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Interaction between balancing market design and market behaviour of wind power producers in China

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ABSTRACT

To fulfil a commitment to reduce greenhouse gas emissions, promoting renewable energy accommodation is a major goal in establishing a spot market in light of China's 2015 electricity market reform. Eight representative provinces with different power supply structures and generation portfolios carry out simulated operations as initial pilot spot markets. The balancing market, a significant section of the spot market that addresses fair transaction settlements to eliminate system imbalance in real time, is diverse among these pilot spot markets. Therefore, effective methodological support is needed to analyse the interaction between balancing market design and participant behaviour considering the market environment in China. Based on the incentive compatibility of the market design with the actual situation in China, this paper assigns wind power producers as market participants, since wind power integration aggravates real-time imbalances due to its natural uncertainty and fluctuation. This study first summarizes the key elements of balancing market design in China that exert great influence on wind power producers; then, an offering strategy model of wind power producers is proposed embedding into the balancing market clearing model to reveal the interactive effect between balancing market design and the behavioural decisions of market participants and to investigate the adequacy of the entire market. Using an example, the effects of key factors on market adequacy and wind power revenue are discussed, including the tolerance margin, programme time unit (PTU) duration, and imbalance pricing mechanism. Finally, corresponding recommendations for balancing market design in China are put forward.

1. Introduction

In September 2015, "Document 9" was issued and signified a new round of reforms of the electricity market centred around establishing electricity spot markets in China, aiming to address a series of problems such as the absence of market trading mechanisms, the lack of market-oriented pricing mechanism, and the difficulties of clean energy accommodation [1]. Subsequent relevant supporting documents made clear that China's electricity market is mainly composed of mid- and long-term transactions and an electricity spot market, and thus, a market-based energy balancing mechanism dominated by mid- and long-term transactions and supplemented by spot transactions will be constructed in a staged manner. Finally, an electricity market that avoids risks through mid- and long-term transactions, discovers prices through the spot market, and includes complete trading products and functions will ultimately be established [2].

China selected eight representative provinces with different power supply and demand structures and generation portfolios as the first batch to carry out pilot projects of the electricity spot market. For example, from the perspective of the power supply structure, by 2018, the following will be true—Shanxi: coal-fired power accounts for 70%, Sichuan: hydropower accounts for 80%, and Gansu: wind and solar power accounts for 42%. From the perspective of the supply and demand balance, Shanxi, Mengxi, Gansu and Sichuan are power-rich provinces, which need to export electricity, while the other four provinces are supposed to import electricity. In the eight pilot provinces where market-oriented reforms have been quickly implemented, electricity spot market simulation operations were initiated in late 2018 and early 2019 to simulate market-oriented operation and allow market participants to become familiar with the processes of spot markets [3]. Guangdong and Shanxi have taken the lead in the settlement stage of the spot market simulation, while the spot markets in other provinces only

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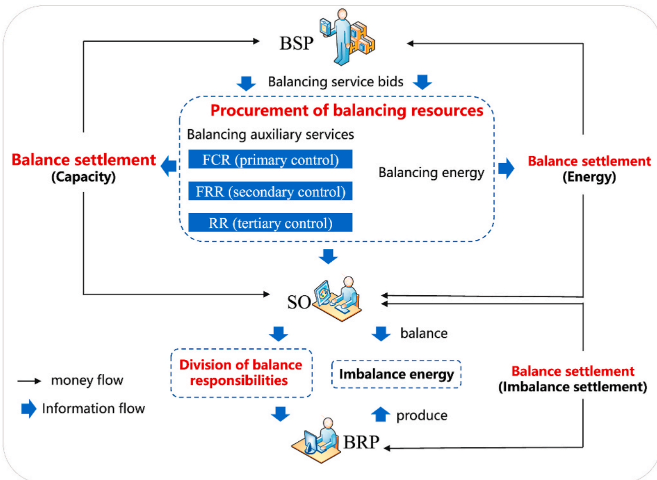

Fig. 1. The operation framework of a balancing market. The operation framework of a balancing market mainly comprise three parts: the procurement of balancing resources, the division of balance responsibilities, and balance settlement.

simulate operation without settlement. At this stage, mid- and long-term electricity bilateral transactions and monthly market trading are still in practice in most provinces in China [4]. The current balancing mechanism and settlement rules of long-term transactions in the eight pilot provinces also vary based on their actual situations. The deviation of monthly transactions refers to **energy** deviation within a settlement duration that is not applicable for the short-term **power** balance in the spot trading stage, which is relatively weak for the market-based balancing mechanism. Therefore, how to explore an appropriate balancing market design approach that can accommodate the diversified balancing needs of each province and smooth the transition from a mid- and long-term energy market to an electricity spot market is of great importance.

As an important component of a spot market, the balancing market plays a physical real-time balancing role, ensuring the power supply and demand balance while detecting price signals for electricity and various ancillary service transactions to facilitate fair and reasonable settlements [5]. Therefore, the design of the balancing market involves complex system engineering. In the early stages of the construction of China's spot market, mid- and long-term contract volumes are expected to comprise a large proportion and to mostly require physical settlements, making operating the balancing market very difficult [6]. The majority of market entities have an insufficient understanding of competitive electricity markets and expectations of guaranteed revenues stemming from the long planned economy history of China, leading to high operational risk in the balancing market. These unique market environments make directly drawing on the experience of existing mature balancing market models for the design of China's energy balancing market difficult. In addition, if China is to meet its targets for renewable electricity generation, a very large wind power and solar power capacity needs to be installed. However, the natural uncertainty and fluctuation of wind power results in substantial reliability defects and brings about great challenges for power system operation, especially for real-time power balancing [7]. Additionally, wind power curtailment is still a serious problem in China (By 2018, the average rate of wind abandonment in China was 7.2%, much higher than the world average [8]), which is partly motivating this new electricity market reform, namely, by promoting wind power accommodation via the establishment of effective market mechanisms [9]. The balancing market designs that have been announced in eight pilot provinces are different and have not been tested in actual market operations. There is currently no effective tool to investigate the impact of balancing mechanism design on the overall market operation and the integration of wind power in the electricity market reform in China. Fabian Ocker and Karl-Martin Ehrhart [10] point out that a well-designed balancing market can mitigate the pressure on the balancing services demand for systems with the increase of renewable energy integration. Therefore, it is imperative to study the design of a balancing market that fits China's market-oriented reform and facilitates wind power integration.

There exist, however, several challenges in designing a balancing market that fits China's market-oriented reform. First, it is crucial to support higher share of variable renewables generation in balancing market design with the energy transition and the increase in flexibility. Second, it is difficult to reach an agreement on the key elements in balancing market design, e.g. the tolerance margin and the imbalance pricing mechanism, which should not be biased toward any market participants, and the fairness and effectiveness of balancing market operation can be ensured. Third, it would be important for market regulators to have approximate estimate of the possible behaviours of market participants, e.g. the wind power producers, so that the incentive compatibility principle in balancing market design is satisfied.

There have been some efforts in the literature to solve the first challenge associated with wind power integration [11–15]. For example, Iain MacGill [11] draws upon experiences of the electricity market in Australian to date to investigate the policy and balancing market design to facilitate wind energy integration. Christoph Weber [12] discusses the liquidity under different market designs, both for day-ahead and for balancing markets, to deal with the inherent fluctuations of wind power output. LeenVandezande et al. [13] propose the framework of balancing market design in Europe considering increasing wind power penetration. However, references [11–15] are mostly focus on the market design adaptation of the original mature electricity market and are not applicable to China, where the spot market has not been fully established.

In solving the second and third challenges associated balancing market design and the corresponding behaviours of market participants, especially for wind power producers, some studies focus on the influence of balancing market design on wind power producers and the offering strategies of wind power producers under different electricity market designs [16–22]. In these researches, wind power producer is assumed to be the price-takers, and the revenue of wind power producer generally consists of two parts: the revenue in the day-ahead market and the imbalance settlement of the balancing market. For example, in Ref. [17], an assessment of imbalance settlement exemptions for offshore wind power in Belgium is offered from the perspectives of regulatory complexity, financial impact and justification. In Ref. [20], the impact of balancing market design on the economics and offering strategies of wind power producers is analysed, and the results show that the imbalance pricing mechanism and balancing responsibility allocation method significantly affect the revenue of wind power producers. However, these authors have either studied how the balancing market design influences the integration of wind power or focused on the optimal market behaviour under a certain set of balancing rules. In other words, these studies have not considered the above two issues as a whole, the interaction of balancing market design and the market behaviour of wind power producer is not well evaluated.

The aforementioned challenges have not been fully addressed in a unified framework, thus designing a balancing market in China that can take into account the interaction between market participants and the market design while guaranteeing the fairness and effectiveness of balancing market operation remains an open question. Therefore, in this paper, to reveal and evaluate the interaction between balancing market design and the behaviours of market participants, here, specifically taking wind power producers as the representatives. We focus on the exploration of a well-designed balancing market that can incentivize market participants to act truthfully to maximize individual profits whilst minimizing the system balancing cost, which is the basis of effective and fair operation of balancing markets. The contributions are summarized as follows:

(1) We propose an analytical framework that integrates wind power producer strategic offerings in the day-ahead market considering the imbalance settlement into the balancing market clearing model based on the current electricity market reform in China. The impacts of the balancing market design on wind power producers are quantitively analysed. Our goal is to investigate whether the interests of the participants in the balancing market, especially wind power producers, are consistent with the established goals of the market designer under different settings of balancing market design elements. That is, the proposed balancing market design can effectively take into account the behaviours of market participants and satisfy the incentive compatibility principle.
(2) Current provincial settlement mechanisms of the monthly market trading in China are compared with each other and a few key elements, e.g. the tolerance margin and penalty factors, are extracted. An offering strategy for wind power producers incorporating the aforementioned key elements is presented to quantify the impacts of balancing market design on wind power producers. The offering strategy of wind power producers is formulated as a two-stage risk-constrained stochastic optimization model in a two-price balancing market, which is embedded in the balancing market clearing model. The corresponding settlement rules of the balancing market derived from the current provincial settlement mechanisms in China.
(3) Some policy recommendations for balancing market design in China are put forward from the aspects of the key elements design of the imbalance settlement in the balancing market (e.g. the tolerance margin, the PTU and the imbalance pricing mechanism) and the transition approach from the monthly trading market to spot market.

The remainder of the paper is structured as follows. Section 2 describes the framework of the balancing market and presents the interactions between balancing market design and behaviours of market participants. The impacts of key balancing market design elements on wind power producers are discussed in Section 3. Section 4 develops a balancing market clearing model embedded with strategic offerings of wind power producers to quantitatively evaluate the interactions. Simulation results are provided in Section 5 and Section 6 presents the conclusion and policy recommendations for balancing market design in China.

2. Balancing market framework and overview of balancing mechanism in China

This section first briefly introduces the framework of the balancing market as well as the interaction between balancing market design and behaviours of market participants. Then based on the electricity market reform situation in China, the overview of balancing mechanism, especially the settlement rules are presented.

2.1. Balancing market framework

The system operation services that maintain the supply and demand balance of the power system are known as balance management, and the balancing market includes the institutional arrangements that establish market-oriented balance management in a competitive electricity market [23]. A balancing market mainly consists of the following three types of market members: (1) the system operator (SO) responsible for the operation of the entire energy system, including organizing and operating the balancing market and maintaining the power balance of the system; (2) the balancing service provider (BSP) responsible for providing various balancing services in the real-time operation phase of the system to ensure the real-time supply and demand balance of the system, which is the main entity of settlements for balancing services; and (3) the balance responsible party (BRP), which is the party responsible for market imbalances and is the main entity of imbalance settlement [24].

The operation framework of a balancing market is shown in Fig. 1, mainly comprising three parts: the procurement of balancing resources, the division of balance responsibilities, and balance settlement. The procurement of balancing resources refers to the management process of the SO in procuring and scheduling various balancing services provided by the BSPs, wherein the balancing services include the reserve capacity and balancing energy. The division of balance responsibilities refers to determining the imbalance volume required to be accepted in each period during the real-time operation phase based on the deviation between the actual energy generation/consumption of the BRP in each programme time unit (PTU) and the next-day operation planned value that the BRP submitted day-ahead to the SO. Accurate division of the balance responsibilities helps each BRP to be as consistent as possible with the energy generation/consumption plan to lower the system balancing cost.

Balance settlement consists of two aspects. One aspect is the settlement of procured balancing services of BSPs, which corresponds to the balancing cost of the system, and the other aspect is the settlement of the energy schedule deviations generated by BRPs in each PTU, which is also called **imbalance settlement**, corresponding to the allocation of the system balancing cost and is an important part of balancing market settlement. The imbalance settlement includes two parts, namely, the division of the imbalance volume and the determination of the imbalance price. Penalty imbalance prices are mostly used in imbalance settlement, which incentivizes BRPs to offer truthfully and makes the BRPs strictly comply with the energy schedule plan in real-time operation, thereby minimizing the system imbalance and reducing the system balancing cost.

Balance settlement can be considered the development of a set of “ex post” balancing market rules, including balance responsibility division, PTU duration, and a pricing mechanism for the imbalance volume. Under this set of rules, market participants are able to choose the offering strategy that is the most beneficial to themselves, that is, the rules of balance settlement guide the behaviour of market participants. However, as inconsistency between the interests of individual market participants and the system operator is common, a well-designed settlement mechanism can incentivize each participant to maximize individual profits whilst achieving minimization of the system balancing cost. In this way, market participants can offer truthfully regarding the energy quantities and prices, and the actual cost of balancing services can be revealed. **Therefore, the design of the balance settlement rules is of vital importance in balancing market design.** The interaction between balancing settlement rules and the market behaviours of

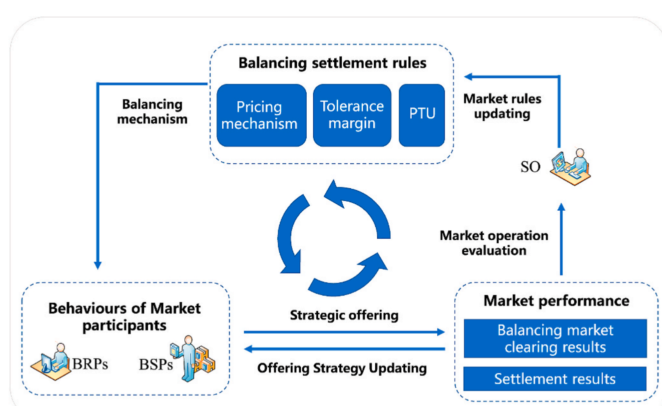

Fig. 2. Interaction between balancing settlement rules and the behaviour of market participants. In a balancing market, strong interaction exists between market design and behaviours of market participants.

market participants is shown in Fig. 2. First, the SO develops a set of balance settlement rules, including the division of the balance responsibility and an imbalance-related penalty mechanism. Based on this set of rules, market participants can choose the most beneficial market behaviours. In the long-term operation process, market participants will continuously optimize and adjust their market behaviours based on the overall market results as well as their own revenues, while the SO will evaluate the market performances and make necessary improvements to the balance settlement rules to improve the market efficiency.

2.2. Overview of balancing mechanism in China

There is no real spot market for electricity in China at present. Instead, mid- and long-term electricity transactions and the provincial monthly market trading are still in practice in most provinces in China. In this paper, we mainly focus on the settlement part of the balancing market, which lies at the intersection of financial transactions and physical electricity exchanges and plays a crucial role in delivering the monetary results to market participants. As a result, we will mainly introduce the current settlement mechanisms of the provincial monthly market trading in China. Note that the biding and auction process of the provincial monthly market trading as well as the market entry and exit are outside the scope of this paper. Interested readers can find the detailed introduction of the electricity market reform implementation in Ref. [9].

For market participants with flexibility resources (BSPs), bid prices for additional power output (up-regulation) and down-regulation in real-time balancing can be submitted when monthly transactions end. The submitted prices are used to determine the merit order in real-time balancing when the system needs up- or down-regulation services. For market participants with balance responsibilities (BRPs), the deviation between the actual output or consumption and the monthly contractual volume needs to be settled through the imbalance settlement process when monthly transactions end. The imbalance settlement generally follows a rule of “Daily Accounting, Monthly Setting, and Liquidating [4]”, and corresponding rules mainly consist of the following two parts:

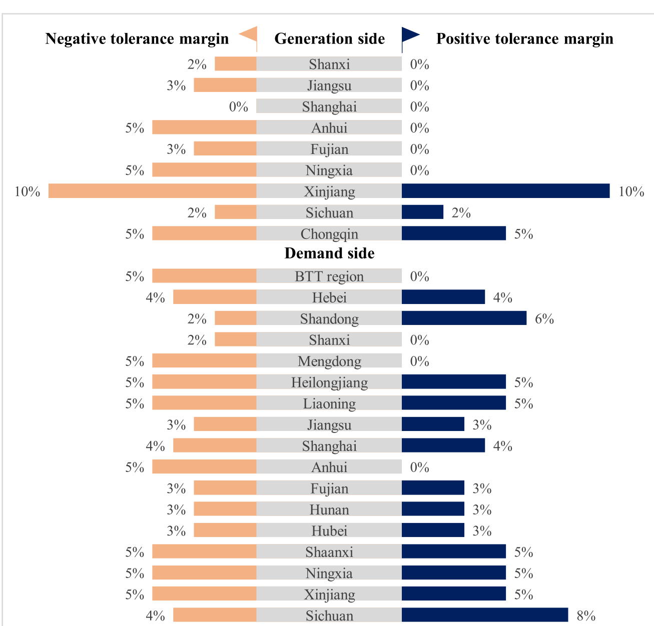

Fig. 3. The tolerance margin of generation side and demand side in provincial electricity market. The dark and light parts in the figure represent positive and negative tolerance margin respectively.

Table 1
The benchmark price in the penalties at provincial level of China.

Benchmark price in the penalty	Provinces of China
Weight average price of bilateral transactions	**Gansu**, Guizhou, **Shandong**, Beijing, Tianjin
Coal-fired unit benchmark tariffs/catalog price	Jilin, Hebei, Qinghai, Henan, Jiangsu, **Zhejiang**, **Fujian** Inner Mongolia(**Mengxi**, Mengdong)
Fixed penalty price	Shaanxi, Hubei
Up- and down- regulation price	Xinjiang, Yunnan, **Sichuan**, Hunan, Jiangxi, **Shanxi**
Monthly centralized bidding market prices	**Guangdong**, Guangxi, Heilongjiang, Liaoning

1) Tolerance margin: the tolerance margin is adopted in most provinces to exempt part of the balance responsibility in order to encourage market participants to actively participate in market transactions. The tolerance margin of generation side and demand side in provincial electricity market within the operation area of State Grid Corporation of China are shown in Fig. 3.

As shown in Fig. 3, the tolerance margin varies from province to province, but on the whole, the tolerance margin of negative deviation is generally greater than that of positive deviation for both generation and demand side. This is mainly because the higher negative tolerance margin is conducive to encouraging market participants to participate in the monthly trading market.

2) Imbalance penalty prices: the deviation beyond the tolerance margin will incur penalties, as there is no spot market to give a price signal, the penalty price is generally given in advance based on a benchmark price, e.g. the highest transaction price in monthly market trading, or the weighted average price of contract prices and coal-fired unit benchmark generation tariffs. The benchmark price in the penalties at provincial level of China are presented in Table 1 and the bold parts refers to the pilot spot market provinces.

As illustrated in Table 1, China’s electricity market-oriented reform is put into trial operation in eight representative provinces. However, due to various problems in each province, there are various transaction settlement rules. Due to the difference of power system and market-oriented degree in each province, the benchmark price in the penalties in balancing mechanism are also varying. Although there are still some provinces where the penalties are based on fixed prices or benchmark tariffs, the balancing mechanism in many provinces have already had the market-oriented component in the penalty prices. At present, the spot market pilot is on trial, and the renewable generation has been permitted to participate in the spot market pilot as the priority unit in some provinces, but the well-functioning market-based balancing mechanism is still far from practical implementation. How to design a reasonable balancing market, especially the corresponding settlement mechanism, considering the output uncertainty and environmental benefits of renewable generation needs further exploration.

3. The impacts of balancing market design on wind power producers

As shown in Fig. 2, the design of a balancing market affects the behavioural decisions of the market players and the efficiency of the entire market. To achieve an incentive compatibility balancing market design, the influence of balancing design elements on market participants should be considered. Volatile renewable generators such as wind power producers are one of the major BRPs in a balancing market due to the inherent uncertainty and volatility. Therefore, in this section, based on the aforementioned balancing market framework, we take wind power producers as the representatives of BRPs to explore the interaction between balancing market design and the behaviour of wind power producers from the following aspects.

3.1. Balancing market operation plan

The balancing market operation plan is primarily the organizational process and the corresponding time settings of the marketization of various balancing services, including the offers of various balancing services, the frequency and time units corresponding to the clearing, and the final market gate closure time.

In a balancing market operation plan, the opening and closure times for offers of balancing services from BSPs to the SO, the frequency of balancing market clearance and the energy schedule submission of BRPs significantly affect the market performance of a balancing market. This is because the above balancing planning elements exert an influence on the market behaviours of both BSPs and BRPs and thus may affect the balancing resource price and imbalance price, ultimately affecting the revenue of market participants. Additionally, as operation time approaches, the prediction accuracy of wind power significantly improves, so before the final gate closure time, especially for wind power producers, BRPs are able to correct their output plans based on the latest predictive results to reduce real-time output imbalances, not only improving the overall operational stability of the market and reducing the balancing cost but also promoting renewable energy consumption and improving the market profits of wind power producers. Therefore, if the gate closure time of the balancing market is close to real time, the real-time imbalance volume will be relatively low in general. However, late market gate closure times shorten the preparation time of each market participant after the dispatching order is issued, likely increasing the corresponding market operating cost [24]. Thus, an appropriate balancing market operation plan is particularly important for encouraging wind power producers to participate in the market.

3.2. PTU

The PTU refers to the balance settlement period and can also be considered as the settlement frequency. Currently, the PTU is usually set to 1 h, 30 min or 15 min in different countries.

The PTU can be essentially understood as a way of dividing the balance responsibility between the SO and BRP. The SO is responsible for the momentary imbalance intra-PTU, which is defined as a function of both the frequency deviation and the deviation from the agreed cross-border exchange, while the BRPs are only concerned about the energy content of their trade in a PTU and are only responsible for the cross-PTU energy imbalance. That is, for BRPs, positive and negative imbalances in the same PTU can be offset, and the offset part does not need to assume balance responsibility. Due to the uncertain nature of variable renewable power, it is particularly important to reduce the partial balance responsibilities through this offset effect. Accordingly, the PTU length has a great impact on the imbalance settlement results. In general, smaller PTUs will give stronger incentives for BRPs to balance their energy portfolio, as deviations from scheduled energy exchanges in a PTU even out to a lesser degree. However, a smaller PTU also mitigates the effort of the SO and may aggravate the phenomenon of internal balancing, i.e., the BRP may keep balancing resources for individual balancing rather than providing balancing services to the SO, which can reduce the utilization efficiency as well. Therefore, how to determine an appropriate PTU length is of great importance in balancing market design.

3.3. Imbalance settlement scheme

The imbalance pricing mechanism is applied to determine the imbalance price for balancing cost allocation. Currently, two pricing mechanisms (single pricing and dual pricing) are widely used. Under a single pricing mechanism, real-time deviations of BPRs are settled at a unique regulation price, regardless of the imbalance direction of both BRPs and the system. In general, the regulation price is higher than the day-ahead price if the system needs up-regulation. In contrast, the regulation price is lower than the day-ahead price when the system has a surplus of power production. Under a two-price pricing mechanism, BRPs are settled at different prices depending on the imbalance direction. Deviations that are in the same direction as the system imbalance, a situation which actually aggravates the imbalance of the system, are settled at the regulation price of the balancing market. Conversely, imbalances opposite to the system are settled at the day-ahead price. The dual pricing mechanism can be expressed as follows:

$$\lambda^{-} = \begin{cases} \lambda_{RT}, & \text{if} \quad \lambda_{RT} \geq \lambda_{DA} \\ \lambda_{DA}, & \text{if} \quad \lambda_{RT} < \lambda_{DA} \end{cases} \tag{1}$$

$$\lambda^{+} = \begin{cases} \lambda_{DA}, & \text{if} \quad \lambda_{RT} \geq \lambda_{DA} \\ \lambda_{RT}, & \text{if} \quad \lambda_{RT} < \lambda_{DA} \end{cases} \tag{2}$$

where λ^{+} and λ^{-} denote the positive imbalance price and negative imbalance price, respectively. λ^{RT} and λ^{DA} denote the clearing prices of balancing and day-ahead markets, respectively. The dual pricing mechanism has been widely used in many countries in Europe, such as in Nordic countries and the Netherlands.

The imbalance settlement scheme, as an important part of a balancing market, directly affects the final income and market behaviours of the relevant market participants. As one of the main sources of system imbalances, the impact of the imbalance settlement scheme on wind power producers mainly comes from the following aspects.

One aspect is the imbalance pricing mechanism. Under a single pricing mechanism, the imbalance cost is low, but this mechanism lacks sufficient incentives for BRPs to minimize the imbalance of themselves. Although the dual pricing mechanism may generate a certain imbalance penalty cost, compared with the single pricing method, this pricing mechanism eliminates arbitrage opportunities for BRPs. In addition, the dual pricing mechanism is more in line with the current long-term transaction settlement rules in China, under which both side imbalances are settled at the regulation price of the balancing penalty prices based on variable penalty factors.

Another aspect is the tolerance margin, which refers to a specific support mechanism exempting certain kinds of BRPs from their balance responsibilities, and this support mechanism has been enforced in some European countries and in China for long-term transactions. An appropriate tolerance margin is of vital importance—situations without a tolerance margin or with a low tolerance margin may not be able to support wind power producers and other BRPs participating in the spot market, especially in China, where the construction of the spot market just started. However, an excessive tolerance margin may harm the incentives to invest in ways to reduce imbalance costs, such as improving forecasting accuracies, offering strategies or the incorporation of flexible portfolios, and other BRPs will actually suffer higher balancing costs, which can be considered as a kind of cross-subsidization.

4. .Balancing market clearing model embedded with the offering strategy of wind power producers

To quantitatively assess the effect of each of the above design elements on the market clearing results, system balancing cost, and especially market behaviours and revenue of wind energy producers in the balancing market, given that a balancing market has not been constructed in China, it is necessary to construct a model capable of evaluating the interaction between balancing market design and the behaviour of wind power producers.

Therefore, a balancing market clearing model embedded with strategic offerings of wind power producers is established, and we take the perspective of a wind power producer in a two-settlement electricity market. The wind power producer aims to maximize its profits from offering in day-ahead markets while considering the imbalance settlement in the balancing market. In addition, the energy deviation of wind power producers in the balancing market is also obtained from the strategic offering strategy, in which the balance settlement rules and their output uncertainty are taken into account.

4.1. Model assumptions

For the brevity of the mathematical model, we propose the following assumptions:

1) Without the loss of generality and considering the current settlement rules for mid- and long-term trading rules of various provinces in China, in this paper, an imbalance pricing mechanism based on dual pricing is applied, in which both positive and negative imbalance volumes are settled with penalty prices.
2) Considering that China is currently in the early stage of spot market construction and the market operations may not be sufficiently stable, in general, a relatively stable balance between supply and demand has been reached at each time period after the clearing of the day-ahead market, and the balancing market is essentially intended to solve the deviation from this balance, which is more prone to extreme situations. Therefore, we assume that the imbalance prices are based on the day-ahead market price, are not linked to the clearing price of the balancing market, and are adjusted through the positive and negative imbalance price penalty factors.
3) The BSP only submits a single-block offer, including the up- and down-regulation power that can be provided in each period and the corresponding price. The selected balancing services are settled at the marginal price of the balancing market.
4) Only the imbalance caused by the wind power producer is considered in the proposed balancing market clearing model, while the uncertainty of the demands is neglected. The uncertainty of the wind power is characterized by a series of scenarios based on prediction data. Considering the relatively small capacity, the wind power producer is assumed as a price-taker in the day-ahead market and submits non-priced (quantity-only) offers.
5) To make the offering strategy model of the wind power producer more realistic, the risk preferences of wind energy providers are considered, and the risk preference coefficient β is used to measure the relationship between the total revenue of the wind power producer and the risk value of revenue changes after considering imbalance settlement.

4.2. Balancing market clearing model

The objective function of the balancing market clearing model is intended to minimize the balancing cost for the system, in which up- and downregulation offers of BSPs and the imbalance volume of wind power producers are considered. The clearing model in time slot t can be represented as follows:

$$\min \sum_{i\in\Phi^{\mathrm{BSP}}} \left(C^U_{B,i,t}P^U_{B,i,t} - C^D_{B,i,t}P^D_{B,i,t}\right) \tag{3}$$

$$\sum_{i\in\Phi^{\mathrm{BSP}}} \left(P^U_{B,i,t} - P^D_{B,i,t}\right) = -P^{\mathrm{WPP}}_{im,t} \tag{4}$$

$$0 \le P^U_{B,i,t} \le P^U_{B,i,\max} \tag{5}$$

$$0 \le P^D_{B,i,t} \le P^D_{B,i,\max} \tag{6}$$

$$P^{\mathrm{WPP}}_{im,t} = P^{\mathrm{WPP}}_{t} - P^{\mathrm{WPP}}_{DA,t} \tag{7}$$

where $C^U_{B,i,t}$ and $C^D_{B,i,t}$denote the up- and down-regulation price offers by BSP i in time slot t and $P^U_{B,i,t}$ and $P^D_{B,i,t}$ denote the selected up- and down-regulation energy offers by BSP i in time slot t. $P^U_{B,i,max}$ and $P^D_{B,i,max}$ denote the maximum level of up- and down-regulation for BSP i. P^{WPP}_{t} and $P^{\mathrm{WPP}}_{im,t}$ denote the actual output and energy deviation of wind power producer. $P^{\mathrm{WPP}}_{DA,t}$ is the energy offer of the wind power producer in time slot t, which is obtained from the offering strategy model in Section 3.3. Constraints (4)–(6) are the power balance constraints and limit the regulation offers of BSPs. In (7), the energy deviation of the wind power producer is calculated according to the actual output and energy offers in the day-ahead market.

4.3. Offering strategy of the wind power producer

The offering strategy of wind power producers can be formulated via the following two-stage risk-constrained stochastic optimization model.

4.3.1. Objective function

$$\max \; R_{DA} + R_{IM} + \beta \mathrm{CVaR} \tag{8}$$

The objective function to be maximized includes the following three parts: the profits in the day-ahead market, R_{DA}, the income from imbalance settlements, R_{IM}, and the conditional variance at risk (CVaR) of the profit multiplied by the risk preference coefficient $\beta \in [0, \infty)$. The risk preference coefficient enforces the tradeoff between the expected profit and risk in such a way that the higher value of β, the more risk averse is the wind power producer in offering. Therefore, if the wind power producer is risk-neutral, the value of β is 0.

The profits of wind power producers in the day-ahead market R_{DA} can be presented as follows:

$$R_{DA} = \sum_{t\in\Phi^t} \lambda_{DA,t} P^{\mathrm{WPP}}_{DA,t}, \quad \forall t, \tag{9}$$

where $\lambda_{DA,t}$ denotes the market price of day-ahead market in time slot t.

As shown in Fig. 4, the income from imbalance settlement R_{IM} consists of two parts: 1) the imbalance within the tolerance margin and 2) the imbalance beyond the tolerance margin, which can be formulated as a piecewise function:

$$R_{IM} = \begin{cases} \sum_{t\in\Phi^t}\sum_{s\in\Phi^s} \pi_s\left(-\lambda^-_{t,0}\gamma^- P^{\mathrm{WPP}}_{s,t} + \lambda^-_{t,1} P^{\mathrm{WPP-}}_{s,t,1}\right), & \overline{P} \le P^{\mathrm{WPP}}_{s,t} - P^{\mathrm{WPP}}_{DA,t} \\ \sum_{t\in\Phi^t}\sum_{s\in\Phi^s} \pi_s\left(-\lambda^-_{t,0} P^{\mathrm{WPP-}}_{s,t} + \lambda^+_{t,0} P^{\mathrm{WPP+}}_{s,t}\right), & \underline{P} < P^{\mathrm{WPP}}_{s,t} - P^{\mathrm{WPP}}_{DA,t} \le \overline{P} \\ \sum_{t\in\Phi^t}\sum_{s\in\Phi^s} \pi_s\left(\lambda^+_{t,0}\gamma^+ P^{\mathrm{WPP}}_{s,t} + \lambda^+_{t,1} P^{\mathrm{WPP+}}_{s,t,1}\right), & P^{\mathrm{WPP}}_{s,t} - P^{\mathrm{WPP}}_{DA,t} < \underline{P} \end{cases} , \forall s, t, \tag{10}$$

where π_s denotes the probability of scenario s and $\lambda^+_{t,0}$ and $\lambda^-_{t,0}$ denote the positive imbalance price and negative imbalance price within the tolerance margin, respectively. $\lambda^+_{t,1}$ and $\lambda^-_{t,1}$ denote the positive imbalance price and negative imbalance price beyond the tolerance margin, respectively. $P^{\mathrm{WPP+}}_{s,t}$, $P^{\mathrm{WPP-}}_{s,t}$, $P^{\mathrm{WPP+}}_{s,t,1}$ and $P^{\mathrm{WPP-}}_{s,t,1}$ denote the total positive and negative imbalances of the wind power producer and the imbalances beyond the tolerance margin, respectively. γ^+ and γ^- denote the positive and negative tolerance margin, respectively.

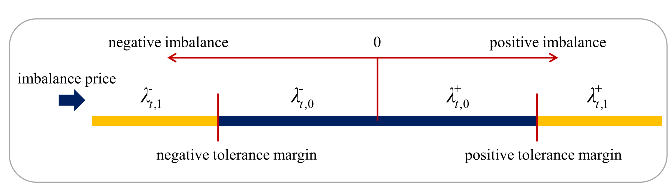

Fig. 4. The income from imbalance settlement of wind power producers. The income from imbalance settlement consist of two parts: the imbalance within the tolerance margin and (the dark parts) the imbalance beyond the tolerance margin (the light parts).

Specifically, to linearize the piecewise function (10), two auxiliary binary variables $\Psi_{s,t}^{+}$ and $\Psi_{s,t}^{-}$ are introduced to represent the status of imbalance, which are equal to 1 when positive and negative imbalances are higher than the tolerance margin, respectively. The income from imbalance settlement can be reformulated as follows:

$$R_{IM} = \sum_{t\in\Phi^t}\sum_{s\in\Phi^s} - \pi_s\lambda_{t,0}^{-}((1-\psi_{s,t}^{-})P_{s,t}^{\mathrm{WPP}-} + \gamma^{-}P_{s,t}^{\mathrm{WPP}}\psi_{s,t}^{-}) + \pi_s\lambda_{t,0}^{+}((1 - \psi_{s,t}^{+})P_{s,t}^{\mathrm{WPP}+}) + \gamma^{+}P_{s,t}^{\mathrm{WPP}}\psi_{s,t}^{+}) + \pi_s(\lambda_{t,1}^{-}P_{s,t,1}^{\mathrm{WPP}-} + \lambda_{t,1}^{+}P_{s,t,1}^{\mathrm{WPP}+}), \forall s,t, \tag{11}$$

4.3.2. Constraints

(1) Imbalance equality constraints

$$P_{s,t}^{\mathrm{WPP}} - P_{DA,t}^{\mathrm{WPP}} = P_{s,t}^{\mathrm{WPP}-} + P_{s,t}^{\mathrm{WPP}+}, \forall s,t, \tag{12}$$

$$0 \le P_{DA,t}^{\mathrm{WPP}} \le P_{\max}^{\mathrm{WPP}}, \forall t, \tag{13}$$

$$-P_{\max}^{\mathrm{WPP}} \le P_{s,t}^{\mathrm{WPP}-} \le 0, \forall s,t, \tag{14}$$

$$0 \le P_{s,t}^{\mathrm{WPP}+} \le P_{s,t}^{\mathrm{WPP}}, \forall s,t, \tag{15}$$

$$P_{s,t,1}^{\mathrm{WPP}-} = P_{s,t}^{\mathrm{WPP}-}\psi_{s,t}^{-} \ + \ \gamma^{-}P_{s,t}^{\mathrm{WPP}}\psi_{s,t}^{-}, \forall s,t, \tag{16}$$

$$P_{s,t,1}^{\mathrm{WPP}+} = P_{s,t}^{\mathrm{WPP}+}\psi_{s,t}^{+} \ - \ \gamma^{+}P_{s,t}^{\mathrm{WPP}}\psi_{s,t}^{+}, \forall s,t, \tag{17}$$

$$\psi_{s,t}^{-} + \psi_{s,t}^{+} \le 1, \forall s,t. \tag{18}$$

Constraint (12) calculates the positive and negative output deviation bias of the day-ahead offer. Constraint (13) limits the day-ahead offer power to its capacity $P_{i,max}^{\mathrm{WPP}}$. Constraints (14) and (15) present the imbalance limits of wind power producers. In (16)–(18), positive and negative energy deviations beyond the tolerance margin are calculated.

(2) CVaR constraints

For a given confidence level $\alpha \in (0,1)$, the CVaR is defined as the expected value of the profit smaller than the (1-α)-quantile of the profit distribution. In this paper, the CVaR is used to measure the risk of market revenue changes of wind power producers due to the uncertainty of market prices and wind power output. The CVaR constraints can be presented as follows:

$$\mathrm{CVaR} = \xi - \frac{1}{1-\alpha}\sum_{s\in\Phi^s}\pi_s\eta_s \ \forall s \tag{19}$$

$$\xi - (R_{DA} + R_{IM}) \le \eta_s \ \forall s, \tag{20}$$

$$\eta_s \ge 0, \ \forall s, \tag{21}$$

where ξ is an auxiliary variable, which is also known as the value at risk (VaR), and η_s denotes the difference between the market revenue and VaR in scenario s.

4.4. Solution method

The aforementioned balancing clearing model embedded with the offering strategy model needs to be solved sequentially. That is, the offering strategy model of wind power producers is solved first, and then the day-ahead offer $P_{DA,t}^{\mathrm{WPP}}$ can be obtained. Then, the balancing market clearing model can be solved, producing the final market clearing result. In addition, the previous formulation is non-linear due to being the product of two variables, $P_{s,t}^{\mathrm{WPP}-}\Psi_{s,t}^{-}$ and $P_{s,t}^{\mathrm{WPP}+}\Psi_{s,t}^{+}$ in constraints (16)–(17), and a linearization method has been proposed in Ref. [25], involving replacing non-linear terms with two new continuous variables ($D_{s,t}$, $U_{s,t}$) and a set of constraints:

$$-P_{s,t}^{\mathrm{WPP}+} + D_{s,t} \le 0, \ \forall s,t, \ \forall s,t, \tag{22}$$

$$P_{s,t}^{\mathrm{WPP}-} - U_{s,t} \le 0, \forall s,t, \forall s,t, \tag{23}$$

$$-P_{s,t}^{\mathrm{WPP}+} - D_{s,t} + P_{s,t}^{\mathrm{WPP}}\psi_{s,t}^{+} \le P_{s,t}^{\mathrm{WPP}}, \forall s,t, \forall s,t, \tag{24}$$

$$-P_{s,t}^{\mathrm{WPP}-} + U_{s,t} + P_{\max}^{\mathrm{WPP}}\psi_{s,t}^{-} \le P_{\max}^{\mathrm{WPP}}, \forall s,t, \ \forall s,t, \tag{25}$$

$$-U_{s,t} \le P_{\max}^{\mathrm{WPP}}\psi_{s,t}^{-}, \forall s,t, \tag{26}$$

$$D_{\omega t} \le P_{s,t}^{\mathrm{WPP}}\psi_{s,t}^{+}, \forall s,t. \tag{27}$$

Thus, the objective function (3) and the constraints (4)–(7) constitute a linear programming problem. The stochastic programming model consisting of the objective function (8) and the constraints (12)–(27) is a mixed integer linear optimization problem.

5. Case studies

Case studies are performed using MATLAB R2016a and CPLEX 12.4 [26]. To better illustrate the interaction between wind power producers and balancing market design, a balancing market with 5 BSPs and a wind power producer is considered to simulate the balancing market clearance of a certain operating day. Generation data of BSPs are shown in Table 2. The wind data comes from the NREL database, and we generate 300 trajectories for the outputs of wind power producers and keep the 20 most representative [27]. We adopt 15 price scenarios for the day-ahead scenario, which are derived from Ref. [28]. Except for special instructions, the confidence level of the CVaR $\alpha = 0.95$, and the risk preference coefficient of the wind power producer $\beta = 1$.

5.1. Scenario settings

Based on the various imbalance settlement rules of different provinces/regions in China in the early stages of the electricity spot market, we set up three scenarios with different imbalance pricing rules. On this basis, we compared and analysed various design elements (**tolerance margin, imbalance pricing mechanism, and PTU**) of a balancing market through market performance indicators such as the system balancing cost, market behaviours of market participants and net settlement sum. The representative rules of each scenario are presented in Table 3, where λ_{Avg} denotes the load-weighted average day-ahead market prices.

5.2. Impact of the tolerance margin on the market adequacy

To study the impact of **different tolerance margins** on the **operation of a balancing market**, we obtained balancing market clearing results under different wind power prediction accuracies (15% and 25%) and tolerance margins, as shown in Fig. 5. The points on the line represent the proportions of imbalance cost relative to the total revenue of the wind power producer, and the tolerance margin refers to the upper and lower limits of the exemption interval of balance responsibility.

As seen, with the increase of the tolerance margin, the proportion of the imbalance cost to wind power producers relative to the total revenue gradually decreases, and the system position gradually changes from over-supply (in which downregulation is needed) to a high level of under-supply (in which significant upregulation is needed). In particular, when the tolerance margin is 20%, the required upregulation is approximately 10% of the predicted wind power output, indicating that the day-ahead offer of the wind power producer significantly exceeds the predicted output (110%), and the wind power producer is considered over-contract in the day-ahead market. This is because when the tolerance margin is zero or relatively low, the offering strategy of the

Table 2
The bidding data of balancing service providers.

	Bids ($/MWh)												Regulation limit (MW)	
	1-4		5-8		9-12		13-16		17-20		21-24			
BSP	$C^U_{B,i}$	$C^D_{B,i}$	$C^U_{B,i}$	$C^D_{B,i}$	$C^U_{B,i}$	$C^D_{B,i}$	$C^U_{B,i}$	$C^D_{B,i}$	$C^U_{B,i}$	$C^D_{B,i}$	$C^U_{B,i}$	$C^D_{B,i}$	$P^U_{B,i,\max}$	$P^D_{B,i,\max}$
1	22.0	19.9	22.9	20.7	34.4	31.1	48.2	43.6	53.2	48.1	32.7	29.6	100	100
2	23.1	18.9	24.0	19.7	36.1	29.5	50.6	41.5	55.8	45.7	34.3	28.1	100	100
3	24.3	18.0	25.2	18.7	37.9	28.1	53.2	39.4	58.6	43.4	36.1	26.7	100	100
4	25.5	17.1	26.5	17.7	39.8	26.7	55.8	37.4	61.5	41.2	37.9	25.4	100	100

Table 3
Scenario settings.

Scenario number	Benchmark prices	Positive penalty factors	Negative penalty factors
1 (base scenario)	λ^{DA}	-0.2	+0.2
2	λ_{Avg}	-0.2	+0.2
3	λ^{DA}	-0.15	+0.25

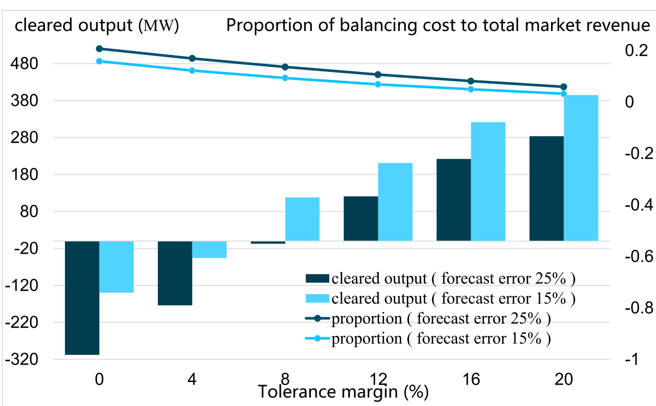

Fig. 5. Balancing market clearing results under different tolerance margins. The points on the line represent the proportions of imbalance cost relative to the total revenue of the wind power producer, and the tolerance margin refers to the upper and lower limits of the exemption interval of balance responsibility.

wind power producer is conservative, and as the tolerance margin increases, the wind power producer chooses to submit a radical offer that exceeds the output prediction to maximize profits because the wind power producer needs to not assume the balance responsibilities for the energy deviation within the exemption interval.

In addition, by comparing the balancing market clearing results under different forecast errors, the system balancing cost is negatively correlated to the prediction error of wind power if the tolerance margin is larger than 8%. This is because the wind power producer deliberately chooses a more conservative offering strategy under a higher prediction error for risk aversion, and as the wind power prediction accuracy increases, the wind power producer is able to over-contract in the day-ahead market to earn higher profits by making better use of the tolerance margin, resulting in a higher system balancing cost. This phenomenon is even more profound when the tolerance margin is larger.

Since the wind power forecasting error is closely correlated with the time scale, the operation plan of the balancing market determines the forecasting error faced by wind power producers in day-ahead offerings to some extent. For different wind power forecasting errors, an appropriate tolerance margin helps reduce the total balancing cost of the system. As shown in Fig. 5, the system balancing costs are relatively low under a tolerance margin of 8% for a large prediction error scenario and

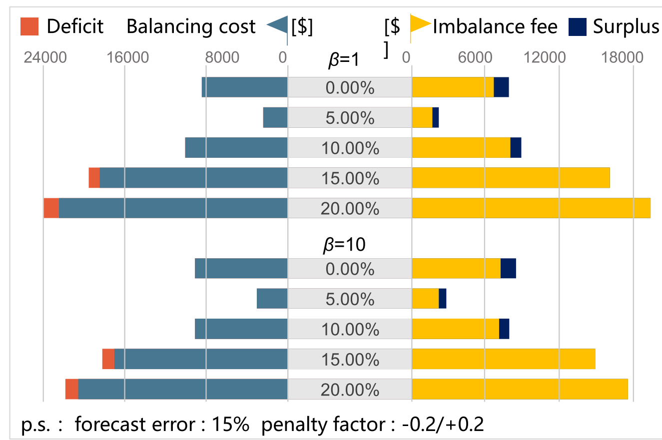

Fig. 6. Balance account surplus and deficit under different tolerance margins. The penalty factor −0.2/+ 0.2 indicate that the positive and negative imbalance prices are 80% and 120% of the benchmark prices, respectively.

a tolerance margin of 4% for a small prediction error scenario.

Given that the tolerance margin is essentially intended to exempt the relevant BRP from the balance responsibility, it may have an impact on the balancing cost allocation. According to the mechanism design theory, a well-designed imbalance settlement mechanism should identify the different deviations of BRPs and allocate the appropriate balancing cost to them, including renewable generators. Here, we take the perspective of a wind power producer to explore whether the imbalance cost paid to the SO can cover the system balancing cost. The surplus and deficit of the balance account under different tolerance margins are shown in Fig. 6, and different market conditions are distinguished through risk preference factors.

Fig. 6 shows that the balance account starts to have a deficit when the tolerance margin is increased to 15%, and the deficit increases with increasing tolerance margins. This result mainly occurs because when the tolerance margin is too large, the system balancing cost significantly increases due to the strategic offering of the wind power producer, as

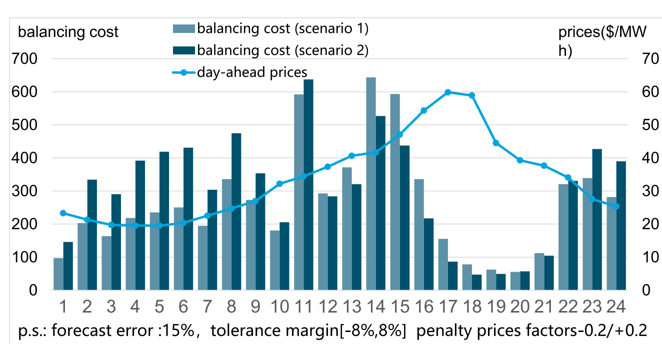

Fig. 7. Balancing costs under different penalty prices. The points on the line represent the day-ahead prices of each period, and the histogram represents the balancing cost of each duration based on scenarios 1 and 2, respectively.

indicated in Fig. 5, while the tolerance margin reduces the balance responsibilities of the wind power producer to a greater extent, eventually leading to a deficit in the balance account.

Additionally, as seen in Fig. 6, as the risk preference factor increases (that is, as the wind power producer becomes more risk-averse and may choose a more conservative offering strategy), both the imbalance cost to the wind power producer and the balancing cost of the system decrease slightly. In particular, the balance account deficit under a high tolerance margin is eased. In addition, the balance account surplus significantly increases when the tolerance margin is small, especially at 0. This is because the wind power producer is tending to choose an overly conservative offering strategy without the support of a tolerance margin, which in turn increases the imbalance, and the balance account surplus increases. This result is also consistent with the balancing market clearing results shown in Fig. 5.

5.3. Impact of the imbalance pricing mechanism on the balancing cost

Fig. 7 shows the balancing cost of each duration under different imbalance pricing mechanisms based on scenarios 1 and 2, respectively. Additionally, the corresponding day-ahead prices of each period are also shown in Fig. 7 to facilitate comparison. As seen, the balancing cost during the peak load period is smaller due to the "anti-peak regulation" character of wind power. In addition, during the off-peak hour, the balancing costs in scenario 2 are higher than those in scenario 1. This is because scenario 2 uses a day-ahead weighted average price-based fixed penalty price in imbalance settlement, and the energy deviations of wind power producers are relatively high during off-peak load hours, which can lead to a higher balancing cost.

5.4. Impact of different PTU settings on the wind power revenue

To study the impact of the **PTU on the clearing results of wind power producers under different imbalance pricing mechanisms**, we investigate three specific periods (6 h, 12 h, and 18 h), and the revenue of wind power producers and imbalance cost proportions under different PTU settings in scenarios 1 and 3 are shown in Fig. 8.

Fig. 8 clearly shows that when the PTU changes from 1 h to 0.5 h, the clearing output of wind power producers decreases, while the proportion of the imbalance cost relative to the total revenue of the wind power producer significantly increases, with the highest proportion of 30%. This is mainly because as the PTU shortens, the settlement frequency increases, and the portion that can be offset through the positive and negative imbalances within the same PTU decreases, thereby increasing the imbalance costs. Additionally, for wind power producers, positive and negative imbalance energy can be offset within the PTU; however, for the SO, the balance between the supply and demand of the overall system must be maintained at all times.

By comparing the clearing results under scenarios 1 and 3, we found that relative to the case in which the symmetric imbalance pricing mechanism (scenario 1) is applied, the penalty for upregulation is harsher than that for downregulation, so the over-contract characteristic is alleviated to some extend when adopting the asymmetric imbalance pricing mechanism in scenario 3. This outcome suggests that the wind power producer is more inclined to over-contract in the day-ahead market to maximize profits in a symmetric imbalance pricing mechanism, resulting in excessive day-ahead clearing and the need for more upregulation in real-time operation, thereby increasing the system balancing cost.

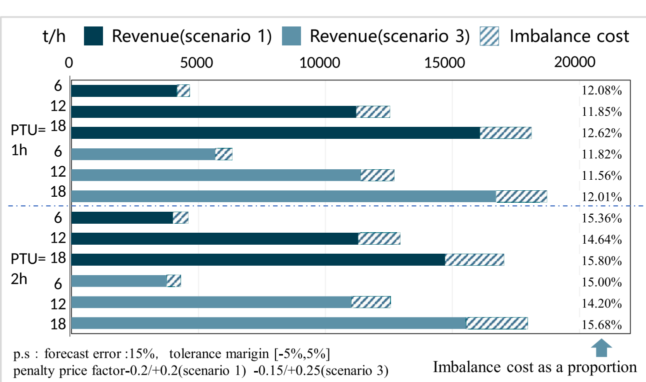

Fig. 8. The clearing results of the wind power producers under different PTUs. The histogram on the left represents the revenue and imbalance cost of the wind power producer, and the numbers on the right represent the proportion of the imbalance cost relative to the total revenue of the wind power producer.

6. Conclusion and policy recommendations

The balancing market actually offers a connecting thread between the financial transactions and physical electricity trading, and pay remuneration for behaviours of market participants' response to market incentives, which is closely related to economic interests of market participants. As a result, a well-designed balancing market can effectively guide behaviours of market participants and minimize the balancing cost of the whole system, which is the basis of effective and fair operation of balancing markets. Currently, there is no spot market for electricity in China and the market-based balancing mechanism has not been established yet. Therefore, the aim of this paper is to reveal and evaluate the interaction between balancing market design and the behaviours of market participants and to investigate an appropriate balancing market design that can accommodate the diversified balancing needs of each province and smooth the transition from a mid- and long-term energy market to an electricity spot market in China. Specifically, we take wind power producers as representative BRPs and propose an analytical framework that integrates wind power producer strategic offerings in the day-ahead market considering the imbalance settlement into the balancing market clearing model. Based on the current balancing mechanism in China, several design elements (e.g. the tolerance margin, imbalance pricing mechanism and PTU) related to the division of balance responsibility and balance settlement in balancing market design are investigated in the proposed model to analyse the interaction between balancing market design and market behaviours of wind power producers. Based on the above analysis and considering the fact that China is in the transition from the medium and long-term electricity market to the spot market and the actual demand for a balancing market in the construction of the spot market, we propose the following recommendations:

1) Tolerance margin: The goals of the tolerance margin are essentially to reduce the balance responsibility of the BRPs by reducing the imbalance risk of participators such as wind power producers due to output uncertainty and to familiarize the market participants with the market environment as well as help the participants develop market awareness in the early stages of market reform. Through the analysis of this study, we found that the wind power producer may use the tolerance margin to over-offer in the day-ahead market, which is also applicable for other kinds of BRPs. The behaviour of over-offering can increase the balancing cost of the whole system and obviously is not in line with the original intention of the market designer. Moreover, the tolerance margin reduces the responsibility of the relevant entities, meaning that other participants in the market need to experience more balance responsibilities, which may harm the fairness and efficiency of market operation. Even if the tolerance margin is only for renewable power providers due to its natural uncertainty and volatility, it can also lead to underinvestment in flexible generation and is not conducive to the development of new forecasting technology. Through the current monthly trading market and the pilot spot market started last year, most market participants

have gained a deeper understanding of spot market transactions. **Therefore, it is recommended that renewable energy generators such as wind power producers may have a tolerance margin of 8%-10%, which is expected to further shrink according to the market operation plan and wind power forecasting improvement, while exemption margins for other BRPs besides renewable generators should be cancelled.** In addition, the specific value of the tolerance margin can be adjusted according to the different actual conditions of each province, e.g. the forecast accuracy of wind power and the construction process of the spot market.

2) Imbalance pricing mechanism: The imbalance prices offer an incentive for market participants to limit individual imbalances and submit accurate energy schedules. Especially for wind power producers, a reasonable imbalance pricing mechanism can effectively motivate them to improve their forecasting technique, which is also helpful to the system balancing cost reduction and market operation efficiency improvement. However, it should be noted that the imbalance pricing mechanism should be consistent with the degree of electricity marketization. For China's electricity market, it is very difficult to establish a well-functioning market-oriented balancing mechanism in a short period, since there is no real spot market yet. As a result, it is recommended that the imbalance settlement price should be based on the day-ahead price with a certain penalty factor in the initial stage of China's electricity spot market. Additionally, according to the simulation results, an asymmetric measure that sets a slightly higher penalty on negative imbalances than on positive imbalances is recommended to prevent over-contractual behaviour of market participants.
3) Concerning PTU settings, the PTU is important for imbalance settlement. If technically allowed, the settlement cycle should be maximally shortened, since a short PTU is conducive to incentivizing wind power producers to offer truthfully so that the actual balancing cost can be revealed. A long PTU may make it difficult for the imbalance settlement to truly reflect the actual balancing cost of the overall system due to the offset produced by positive and negative imbalances within a PTU. **It is recommended that in the initial stage of electricity spot market operation, a 1-h PTU should be used to ensure the smooth operation of the market and enable the market participants to better adapt to the spot market environment. As the spot market evolves, the PTU should be gradually shortened to 30 min, 15 min, or even 5 min to better divide the imbalance responsibilities, promoting a fairer and more efficient market.**
4) For those countries like China that are undergoing electricity market reforms or are about to proceed, due to an insufficient understanding of market reforms and the dependence of the guaranteed revenues derived from long planned economy history, the original market players may have little activeness in electricity market trading participation. The electricity market reform is not a one-step process, price control and overall market-oriented proportion should be gradually liberalized. The tolerance margin as well as the deterministic penalties in balancing mechanism may be an effective approach, on the one hand, it can encourage market players to actively participate in the electricity market. On the other hand, it is also conducive to market players gradually adapting to market transactions, and finally achieve the transition of the power system from planned economy to market economy. The simulation results also show that the rational market participants will make the best use of market rules to maximize their own profits, which indicates the importance of the establishment of timely market supervision mechanism or credit rating system.

In general, market designers are supposed to fully evaluate the actual market situation and the possible behaviours of market participants under different balancing market designs. Only in this way can the incentive compatibility of market design be guaranteed and the real system balancing cost be revealed. In this study, we take the perspective of a wind power producer to investigate the impact of balancing market design on the market behaviour, but the proposed recommendation are mainly about the division of balancing responsibilities and balancing settlement, e.g. the tolerance margin, PTU length and imbalance pricing mechanism, which are provided for the whole balancing market, not for individual services. Besides, the analytical method and simulation model proposed in this paper are also applicable to market design considering the participation of other market entities, such as virtual power plants, energy storage entities, etc. It is expected to provide methodological guidance for spot market design in China.

Credit author statement

Zhaoyuan WU: Conceptualization, Methodology, Software. Ming Zhou: Supervision, Writing - review & editing, Funding acquisition. Gengyin Li: Supervision, Project administration. Tong Zhao: Methodology, Investigation, Formal analysis. Yan Zhang: Visualization, Data curation. Xiaojuan Liu: Data curation, Funding acquisition

Declaration of competing interest

The authors declare that we 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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