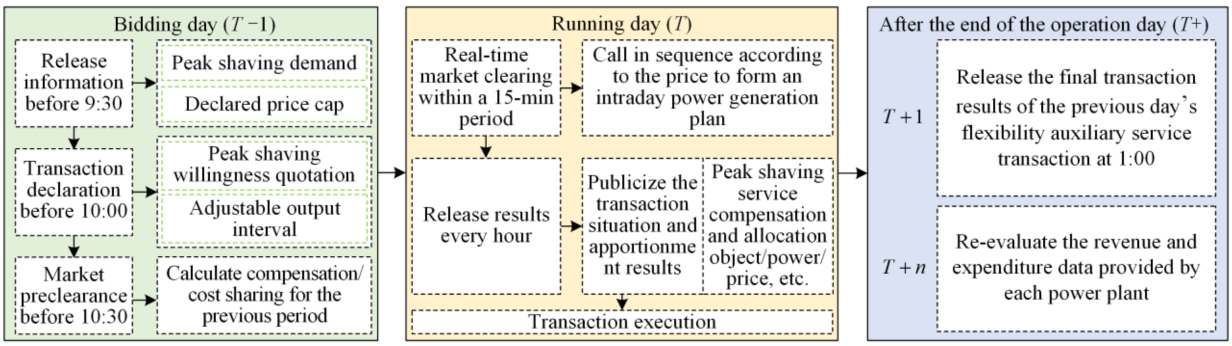

Fig. 7. Market transaction flow chart.

C. Mathematical Model of HCM

1) Objective Function

To ensure stable operation, the market mechanism should not only balance the supply and demand of the power system but also attempt to maximize the total social benefits, absorb as much new energy as possible, and guide the market to develop in a healthy and benign direction [28]. The realization of this goal is closely related to the interest distribution of the MPs [29], [30]. The goal of the hierarchical compensation mechanism is to maximize the comprehensive incomes of all participants in the market:

$$\begin{cases} \max U_{\mathrm{D}}^{t} = \sum_{i=1}^{n} R_{\mathrm{D}\text{-}i,t} + \sum_{i=1}^{n_1} I_{\mathrm{D}\text{-}i,t} - \sum_{i=1}^{n} C_{i,t} - \\ \qquad \min\left\{ \sum_{i=1}^{n_2} F_{\mathrm{D}\text{-}i,t}, F_{\mathrm{D}\text{-}i\text{-}m,t}^{\mathrm{lim}*} \right\} \\ \max U_{\mathrm{W}}^{t} = \sum_{i=1}^{n_3} R_{\mathrm{W}\text{-}i,t}^{\mathrm{A\text{-}on}} + \sum_{i=1}^{n_4} R_{\mathrm{W}\text{-}i,t}^{\mathrm{C}} - \min\left\{ \sum_{i=1}^{n_3} F_{\mathrm{W}\text{-}i,t}, F_{\mathrm{W}\text{-}i\text{-}m,t}^{\mathrm{lim}*} \right\} \\ \max U_{\mathrm{S}}^{t} = \sum_{i=1}^{n_5} R_{\mathrm{S}\text{-}i,t}^{\mathrm{A\text{-}on}} - \min\left\{ \sum_{i=1}^{n_5} F_{\mathrm{S}\text{-}i,t}, F_{\mathrm{S}\text{-}i\text{-}m,t}^{\mathrm{lim}*} \right\} \\ \max U_{\mathrm{N}}^{t} = \sum_{i=1}^{n_6} R_{\mathrm{N}\text{-}i,t}^{\mathrm{A\text{-}on}} - \min\left\{ \sum_{i=1}^{n_6} F_{\mathrm{N}\text{-}i,t}, F_{\mathrm{N}\text{-}i\text{-}m,t}^{\mathrm{lim}*} \right\} \end{cases} \tag{10}$$

where U_{D}^{t}, U_{W}^{t}, U_{S}^{t}, and U_{N}^{t} are the comprehensive incomes of all thermal power plants (TPUs), wind, photovoltaic and nuclear power participating in the FAS market at time t, respectively; $R_{\mathrm{D}\text{-}i,t}$ is the electricity revenue of TPU i at time t; $I_{\mathrm{D}\text{-}i,t}$ is the compensation for flexibility value of TPU i at time t; $C_{i,t}$ is the cost of providing FAS for TPU i at time t; $F_{\mathrm{D}\text{-}i,t}$, $F_{\mathrm{W}\text{-}i,t}$, $F_{\mathrm{S}\text{-}i,t}$, and $F_{\mathrm{N}\text{-}i,t}$ are the FAS sharing amounts of TPU, wind turbine unit, photovoltaic array and nuclear power unit i at time t, respectively; $F_{\mathrm{D}\text{-}i\text{-}m,t}^{\mathrm{lim}}$, $F_{\mathrm{W}\text{-}i\text{-}m,t}^{\mathrm{lim}}$, $F_{\mathrm{S}\text{-}i\text{-}m,t}^{\mathrm{lim}}$, and $F_{\mathrm{N}\text{-}i\text{-}m,t}^{\mathrm{lim}}$ are the respective upper limits of the apportionment of the participant m (TPU, wind farm, photovoltaic power plant, and nuclear power plant), where the generator unit i (thermal power unit, wind turbine unit, photovoltaic array, and nuclear power unit) is located at time t; $R_{\mathrm{W}\text{-}i,t}^{\mathrm{A\text{-}on}}$ is the electricity revenue obtained by wind turbine i participating in the FAS market at time t; $R_{\mathrm{W}\text{-}i,t}^{\mathrm{C}}$ is the income of wind turbine i from participating in the cross regional spot market at time t; $R_{\mathrm{S}\text{-}i,t}^{\mathrm{A\text{-}on}}$ and $R_{\mathrm{N}\text{-}i,t}^{\mathrm{A\text{-}on}}$ are the electricity revenues obtained by photovoltaic array and nuclear power unit i participating in the FAS market at time t, respectively.

The electricity revenue of TPU can be expressed as:

$$R_{\mathrm{D}\text{-}i,t} = Q_{\mathrm{D}\text{-}i,t}^{\mathrm{on}} \times \rho_{\mathrm{e}} \tag{11}$$

where $Q_{\text{D-}i,t}^{\text{on}}$ is the on-grid power of TPU i at time t; and ρ_{e} is the electricity price of TPU.

The compensation cost for the flexibility value of TPUs can be expressed as:

$$I_{\text{D-}i,t}=\sum_{j=1}^{2}(Q_{j,i,t}^{\text{A}}\times\rho_j)\times k \tag{12}$$

where $Q_{j,i,t}^{\text{A}}$ is the flexible regulation power provided by TPU i in the j stage at time t; ρ_j is the actual clearing price of the j stage; and K is the correction factor, with $K=1$ during the heating period and $K=0.5$ during the non-heating period.

The total operating cost of all thermal power units can be divided into two parts. One part is the thermal power unit cost that provides flexibility auxiliary services, i.e., the thermal power unit flexibility service cost. The other part is the thermal power unit cost with load factors higher than the compensated peaking benchmark, i.e., the thermal power unit coal consumption cost. Thus, the total operating cost of all thermal power units is given as [31], [32]:

$$\sum_{i=1}^{n}C_{i,t}=\sum_{i=1}^{n_1}C_{\text{peak},i,t}+\sum_{i=1}^{n_2}C_{\text{coal},i,t} \tag{13}$$

The thermal power unit coal consumption cost can be expressed as:

$$C_{\text{coal},i,t}=a_iP_{\text{D-}i,t}^2+b_iP_{\text{D-}i,t}+c_i \tag{14}$$

where $P_{\text{D-}i,t}$ is the actual output of the thermal power unit i at time t; while a_i, b_i, and c_i are the consumption characteristic parameters of unit i.

The flexibility service cost can be expressed as the sum of the lost generation revenue to provide flexibility services and the coal consumption cost resulting from changes in unit combustion efficiency due to the provision of flexibility services, as:

$$\begin{aligned}C_{\text{peak},i,t}&=C_{\text{peak},i,t}^1+C_{\text{peak},i,t}^2=\\&\rho_{\text{e}}[P_{\text{D-}i,t}^{\text{plan}}-P_{\text{D-}i,t}]+\\&\rho_{\text{r}}[a_i(P_{\text{D-}i,t}^2-(P_{\text{D-}i,t}^{\text{plan}})^2)+b_i(P_{\text{D-}i,t}-P_{\text{D-}i,t}^{\text{plan}})]\end{aligned} \tag{15}$$

$$\begin{aligned}C_{\text{peak},i,t}^1&=\rho_e(P_{\text{D-}i,t}^{\text{plan}}-P_{\text{D-}i,t})-\\&\frac{P_{\text{D-}i,t}^{\text{plan}}-P_{\text{D-}i,t}}{P_{\text{D-}i,t}^{\text{plan}}}(a_iP_{\text{D-}i,t}^{\text{plan}2}+b_iP_{\text{D-}i,t}^{\text{plan}}+c_i)\rho_{\text{r}}\end{aligned} \tag{16}$$

$$\begin{aligned}C_{\text{peak},i,t}^2&=\rho_{\text{r}}(a_iP_{\text{D-}i,t}^2+b_iP_{\text{D-}i,t}+c_i)-\\&\frac{P_{\text{D-}i,t}}{P_{\text{D-}i,t}^{\text{plan}}}(a_i(P_{\text{D-}i,t}^{\text{plan}})^2+b_iP_{\text{D-}i,t}^{\text{plan}}+c_i)\rho_{\text{r}}\end{aligned} \tag{17}$$

where $C_{\text{peak},i,t}^1$ is the lost power generation income and $C_{\text{peak},i,t}^2$ is the generated coal consumption cost; ρ_{r} is the coal-fired price; ρ_{e} is the on-grid price of the thermal power unit; and $P_{\text{D-}i,t}^{\text{plan}}$ is the estimated output of thermal power unit i at time t.

The electricity revenue obtained by new energy participating in the FAS market can be expressed as:

$$R_{\text{W-}i,t}^{\text{A-on}}=Q_{\text{W-}i,t}^{\text{A}}\times\rho_{\text{e}} \tag{18}$$

$$R_{\text{S-}i,t}^{\text{A-on}}=Q_{\text{S-}i,t}^{\text{A}}\times\rho_{\text{e}} \tag{19}$$

$$R_{\text{N-}i,t}^{\text{A-on}}=Q_{\text{N-}i,t}^{\text{A}}\times\rho_{\text{e}} \tag{20}$$

where $Q_{\text{W-}i,t}^{\text{A}}$, $Q_{\text{S-}i,t}^{\text{A}}$, and $Q_{\text{N-}i,t}^{\text{A}}$ are the flexible regulated power purchased by the wind turbine, photovoltaic array and nuclear power unit i at time t, respectively.

The benefits obtained from wind turbines participating in the cross regional spot market can be expressed as:

$$R_{\text{W-}i,t}^{\text{C}}=Q_{\text{W-}i,t}^{\text{C}}\times\rho_{\text{c}} \tag{21}$$

$$F_{\text{D-}m,t}^{\text{lim*}}=\sum_{i=1}^{n_2}Q_{\text{D-}i,t}\times\rho_{\text{e}}\times0.25\times\alpha_1 \tag{22}$$

$$\begin{cases}F_{\text{W-}m,t}^{\text{lim*}}=\sum_{i=1}^{n_{3\text{-}1}}Q_{\text{W-}i,t}\times\rho_{\text{e}}\times0.3\times\alpha_2\\F_{\text{W-}m,t}^{\text{lim*}}{}'=\sum_{i=1}^{n_{3\text{-}2}}Q_{\text{W-}i,t}\times\rho_{\text{e}}\times0.6\times\alpha_3\end{cases} \tag{23}$$

$$\begin{cases}F_{\text{S-}m,t}^{\text{lim*}}=\sum_{i=1}^{n_{5\text{-}1}}Q_{\text{S-}i,t}\times\rho_{\text{e}}\times0.2\times\alpha_4\\F_{\text{S-}m,t}^{\text{lim*}}{}'=\sum_{i=1}^{n_{5-2}}Q_{\text{S-}i,t}\times\rho_{\text{e}}\times0.4\times\alpha_5\end{cases} \tag{24}$$

$$F_{\text{N-}m,t}^{\text{lim*}}=\sum_{i=1}^{n_6}P_{\text{N-}i,t}\times\rho_{\text{e}}\times0.3\times\alpha_6 \tag{25}$$

where $Q_{\text{D-}i,t}$, $Q_{\text{W-}i,t}$, $Q_{\text{S-}i,t}$, and $Q_{\text{N-}i,t}$ are the actual generating capacities of TPU, wind turbine unit, photovoltaic array and nuclear power unit i at time t, respectively; a is the dynamic allocation upper limit adjustment coefficient.

The compensation flexibility values can be expressed as:

$$\begin{cases}F_{\text{comp}}^1=F_{m,t}^{\text{lim*}}-F_{m,t}\\F_{\text{comp}}^2=F_{m,t}-F_{m,t}^{\text{lim}}\\F_{\text{comp}}^1=F_{m,t}^{\text{lim*}}-F_{m,t}^{\text{lim}}\end{cases} \tag{26}$$

where F_{comp}^1, F_{comp}^2, and F_{comp}^3 are the first, second and third stage flexibility compensation values, respectively; $F_{m,t}$ is the flexibility service allocation amount; while $F_{m,t}^{\text{lim*}}$ and $F_{m,t}^{\text{lim}}$ are the dynamic ceiling and current ceiling, respectively.

2) Constraint Conditions

a) System Power Balance Constraint

System power balance constraint [33], [34] is as follows:

$$\sum_{i=1}^{n_3}P_{\text{W-}i,t}+\sum_{i=1}^{n_5}P_{\text{S-}i,t}+\sum_{i=1}^{n_6}P_{\text{N-}i,t}=\sum_{i=1}^{n_1}P_{\text{D-}i,t} \tag{27}$$

where $P_{\text{D-}i,t}$ is the flexible regulation capacity transferred by TPU i willing to participate in flexible regulation at time t; while $P_{\text{W-}i,t}$, $P_{\text{S-}i,t}$, and $P_{\text{N-}i,t}$ are the respective output values of wind turbine, photovoltaic array and nuclear power units i at time t.

b) TPU Operational Constraints

Ramp rate constraint can be seen [35]:

$$\begin{cases} \sum_{i=1}^{n_1} P_{\text{D-}i,t} - \sum_{i=1}^{n_1} P_{\text{D-}i,t\text{-}1} \leqslant \sum_{i=1}^{n_1} P_{\text{D-}i}^{\text{up}} \times \Delta T \\ \sum_{i=1}^{n_1} P_{\text{D-}i,t\text{-}1} - \sum_{i=1}^{n_1} P_{\text{D-}i,t} \leqslant \sum_{i=1}^{n_1} P_{\text{D-}i}^{\text{down}} \times \Delta T \end{cases} \tag{28}$$

where $P_{\text{D-}i}^{\text{up}}$ and $P_{\text{D-}i}^{\text{down}}$ are the maximum upward/ downward climbing rates of TPUs willing to participate in flexible regulation in the system; and ΔT is the statistical period of 15 minutes.

Unit output constraints are as follows:

$$P_{\text{D-}i}^{\min} \leqslant P_{\text{D-}i,t}^{\text{plan}} - P_{\text{D-}i,t} \leqslant P_{\text{D-}i}^{\max} \tag{29}$$

where $P_{\text{D-}i}^{\max}$ and $P_{\text{D-}i}^{\min}$ are the maximum and minimum technical output values of TPUs willing to participate in flexible regulation in the system; while $P_{\text{D-}i,t}^{\text{plan}} - P_{\text{D-}i,t}$ is the actual output value of TPU i at time t after implementing the auxiliary service market.

c) New Energy Output Constraints

The above mentioned constraints are as follows:

$$0 \leqslant P_{\text{W-}i,t} \leqslant P_{\text{W-}i,t}^{\max} \tag{30}$$

$$0 \leqslant P_{\text{S-}i,t} \leqslant P_{\text{S-}i,t}^{\max} \tag{31}$$

$$0 \leqslant P_{\text{N-}i,t} \leqslant P_{\text{N-}i,t}^{\max} \tag{32}$$

where $P_{\text{W-}i,t}^{\max}$, $P_{\text{S-}i,t}^{\max}$ and $P_{\text{N-}i,t}^{\max}$ are the respective maximum output capacities of wind turbine, photovoltaic array and nuclear power unit i at time t.

d) Wind/solar Abandonment Rate Constraints

The related constraints are as follows:

$$0 \leqslant \sum_{i=1}^{n_3} P_{\text{W-}i,t}^{\text{loss}} \leqslant \sum_{i=1}^{n_3} P_{\text{W-}i,t}^{\text{cal}} \tag{33}$$

$$0 \leqslant \sum_{i=1}^{n_5} P_{\text{S-}i,t}^{\text{loss}} \leqslant \sum_{i=1}^{n_5} P_{\text{S-}i,t}^{\text{cal}} \tag{34}$$

where $P_{\text{W-}i,t}^{\text{loss}}$ and $P_{\text{S-}i,t}^{\text{loss}}$ are the amounts of wind/solar abandoned by wind turbine and photovoltaic array i at time t, respectively; while $P_{\text{W-}i,t}^{\text{cal}}$ and $P_{\text{S-}i,t}^{\text{cal}}$ are the respective predicted output values of wind turbine and photovoltaic array i at time t.

IV. RESULTS AND DISCUSSION

To explore the impact of the compensation mechanism on flexibility service cost allocation, two days in each of the heating and non-heating periods are selected for multi-objective optimization. A non-dominated solution sorting genetic algorithm with elite strategy is used to analyze the multi-objective optimization model [36], [37]. After the Pareto optimal frontier is formed by objective function mapping, the final equilibrium value is determined using a crowded-comparison approach. The calculation results are then compared with the static apportionment cap, as shown in Figs. 8–11.

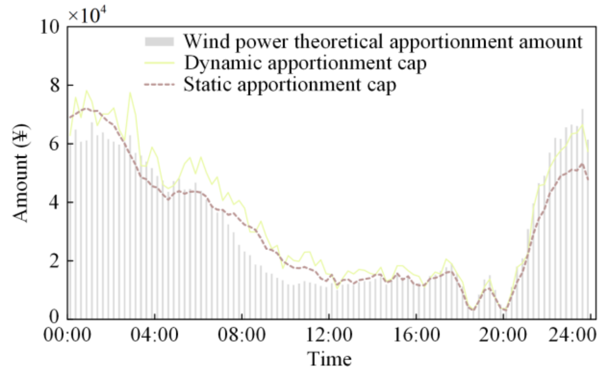

Fig. 8. Wind power FAS apportionment amount on sampling day 1 during non-heating period.

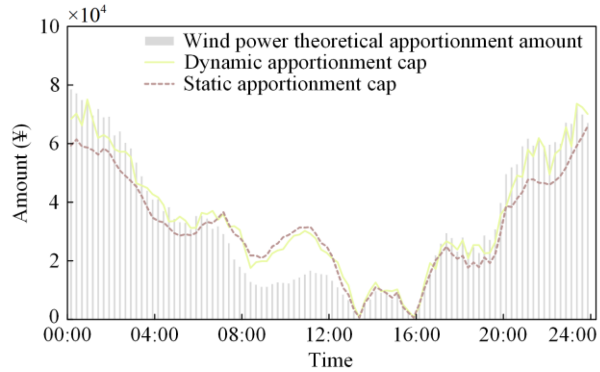

Fig. 9. Wind power FAS apportionment amount on sampling day 2 during non-heating period.

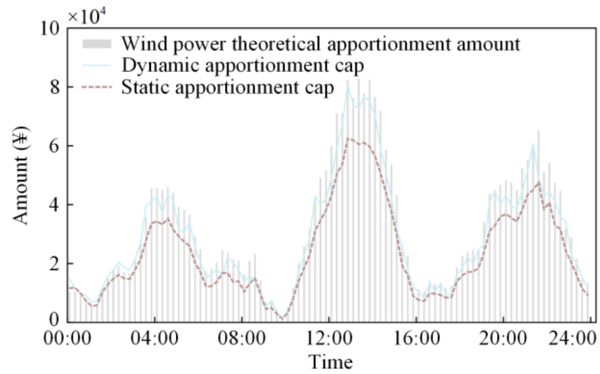

Fig. 10. Wind power FAS apportionment amount on sampling day 3 during heating period.

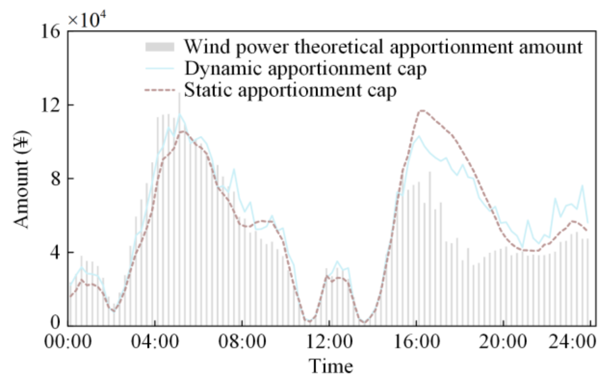

Fig. 11. Wind power FAS apportionment amount on sampling day 4 during heating period.

From Figs. 8–11, it can be seen that, in most periods under the static mechanism, the upper limit of flexibility auxiliary services cost allocation is lower than the actual amount that wind power should pay, resulting in a large capital gap in the auxiliary service transaction. This indicates that the actual income of TPUs is lower than expected, and the willingness of TPUs to participate in flexible regulation is reduced. Once the dynamic compensation mechanism has been introduced, the upper limit of wind power allocation better adapts to the actual amount to be allocated. After considering the comprehensive income of TPUs and wind power, the upper limit coefficient of wind power allocation is optimized by enabling dynamic changes. This shows that when the wind power prediction deviation is large, the upper limit generally increases, and vice versa. The wind power forecast deviation affects the upper limit of dynamic allocation to a great extent. The optimized wind power allocation coefficient is shown in Fig. 12, while the corresponding compensation amount is shown in Fig. 13.

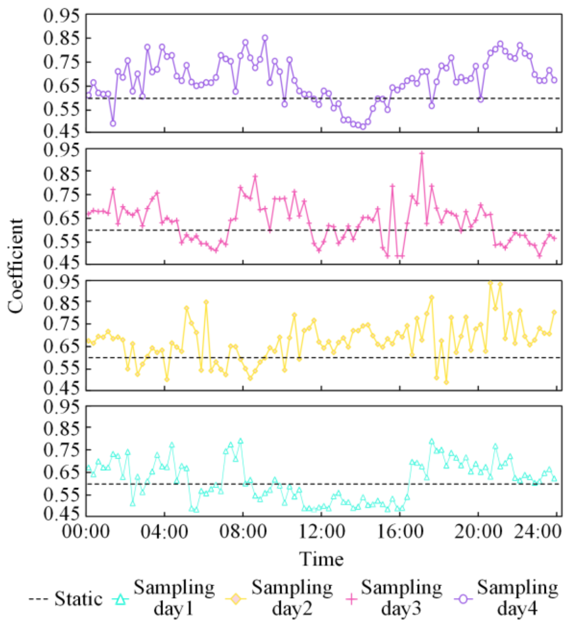

Fig. 12. Comparison of apportionment coefficients.

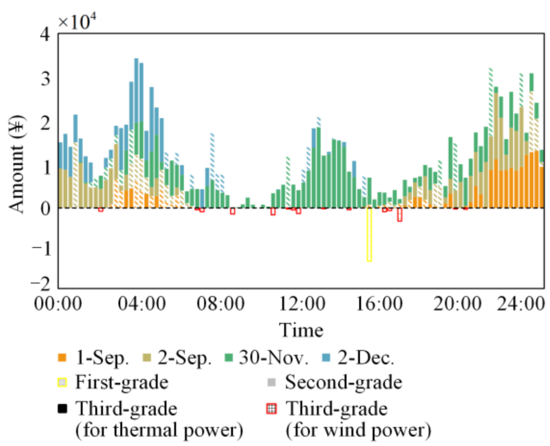

Fig. 13. Sampling day multi-grade compensation amount.

As can be seen from Fig. 12, the allocation coefficient has dynamic characteristics. This improves the flexibility of the allocation upper limit compared with the allocation coefficient generated by the static mechanism. On most days, the allocation coefficient after optimization has increased compared with the allocation coefficient generated by the static mechanism, which reveals the disadvantage that the static mechanism does not guarantee the income of TPUs. In Fig. 13, the upper part of the coordinate axis represents the compensation obtained by TPUs, and the lower part of the coordinate axis represents the compensation obtained by wind power. Figure 14 shows that, at 15:15 on December 2, because the static allocation upper limit was greater than both the theoretical allocation amount and the dynamic allocation upper limit, the wind power received a higher compensation of 12 278.7 yuan (i.e., the yellow area in Fig. 13), while the red area in Fig. 13 shows that wind power received a third-class compensation. These two cases illustrate the phenomenon of granting excessive subsidies to TPUs under the static mechanism. It can also be seen from Fig. 13 that, in most cases, the flexibility auxiliary services provided by TPUs have not received reasonable returns, and it is difficult for the static allocation mechanism to truly reflect the value of flexible adjustment resources, indicating additional compensation requirement. Through a practical and effective value compensation mechanism, the benefits of regulatory power supply, e.g., TPUs, can be guaranteed. At the same time, correct incentive signals for long-term flexibility regulation can be provided to ensure system flexibility first.

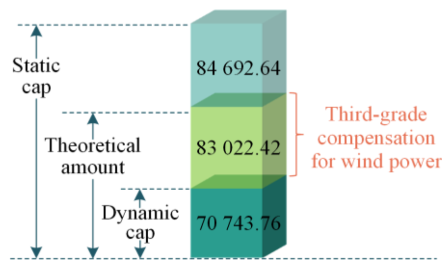

Fig. 14. Compensation amount at a certain time on sampling day 4.

Next, the economic benefits of all MPs are analyzed, and the results are shown in Figs. 15–18 and Table VII.

In Figs. 15–18, the shaded parts represent the differences in benefit to TPUs provided by the dynamic compensation mechanism and the static mechanism. The potential incomes of TPUs within the sampling day in the non-heating period and heating period, for sampling days 1, 2, 3, and 4, are ¥ 189 600, ¥ 310 500, ¥ 459 700, and ¥ 190 200, respectively. The potential benefit of TPUs is the largest on sampling day 3. This is because the cost sharing amount of wind power flexibility auxiliary services on that day has almost reached the upper limit, and there is a large potential space for TPUs to benefit. By introducing a compensation mechanism, the flexibility value of TPUs is reasonably guaranteed. The wind power income on each sampling day before and after the compensation mechanism are given, both with and without consideration of wind abandonment. When considering wind abandonment, wind power benefits by ¥ 165 000, ¥ 96 000, ¥ 439 000, and ¥ 998 000 in a day, for sampling days 1 to 4, respectively. Similarly, without considering wind abandonment, wind power gains more than ¥ 171 000, ¥ 90 000, ¥ 449 000, and ¥ 1 009 000 in a day, for sampling days 1 to 4, respectively. The benefits are greater on sampling days 3 and 4 than on sampling days 1 and 2 because the selected months are high wind months and low wind months, respectively, and with the increase of wind power output, the demand for flexibility increases significantly. The compensation mechanism provides flexibility value by encouraging regulatory units to sell generation capacity, ensuring that wind power can profit more.

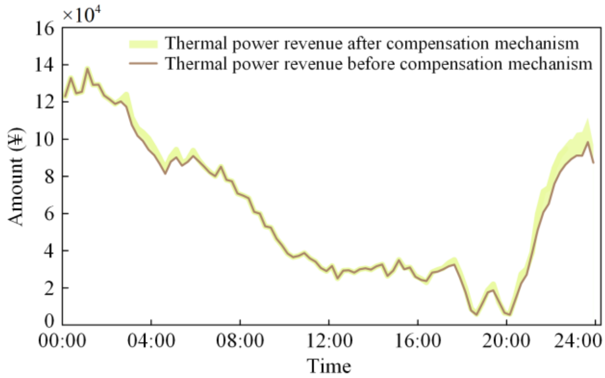

Fig. 15. Comparison of FAS income of TPU on sampling day 1 during non-heating period.

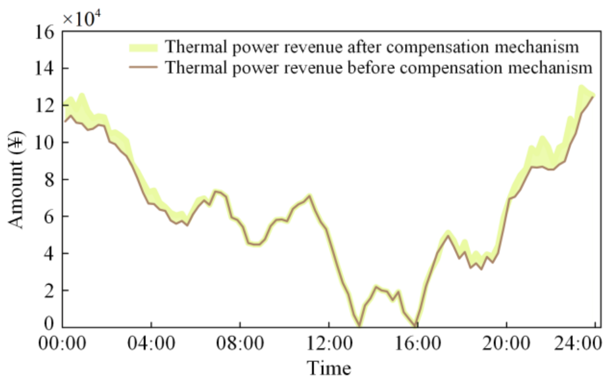

Fig. 16. Comparison of FAS income of TPU on sampling day 2 during non-heating period.

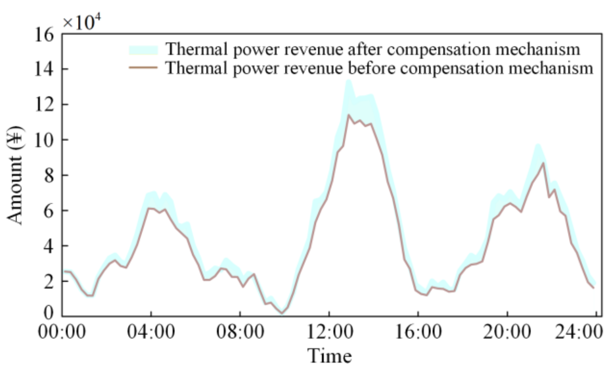

Fig. 17. Comparison of FAS income of TPU on sampling day 3 during heating period.

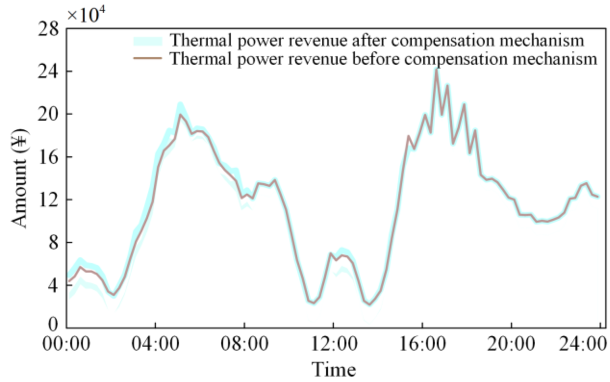

Fig. 18. Comparison of FAS income of TPU on sampling day 4 during heating period.

TABLE VII
COMPARISON OF WIND POWER REVENUE BY SAMPLING DAY (¥)

		Non-heating period		Heating period	
		Day 1	Day 2	Day 3	Day 4
Static mechanism	Wind curtailment	3670.0	3499.1	6243.9	4039.8
	Wind curtailment is not considered	3747.8	3574.0	6374.6	4126.7
Dynamic mechanism	Wind curtailment	3686.5	3508.7	6287.8	4139.6
	Wind curtailment is not considered	3764.9	3583.0	6419.5	4227.6

In summary, under the compensation mechanism proposed in this study, both wind power and TPUs can obtain higher income. The TPUs' income comes mainly from the potential income of flexibility service, while the wind power income comes primarily from the power income brought by the power space transferred by TPUs. This verifies that the compensation mechanism proposed in this study can play a leading role in the market by using economic levers to enhance TPUs' willingness for flexible regulation.

V. CONCLUSION AND POLICY RECOMMENDATIONS

The compensation mechanism for flexibility auxiliary services provides remuneration for the responses of market participants to market incentives. It also offers a means for flexibility providers in the power system to offset external costs generated by ensuring the flexibility of new energy consumption. This mechanism is closely linked to the economic interests of market participants. Therefore, a well-designed flexibility auxiliary services compensation mechanism can effectively guide MPs' behaviors, maximize the effective excavation of flexibility, and ensure the power system's safe and stable operation. At present, the flexibility auxiliary services compensation mechanism used in China to incentivize MPs to provide flexibility is not perfect.

In this study, an analytical framework for designing a flexibility auxiliary services dynamic mechanism is developed to provide an alternative to the current typical static peak shaving auxiliary service compensation mechanism. The time factor considered is integrated into the design model of the compensation mechanism. Based on the current peak shaving auxiliary service compensation mechanism in China, a specific dynamic hierarchical compensation mechanism is given, and its function and effect are analyzed through a case study. The results show that a reasonable compensation mechanism for peak load regulation auxiliary service can effectively ensure the income of thermal power enterprises and encourage them to provide flexibility, thus improving the overall economy and operation efficiency of a power system.

It should be noted that all conclusions are based on the current situation of China's flexibility auxiliary services compensation mechanism. Considering that various units have certain differences, due to different equipment and operational characteristics, and other aspects, the topic of flexibility auxiliary services involves not only peak shaving products but also products such as frequency modulation and the capacity market, which are worthy of further in-depth study. In addition, the framework concept, analytical method, and simulation model proposed in this study are also applicable to market design, considering the participation of other market entities. It is expected that this study can provide methodological guidance for spot market design in China.

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AUTHORS' CONTRIBUTIONS

Yibo Wang and Yifan Wang: theoretical analysis and modeling of the process and performed simulation and experiment to verify the proposed method. Chuang Liu: proposed methods for processing and solving the optimization model. Yuan Fang, Guowei Cai and Weichun Ge: offered help in theory and practice, read and put forward suggestions for the paper. All authors read and approved the final manuscript.

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AVAILABILITY OF DATA AND MATERIALS

Not applicable.

DECLARATIONS

Competing interests: 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 article.

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