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Modeling multi-market coupling effects considering the consumption above quota trading market in renewable portfolio standards: An agent-based perspective

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ABSTRACT

The current renewable portfolio standards (RPS) mechanism implemented in China requires electricity consumers to comply with quota obligations by consuming renewable electricity, purchasing tradeable green certificates (TGCs), or engaging in consumption above quota (CAQ) transactions. However, most existing studies on RPS policy seldom consider the CAQ market and ignore the dynamic interactions among microlevel obligated entities, which limits the model from considering the heterogeneity among obligated entities and weakens the capture of macrolevel emergence properties. To fill this research gap, a novel agent-based model for China's RPS policy is established, in which the microlevel obligated subjects' complex interactions and decision-making process in coordinating three compliance approaches, i.e., electricity consumption, TGC consumption and CAQ transactions, are depicted, and the dynamic macrolevel emergence in the electricity market, TGC market and CAQ market in terms of multimarket coupling trading, multimarket price-linkage, renewable energy electricity diffusion and RPS target compliance are captured. Notably, a genetic algorithm-based training stage is structured to calibrate and stabilize the heterogeneous behavioral parameters of obligated entities. The results illustrate that 1) the existence of the CAQ market in RPS policy can significantly stimulate obligated entities to consume more renewable energy electricity earlier, promote individual and aggregate profits, and improve the overall compliance rate and RPS implementation effectiveness and 2) a combined penalty–reward mechanism with an effective reward interval is highly important for promoting RE consumption diffusion and the effective operation of the CAQ market.

1. Introduction

In recent decades, the worldwide energy crisis and climate change have received extensive attention from the international community. China has also proposed a series of goals and visions, such as carbon peaking and carbon neutrality. Evidence has shown that reliance on high-emission fossil fuels such as coal and oil is one of the main causes of these problems (Hu et al., 2022). Developing renewable energy (RE) is of key importance for the low-carbon, sustainable energy transition by optimizing the energy supply structure (Zhou and Zhao, 2021), overcoming high-carbon production lock-in (Zhao et al., 2022b), enhancing scientific and technological capabilities (Dong et al., 2022) and reducing carbon dioxide emissions (Yi et al., 2019). China explored its own renewable energy policy by first implementing the Feed-in-Tariff (FIT) policy in 2009 (Wu et al., 2023). Despite the extensive expansion of RE installations boosted by FITs (Meng and Yu, 2023), this has also resulted in a large subsidy gap and blind RE investment (Corwin and Johnson, 2019; Song et al., 2021), bringing enormous financial pressure to the government (Yang et al., 2021) and the critical phenomenon of "abandoned RE power" (Yu et al., 2022a; Qi et al., 2023). To alleviate the subsidy deficit and promote RE electricity consumption, China officially implemented the Tradable Green Certificates (TGC) scheme in 2017 and a new Renewable Portfolio Standards (RPS) policy in 2019, in which consumption entities in the electricity market were required to comply with quota obligations.

In contrast to direct subsidies under the FIT policy, the RPS policy

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compensates for the spillover costs of renewable electricity generation through market competition (Wang et al., 2021a). Typically, RPS policy is implemented in conjunction with the Tradable Green Certificates (TGC) scheme, as has been practiced in most countries implementing RPS policy, e.g., Australia, the United States, Japan, Belgium, the United Kingdom, Denmark, the Netherlands, and Italy. Among them, the United States was the first and most successful country in implementing RPS policy. To date, >30 states in the United States have adopted the RPS + TGC mechanism. However, the RPS + TGC mechanism of the United States is not applicable to China due to the following three aspects. First, China's power structure is dominated by coal, lacking other energy resources with flexible adjustment capabilities, leading to the limited peak-shaving capacity of China's power system; furthermore, the large peak-to-valley difference in the power system exacerbates the difficulties in RE electricity consumption diffusion (Wu et al., 2023). Second, unlike the U.S. regional electricity market, which basically realizes the regional self-balancing of demand and supply, China's energy resources are characterized by reverse distribution, and it is difficult to realize the local consumption of renewable energy (Hu et al., 2022; Zhang et al., 2022); in addition, due to the lack of sufficient market incentive mechanisms, there are numerous barriers to off-site consumption of RE electricity (Zhang et al., 2019). Third, although the RPS + TGC mechanism established in the United States ignores the individual heterogeneity of electricity users in terms of RE electricity consumption capabilities (Zeng et al., 2023a) and attitudes toward RE consumption, it functions well in terms of satisfactory RE electricity consumption; however, it can hardly inspire friendly, responsive, or inexpensive in RE consumption to consume more, or examine the contribution of various users to RE consumption diffusion.

Therefore, owing to the inflexibility of China's power supply structure, establishing a viable mechanism that considers the RE consumption capacity of electricity consumers and stimulates the interaction of all electricity consumers (i.e., obligated entities in China's RPS policy) to actively participate in RE electricity consumption is urgently needed. On the basis of institutional economics theory, the RPS system design should stimulate enthusiasm among low-cost electricity consumers to consume more and accurately evaluate the corresponding contribution, compensate for those who contribute more and minimize the total social cost of renewable energy consumption in a market-based manner (Zhang et al., 2019). For this purpose, in the newly established RPS, the consumption above quota (CAQ) market has been especially introduced into China's RPS mechanism; obligated entities are required to comply with the quota obligation mainly through RE electricity transactions or supplementary transactions in either the TGC market or the CAQ market. Notably, TGCs are certificates issued to RE power manufacturers to subsidize their spillover costs, and CAQs are certificates issued to electricity consumers who consume excess RE electricity to motivate those low-cost RE electricity consumers to consume more. Specifically, the CAQ market provides a platform for realizing substitution consumption between electricity consumers. This approach enables low-cost obligated entities who hold excess consumption quotas to trade with those holding deficit consumption quotas and allows the latter to bear the reasonable cost of the former at the same time so that the consumption of RE electricity can be realized at the minimum cost for the whole society. In addition, in response to the uneven distribution of RE resources in China, the CAQ market can realize alternative transregional consumption of RE power, effectively reducing transaction costs.

The existing studies on multimarket coupling under RPS can be divided into two categories. The first group is the coupling effect analysis of the electricity market and the TGC market under a single RPS policy. A majority of studies have demonstrated that a scientifically designed RPS in conjunction with the TGC mechanism is conducive to the development of the power industry (Yu et al., 2022b) in terms of improving the power structure (Fan et al., 2019), developing the RE industry and diffusing RE consumption (Dong and Shi, 2019; Zhang et al., 2022; Zhou et al., 2022) and promoting the grid parity of RE (Tu et al., 2020; Zhang et al., 2021), sustainability (Kwag et al., 2023), low-carbon transition (Yi et al., 2019; Zhou and Zhao, 2021), cost-effectiveness (Sun and Nie, 2015; Sanya et al., 2018; Chen et al., 2018) and social welfare (Wang et al., 2021b, 2021c). Zeng et al. (2023b) analyzed the coupling mechanism between the electricity market and TGC market and compared the fixed-price model and the market-based transaction of the TGC mechanism. The results demonstrated that the latter can increase the consumption of RE and the transaction volume of TGC without significantly increasing the cost of obligated subjects. Zhou et al. (2022) established an SD-based model of China's TGC system and studied the incentive effect of important institutional parameters and marketed on-grid prices on the supply side of the power industry. Some scholars further explored the impact of RPS in conjunction with TGC on the behaviors of multimarket participants. For example, Zhao et al. (2018) developed an evolutionary game model of power producers to analyze the symbiotic evolution between an RPS and electric producers' behavioral strategies and discussed the impacts of key institutional parameters on the dynamic evolutionary process of electric producers. The second group is the multimarket coupling effect analysis of the TGC market, electricity market and carbon emission trading (CET) market under the coexistence of RPS and CET policies. Some studies have focused on the synergistic effect of these two policies on multimarket interactions (Feng et al., 2018; Zhou and Zhao, 2021; Wang et al., 2021a; Zha et al., 2023). Yi et al. (2019) demonstrated that these two policies contain overlapping elements but have different impacts on regional power structures and estimated an effective policy interval. Yan et al. (2022) explored whether the synergy of RPS and CET policies can drive the development of the power industry in terms of electricity companies' investment decisions, total carbon emissions, consumer surplus and social welfare. Yue et al. (2023) studied the synergies between CET and RPS policy in promoting the diffusion of RE electricity based on complex network evolutionary game theory. Zha et al. (2023) evaluated the synergistic effects of renewable energy policies and CET on carbon emission reduction in China's power sector based on a continuous difference-in-differences model. Some scholars have investigated multimarket price interactions in the context of both RPS and CET. Schusser and Jaraitė (2018) empirically examined the interplay between the prices of the three markets and concluded that increases in carbon prices positively affect TGC prices in the short run. In addition, the interactions between market players' strategies in these three markets were also investigated. Wang and Li (2022) utilized game theory to explore the impact of RPS + TGC and CET mechanisms on the power market and corresponding decisions and behaviors. Hu et al. (2023) constructed a game model to analyze the evolutionary process of group strategies under different policy parameters.

The literature on the multimarket coupling of RPS policy is plentiful but seldom considers the CAQ market; therefore, both the heterogenous decision-making process and interaction behaviors of participants in CAQ market at micro level and the corresponding emergence properties at macro level are ignored in existing research. For example, Zhang et al. (2020) theoretically and systematically outlined the organization of the CAQ trading system, including the generation and distribution of CAQ, the transaction system, and the verification and calculation system; however, they did not quantitatively analyze the impacts of multimarket coupling trading. In addition, they proposed a connection approach between the CAQ and TGC markets in that TGC transactions precede CAQs for supplementary trading. However, Song et al. (2021) constructed a system framework for the internal connection of the electricity market, the TGC market, and the CAQ market, but with the assumption that CAQ trading precedes TGC trading in RPS. They conducted numerical simulations based on an SD model and analyzed the evolutionary process to explore the system design of an RPS; however, the microlevel heterogenous transactions of these market participants in CAQ market were ignored. Similarly, Wu et al. (2022) comprehensively examined the complex relationship between the above three markets and the CET market for policy coordination analysis, but the model investigated only the aggregate relationship at the macro level without describing the transactions in the CAQ market in detail. Hu et al. (2022) constructed a simulation model for the coupling analysis of the above three markets under RPS, but only one sending-end grid and one receiving-end grid were used to evaluate the impacts of different policy parameters, which limited the ability of the model to consider heterogeneity among obligated entities.

Current models for analyzing the multimarket coupling effect of RPS policy can be divided into three strands, i.e., optimization models (Yi et al., 2019; Yan et al., 2022), partial equilibrium models represented by game models (Bao et al., 2019; Fang et al., 2019; Dong et al., 2022; Wang and Li, 2022), and simulation models represented by SD models (Zhou and Zhao, 2021; Song et al., 2021; Zhou et al., 2022) and ABMs (Wang et al., 2021a; Zhao et al., 2022b). Among them, optimization models and equilibrium-based models with a series of simplifying assumptions and constraints have many limitations, such as difficulty in modeling the heterogeneity and interactions among agents, which weakens the capture of emergence properties and uncertainty of the system (Yu et al., 2020). In addition, SD models have been widely utilized in describing the time-varying behaviors and nonlinear dynamic feedback processes in complex systems according to system thinking and feedback control theory (Faezipour and Ferreira, 2018). However, SD models depict a same set of correlations for the system and ignore heterogeneity among agents and cannot describe the interactions, learning, or behavioral adjustment of individuals at the micro level (Tang et al., 2017). Comparatively, ABM models outperform the others as they provide more realistic representations of socioeconomic system by modeling agent interactions, heterogeneity, bounded rationality (including incomplete information), and learning on the basis of specific behavioral rules (Castro et al., 2020; Yu et al., 2020; Wang et al., 2021a) at the micro-level, and capture emergence properties at the macro-level which cannot be get through micro-summing, hence have been widely used to model complex systems.

Overall, the literature shows important findings regarding the multimarket coupling of China's RPS, however, an obvious gap exists in quantitatively analyzing how to coordinate the three compliance options at the micro level and how would it dynamically affect the multimarket coupling of the TGC market, the CAQ market and the electricity market at the macro level in the context of China's current RPS policy, especially considering the interactions, heterogeneity and learning behaviors of obligated entities.

Consequently, our innovations and contributions to the academic literature and managerial practice are threefold:

(1) This study proposes a novel agent-based simulation model integrated with a GA-based learning algorithm for China's RPS policy, in which a "training stage" is introduced to initialize the "behavioral parameters" of the heterogeneous agents without relying on the empirical data, and then the impact of policies is simulated and evaluated.
(2) This paper extends research perspectives from three aspects. First, at the microlevel, the heterogeneous coordination among optional compliance behaviors and evolutionary decision-making processes of obligated entities are reflected and modeled. Second, at the macrolevel, the aggregate emergence properties, uncertainties and dynamics in multimarket coupling are captured. Third, different from the existing simulation models for RPSs, in which it is assumed that CAQ transactions precede TGC transactions in supplementary trading or the other way around, this paper loosens that assumption by introducing the CAQ consumption share parameter and making it a dynamic strategy adopted and adjusted by heterogeneous agents through learning and forecasting.
(3) In terms of application value, this study proposes a basic technical framework for China's RPS policy in terms of mechanism design and policy evaluation and provides a helpful tool for disclosing the complex interactions and evolution of energy systems.

Based on the proposed framework, this study helps us answer the following questions: (1) How does the existence of the CAQ market influence the implementation of RPS? (2) How does the existence of obligated agents' heterogeneity and evolutionary learning influence their behaviors and strategies? (3) What is the emergence of multimarket coupling at the macro level driven by behaviors at the micro level? The results could provide implications for market participants' decision-making and for the design of RPS policy.

The remainder of this paper is organized as follows: Section 2 introduces the overall framework and formulates the proposed novel model. Section 3 describes the parameters involved in the model. Section 4 presents the validity of the proposed model and analyses and discusses the empirical results. Section 5 summarizes the paper and provides policy implications.

2. Methodology formation

In this section, an agent-based simulation model (ABM) is formulated to examine China's RPS policy considering the consumption above quota (CAQ) trading market. The model is implemented in Python using the Melodie[1] package (Yu and Hou, 2023). In the proposed model, the heterogeneous obligated entities and three markets, i.e., the electricity market, the TGC market and the CAQ market, are modeled. Noticeably, all the obligated entities are regarded as one type of agent for simplicity. Fig. 1 illustrates the general frame of the proposed model.

As shown in Fig. 1, under the RPS policy, obligated entities are compulsorily stipulated to consume a minimum percentage of RE electricity. The obligation can be accomplished through three approaches, i.e., RE electricity consumption, CAQ consumption and TGC consumption. The main compliance approach for RPS obligation is RE electricity consumption, with the other two as supplementary approaches. In the electricity market, both thermal electricity and RE electricity are provided, and individual agents have to make decisions about the share of RE consumption. The CAQ market is formed when individual agents with surplus RE consumption quotas transact with those with deficit quotas. Moreover, individual agents with deficient RE consumption have to make decisions about the share of CAQ consumption and TGC consumption. In each compliance period, obligated entities make the above decisions based on bounded rationality and tend to maximize their profits by coordinating the abovementioned three compliance behaviors under the obligation of the RPS policy. The model not only involves microlevel heterogeneous agents to depict their decision-making process, learning and strategy adjustment, and complex behaviors and interactions with the three markets but also involves macrolevel multiple markets to capture their linkage mechanism, dynamic evolution and coupling effects. To initialize the heterogeneous behavioral parameters of obligated subjects, a multiple-population genetic algorithm (MPGA)-based learning module is built into the agent-based model (ABM) module. Based on the integrated model, macrolevel emergence can be captured regarding RE electricity consumption, compliance rate, and market performance in both the CAQ market and TGC market.

Based on the proposed model, this study attempts to examine the effects of incorporating CAQ market into the RPS policy. Therefore, two scenarios (i.e., Scenario A and Scenario B) are structured, and the specific explanation is presented below.

Scenario A simulates the application of the current RPS policy in China's power sector. All three markets in Fig. 1 are built in the model,

[1] Melodie (https://github.com/ABM4ALL/Melodie) is a general framework for developing agent-based models in Python. The Melodie package provides the evolutionary training module used in this study.

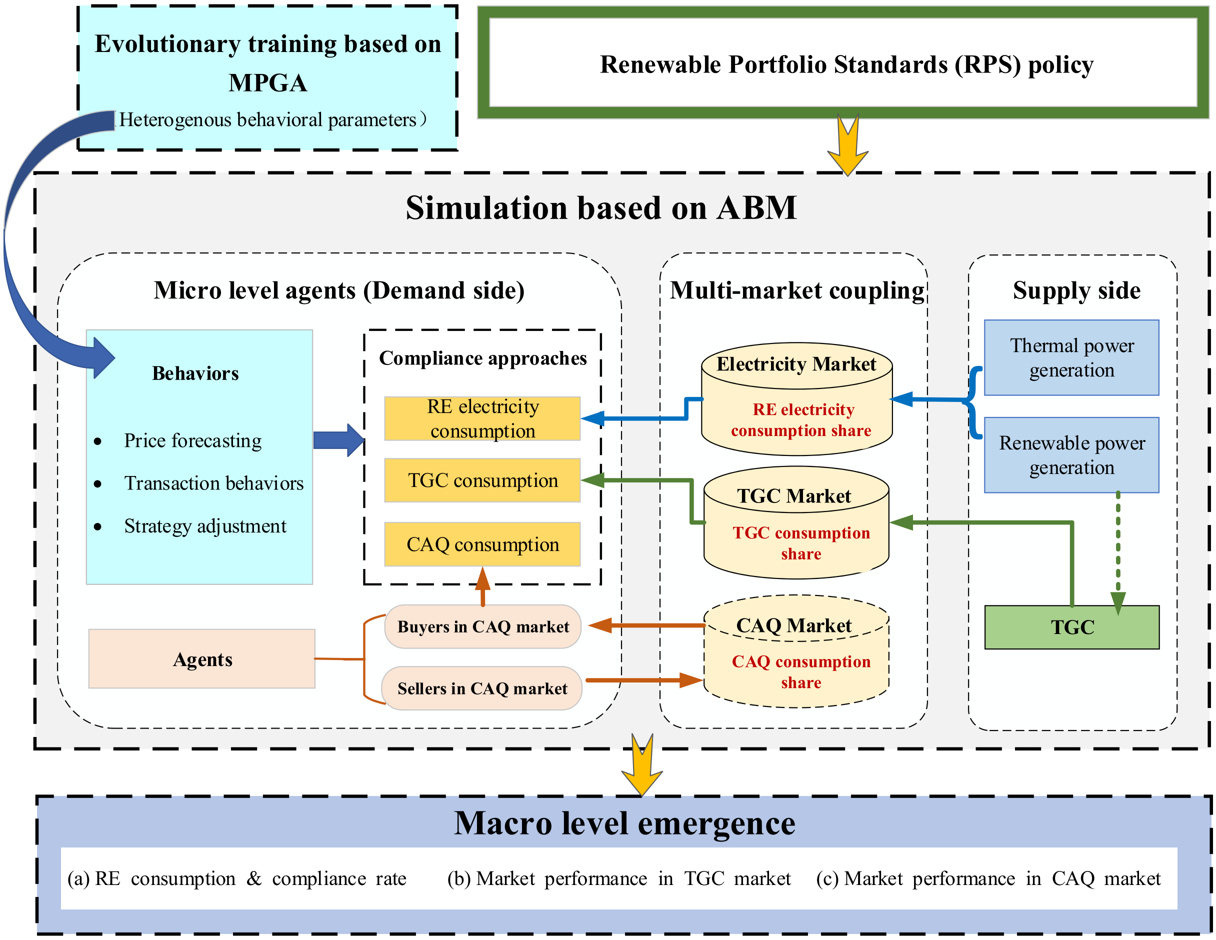


Fig. 1. General frame for multimarket coupling under an RPS policy integrated with the CAQ market.

and the obligated entities comply with the RPS obligation through the abovementioned three compliance approaches.

Scenario B is designed as a benchmark for Scenario A, in this scenario, there is no CAQ market, implying that obligated entities can only accomplish the RPS obligation through RE electricity consumption and TGC consumption.

For clarification, the model in Scenario A, which contains all the modules described in Fig. 1, is introduced in detail in this section, and Scenario B can be simplified as a special case of Scenario A by assigning values of 0 to the variables relevant to the CAQ market.

2.1. Flowchart of the integrated model

The integrated model simulates a T period compliance phase of obligated entities in the power industry under RPS policy, in which each period is represented by t. In each period t in the simulation stage, the obligated entities first make decisions about the consumption share of different energy types and calculate the retail profits in the electricity market, then make decisions about the consumption share in the CAQ market and TGC market, and finally verify the total compliance. With the RE consumption obligation, individual agents in the model attempt to maximize their profits by coordinating the three compliance approaches.

Noticeably, to improve or partially guarantee the validity of the model, a “training stage” is introduced to initialize individual agents’ behavioral parameters based on an evolutionary training method.

A detailed flow chart of the model is illustrated in Fig. 2.

(1) In the simulation stage, two categories of parameters are exogenously initialized, i.e., the environment parameters and the individual agents’ parameters (attribute parameters and behavioral parameters). The parameters are calibrated and introduced in Section 3.1 and Section 3.2, respectively, among which the behavioral parameters are validated beforehand based on an evolutionary learning stage.
(2) In the learning stage, the obligated entities are trained based on the multiple-population genetic algorithm (MPGA) to obtain a set of behavioral parameters with the highest fitness, which is fully described in Section 2.4
(3) At the beginning of period t, as bounded rational agents, obligated entities plan for the current compliance phase by first forecasting the prices in both the CAQ market and TGC market based on historical data and then forming the weighted average price forecast, as introduced in Section 2.2.1.
(4) To comply with the minimum RE electricity consumption responsibility, obligated entities coordinate the three compliance approaches by adjusting the consumption share in each market. Based on the heterogeneous price forecasts and relevant parameters, each obligated entity adjusts its electricity consumption decision between RE power and thermal power, represented by an increase or decrease in the RE electricity consumption share, as introduced in Section 2.2.2.
(5) Then, the obligated entities consume electricity generated from different energy sources in the electricity market according to their updated electricity demand and RE electricity consumption share. The corresponding retail profit and certificate gap are

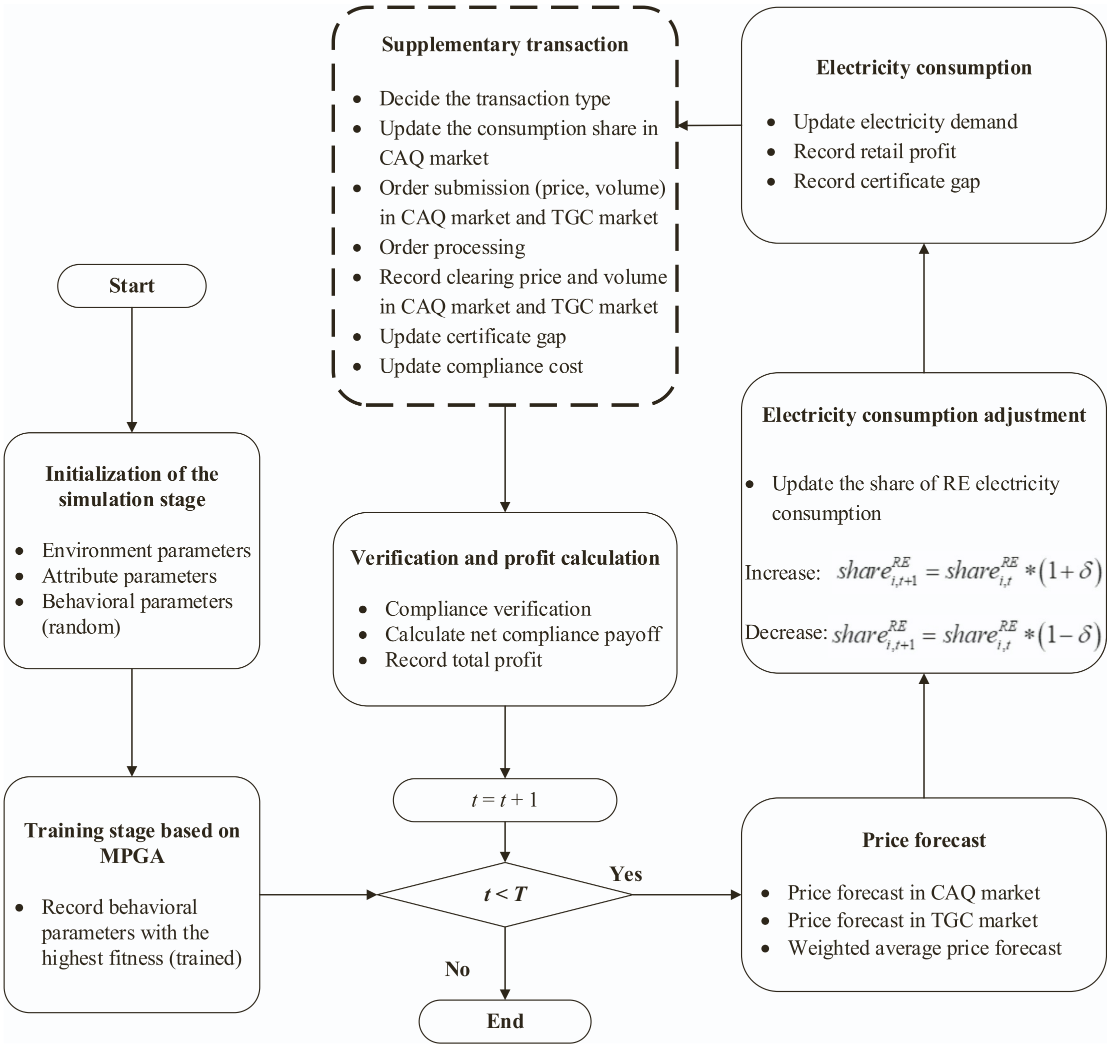


Fig. 2. Flowchart of the agent-based simulation model under China's RPS policy.

thereafter calculated and recorded, as introduced in Section 2.2.3.

(6) In supplementary transactions, obligated entities first decide whether to buy or sell CAQs based on the certificate gap. Specifically, those holding an excess consumption quota will submit an ask order in the CAQ market and become sellers; otherwise, they will submit a bid order in both the CAQ market and TGC market to become buyers with the bidding volume influenced by the CAQ consumption share. Based on the forecasted prices, obligated entities holding deficit certificates update the consumption shares in both markets and then submit their supplementary transaction orders (including the transaction price and volume) in both markets. The double auction mechanism is introduced for order processing. After the order-matching process, the obligated entities' actual trading volumes and the market clearing price are recorded, and the certificate gap and compliance cost are updated. The order processing mechanism is introduced in detail in Section 2.3.2, and the obligated entities' decision-making process is introduced in Section 2.2.4.

(7) By the end of the compliance phase, the total consumption quotas of individual agents are verified. Those who hold fewer certificates than the RPS requirements will be penalized with a fine while those holding surplus certificates will be rewarded. Then the total profit in period t is calculated.

2.2. Agent behavior rules

Under the pressure of RPS obligations, obligated entities minimize their total cost by coordinating the three compliance behaviors in terms of electricity consumption and supplementary transactions. Individual agents' behaviors mainly include price forecasting, electricity consumption adjustment, electricity consumption, supplementary transactions and verification and profit calculations.

2.2.1. Supplementary transaction price forecasts

In period t, obligated agent i forecasts its transaction price in the CAQ market ($FP^{CAQ}_{i,t}$) and TGC market ($FP^{TGC}_{i,t}$) based on historical data of the latest l_i periods. It is assumed that the historical data from period $t - l_i + 1$ to period t within the memory length l_i had been increasing with the same average increase rate, i.e., $\left(FP_{i,t}/FP_{i,t-l_i+1} - 1\right)/(l_i - 1)$. The formulas are shown as Eqs. (1) and (2).

$$FP^{CAQ}_{i,t+1} = FP^{CAQ}_{i,t} * \left(1 + \left(FP^{CAQ}_{i,t} \Big/ FP^{CAQ}_{i,t-l_i+1} - 1\right) \Big/ (l_i - 1)\right) \tag{1}$$

$$FP^{TGC}_{i,t+1} = FP^{TGC}_{i,t} * \left(1 + \left(FP^{TGC}_{i,t} \Big/ FP^{TGC}_{i,t-l_i+1} - 1\right) \Big/ (l_i - 1)\right) \tag{2}$$

In Eqs. (1)–(2), the memory length of agent i (l_i) means that only the historical data from the latest l_i periods are available for agent i to forecast the price in period $t+1$. Based on the above price forecasts, the weighted compliance cost for supplementary transactions ($WCC_{i,t}$) can be calculated by using Eq. (3).

$$WCC_{i,t} = FP_{i,t}^{CAQ} * share_{i,t}^{CAQ} + FP_{i,t}^{TGC} * \left(1 - share_{i,t}^{CAQ}\right) \tag{3}$$

In Eq. (3), $share_{i,t}^{CAQ}$ denotes the consumption share in the CAQ market of agent i in period t.

2.2.2. Electricity consumption adjustment

To focus on the issue of RE electricity consumption diffusion, the paper assumes that the electricity market is oversupplied, and the electricity consumption is totally driven by electricity users' demand. Under RPS, RE electricity consumption is the dominant approach for obligated entities to comply with the RPS obligation. In each period t, agent i makes the decision on whether to adjust its current electricity consumption strategy for the next period $t+1$, i.e., to increase or decrease its current share of RE electricity consumption ($share_{i,t}^{RE}$) by an exogenously set unified percentage (δ).

For cost-effectiveness, the bounded rational agent i adjusts $share_{i,t}^{RE}$ between RE electricity and thermal electricity consumption considering the following four factors: (1) the cost from unit RE electricity consumption in place of unit thermal electricity consumption in the electricity market ($MC_{i,t}$), as calculated by using Eq. (4); (2) the weighted compliance cost for supplementary transactions ($WCC_{i,t}$); (3) the unit fine for noncompliance RPS quota μ_{fine} and the unit reward for surplus RPS quota μ_{reward}; and (4) the compulsory RPS level (RPS_t). It is assumed that the higher $MC_{i,t}$ and the lower $WCC_{i,t}$, μ_{fine} and μ_{reward} are, the stronger the propensity for agent i to decrease RE electricity consumption, and vice versa.

To integrate the above four factors into the decision-making process of RE electricity consumption share adjustment, a threshold profit ($\pi'_{i,t}$) and RPS_t are selected as benchmarks for the decision-making of agent i. The threshold profit can be calculated by using Eq. (5).

$$MC_{i,t} = \left(P_t^{RE} - P_t^{sale}\right) - \left(P_t^{TE} - P_t^{sale}\right) \tag{4}$$

$$\pi'_{i,t} = D_{i,t}^{ele} * P_t^{sale} - D_{i,t}^{ele} * RPS_t * P_t^{RE} - D_{i,t}^{ele} * (1 - RPS_t) * P_t^{TE} \tag{5}$$

P_t^{RE} and P_t^{TE} denote the on-grid electricity prices of RE electricity and thermal electricity, respectively; P_t^{sale} denotes the retail price of electricity to end-users; and $D_{i,t}^{ele}$ denotes the electricity demand of agent i in period t.

Then, agent i compares its actual total profit ($\pi_{i,t}$) with $\pi'_{i,t}$ and its current RE electricity consumption share ($share_{i,t}^{RE}$) with RPS_t. If the current share is higher than the RPS level and the actual profit is higher than the threshold profit or if the current share is lower than the RPS level and the actual profit is lower than the threshold profit, agent i will increase $share_{i,t}^{RE}$ by a percentage of δ, i.e., $share_{i,t+1}^{RE} = share_{i,t}^{RE} * (1+\delta)$, with a probability of $\Psi_{i,t}^1$, which is structured by employing the sigmoid function to guarantee the monotone relations between the decision and its influencing factors, as shown in Eq. (6). Otherwise, agent i will decrease $share_{i,t}^{RE}$ by a percentage of δ, i.e., $share_{i,t+1}^{RE} = share_{i,t}^{RE} * (1-\delta)$, with a probability of $\Psi_{i,t}^2$, as calculated by using Eq. (7).

$$\Psi_{i,t}^1 = \left(\frac{1}{1 + {\alpha_{i,1}}^{MC_{i,t}}}\right)^{\alpha_{i,2}} \left(\frac{1}{1 + {\alpha_{i,3}}^{-WCC_{i,t}}}\right)^{\alpha_{i,4}} \left(\frac{1}{1 + {\alpha_{i,5}}^{-\mu_{fine} - \mu_{reward}}}\right)^{\alpha_{i,6}} \tag{6}$$

$$\Psi_{i,t}^2 = 1 - \Psi_{i,t}^1 \tag{7}$$

In the above formulas, $\alpha_{i,s} (s = 1, 2, \cdots, 6)$ are 6 behavioral parameters that reflect the heterogeneity of obligated subjects in the decision-making process concerning the share of RE electricity consumption. To guarantee the validity of the decision-making process, a learning stage is introduced to initialize the 6 behavioral parameters.

2.2.3. Electricity consumption

Based on the RE electricity consumption share, agent i consumes electricity generated from different energy sources, the retail profit ($RP_{i,t}$) can be calculated, and then both the consumption quota account (QA_i) and the certificate gap, i.e., the net consumption quota account ($NQ_{i,t}$), of agent i are updated. The relationships are shown in Eqs. (8)–(10).

$$RP_{i,t} = D_{i,t}^{ele} * P_t^{sale} - D_{i,t}^{ele} * share_{i,t}^{RE} * P_t^{RE} - D_{i,t}^{ele} * \left(1 - share_{i,t}^{RE}\right) * P_t^{TE} \tag{8}$$

$$QA_{i,t} = share_{i,t}^{RE} * D_{i,t}^{ele} \tag{9}$$

$$NQ_{i,t} = share_{i,t}^{RE} * D_{i,t}^{ele} - RPS_t \times D_{i,t}^{ele} \tag{10}$$

$QA_{i,t}$ represents the total consumption quota held by agent i and is cleared by the end of each period t.

2.2.4. Supplementary transaction adjustment

After the first compliance stage of RE electricity consumption, agent i will make the decision to participate in supplementary transactions by first deciding its transaction type. If $NQ_{i,t} > 0$, agent i has accomplished the RPS quota requirement, and it will submit an ask order to sell excess RE consumption quotas in the CAQ market. Otherwise, it will submit bid orders in the CAQ market and TGC market to comply with the RPS quota requirements.

An ask (or bid) order is a combination of the bottom price (or upper price) ($P_{i,t}^{CAQ}$ in the CAQ market and $P_{i,t}^{TGC}$ in the TGC market) and volume ($V_{i,t}^{CAQ}$ in the CAQ market and $V_{i,t}^{TGC}$ in the TGC market), which means selling (or buying) an amount of $V_{i,t}^{CAQ}$ or $V_{i,t}^{TGC}$ certificates at a price no lower (or higher) than $P_{i,t}^{CAQ}$ or $P_{i,t}^{TGC}$. For an ask order, we assume that $P_{i,t}^{CAQ} = FP_{i,t}^{CAQ} * (1-\varepsilon)$, $\varepsilon \in (0, 0.05)$ and $V_{i,t}^{CAQ} = NQ_{i,t}$. For a bid order, agent i must first decide the consumption share in both markets in terms of $share_{i,t}^{CAQ}$. We assume that $P_{i,t}^{CAQ} = FP_{i,t}^{CAQ} * (1+\varepsilon)$, $\varepsilon \in (0, 0.05)$ and $V_{i,t}^{CAQ} = -NQ_{i,t} * share_{i,t}^{CAQ}$ for a bid order in the CAQ market and $P_{i,t}^{TGC} = FP_{i,t}^{TGC} * (1+\varepsilon)$, $\varepsilon \in (0, 0.05)$ and $V_{i,t}^{TGC} = -NQ_{i,t} * \left(1 - share_{i,t}^{CAQ}\right)$ in the TGC market.

In each period t, agent i makes the decision on the CAQ consumption share ($share_{i,t}^{CAQ}$) adjustment by assessing the comparative compliance cost of the two markets based on price forecasts, as shown in Eq. (11).

$$share_{i,t}^{CAQ} = FP_{i,t}^{TGC} \Big/ \left(FP_{i,t}^{CAQ} + FP_{i,t}^{TGC}\right) \tag{11}$$

By the end of the order processing stage, the clearing price (Pc_t^{CAQ}, Pc_t^{TGC}) and the actual transaction volume ($\mathbb{V}_{i,t}^{CAQ}$and $\mathbb{V}_{i,t}^{TGC}$) in both markets are recorded. Then, the compliance cost ($CC_{i,t}$) of bidders in supplementary transactions can be calculated, and the net consumption quota ($NQ_{i,t}$) of agent i is updated by using Eqs. (12)–(14). The order processing mechanism is introduced in detail in Section 2.3.2.

$$CC_{i,t} = Pc_t^{CAQ} * \mathbb{V}_{i,t}^{CAQ} + Pc_t^{TGC} * \mathbb{V}_{i,t}^{TGC} \tag{12}$$

$$QA_{i,t} = share_{i,t}^{RE} * D_{i,t}^{ele} + \mathbb{V}_{i,t}^{CAQ} + \mathbb{V}_{i,t}^{TGC} \tag{13}$$

$$NQ_{i,t} = share_{i,t}^{RE} * D_{i,t}^{ele} + \mathbb{V}_{i,t}^{CAQ} + \mathbb{V}_{i,t}^{TGC} - RPS_t \times D_{i,t}^{ele} \tag{14}$$

2.2.5. Verification and profit calculation

By the end of the compliance stage, the RPS quota obligation of each agent i is verified and the net compliance payoff ($Payoff_{i,t}$) is calculated. A negative net consumption quota ($NQ_{i,t}$) implies that the obligated entity fails to meet the RPS quota requirement and will be punished with a fine; otherwise, the obligated entity will be rewarded, and the net compliance payoff can be calculated as Eq. (15).

$$Payoff_{i,t} = \begin{cases} \mu_{fine} * NQ_{i,t} & NQ_{i,t} \le 0 \\ \mu_{reward} * NQ_{i,t} & NQ_{i,t} > 0 \end{cases} \tag{15}$$

Then, the actual total profit of agent i in period t can be calculated by subtracting the compliance cost from the retail profit and adding the net compliance payoff, as shown in Eq. (16).

$$\pi_{i,t} = RP_{i,t} - CC_{i,t} + Payoff_{i,t} \tag{16}$$

2.3. Market rules

The obligated entities interact with each other in three markets, i.e., consuming electricity driven by heterogeneous electricity demand in the electricity market and competing with each other in CAQ transactions and TGC transactions. According to "Trading rules for Renewable energy power consumption above the quota (implementation)" issued by Beijing Power Exchange Center in 2021 and "Green Electricity Certificate issuance and trading Rules (Draft for Comment)" issued by the National Energy Administration in 2024, both the CAQ and TGC markets are organized based on the centralized bidding mechanism according to the principle of price priority.

2.3.1. Electricity market

As the focus of this study is obligated entities, which are the demand side of the electricity market, we assume that electricity production is organized according to demand and that two types of electricity, i.e., RE electricity and thermal electricity, are considered to have the same electric energy value and share the same retail price (P_t^{sale}) but different environmentally friendly values. The electricity demand of agent i in period t ($D_{i,t}^{ele}$), which increases at a certain rate (ξ), can be met by consuming either type of electricity at different prices, i.e., the different on-grid electricity prices of RE electricity (P_t^{RE}) and thermal electricity (P_t^{TE}).

2.3.2. CAQ transaction market

In the CAQ transaction stage, agent i submits an ask (or bid) order to the CAQ market, i.e., a combination of price and volume $\left(\left[P_{i,t}^{CAQ}, V_{i,t}^{CAQ}\right]\right)$, which means selling (or buying) $V_{i,t}^{CAQ}$ CAQ at a price no lower (or higher) than $P_{i,t}^{CAQ}$. The CAQ market processes submitted orders based on a double auction mechanism (Chiarella and Iori, 2002). Under this mechanism, in period t, all the bid orders are sorted in descending order of bidding price, denoted by $b_\mu(\mu = 1, 2, \cdots, m)$, and the ask orders are sorted in ascending order, denoted by $a_\nu(\nu = 1, 2, \cdots, n)$, to form the demand curve and the supply curve, respectively, in the CAQ market. The combination of the two curves contains four types, as shown in Fig. 3(a-d).

(1) If the lowest bid price ($P_{b_m,t}^{CAQ}$) is higher than the highest ask price ($P_{a_n,t}^{CAQ}$) and the total volume of bid orders ($\sum V_{b_\mu,t}^{CAQ}$) is higher than that of ask orders ($\sum V_{a_\nu,t}^{CAQ}$), i.e., if the entire demand curve is above the supply curve and the total demand exceeds the total supply, as shown in Fig. 3(a), then all the ask orders can be filled. We assume that b_c represents the bid order of intersection E in Fig. 3(a), then the bid orders with a bidding price higher than that of b_c can be filled, and the bid order represented by b_c can be partially filled with the transaction volume calculated as $V_{b_c,t}^{CAQ} = \sum V_{a_\nu,t}^{CAQ} - \sum_{\mu=1}^{c-1} V_{b_\mu,t}^{CAQ}$. The market clearing price can be calculated as $Pc_t^{CAQ} = 0.5 \bullet \left(P_{b_c,t}^{CAQ} + P_{a_n,t}^{CAQ}\right)$.

(2) If the lowest bid price ($P_{b_m,t}^{CAQ}$) is higher than the highest ask price ($P_{a_n,t}^{CAQ}$) but $\sum V_{b_\mu,t}^{CAQ} < \sum V_{a_\nu,t}^{CAQ}$, i.e., if the entire demand curve is above the supply curve but the supply exceeds demand, as shown in Fig. 3(b), then all the bid orders can be filled. We assume that a_c represents the ask order of intersection E in Fig. 3(b), then the ask orders with an asking price lower than that of a_c can be filled, and the ask order represented by a_c can be partially filled with the transaction volume calculated as $V_{a_c,t}^{CAQ} = \sum V_{b_\mu,t}^{CAQ} - \sum_{\upsilon=1}^{c-1} V_{a_\nu,t}^{CAQ}$. The market clearing price can be calculated as $Pc_t^{CAQ} = 0.5 \bullet \left(P_{b_m,t}^{CAQ} + P_{a_c,t}^{CAQ}\right)$.

(3) If the lowest bid price ($P_{b_m,t}^{CAQ}$) is higher than the highest ask price ($P_{a_n,t}^{CAQ}$) and the two curves intersect at E, as shown in Fig. 3(c), the orders will be processed based on a double auction mechanism, which can be described in Fig. 4. We assume that a_c and b_c represent the ask order and bid order of intersection E, respectively, in Fig. 3(c). As Fig. 4 shows, for each ask order $a_\nu\left(\left[P_{a_\nu,t}^{CAQ}, V_{a_\nu,t}^{CAQ}\right]\right)$ with an asking price no higher than that of a_c, it will be matched with one or several bid orders until there is no bid order with a bidding price no lower than that of b_c. The matched orders are recorded as $[b_K, a_V, \sum q_k], K = \mu, \mu+1, \cdots, \mu+k-1, k \ge 1$, which implies that all the bidders from b_μ to $b_{\mu+k-1}$ transact with the asker a_ν, and the accumulated transaction volume is $\sum q_k$. The corresponding transaction volumes for each asker and bidder are recorded, and the market clearing price is equal to that of the order at intersection E, i.e., $Pc_t^{CAQ} = 0.5 \bullet \left(P_{b_c,t}^{CAQ} + P_{a_c,t}^{CAQ}\right)$.

(4) If the highest bid price ($P_{b_m,t}^{CAQ}$) is lower than the lowest ask price ($P_{a_n,t}^{CAQ}$) and if the two curves do not intersect, there will be no transactions in the CAQ market, as shown in Fig. 3(d).

By the end of the order processing stage in each period t, all the matched orders are recorded; based on the market clearing price and transaction volumes, the individual agents' compliance costs and net consumption quota accounts are updated.

2.3.3. TGC transaction market

In the TGC transaction stage, we assume that there is only one asker in the market with a unified asking price and volume $\left(\left[P_{a,t}^{TGC}, V_{a,t}^{TGC}\right]\right)$, which are exogenously set. The bidding orders $\left(\left[P_{b_\nu,t}^{TGC}, V_{b_\nu,t}^{TGC}\right]\right)$ submitted to the TGC market are also organized following the centralized bidding mechanism introduced in Section 2.3.2. By the end of the order

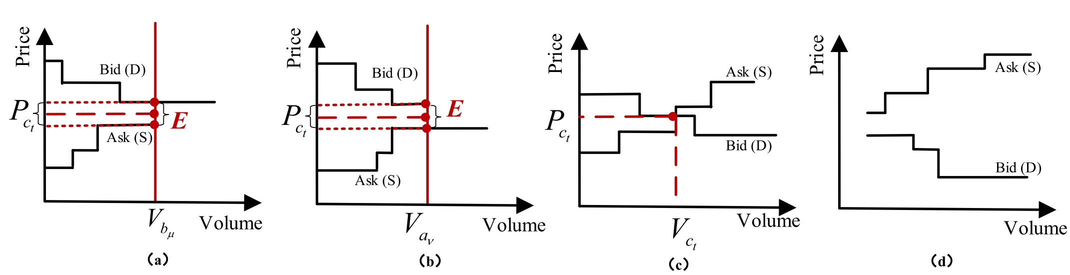


Fig. 3. Different combinations of demand and supply curves in the CAQ market.

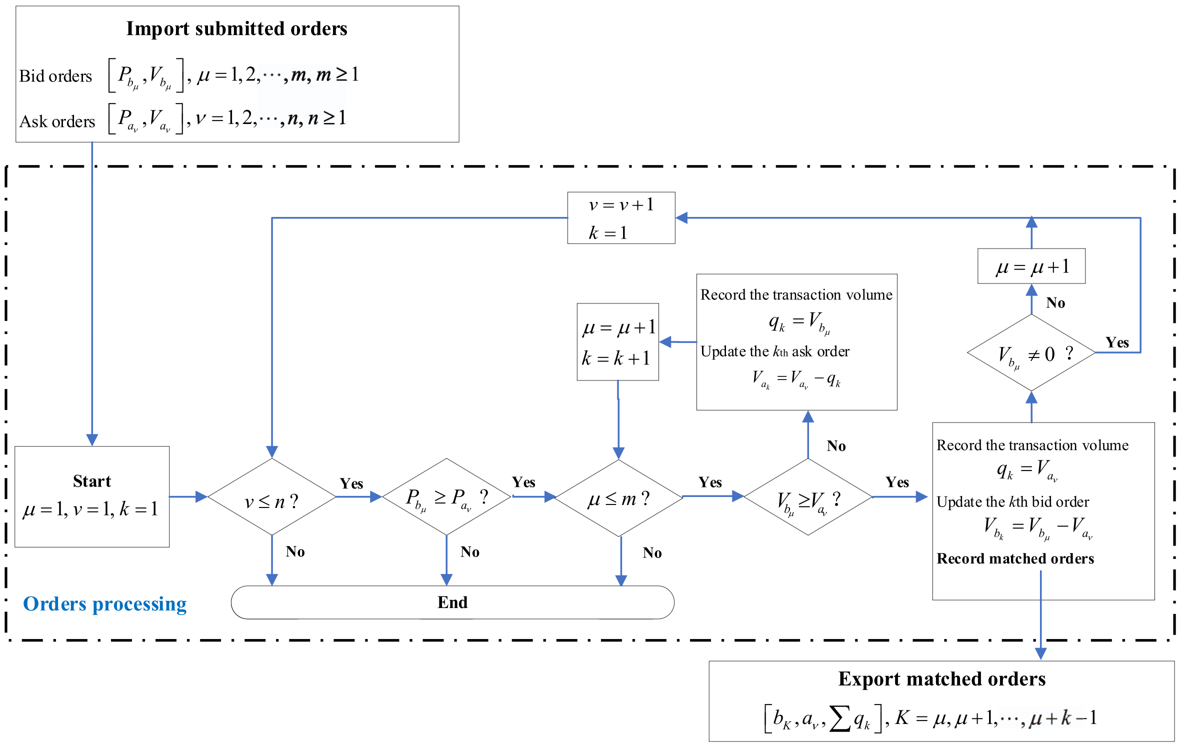


Fig. 4. Flowchart of order processing in supplementary transactions.

processing in the TGC market, all the matched orders are recorded; based on the market clearing price and transaction volumes, the individual agent's compliance cost and net consumption quota account are updated. Finally, each agent's RPS quota account will be verified, and those who fail to cover the RE consumption obligation will be penalized.

2.4. Evolutionary training

As described in Section 2.2, individual agents make decisions based on the same rules but with heterogeneous behavioral parameters. To obtain an appropriate set of behavioral parameters for bounded rational agents, a learning stage is introduced based on the multiple-population genetic algorithm (MPGA) (Yu et al., 2020). Each set of the six behavioral parameters is coded as a 30-digit binary series, which is the "chromosome", representing a strategy for obligated subjects. Each strategy is imported to the simulation stage introduced in Section 2.1, and the corresponding total profit ($\pi_{i,t}$) is recorded. The detailed steps for the above learning stage are listed below and described in Fig. 5.

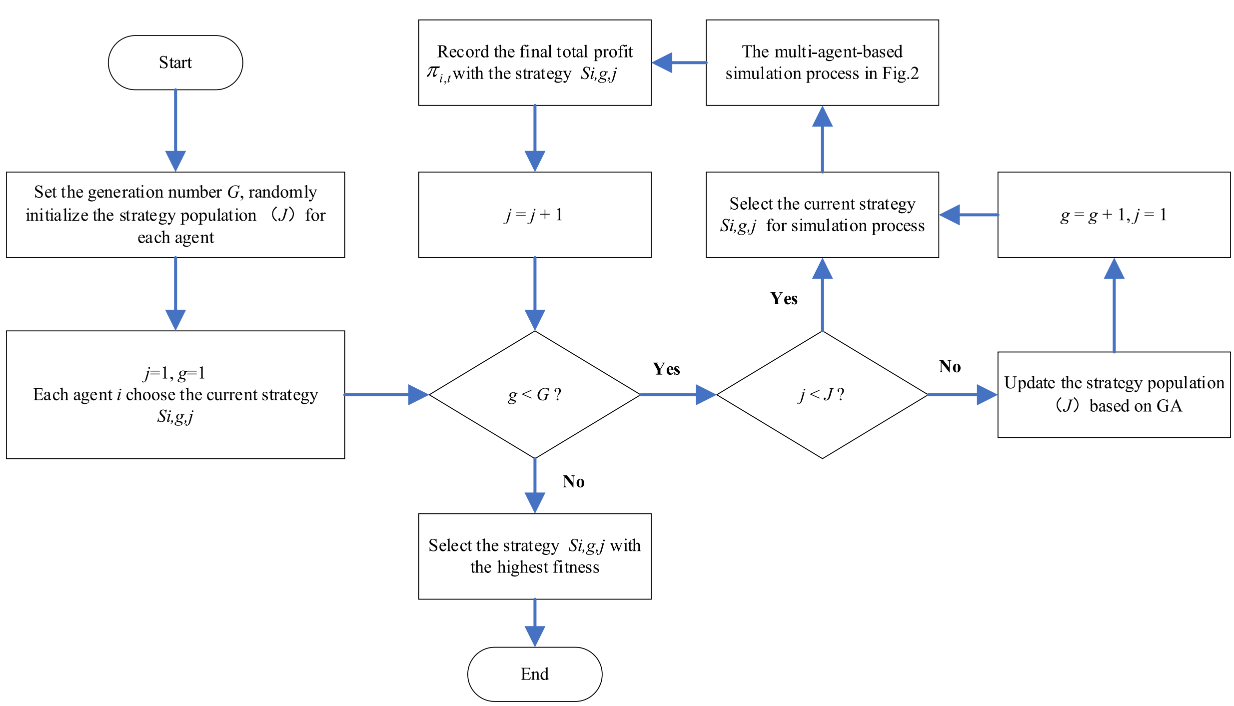


Fig. 5. Flowchart of the GA-based learning stage.

(1) The training stage starts by randomly initializing a population (J) of strategies for each agent *i*, and the training stage lasts for G generations.
(2) In the *g*th generation of training, agent *i* tries each of its strategies ($S_{i,g,j}$) in its current population by applying it to the simulation stage and then records the final total profit ($\pi_{i,t}$) by the end of the simulation process.
(3) When all the strategies in the *g*th generation have already been tested and simulated, individual agents compare the final total profit of each strategy, update its population of strategies based on the GA and produce a new population for the next generation.
(4) As the training stage proceeds, when the strategies of individual agents and the macrolevel results converge, it implies that the agents have learned and trained to obtain a relatively stable and appropriate strategy for the RPS policy obligation.
(5) Finally, the strategy with the highest total profit (fitness) for each individual agent is recorded. Then, the values of the six behavioral parameters for each agent are calculated by mapping the corresponding 30-digit binary series.

3. Data description

The parameters involved in the proposed simulation model mainly include two parts, i.e., the environmental parameters and agents' parameters, which are described in detail in subsection 3.1 and subsection 3.2, respectively.

3.1. Environmental parameters

The environmental parameters of the model denote the common environment that microlevel agents rely on to observe, make decisions, interact with each other, learn, and adjust their behaviors. Under the RPS policy obligation, the environmental parameters can be roughly divided into policy parameters and market parameters.

To examine the effectiveness of implementing the CAQ market for RPS policy, this paper takes the whole electric power industry as the analysis object and mainly focuses on the compliance behavior of heterogeneous obligated entities. The simulation span is set as 10 years with a running step length of one year, and the base year is set as 2020. Regarding the RPS quota, according to the "China Power Development Report 2020", the proportion of non-fossil energy consumption reached 15.9% in 2020. Combined with the provincial level of minimum RE consumption responsibility released by the National Development and Reform Commission (NDRC) in 2020, the RPS quota requirement is initialized as 15%. According to the "Action Plan for Carbon Dioxide Peaking Before 2030", the proportion of non-fossil energy in primary energy consumption will reach approximately 25% in 2030; therefore, the growth step of the RPS quota is set as 5%. Furthermore, to enforce the obligated entities to comply with the RPS obligation, the unit fine for noncompliance is set as 600 yuan/MWh (Zeng et al., 2023b).

Regarding the electricity market parameters, according to the National Industrial Power Statistical Yearbook of 2021, the total electricity demand can be obtained, and the yearly growth rate is calculated based on the data released in the "National Electricity Supply and Demand Situation Analysis and Forecast Report" of the last five years, which is set as 5.67%. The total TGC supply ($V_{a,t}^{TGC}$) and the yearly increase rate (ς) are set according to data collected from the official TGC trading platform of China. The on-grid electricity prices of RE electricity and thermal electricity, as well as the retail price for end-users, are set according to the relevant literature (Zhao et al., 2022b; Zeng et al., 2023b). The other environmental parameters are listed in Table 1.

3.2. Agents' parameters

The parameters of microlevel agents include attribute parameters and behavioral parameters.

Table 1
Initialization of environment parameters.

Parameter	Value	Unit
Initial value of TGC price	70	yuan/MWh
Initial value of CAQ price	70	yuan/MWh
Initial total electricity demand	$58{,}233 \times 10^5$	MWh
Growth rate of the renewable electricity demand	5.67%	–
Initial supply of TGC	7276×10^5	MWh
Growth rate of the TGC supply	2.5%	–
On-gird price of RE electricity	406	yuan/MWh
On-gird price of thermal electricity	371	yuan/MWh
Retail price of electricity	590	yuan/MWh

To reflect the heterogeneity of micro agents, the attribute parameters of agents are randomly set following a set of rules. Regarding the firms' scale and individual demand, a Pareto distribution is introduced with the scale parameter and shape parameter obtained through data fitting. Regarding price forecasting, the memory length of individual agents is randomly initialized within a certain range. The other attribute parameters are listed in Table 2. The behavioral parameters of heterogeneous agents are trained based on the GA, as introduced in Section 2.4, and a full list of behavioral parameters for the two simulation scenarios is provided in Appendix A.

4. Results and discussion

4.1. Training results analysis

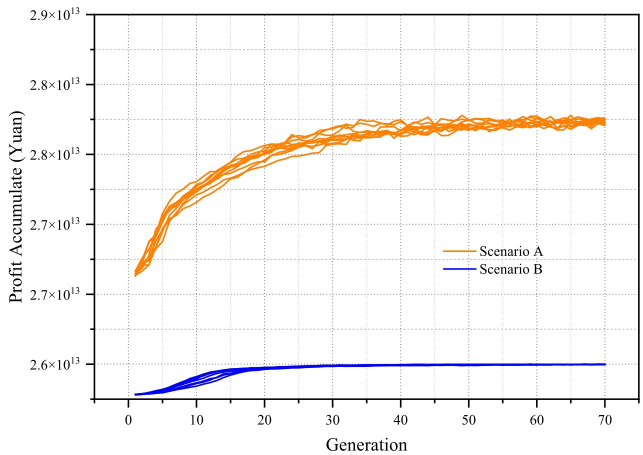
The study selects six macrolevel indicators to reflect the evolutionary training process, including the final accumulated profit of all the agents, the compliance rate, the average RE electricity consumption share, the average CAQ consumption share, the average CAQ transaction volume, and the average CAQ transaction price by the end of the simulation stage.

As shown in Fig. 6, as the training stage progresses, the curves of total profit accumulate (i.e., the "fitness" of each strategy) present an upward trend, the microlevel strategies of individual agents converge after 60 generations, as do the six macrolevel indicators, implying that the agents are evolving to be increasingly intelligent to determine the most reasonable strategy under the current circumstances. The training stage is run ten times with each agent's seed strategies randomly initialized. In each training path, all six indicators show remarkable convergence, and the ten training processes present similar evolutionary pathways, demonstrating the robustness of the learning stage and the reasonability of the selected set of agents' heterogeneous behavioral parameters.

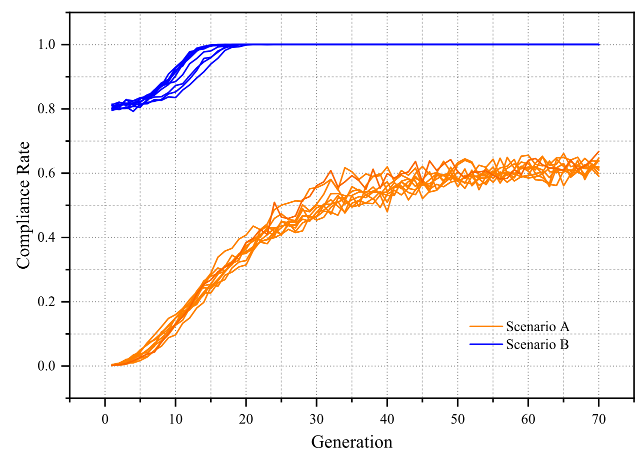
Furthermore, the two scenarios are individually trained to obtain the corresponding set of behavioral parameters due to the different designs of the policy environment. A comparison of the macrolevel training results for the two scenarios is shown in Figs. 6(a)-(c), and two conclusions can be drawn: (1) the total accumulated profit and the average RE consumption share of agents in Scenario A converge to a much higher level than those in Scenario B, implying that the existence of the CAQ

Table 2
Initialization of agents' parameters.

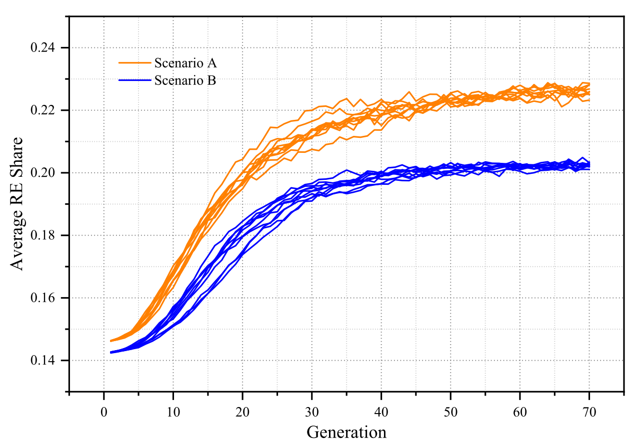
Parameter	Value	Unit
Agent number	100	–
Agent memory length	5	periods
Memory length initialize range	[3, 7]	periods
Initial value of RE electricity consumption share	0.15	–
Initialize range of RE electricity consumption share	[0.14, 0.16]	–
RE electricity consumption share adjustment ratio	10%	–
Initial value of CAQ consumption share	0.5	–
Shape parameter of demand distribution	10,000	–
Scale parameter of demand distribution	5.8233×10^{11}	–



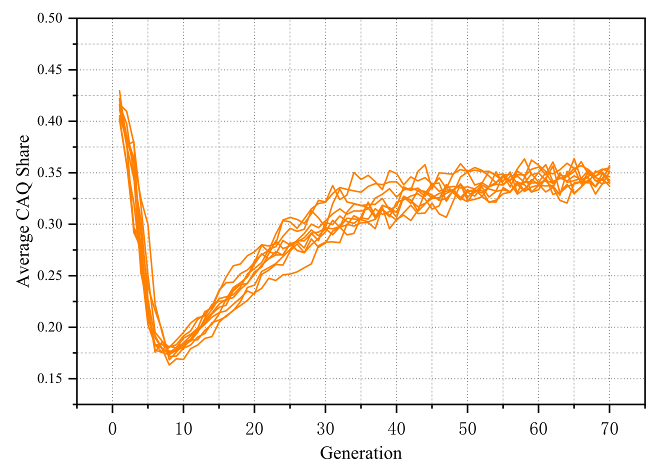
(a) Total accumulated profit



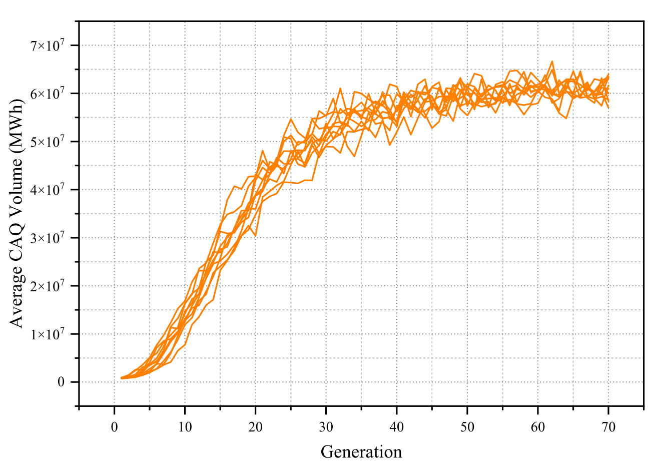
(b) Compliance rate



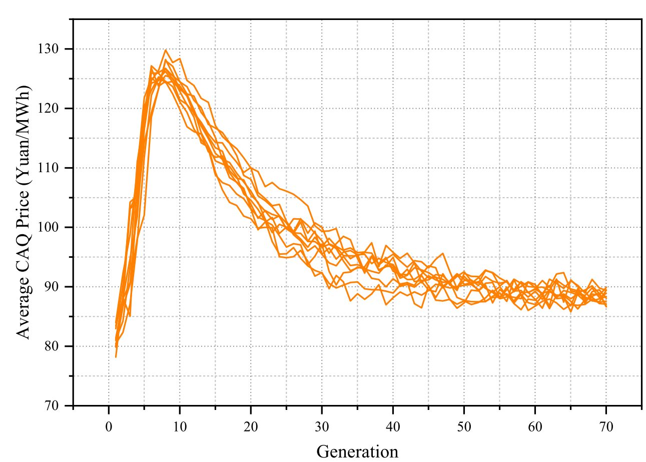
(c) Average RE consumption share



(d) Average CAQ consumption share



(e) Average CAQ transaction volume



(f) Average CAQ transaction price

Fig. 6. Macrolevel results convergence in the training stage.

market enhances the possibility of searching for much more cost-effective solutions for the RPS quota obligation, which can simultaneously contribute to the diffusion of RE electricity consumption; (2) the market results in scenario B converge earlier than those in scenario A, indicating that the establishment of the CAQ market, as an alternative compliance approach, provides heterogeneous agents with more choices to comply with the RPS obligation and broadens the search space (possible solutions) for the GA-based learning process.

4.2. Simulation results analysis and discussion

4.2.1. Impacts of RPS policy considering the CAQ market

To examine the impacts of the incorporation of the CAQ market into the RPS policy, the changes in six key variables in the simulation stage under the two scenarios are compared and analyzed.

Figs. 7(a)-(b) show the changes in the average values and standard deviations of obligated entities' RE consumption shares and the total count of RE diffusion strategy adoptions under the two scenarios. As shown in Fig. 7(a), agents tend to consume more RE electricity in the presence of the CAQ market than in the absence of it. The variance in Scenario A is larger than that in Scenario B since agents have more compliance choices when the CAQ market exists. As shown in Fig. 7(b), most of the obligated entities choose to increase their RE consumption share (i.e., to adopt the strategy of RE share diffusion) in the earlier periods in Scenario A, and the total count of diffusion is greater than that in Scenario B in most periods during the simulation. The results imply that the establishment of CAQ market can significantly promote the enthusiasm of obligated entities for consuming RE electricity and can positively influence their attitude toward RE electricity consumption, which can provide long-term incentives for RE investment through capital recovery from RE sales revenue, thereby promoting RE supply.

Figs. 8(a)-(b) show the changes in the average values of the CAQ consumption share and the total count of CAQ consumption share reduction strategy adoptions of obligated entities under the two scenarios. Given that there is no CAQ market in Scenario B, we can only focus on Scenario A. According to the simulation results, the average CAQ consumption share exhibits a slight downward trend, and all obligated entities adopt the strategy of reducing their individual CAQ consumption share. The hidden reason is that obligated entities make decisions about the CAQ consumption share based on the price forecasts of the two supplementary markets, and the price of CAQ is more likely to increase with increasing RPS quota requirement, as there will be fewer sellers in the CAQ market.

Figs. 9(a)-(b) display the changes in the average values and standard deviations of obligated entities' final total profit and the compliance rate under the two scenarios. As shown in Fig. 9(a), the average final total profit of agents in Scenario A is greater than that in Scenario B with a larger variance. The results indicate that obligated entities have a greater probability of reducing their compliance cost and obtaining a higher profit, and the heterogeneity among agents increases with the existence of the CAQ market. As shown in Fig. 9(b), the compliance rate is higher in Scenario A than in Scenario B, and the advantage of Scenario A becomes increasingly significant over time, which demonstrates the positive impacts of the CAQ market in stimulating the effectiveness of implementing the RPS policy.

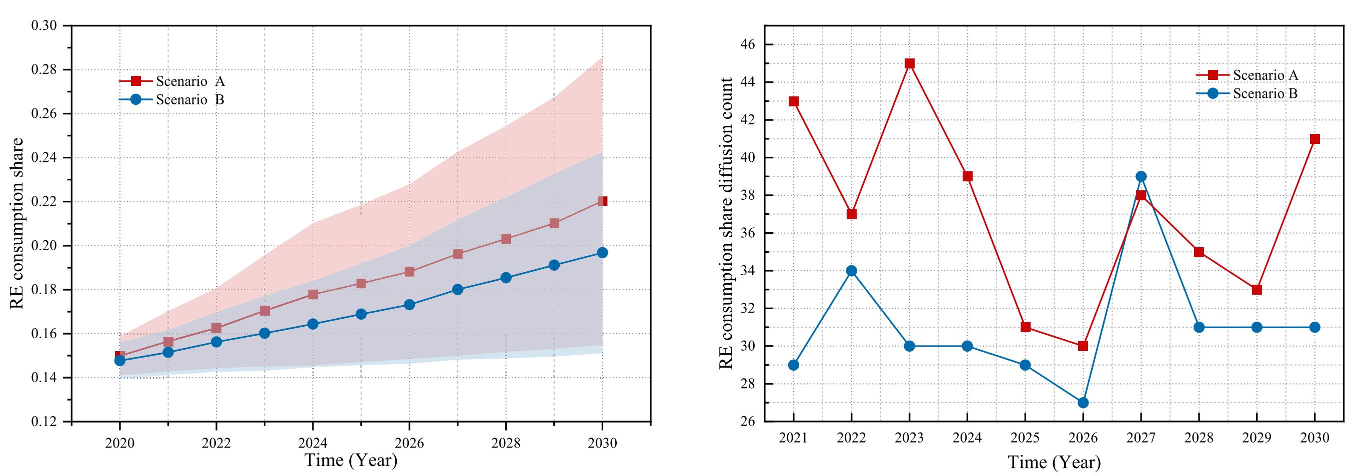
In summary, the establishment of the CAQ market positively influences the share of RE electricity consumption, obligated entities' attitudes toward RE electricity consumption, total profit and total compliance rate. On the one hand, the existence of the CAQ market in RPS policy provides broader space for obligators' decision-making and strategy adoption, improving the possibility of finding solutions to enhance overall implementation effectiveness and individual profit. On the other hand, the function and theory of the CAQ market are similar to those of the secondary market in terms of the carbon emission trading scheme. The existence of the CAQ market makes it possible to further allocate the total amount of RE consumption among microlevel individual agents in a rational way, thus promoting the overall compliance level and reducing the aggregate noncompliance penalty and total compliance cost at the macrolevel.

4.2.2. Transaction in the CAQ market

To reveal the transaction process in the CAQ market in Scenario A, the submitted prices, submitted volumes, traders' counts and market clearing results are selected as indicators.

Based on the price forecast and RPS quota gap, the traders submitted their bid (or ask) prices and volumes to the market. Figs. 10(a)-(b) show the changes in the average values and standard deviations of individual traders' submitted prices and volumes. As shown in Fig. 10(a), the bidding prices are slightly higher than the asking prices, and both increase over time. As shown in Fig. 10(b), the asking volume is slightly greater than the bidding volume in general, and the average gap between the two parties first expands and then contracts within a relatively small range, indicating a relatively even distribution between the transaction volume of the bidders and askers, which, to some extent, guarantees a balance of supply and demand.

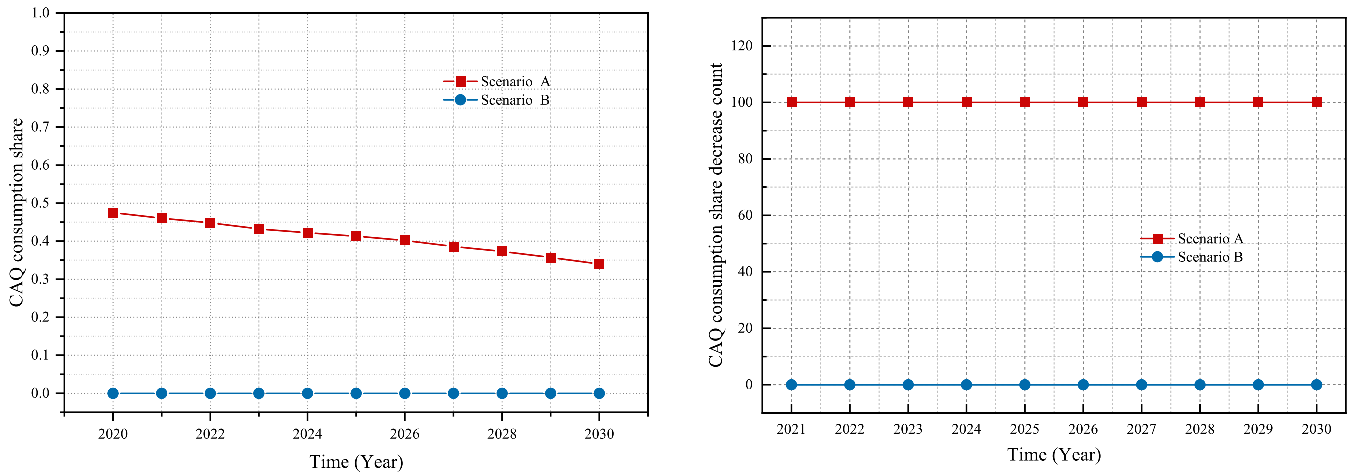
Fig. 10(c) reveals the changes in the traders' counts in the CAQ



(a) Changes in RE consumption share

(b) Changes in RE consumption share diffusion strategy count

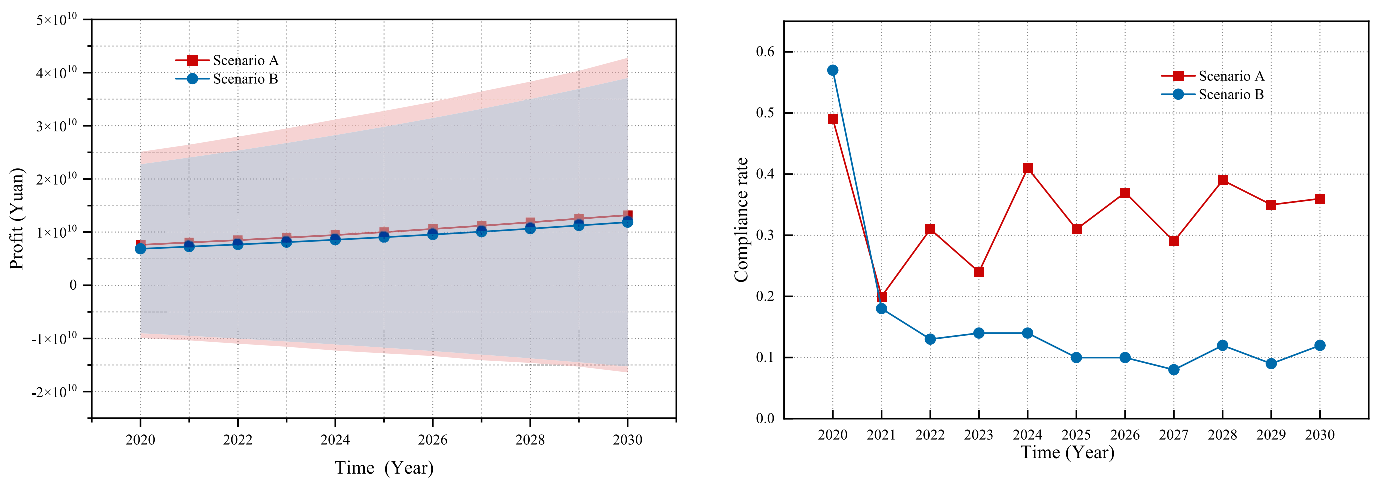
Fig. 7. Impacts on RE consumption share.



(a) Changes in CAQ consumption share

(b) Changes in CAQ consumption share reduction strategy count

Fig. 8. Impacts on CAQ consumption share.



(a) Changes in final total profit

(b) Changes in compliance rate

Fig. 9. Impacts on final total profit and compliance rate.

market. As the simulation proceeds, the number of buyers and sellers varies within a decreasing range, which proceeds toward a relatively equilibrium level. Throughout the simulation, the number of buyers is greater than the number of sellers, indicating that there are a certain number of agents who choose to accomplish the RPS quota obligation through supplementary trading rather than consuming sufficient RE electricity. Similarly, a certain number of obligated entities choose to consume excess RE electricity due to the increasingly higher RPS pressure. The reason is that both parties are initialized following the same rules but with heterogeneous attributes and behavioral preferences, which is in line with the situation of electricity consumption entities endowed with different RE consumption abilities and compliance costs in the real world.

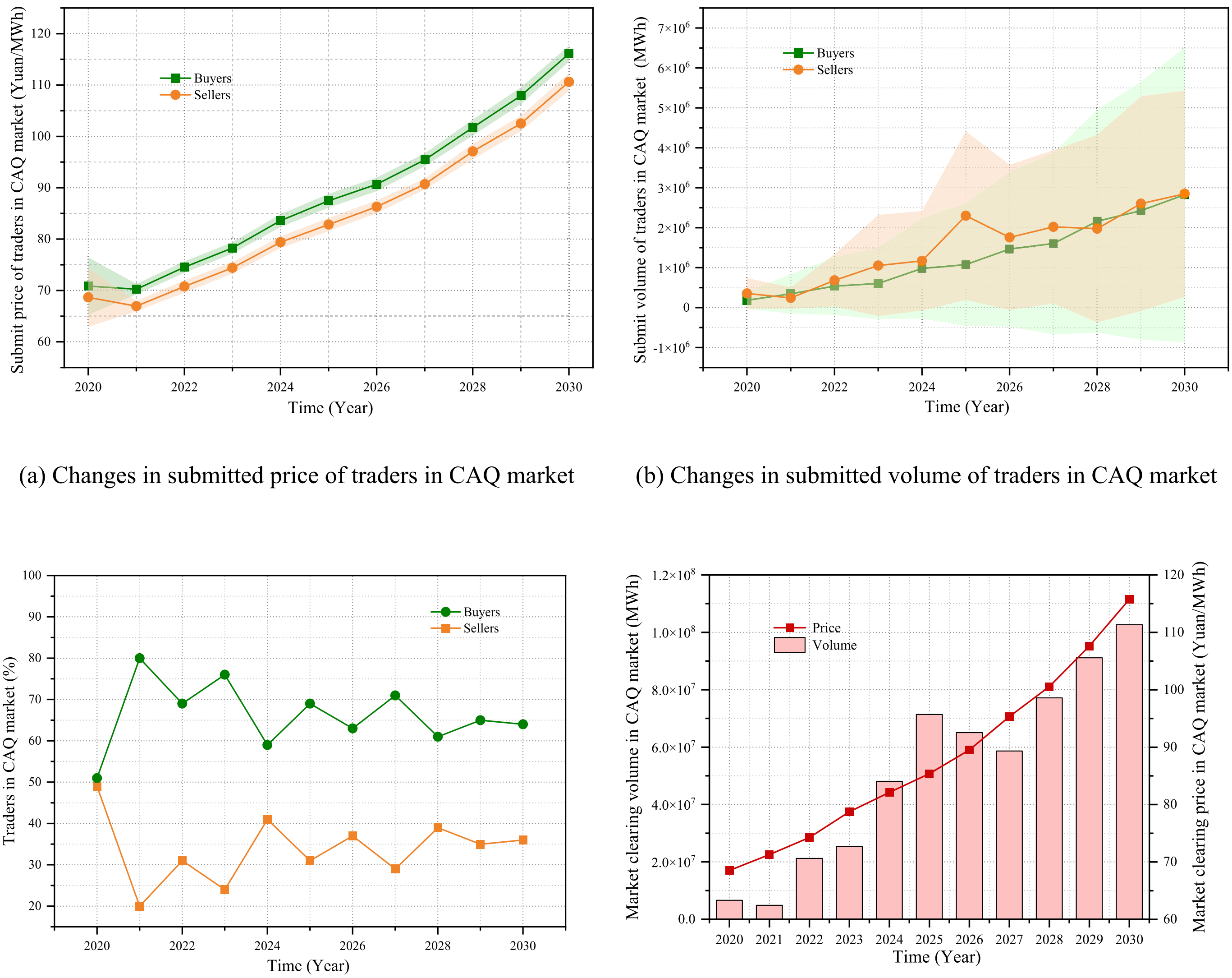
Regarding the market clearing results in the CAQ market, as shown in Fig. 10(d), the market clearing price and volume display a steady upward trend, indicating that the transaction scale in the CAQ market is gradually expanding and that the market is efficient with a healthy state of operation. Based on the performance of the CAQ market, we can further conclude that this market can be well integrated with the RPS policy mechanism.

In summary, the CAQ market can operate stably for supplementary transactions as the RPS target becomes tighter over time based on the proposed model. Moreover, the steady increase in the number of sellers and buyers in the CAQ market guarantees that CAQs flow from surplus to deficiency, which optimizes the allocation of RE consumption among obligated entities and provides compensation for those with surplus RE consumption.

4.2.3. Transaction in the TGC market

In this section, we compare the performance of the TGC market in the two scenarios through changes in the bidding price and volume of the buyers, the number of buyers, and the market clearing results. Due to the assumption that there is only one TGC supplier with the asking volume exogenously set, we only focus on the bidders in the TGC market.

Fig. 11(a) displays the changes in the average values and standard deviations of the bidding prices in the TGC market. The average bidding price in Scenario B is slightly higher than that in Scenario A, and both curves quickly decrease at the very beginning of the simulation, followed by a stable level of 63 yuan/MWh in Scenario A and 64 yuan/MWh in Scenario B in the following 9 periods. The changes in the



(a) Changes in submitted price of traders in CAQ market

(b) Changes in submitted volume of traders in CAQ market

(c) Changes in traders' count in CAQ market

(d) Changes in market clearing price & volume in CAQ market

Fig. 10. Transaction in CAQ market.

average bidding price come from the slight oversupply of TGC, which is consistent with the actual situation in the TGC market. As the simulation proceeds, the average bidding volume in the TGC market shows an upward trend, with a higher level and larger variance in Scenario B than in Scenario A, as shown in Fig. 11(b). The reason is that the bidders in Scenario B can only accomplish the RPS quota gap after RE electricity consumption through TGC consumption, while the bidders in Scenario A can allocate the consumption gap to both the TGC and CAQ markets.

Concerning participation in the TGC market, as shown in Fig. 11(c), the percentage of bidders in total obligated subjects rises drastically in the first period in both scenarios; then, the percentage in Scenario B stays at approximately 85%, and the percentage in Scenario A presents a downward fluctuation in the following nine periods. The reason is that some supplementary transaction demanders have shifted from the TGC market to the CAQ market.

The market clearing price and volume in the TGC market for both scenarios are shown in Fig. 11(d). By comparing the two scenarios, two conclusions can be drawn. First, the existence of the CAQ market in Scenario A results in an overall lower transaction volume but a higher market clearing price than in Scenario B throughout the simulation, indicating that the integration of the CAQ market not only influences the consumption demand of TGC but also leads to macrolevel market coupling and price linkage through microlevel interactions. Second, the TGC market in both scenarios can operate effectively and develop steadily, functioning well to supplement the RPS mechanism and promote RE development. Furthermore, by combining the results in Fig. 10 (d) and Fig. 11(d), it can be found that both the CAQ and TGC markets play a significant role in supplementing the RE consumption requirements, but the TGC transaction volume is much larger than that in CAQ market.

In summary, the TGC market provides prominent support for supplementary transactions to meet RPS requirements. However, the establishment of the CAQ market has to some extent suppressed the participation of obligated entities in the TGC market, weakening the vitality of the TGC market, which may in turn have a negative effect on the TGC sales revenue of RE electricity manufacturers, thereby suppressing the supply of renewable energy.

4.3. Impacts of the penalty–reward mechanism

To investigate how the penalty–reward mechanism affects the performance of the national-based unified CAQ market, we design a group

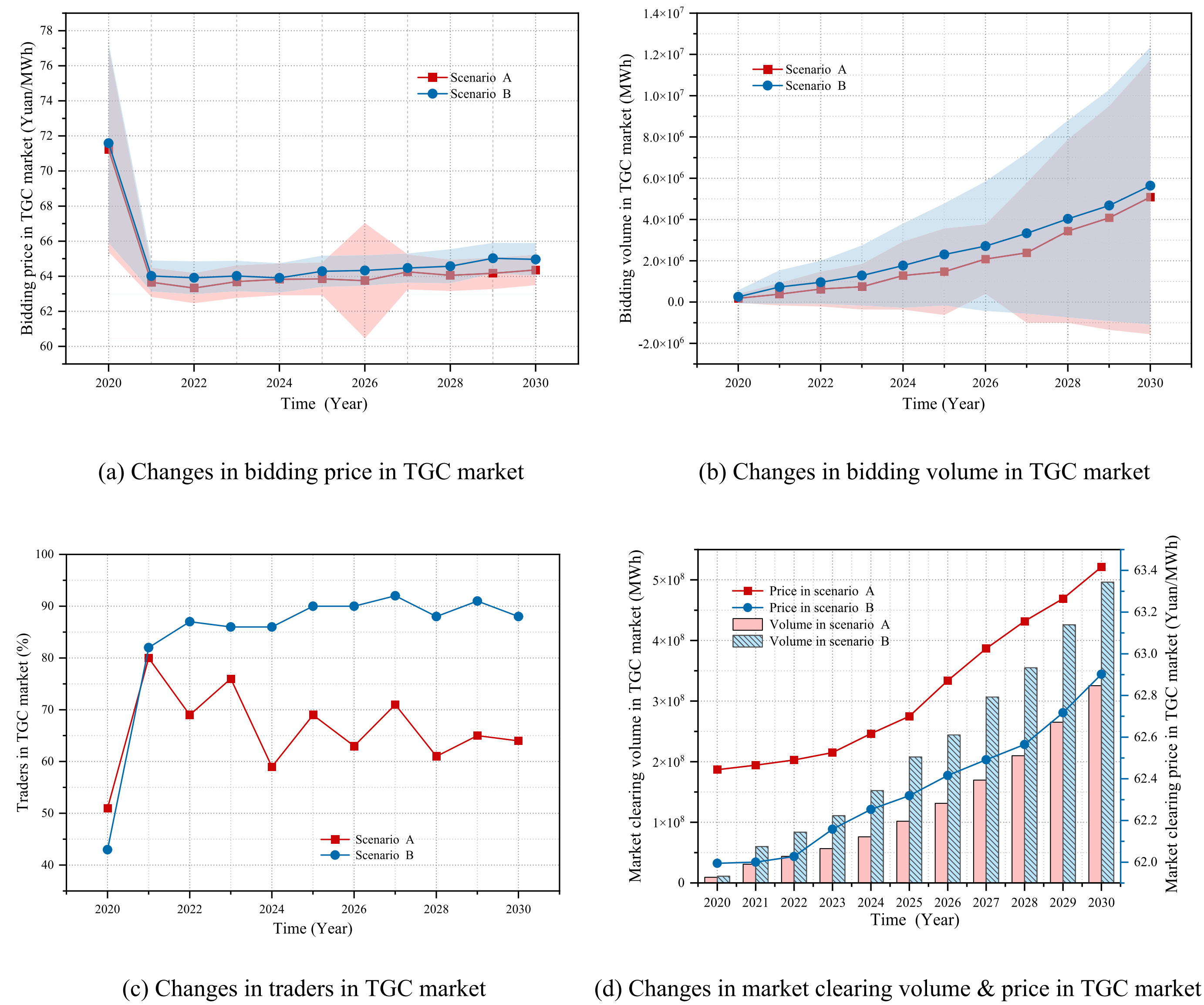


Fig. 11. Transaction in TGC market.

of scenarios with different values of penalty (μ_{fine}) and reward (μ_{reward}) parameters for the deficiency and surplus in the net consumption quota account, based on Scenario A, in which the CAQ market is established, as shown in Table 3. Considering the trade-off between the retail profit of RE consumption (the gap between the on-grid price of RE electricity and the retail price of electricity) and the forecasted CAQ price (relevant to the initial value of the CAQ price), we set the reward for the unit surplus RE quota as 20, 70, 200, 300 and 600 yuan/MWh.

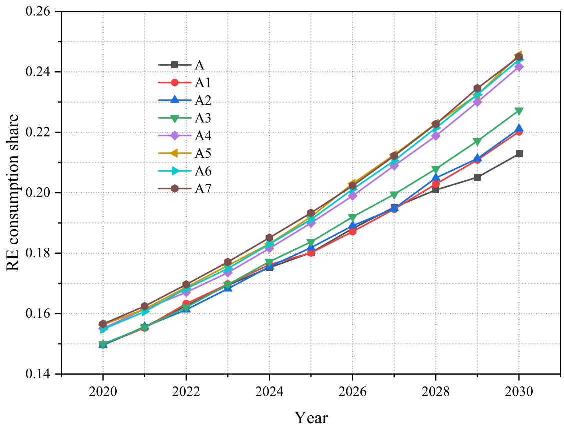
The simulation results are shown in Fig. 12.

The results in Fig. 12(a) reveal that the combined penalty–reward mechanism provides many more incentives for obligated entities to improve their RE consumption share than does the separate penalty mechanism, even when the reward is set at a much lower level than forecasted CAQ sales income (represented by scenario A3). However, the positive effect is limited after the reward increases to some degree. In addition, varying the penalty separately has no significant effect on improving the RE consumption share.

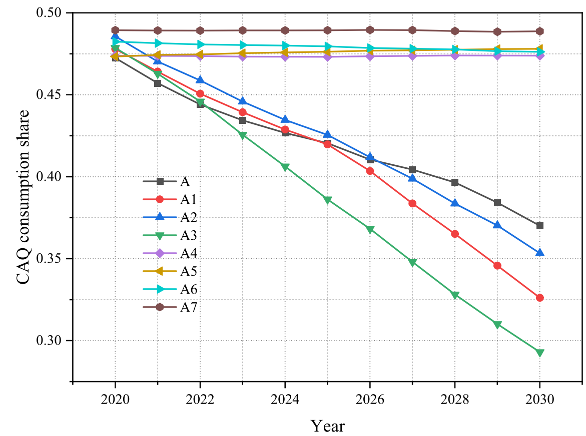
As shown in Figs. 12(b-c), varying the penalty separately can slow the rate but has no significant effect on changing the downward trend in the CAQ consumption share. Only when the reward in a combined penalty–reward mechanism exceeds a certain level (represented by scenario A4) can the number of entities that adopt the CAQ consumption share reduction strategy start to decrease. Furthermore, compared with the separate penalty mechanism (represented by scenario A), the combined penalty–reward mechanism can better stimulate the CAQ market, as many more CAQ askers can be generated due to a higher RE consumption share, as shown in Figs. 12(d-e). However, the incentive is not positively correlated with the unit reward level, which rebounds after a certain level (represented by scenario A5). The hidden reason is that the bounded rational obligated entities are more likely to obtain the reward than to participate in the CAQ market when the unit reward reaches a high enough level.

Table 3
Scenario design of the penalty–reward mechanism in RPS policy.

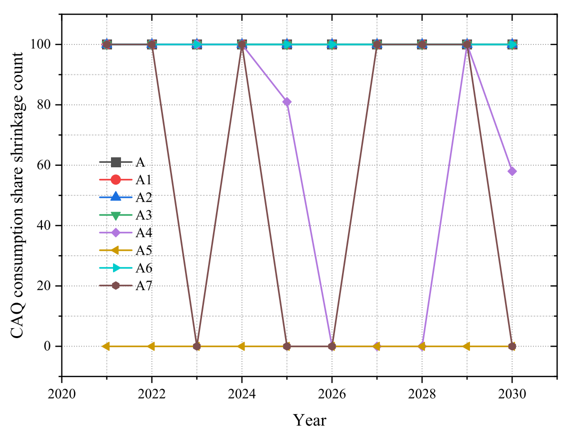
Scenario	Fine	Reward	Unit
A	600	0	yuan/MWh
A1	300	0	yuan/MWh
A2	900	0	yuan/MWh
A3	600	20	yuan/MWh
A4	600	70	yuan/MWh
A5	600	200	yuan/MWh
A6	600	300	yuan/MWh
A7	600	600	yuan/MWh



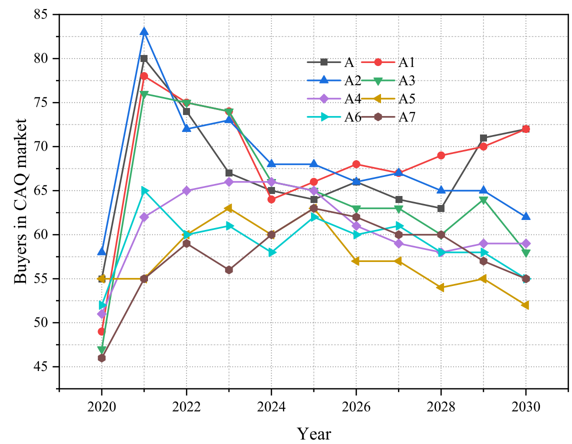
(a) Changes in RE consumption share



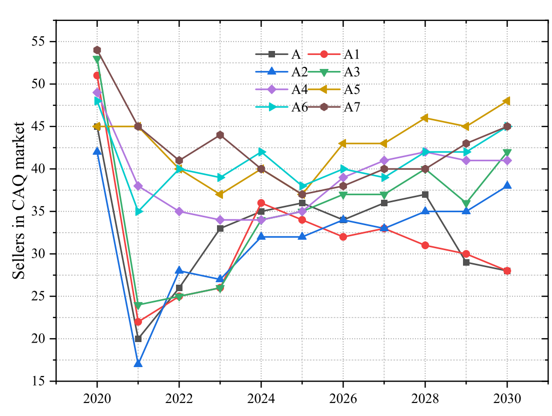
(b) Changes in CAQ consumption share



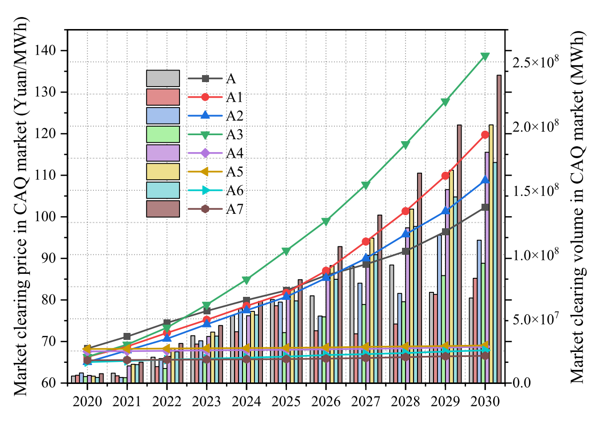
(c) Changes in CAQ consumption share reduction strategy count



(d) Changes in buyers in CAQ market



(e) Changes in sellers in CAQ market



(f) Changes in market clearing volume & price in CAQ market

Fig. 12. Impacts of the penalty–reward mechanism on RPS policy.

As shown in Fig. 12(f), the CAQ market is in short supply with the market clearing price presenting an upward trend and thin transaction volume in scenarios with separate penalty mechanisms or a combined mechanism with a low reward level, whereas the market clearing price remains stable and a heavy transaction volume is realized in a combined mechanism with a relatively high level of unit reward. This finding reveals that when the positive incentive (represented by rewards) is not enough even with a higher negative constraint (represented by penalties), the CAQ market, as a second trading market for RE electricity consumption, will be severely limited.

In summary, the combined penalty–reward mechanism is more effective than the separate penalty constraint mechanism at boosting RE consumption share, CAQ market transaction volume and CAQ market vitality. Moreover, there is an effective interval for the unit reward level, which should be set between the retail profit of RE consumption and the forecasted CAQ price. The results also indicate that the key to improving CAQ market vitality and market performance is expanding market participation.

4.4. Sensitivity analysis

To evaluate the effects of changes in the exogenous parameters on the ABM model, we perform a sensitivity analysis using Scenario A in which the CAQ market is established. Five critical environment/agent parameters are changed by plus or minus 5% based on the initial value. Thus, ten scenarios are generated, as shown in Table 4.

In this section, we select four indicators, i.e., RE consumption share, CAQ consumption share, the final profit, and the compliance rate, to analyze the impact of the changes in these five parameters. The simulation results can be seen in Fig. 13.

As shown in Fig. 13(a), changes in the five parameters have no significant effect on the RE consumption share throughout the simulation span. The pillars in all the scenarios present similar trends and vary within a rather small range, indicating that these five environment/agent parameters play a minimal role in stimulating RE consumption diffusion.

As shown in Fig. 13(b), the CAQ consumption share in all the scenarios displays a slight downturn over time but decreases much more slowly with a higher initial value of the TGC/CAQ price in Scenario C1+. The hidden reason is that the TGC price is bound to decrease at the beginning period due to a sufficient supply, which negatively influences the CAQ consumption share. The changes in the other parameters do not show prominent differences.

As shown in Fig. 13(c), the final total profit in all the scenarios tends to increase over time but is slightly sensitive to the initial value of the TGC/CAQ price and TGC supply. The increase in the initial value of the TGC/CAQ price promotes the total profit of electricity users owing to a more active supplementary transaction market supported by a higher TGC/CAQ price. Both parameters related to TGC supply, i.e., the initial supply of TGC and the growth rate of the TGC supply, can to some extent influence the total profit, and the sensitivity results illustrate that there is a proper interval of TGC supply to promote the final total profit.

As shown in Fig. 13(d), as the compliance process involves multiple microlevel obligated agents' complex interactions through multimarket coupling, the compliance rate has no linear association rules with the five parameters, but the pillars vary within a certain range and present similar variation tendencies.

In summary, the sensitivity results show that the impact of the above parameters does not have more apparent fluctuations, the results are in line with reality, and the sensitivity of the model to parameter changes is within a reasonable range.

Table 4
Parameter adjustment under scenario design of sensitivity analysis.

Scenario	Parameter adjustment	Adjust value
C1+	Initial value of TGC/CAQ price	$1.05\times P_{i,t}^{CAQ}$; $1.05\times P_{i,t}^{TGC}$
C1-	Initial value of TGC/CAQ price	$0.95\times P_{i,t}^{CAQ}$; $0.95\times P_{i,t}^{TGC}$
C2+	Growth rate of the renewable electricity demand	$1.05\times D_t^{ele}$
C2-	Growth rate of the renewable electricity demand	$0.95\times D_t^{ele}$
C3+	Initial supply of TGC	$1.05\times V_{a,t}^{TGC}$
C3-	Initial supply of TGC	$0.95\times V_{a,t}^{TGC}$
C4+	Growth rate of the TGC supply	$1.05 \times \varsigma$
C4-	Growth rate of the TGC supply	$0.95 \times \varsigma$
C5+	RE electricity consumption share adjustment ratio	$1.05 \times \delta$
C5-	RE electricity consumption share adjustment ratio	$0.95 \times \delta$

5. Conclusions and policy implications

5.1. Conclusions

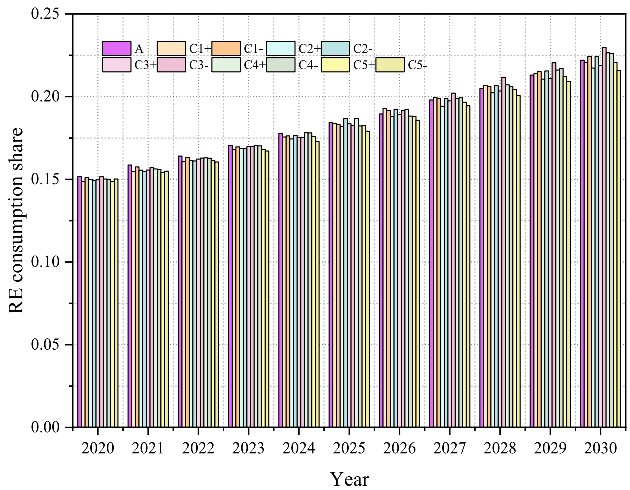
By combining the agent-based simulation model and GA-based evolutionary training, this paper established a technical framework for China's consumption-side RPS policy in which the coordination among the three compliance approaches of obligated entities is modeled, the microlevel decision-making process and complex interactions are depicted, and the macrolevel multimarket coupling effects and aggregate market emergence are captured. Based on the proposed novel simulation model, this paper attempts to examine the impact of the incorporation of the CAQ market into the RPS policy on RE consumption diffusion and on multimarket coupling effects considering the electricity market, CAQ market, and TGC market from a bottom-up perspective. Finally, the following conclusions are drawn, which correspond to the three questions raised in the introduction.

5.1.1. How does the existence of the CAQ market influence the implementation of RPS?

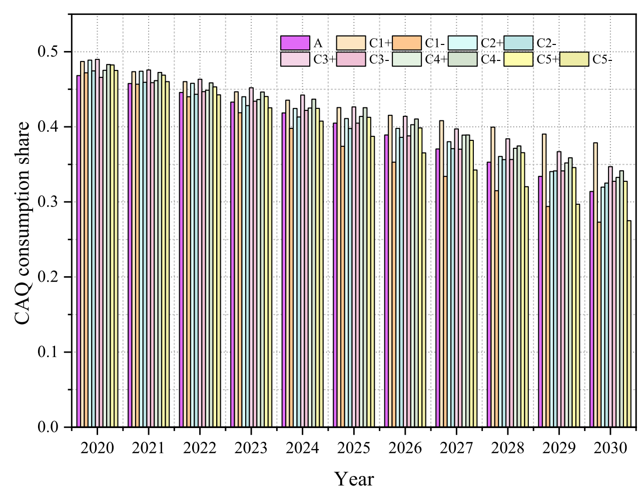
The simulation results show that the existence of the CAQ market in RPS policy can significantly stimulate obligated entities to consume more RE electricity earlier. As illustrated by Zhao et al. (2024), the CAQ market provides a new approach to accomplish RPS quota requirements, which encourage obligated entities to consume RE electricity intuitively and contribute to avoiding risks in electricity demand and supplementary transaction price volatility through adjusting compliance strategies. Furthermore, as confirmed by Li et al. (2024), the RPS requirement can be fulfilled through CAQ trading in actual RE consumption, and it is necessary to consider the existence of the CAQ market and the trading behavior of supply and demand in the CAQ and TGC markets for an in-depth exploration of RE consumption.

Furthermore, the existence of the CAQ market in RPS policy is conducive to improving individual and aggregate profits and boosting the overall compliance rate when the CAQ flows from surplus to deficiency. CAQ transactions enrich RPS compliance approaches and hence broaden the strategy search space when individual agents make decisions by coordinating the three compliance approaches.

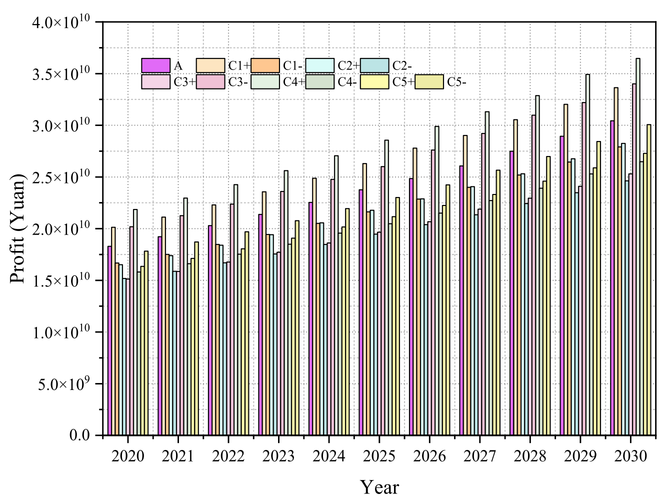
Finally, the analysis reveals that a combined penalty–reward mechanism is highly important for the CAQ market and RE consumption diffusion. A previous study by Dong et al. (2022) claimed that it is necessary to set punishment and incentive mechanisms in RPS policy and that power grid enterprises are very sensitive to the penalty coefficient but have little sensitivity to changes in the incentive coefficient; however, further exploration of this research revealed that the combined penalty–reward mechanism is more effective with a proper interval at the reward level, which is consistent with the conclusion of Zhao et al. (2022a).



(a) RE consumption share under sensitivity analysis



(b) CAQ consumption share under sensitivity analysis



(c) Final total profit under sensitivity analysis

(d) Compliance rate under sensitivity analysis

Fig. 13. Sensitivity analysis.

5.1.2. How does the existence of obligated agents' heterogeneity and evolutionary learning influence their behaviors and strategies?

The simulation results reveal that the variance in aggregate market results is greater with the existence of the CAQ market due to the enhanced heterogeneity among microlevel agents in strategy adoption. In the real world, agents in energy systems have different RE electricity consumption capabilities with different compliance costs because of their different technical levels and uneven distributions of RE energy resources. As demonstrated by Yu et al. (2020), heterogeneity of obligated agents enhances the capture of emergence properties and the uncertainty of the system.

Given the uncertainty mentioned above, the training results analysis and sensitivity analysis demonstrate the calibration of the selected set of agents' heterogeneous behavioral parameters and the robustness of the model. As confirmed by Yu (2022), without relying on agent-level empirical data, model validity can be supported by direct calibration and evolutionary training. In this study, based on the behavioral parameters selected from evolutionary training, the obligated subjects in Scenario A are more likely to make rational decisions to comply with the RPS quota requirements with a higher profit than those in Scenario B are.

5.1.3. What is the emergence of multimarket coupling at the macro level driven by behaviors at the micro level?

The simulation results illustrate that there is a positive price linkage and a negative transaction volume linkage between the CAQ and TGC markets. A previous study by Song et al. (2021) also concluded that the CAQ price is positively correlated with the price ceiling of the TGC and thereby influences market transactions by comparing scenarios with different price limit settings. However, in this paper, the macrolevel coupling emergence between the CAQ and TGC markets is driven by microlevel price forecasting and compliance behavior coordination among the three approaches. In the proposed model, obligated entities make decisions following the "Observe-Forecast-Decision" mode, and price forecasting plays an adjustment role in their market transaction decision-making, leading to synergistic interactions in the market clearing price and expanding market transactions.

Furthermore, the existence of the CAQ market is conducive to improving obligated entities' willingness to expand RE electricity consumption, and a proper penalty–reward mechanism can positively expand both the primary RE electricity trading market and the secondary CAQ market. Many previous studies (Hu et al., 2022; Li et al., 2024) have also indicated that various factors can trigger shifts in the supply–demand relationship and trading enthusiasm among market players in multi-markets, ultimately influencing the investment in and consumption of RE. In the proposed model, a sigmoid function is used to construct microlevel obligated entities' decision-making rules while considering various factors, thereby modeling the microlevel behaviors affected by external factors.

5.2. Policy implications

Based on the above conclusions, the following implications are drawn.

(1) The results demonstrate the importance of establishing the CAQ market in fostering RE consumption and promoting total profit when the RPS policy is implemented. However, China's CAQ market mechanism is still in the exploratory stage. The current degree of CAQ marketization is insufficient, the market structure is imperfect, and the construction of interprovincial and interregional power grids is limited. In most regions, RE generation has not even entered the trading market. Furthermore, there are interprovincial barriers to RE electricity consumption and CAQ transactions in practice. Therefore, to ensure the healthy operation of the CAQ market, efforts should be made in three ways. First, regional protectionism should be broken down to introduce more market participants into the RE electricity market and CAQ market to improve market efficiency. Second, the construction of the power grid system should be strengthened while considering the investment construction cycle, and new technologies should be actively developed and applied to improve the power grid transmission capacity. Third, the regulation and supervision mechanisms of the power system should be enhanced, and the coordination between the development of the power grid and the power source and load should be improved.

(2) The simulation results of the penalty–reward mechanism reveal that the willingness of obligated entities to consume RE electricity and the vitality of the CAQ market can be triggered through appropriate incentive mechanisms. However, the effectiveness of the reward mechanism is limited because of an effective interval. Therefore, in addition to reasonably setting the penalty–reward mechanism, further mechanism designs should be considered and applied in RPS implementation, such as RPS quota indicators, benchmark prices and conversion methods between CAQs and TGCs.

(3) The results show that there is a linkage mechanism between multimarket coupling at the macro level and behaviors at the micro level, which influences the ultimate policy effects. Therefore, RPS mechanisms should be reasonably designed to guide the behavior of micro level individuals, thus forming benign multimarket coupling effects at the macro level. However, current official documents rarely illustrate the explicit institutional arrangements for supplementary trading in the CAQ and TGC markets for RPS requirements or how to connect with the existing power market system, hence many institutional uncertainties exist. For example, several provinces have proposed four methods for CAQ transactions, i.e., bilateral negotiation, centralized bidding, listing, and rolling matching, but without detailed transaction rules. In this study, given the complexity of the model, the centralized bidding mechanism is primarily employed, and the simulation step is set as one year. Therefore, more market-oriented transaction mechanisms can be considered in future studies, and the government should continuously improve institutional details such as trading varieties, trading rules, trading cycles, the validity period of the certificates, market accesses and supervision mechanisms.

(4) The simulation results reveal that the microlevel heterogeneity of market players has a significant influence on the macrolevel emergence properties of the system. This study establishes a nationwide unified trading market for RE consumption and CAQ trading but ignores heterogeneity in regional characteristics in terms of energy sources and power loads. Therefore, the modeling of RE consumption considering the heterogeneity in provincial resource endowment with the existence of the CAQ market under the RPS policy deserves further study.

CRediT authorship contribution statement

Jiaqian Wu: Writing – original draft, Software, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Xiaolin Zheng:** Writing – original draft, Resources, Formal analysis, Data curation. **Songmin Yu:** Validation, Supervision, Software, Methodology, Conceptualization. **Lean Yu:** Writing – review & editing, Validation, Supervision, Project administration.

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Appendix A. Appendix

Table A.1
Agents' behavioral parameters trained based on GA with the existence of CAQ market.

Id	$\alpha_{i,1}$	$\alpha_{i,2}$	$\alpha_{i,3}$	$\alpha_{i,4}$	$\alpha_{i,5}$	$\alpha_{i,6}$	Id	$\alpha_{i,1}$	$\alpha_{i,2}$	$\alpha_{i,3}$	$\alpha_{i,4}$	$\alpha_{i,5}$	$\alpha_{i,6}$
0	2.2517	1.0384	1.0133	3.9743	3.3767	1.2437	**50**	3.8335	0.8280	1.0054	0.2537	4.2189	2.2379
1	3.7625	0.4044	1.1200	0.6812	2.0699	2.3016	**51**	1.5523	3.0008	1.0068	1.1123	2.0478	1.6675
2	1.4231	3.0388	1.0180	3.1404	2.4507	2.1131	**52**	4.0408	1.7438	1.0131	0.3658	4.7189	1.0770
3	2.1006	3.6730	1.0122	0.6685	2.7348	2.4463	**53**	1.8226	1.0438	1.0013	0.2508	4.8685	2.9314
4	4.4242	1.6111	1.0149	0.4562	1.8645	0.5985	**54**	4.1048	0.2965	1.0092	0.8219	3.8215	2.7764
5	3.1384	2.9225	1.0463	0.3431	1.3364	3.2312	**55**	2.3416	2.1042	1.0076	0.4749	1.6820	1.6543
6	3.6797	0.3143	1.0685	0.2999	1.5298	0.6208	**56**	3.5741	2.3953	1.0270	0.4840	4.4642	1.7772

(*continued on next page*)

Table A.1 (*continued*)

Id	$\alpha_{i,1}$	$\alpha_{i,2}$	$\alpha_{i,3}$	$\alpha_{i,4}$	$\alpha_{i,5}$	$\alpha_{i,6}$	Id	$\alpha_{i,1}$	$\alpha_{i,2}$	$\alpha_{i,3}$	$\alpha_{i,4}$	$\alpha_{i,5}$	$\alpha_{i,6}$
7	3.5176	0.5903	1.0128	0.5365	1.5395	2.2662	**57**	2.0028	1.9354	1.0165	0.3483	1.7122	2.2313
8	4.4755	2.9753	1.0018	1.1333	3.8348	3.2899	**58**	1.4983	2.7974	1.0013	0.2835	2.2113	2.1382
9	3.8619	1.1561	1.0016	0.3051	1.5201	3.0543	**59**	3.6155	2.7223	1.2340	0.4154	3.1765	2.8796
10	3.2276	1.1124	1.4823	3.9877	4.0667	3.2124	**60**	3.6788	2.3888	1.0291	0.2599	2.0148	2.9629
11	4.2409	1.2502	1.0095	0.3031	1.9022	2.3150	**61**	4.6204	1.0972	1.0123	2.0142	3.6651	2.8634
12	1.2358	2.1352	1.0571	0.3359	2.2086	0.6605	**62**	4.9006	0.8002	1.4526	3.7195	4.0599	0.5679
13	4.2972	1.7497	1.0025	0.2887	2.4069	2.2221	**63**	2.0427	3.9021	1.0126	0.2930	2.9270	1.9953
14	3.4555	1.1880	1.0608	0.4367	2.9422	3.6606	**64**	4.7576	0.9899	2.5476	0.5703	4.4137	3.3749
15	3.3232	3.3120	1.4960	0.2580	1.1595	3.1921	**65**	2.0234	1.3451	1.0010	2.0152	4.0550	1.1126
16	4.7328	2.0984	2.0620	0.4863	3.1468	0.6715	**66**	3.4900	0.6586	1.1006	0.3115	3.7682	3.2286
17	3.8336	2.7349	1.2479	0.3438	4.5711	2.0673	**67**	3.2090	1.6133	1.0095	0.4365	2.7515	3.9864
18	1.6462	0.4130	1.2445	0.4717	2.3797	3.9241	**68**	4.9389	3.1977	2.8578	1.2126	1.4157	1.9189
19	2.2547	0.2890	1.0215	0.3017	4.0115	2.4018	**69**	1.5518	1.5690	1.0075	0.3663	3.8557	0.9412
20	3.7498	0.5065	1.4526	0.2622	4.3123	2.7075	**70**	2.4755	1.6502	1.9928	0.3579	1.4346	3.2140
21	4.0207	2.2690	1.9717	0.2689	4.3228	1.2902	**71**	2.7331	3.9291	1.0028	0.2690	4.6514	0.3183
22	2.1830	2.4915	1.4624	0.2778	2.4333	1.8979	**72**	3.4768	1.2578	1.1164	0.2604	4.6805	3.0285
23	4.5429	1.8476	1.0020	0.2859	2.8986	3.3142	**73**	4.9780	0.7350	1.0014	0.6714	3.9103	1.1344
24	3.6133	2.7291	1.0130	0.3057	2.5927	1.5270	**74**	4.0161	0.9268	1.0224	3.8110	1.9128	3.5513
25	1.3533	0.9923	1.0089	0.4006	1.6862	2.1753	**75**	2.7665	2.8054	1.0197	2.0728	4.9149	3.6870
26	2.5537	2.1054	1.0032	3.8636	3.3803	2.1029	**76**	3.4971	3.1502	1.0077	0.3236	4.1915	3.5473
27	1.6145	1.4486	2.9758	0.3282	4.2132	2.8314	**77**	4.8167	3.4866	1.0019	0.4200	2.2257	2.6612
28	4.4059	1.7958	1.1159	1.0971	3.6675	0.4449	**78**	4.5689	1.3081	1.0183	0.3042	3.1998	3.3407
29	3.6727	3.0415	2.9986	3.6674	1.1378	2.7703	**79**	1.9072	0.6375	1.0013	0.3504	4.7054	3.8692
30	1.6656	1.3657	1.9702	0.2987	1.8463	0.6484	**80**	1.6427	3.7659	1.4760	0.2964	2.6826	3.9524
31	2.3672	3.6891	2.9908	0.4201	1.0612	3.8100	**81**	4.9684	0.9970	1.0086	0.2681	1.3562	1.8947
32	4.3749	1.9305	1.0376	0.2769	2.9927	1.7086	**82**	3.9707	2.7863	1.0087	0.4443	2.4724	1.4384
33	4.1689	3.3694	1.0235	2.1214	1.7212	2.7909	**83**	1.8449	2.5251	1.0559	0.2510	4.0867	1.0633
34	3.1722	2.0009	1.0474	2.0788	1.3304	3.5222	**84**	1.9240	2.1701	1.0096	0.2989	1.8740	1.5992
35	3.2022	0.9487	2.9976	0.2697	1.9818	2.9095	**85**	1.2866	0.8115	1.0074	0.2702	3.2783	1.8445
36	1.3970	3.9198	2.9756	0.7157	2.8950	3.7931	**86**	3.5230	0.4729	1.0094	2.0088	1.3529	3.8459
37	2.8506	3.7052	1.0519	0.4253	4.4720	0.6912	**87**	3.3307	1.3276	1.0549	0.3411	4.4588	3.5476
38	3.0320	3.7696	1.0052	0.5331	1.8447	2.8542	**88**	4.3570	3.9388	1.0306	0.7153	4.5861	1.6282
39	2.9044	2.6941	1.1185	0.2837	2.7722	2.3648	**89**	4.4337	1.4967	1.4861	0.4234	3.4085	2.6707
40	3.3550	3.2765	2.9599	0.2976	1.2240	3.3881	**90**	4.1789	1.3573	1.0001	1.9230	3.8676	1.8525
41	4.8237	2.3622	1.2461	3.8320	2.3844	0.8280	**91**	1.6226	2.0599	1.0046	0.4393	2.3494	3.0703
42	2.4309	3.0284	1.0124	0.9588	1.4773	0.7732	**92**	1.3445	1.7759	1.0052	0.3927	4.7795	0.3126
43	2.1979	3.5147	1.0044	0.4383	2.1873	3.7200	**93**	4.0392	2.4603	1.4863	0.3207	3.7214	1.7211
44	3.7468	3.1904	1.0143	0.3040	4.5323	1.8264	**94**	1.3054	1.9775	1.0043	0.3457	1.1860	2.8185
45	1.0660	0.6439	1.0048	0.3216	1.6254	1.1170	**95**	1.3467	3.2483	1.1173	0.3236	1.0123	1.1604
46	2.5870	2.6281	1.0098	0.6038	4.9893	1.1159	**96**	3.1953	3.2272	1.9765	0.3161	1.8060	2.9924
47	3.3575	2.2595	1.0655	0.3629	4.7302	1.2500	**97**	4.7393	1.6312	1.9600	0.2749	4.6916	2.6509
48	4.8913	3.2588	1.0031	0.2552	3.0371	0.7760	**98**	4.1715	0.4427	1.0139	0.2826	4.7856	3.5089
49	4.3842	3.2638	1.4855	2.1145	3.2161	0.6810	**99**	3.7646	2.1267	1.0034	0.2762	2.2042	1.8106

Table A.2
Agents' behavioral parameters trained based on GA without the existence of CAQ market.

Id	$\alpha_{i,1}$	$\alpha_{i,2}$	$\alpha_{i,3}$	$\alpha_{i,4}$	$\alpha_{i,5}$	$\alpha_{i,6}$	Id	$\alpha_{i,1}$	$\alpha_{i,2}$	$\alpha_{i,3}$	$\alpha_{i,4}$	$\alpha_{i,5}$	$\alpha_{i,6}$
0	4.3819	3.9943	1.0057	0.7106	4.4152	1.0959	**50**	3.2053	1.3982	1.0024	0.2571	2.6087	2.9764
1	1.4650	1.1560	1.0071	2.5314	1.8952	3.8695	**51**	3.9383	2.5293	1.0113	0.2681	4.5978	2.1056
2	2.1547	3.1374	1.4893	1.0907	4.7748	0.8142	**52**	1.9232	1.8554	1.0297	1.4864	4.9130	3.1729
3	1.2352	3.3621	1.1448	0.3557	4.9065	1.8157	**53**	1.1045	0.6843	2.9880	0.4351	3.1452	3.0514
4	2.7122	2.1077	1.0021	1.2301	2.3694	0.7048	**54**	4.0188	1.7633	1.0497	1.0853	4.9126	1.5971
5	1.4946	2.6833	1.5326	1.0748	4.1837	1.6841	**55**	1.1252	1.8262	1.0004	2.0985	2.5738	0.5868
6	2.3981	3.3513	1.4808	0.2916	2.0352	3.4682	**56**	3.3350	3.7812	1.0280	0.3517	3.7175	2.4233
7	3.0404	0.7693	1.0026	2.0803	3.6161	0.8949	**57**	3.1404	1.6953	1.1141	0.2720	1.5263	3.2821
8	3.6067	0.2798	1.0426	0.2705	4.0032	1.3525	**58**	4.3678	3.9178	1.0015	0.3166	1.1389	1.9462
9	3.8321	1.6468	1.0112	1.0660	4.4764	3.8915	**59**	2.6488	3.1454	1.2410	0.3268	2.1927	0.6200
10	2.6245	1.3275	1.0051	0.4412	3.4514	0.3468	**60**	2.4008	2.9123	4.8962	0.2734	1.2395	3.5840
11	1.6294	3.6439	2.9512	0.2832	2.4247	3.5345	**61**	3.6039	3.3227	1.1937	0.2878	3.0690	0.3337
12	4.5408	1.2929	2.9921	1.8939	2.1217	1.5734	**62**	4.2329	1.5642	1.0020	0.2585	3.8702	0.5526
13	2.5679	3.5933	1.0165	0.2525	2.2801	0.4949	**63**	2.6977	3.6971	1.0033	0.7177	2.8262	2.2748
14	3.6510	2.5249	1.0378	3.8871	3.0580	1.9100	**64**	4.0662	0.8428	1.0075	1.7610	1.3227	2.2888
15	3.0107	1.1927	1.0071	0.2698	4.9132	2.2024	**65**	1.6885	3.0679	1.0274	0.3741	3.2905	1.8364
16	3.0238	0.8856	4.9989	0.2513	3.5132	3.5464	**66**	4.5265	1.7126	4.9851	1.1010	1.3883	1.1149
17	2.8848	0.9772	4.9973	0.2615	4.6179	3.4568	**67**	4.6545	0.4654	1.0051	0.4018	4.1607	2.1677
18	2.5253	1.3873	1.0105	0.2529	1.6602	0.4640	**68**	1.7746	1.5170	3.6276	1.5085	1.5058	3.7982
19	3.6628	2.3423	1.0234	0.3315	1.0397	0.8493	**69**	4.8426	1.7922	1.0174	1.5638	4.8874	3.1082
20	3.1773	3.2021	1.5574	0.3519	4.7318	3.5209	**70**	2.9194	3.2353	1.0224	0.4733	2.4839	1.0742
21	2.8103	0.5395	1.0029	0.2564	3.6709	3.1934	**71**	1.5926	2.7029	1.0343	0.2846	1.6028	3.6462
22	1.8735	2.0662	1.0026	3.9394	4.5640	0.6472	**72**	4.9819	1.0933	1.2490	1.1287	3.8261	1.7941
23	2.5718	2.8926	1.0298	0.3042	1.0866	3.3569	**73**	2.2991	2.5975	1.0062	0.2939	1.6745	2.4818

(*continued on next page*)

Table A.2 (*continued*)

Id	$\alpha_{i,1}$	$\alpha_{i,2}$	$\alpha_{i,3}$	$\alpha_{i,4}$	$\alpha_{i,5}$	$\alpha_{i,6}$	Id	$\alpha_{i,1}$	$\alpha_{i,2}$	$\alpha_{i,3}$	$\alpha_{i,4}$	$\alpha_{i,5}$	$\alpha_{i,6}$
24	2.9092	2.9028	1.1170	0.3762	4.7494	3.8909	**74**	3.0617	3.7918	1.0286	0.2991	2.0503	2.0694
25	4.8800	0.8181	1.0097	1.1350	2.6496	2.3831	**75**	2.3544	1.3794	1.0052	0.2658	2.0746	0.4173
26	2.7817	3.5381	4.9929	0.2672	2.0480	0.5277	**76**	1.2050	1.7321	1.9895	0.6538	4.1186	1.2198
27	3.4951	1.3981	1.0147	0.3552	2.6861	3.9460	**77**	3.9337	0.5675	1.4726	3.9335	4.9854	1.9746
28	2.3284	1.3258	1.0000	0.4323	4.3061	0.4566	**78**	4.5008	1.7805	1.0127	0.2847	2.8172	2.3550
29	3.5138	0.3981	1.0044	1.8049	4.6128	0.2604	**79**	3.2581	0.6911	1.0513	0.2909	3.3054	1.3412
30	4.3702	3.4547	1.0107	2.1050	4.0464	3.0883	**80**	1.4736	1.7036	1.0555	0.3589	2.2068	0.4024
31	4.5387	0.3359	1.0598	0.9087	2.3374	2.6346	**81**	4.9984	1.8386	1.4993	0.2877	4.2515	3.9128
32	3.0880	0.3170	4.9730	0.3033	3.3186	3.3530	**82**	4.6973	1.0859	1.0107	0.3036	2.8663	2.8654
33	4.8290	0.8537	4.9873	0.3131	3.8458	3.4329	**83**	4.1641	1.6526	4.9910	0.3247	4.4368	2.4354
34	3.1304	1.3185	1.0038	0.2602	1.8848	3.4985	**84**	1.7193	3.0079	4.9765	0.6819	3.9430	2.5310
35	4.2869	3.6475	1.0192	0.2615	3.3420	1.8107	**85**	2.8327	0.6211	1.0114	0.2668	4.8653	0.9142
36	1.7955	2.2287	1.0046	3.8556	4.8648	2.1201	**86**	2.5237	1.1654	1.0064	0.2949	3.4530	0.4788
37	4.5348	3.2016	1.0051	0.4075	2.6941	3.6737	**87**	2.8286	0.9648	1.0031	0.4365	2.9650	0.5293
38	2.9179	0.8023	1.0194	0.2991	4.2584	2.1207	**88**	1.0157	1.8198	1.0223	0.6640	2.2202	0.9192
39	2.2347	3.8561	2.8819	0.2864	3.1289	2.8037	**89**	2.3212	2.5195	1.0618	3.9751	2.5419	1.7463
40	4.1851	2.1757	1.0126	3.9333	1.5352	2.6024	**90**	4.6786	1.8748	1.0267	0.3276	1.4414	3.1645
41	1.8619	1.2800	1.0128	0.3960	1.1097	1.3744	**91**	2.2598	1.7952	1.0276	0.2784	2.0332	0.3729
42	4.3118	2.9387	1.9877	0.4157	3.2774	1.8300	**92**	4.2893	1.1127	1.0325	0.4836	2.5242	1.0941
43	2.5592	0.2699	1.4844	1.0762	1.0234	3.0994	**93**	4.9319	0.2910	1.0035	0.6432	1.3964	3.0722
44	3.0467	3.4098	1.0001	1.1795	2.6665	3.4409	**94**	3.2956	3.3026	4.9940	2.1106	1.0661	3.0233
45	2.3480	0.5333	1.0289	0.4829	2.3694	1.8234	**95**	3.1032	0.2942	1.0106	0.4815	2.3755	0.6409
46	3.0975	1.9385	1.0016	0.2990	1.6144	2.4846	**96**	2.0216	2.8803	4.9900	0.2603	2.7501	3.1538
47	1.0318	2.0141	1.0254	0.3060	1.2962	0.3586	**97**	3.6662	3.0834	1.0624	0.3757	1.8375	3.1115
48	4.1340	2.9115	1.0282	0.3595	1.6382	0.6430	**98**	1.4063	3.4363	1.0011	0.2599	3.1870	0.3892
49	1.8353	1.0549	4.9872	0.3377	3.7349	3.6068	**99**	3.3004	2.8380	1.1171	0.2733	4.5121	0.5170

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eneco.2024.107826.

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