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Impact analysis of renewable portfolio standard on retail power market considering quota heterogeneity

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ABSTRACT

To promote the development of the renewable energy (RE) industry, China officially implemented renewable portfolio standard (RPS) in 2020, the policy effect of which is closely related to the amount of renewable power offered to users by power-selling enterprises. We use evolutionary game theory to analyze the behavioral strategies of regional governments, regulatory authorities, and power-selling enterprises under RPS, and build a system dynamics (SD) model to determine the influence of the relevant parameters on stakeholders' strategy making considering quota heterogeneity. The results show that: (1) enterprises evolve to being stable earlier in high-quota area than in low-quota area, which infers that RE development has a certain bottleneck in the initial stage and that RPS can play an effective role; (2) a high certificate price can not only help power selling companies evolve to being stable, but also promote the withdrawal of governments subsidies; (3) to increase the proportion of renewable electricity, the net profit of RE power should not be lower than that of conventional energy; and (4) the incentive effect of subsidy income is not stronger than that of resale income, while when compared with penalty, the incentive effect is stronger, and penalty is not more severe and actually better. Importantly, the results provide policy suggestions for the development of RPS.

1. Introduction

To alleviate the problems of energy shortages and environmental pollution, and compensate for the weak market competitiveness of renewable energy (RE), countries have implemented energy transformation policies for the development and utilization of RE [1–3], represented by feed-in tariffs (FITs) and renewable portfolio standards (RPS). China implemented FITs in 2006 and has made good progress embodied in the installed capacity of RE power generation, which reached $1.063*10^{10}$ kWh and accounted for 44.8 % of the total installed power generation capacity by the end of 2021; At the same time, with the installed capacity of RE increased, the pressure placed on government financial subsidies has increasingly strengthened and has led to the urgent need for institutional innovation to achieve scientific development. With the launch of a new round of power system reform and the orderly opening of the power-selling side, market-oriented RPSwith tradeable green certificate (TGC) support has become an important mechanism through which to promote RE development [4,5]. The National Development and Reform Commission, Ministry of Finance and National Energy Administration jointly issued a notice on piloting the RE green power certificate issuance and voluntary subscription trading system on February 6, 2017, and officially declared the implementation of the TGC subscription on July 1, 2017; The National Development and

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Reform Commission and National Energy Administration issued a draft for comments on the implementation of RPS on three separate occasions in March, September and November 2018 and jointly issued a notice on May 15, 2019, to establish and improve the RE power consumption guarantee mechanism, which marked the formal implementation of RPS to effectively meet the strategic needs of China's top-level system design of low-carbon energy transformation, and had a positive and far-reaching impact on power market reform.

RPS is a mandatory regulation concerning the market share of RE power. It is formulated by a country or region in the form of law and requires the power of manufacturers or retail enterprises to include a minimum proportion of RE power. As the main implementation subject of RPS, power-selling enterprises play a vital role in the implementation effect, and the implementation process cannot be inseparable from the effective guidance and supervision of governments and regulatory authorities in the early stage. Therefore, the study of subsidies and regulation holds great significance for the steady implementation of regional policy. After governments assess quota targets and the regulatory authorities assign supervision, power-selling enterprises can choose to or not to fulfill the quota: when they choose to fulfill the quota, the excess part can not only be resold to other enterprises but can also warrant an excess subsidy from regulatory authorities. Subsidies are regarded as an effective incentive mechanism that deserves special attention. In contrast, when enterprises choose not to fulfill the quota target, the insufficient part can be filled by subscribing to a TGC certificate; otherwise, they will be punished by regulatory authorities in the form of penalty. As the policy promoters, governments can also assess the regulatory effect of regulatory authorities through the quota fulfillment of power-selling enterprises. Based on the above factors, the development of the RE industry in the power retail market under RPS has inevitably involved the evolution of strategies among governments, regulatory authorities, and power-selling enterprises over time.

At present, the research on RPS mainly includes the following aspects: (1) Analysis of the evolution of RPS at the institutional level. Policy design and impact analysis [6], which is reflected in how to coordinate RPS with existing top-level energy policies [7]; summary of experience in quota policies [8], which is reflected in the reasonable design of performance mechanisms [9], and setting quota indicators fairly and reasonably [10,11]; analysis of policy effectiveness evaluation [12,13], which is reflected in the implementation effect of electricity price subsidies based on the development of electricity price mechanisms [14], and the implementation difficulties and price prediction under the green certificate pricing mechanism [15]. (2) Evaluation of the effectiveness of RPS combined with other emission reduction policies. The comparative study of the advantages and disadvantages of the two policies in terms of emission reduction costs [16,17]; The compatibility of RPS and carbon emission trading (CET) [18,19], including the comparison of emission reduction costs of the two policies and the effective coupling of mechanism interaction [20]; RPS and other policies (such as carbon tax, carbon transaction and RE subsidies) in terms of cost and other economic efficiency comparison [21]. (3) Research on trading strategies of quota-mandating entities under RPS [22–24]. Considering the strategic behavior of thermal power entities and green power entities from the generation side [4,25], including the dynamic trading game process [26] and market equilibrium under static decision-making [27,28]; Strategy analysis of the power supply chain under RPS, including the optimal investment decision-making process [29,30], and the impact of green certificates and identification of the key mechanism elements [31,32].

Evolutionary game theory is an effective method through which to study the strategic interactions among two or more players, which extends the assumption of the complete rationality and information of economic subjects to limited rationality and incomplete information and makes it possible for individuals to evolve. Evolutionary game theory has been used in an increasing number of studies, such as those on supply chain management [33,34], the low-carbon economy [35,36], land and resource management [37], security management [38,39], and public services [40]. At the same time, as a popular quantitative analysis framework, evolutionary game analysis has been used to study the performance of energy policy. For example, Gong et al. found that urban gas users have adopted different theoretical responsive pricing models [41], while Zhang et al. constructed an incomplete information evolutionary game model to study the choices of governments, biofuel enterprises and restaurants in the waste oil energy supply chain, and proposed that cracking down on restaurants that sell edible waste oil to illegal hawkers is a long-term task [42]. Moreover, Wang et al. constructed a partnership among investment companies (IC), hydrogen production vehicle (HPV) users and solar photovoltaic power plants (SPP) based on a tripartite evolutionary game, and the results showed that a large subsidy is favorable for the smooth evolution of the partnership [43]. However, traditional evolutionary game theory has limitations in dealing with the complex interactions among individuals in the system [44], and thus, an increasing number of researchers chose to combine it with system dynamics (SD) model to solve complex system problems through more direct, vivid, and realistic systems to provide theoretical basis for policies [45–47].

Through a review and organization of the literature, although the existing research has been conducted from different perspectives, there are still the following unresolved issues: 1) existing literature emphasizes the necessity for the effective design of RPS but mostly based on qualitative research and less on quantitative research; 2) although discussing the strategic impact of RPS on different entities has always been a hot research topic, it has mostly focused on the power generation market or the power supply chain, and research on quota completion in the power retail market is not yet sufficient, which is not completely consistent with China's current policy direction; and 3) according to policy requirements, governments need to cooperate with relevant subsidies and regulatory measures to assess the completion of quotas supervised by regulatory authorities, which is crucial for determining the optimal measures, but the current research foundation is relatively weak. Above all, this article aims to explore the status of electricity-selling enterprises fulfilling their r RE electricity quota obligations from the perspective of governments' assessment and regulators' regulation, as well as how to choose effective subsidies and regulatory strategies. To address the above issues, this study is based on the retail power market and divides RE targets into two types: H-(high)quota area and L-(low)quota area, builds a tripartite evolutionary game among governments, regulatory authorities, and power-selling enterprises in both areas under RPS, then constructs a SD model to study the impact of the key parameters on three agents in both high-quota area and low-quota area by scenario analysis, and proposes policy suggestions that have practical implications for the development of China's RE industry. The main contributions of this paper are as follows: (1) The policy effect evaluation of RPS in this research is based on the electricity-selling market and considers the heterogeneity of quota targets. China's RPS policy has been implemented on the electricity-selling side since 2020, but the existing policy research is mostly based on the power generation market, and research involving the electricity-selling market is very limited. This paper enriches this part of the research. (2) This paper explores the influence process of relevant parameters under RPS on the strategic choices of governments, regulatory authorities, and power-selling enterprises through simulation analysis. The simulation results reveal several policy effects, which facilitate the local governments and regulatory authorities understand and implement RPS. The structure of this paper is as follows. Section 2 constructs a tripartite evolutionary game model of governments, regulatory authorities, and power-selling enterprises under RPS; In Section 3 we develop a SD model based on the evolutionary game model and show the simulation results; Section 4 presents the discussion and prospects; The conclusion showed is in Section 5.

2. Problem description and model construction

2.1. Game relationship among tripartite stakeholders

To vigorously promote the development of RE, "2020 National Renewable Energy Power Development Monitoring and Evaluation Report" [48] (hereinafter referred to as the "Report") clearly stipulated the implementation content of RPS. The governments establish specific RE quota indicators and assess the completion status of quota entities within the specified period, and the regulatory authorities supervise the actual quota of electricity-selling enterprises. Since the entities undertaking quota obligations are numerous and interest relationships are complex, and to facilitate the construction and analysis of game models, we attempt to consider the comprehensive implementation of RPS in the electricity retail market from the perspective of decision-making, namely the electricity-selling enterprises who undertake the RE quota task, the regulators who assume implementation, and the governments who comprehensively assess.

In the process of assessing and regulating RPS, the game strategies of the governments, regulatory departments, and electricity-selling enterprises are complex and variable, and the evolution process of the three strategies has a certain degree of selectivity and relative independence. For power-selling enterprises, if the local governments formulate corresponding punishment measures in advance for the failure of power-selling enterprises to fulfill quota tasks, regardless of the degree of leniency of regulatory authorities, the punishment measures will constrain the power-selling enterprises to fulfill the constraint quota task. And power-selling enterprises will choose strategic behaviors that are conducive to maximizing their own profits, which means their strategic choices are relatively independent. According to the principle of maximizing profits, they either choose not to fulfill their quota obligations, or choose to fulfill the quota goal. In fact, the key factor for the success of the RPS depends on how regulatory agencies implement the quota indicators issued by the governments with strengthening regulatory efforts. Due to the existence of quota targets set by the governments, when monitoring and assessing the implementation of quotas by regulatory authorities, the governments will choose to provide subsidy based on the completion of tasks.

If the electricity-selling enterprises fail to meet the quota target, the governments will impose penalties on the regulatory authorities for not meeting the regulatory standards; If the electricity-selling enterprises meet the quota target, the governments will consider it as regulatory authorities' regulatory compliance and provide corresponding subsidy for the excess part, which directly affects the regulatory strength of the regulatory departments. Moreover, the regulatory strength of the regulatory departments has a significant guiding effect on the electricity-selling enterprise to fulfill the quota task. Electricity-selling enterprises also face penalties for the insufficient part and subsidy for excess part. Therefore, the strategies of the governments, regulatory authorities, and electricity selling enterprises have certain selectivity. Relative independence refers to the fact that in the process of implementing PRS, due to the existence of information asymmetry, the strategic choices of the three players in the game will not be completely influenced by mutual behavioral choices. In addition, regulatory authorities also seek the best strategy to constrain electricity-selling enterprises to fulfill their quota responsibilities through dynamic adjustments and beneficial trial and error methods, in accordance with the policy rules of

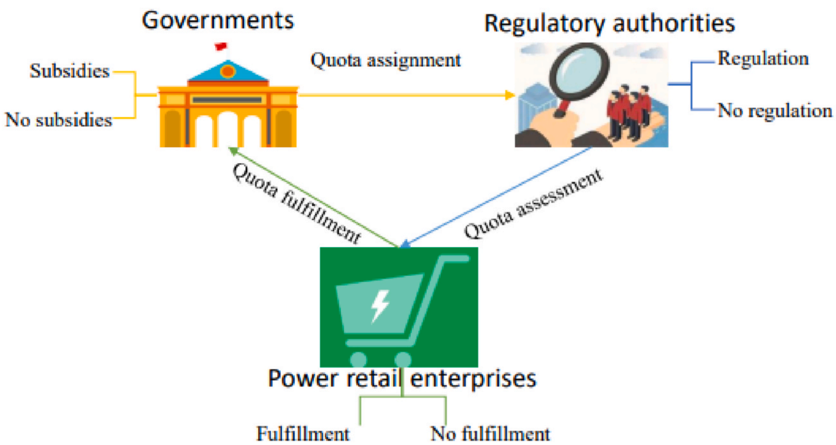

Fig. 1. The relationship and strategy set among the players.

government subsidies and punishments and achieve a balanced state. Under the condition that the governments choose subsidy strategy, regulatory authorities adopt effective and strict regulatory mechanism until the power-selling enterprises choose to fulfill the quota task strategy to adapt to this regulatory mechanism, any irrational behavior that deviates from the equilibrium state will lead to the loss of their respective profits.

2.2. Modeling hypothesis

In the above analysis, the electricity selling enterprises need to fulfill the quota tasks assigned by the governments under the supervision of regulatory authorities with the implement of RPS. For regulatory authorities, the governments will choose to subsidize if they meet the assessment quota target, or the governments will choose not to subsidize, therefore, the governments have formed two strategic choices: subsidies strategy (SS) and no subsidies strategy (NSS). Correspondingly, as electricity selling enterprises are the actual implementers of RPS, if they choose to fulfill the quota target and complete the task, while if they choose not to fulfill the quota target, they will not fulfill the quota task, therefore, they have formed two strategic choices: fulfillment strategy (FS) and no-fulfillment strategy (NFS). Since the completion of quota tasks by power selling enterprises in accordance with requirements directly determines whether the regulatory departments' assignment is qualified and whether they can receive awards, the regulators bear the regulatory responsibility for power-selling enterprises, and they form two strategic choices: regulation strategy (RS) and no regulation strategy (NRS). The relationship and strategy set among the players in the process can be seen in Fig. 1.

To further explain the inherent evolutionary game mechanism of the players, we propose the hypothesis conditions of the model based on the policy requirements and the actual situation under RPS.

Hypothesis 1. Players in the evolutionary game represent their respective interest groups in an asymmetric game, the proportion of governments choosing SS is x(t), the proportion of regulatory authorities choosing RS is y(t), and the proportion of electricity selling enterprises choosing FS is z(t), $0 \leq x(t), y(t), z(t) \leq 1$

Hypothesis 2. Total electricity consumption is equal to total electricity sales q_i, where i = L and i = H represent the RE target in low and high quota area, respectively (the same as below), the quota is θ_i; based on the strategy selection, we set the excess proportion α (insufficient proportion) as β of power-selling enterprises, which directly corresponds to the probability of FS (NFS) and the quota, i.e., $\alpha = k_F z\theta$ ($\beta = k_N(1 -)z\theta$), without losing generality we assume $k_F = k_N = 0.5$.

Hypothesis 3. For the governments, regardless of the regulatory efforts of regulatory authorities, the consumption of renewable electricity implies high environmental effects, which also improves the overall welfare of society, and unit welfare is assumed to be b. Subsidies involve a series of activities such as calculation and evaluation, which inevitably lead to the emergence of corresponding public expenditures, and we quantify these as C_1. When the governments choose NSS they need to purchase additional renewable energy power to help the power-selling enterprises reach the quota target, and we set the outsourcing cost as C_3. For regulatory authorities, if the electricity selling enterprise exceeds the quota task within the specified period, and the strict supervision of the

Table 1
Major variables' initial values.

Participants	Variables	Definition	Initial value	Data source
Governments	b	Regional welfare per unit of RE power	0.018RMB/kW·h	Huang et al.(2020) [47]
	C_1	Energy protection cost of governments when choosing SS	$2*10^8$ RMB	National Energy Administration [38]
	C_3	Energy protection cost of governments when choosing NSS	$5*10^8$ RMB	National Energy Administration [38]
	s_g	Subsidy coefficient for excess part to regulators	0.2	National Energy Administration [38]
	s_a	Reward subsidy coefficient for excess part to regulators	0.05	National Energy Administration [38]
	ω_g	Penalty coefficient for insufficient part	2	Zhang et al. (2017 [42])
Regulators	C_2	Regulation cost of regulatory authorities	$4*10^8$ RMB	National Energy Administration [48]
	s_r	Subsidy coefficient for excess part to power-selling companies	0.2	National Energy Administration [38]
	ω_g	Penalty coefficient for insufficient part to power-selling companies	2	Zhang et al. (2017 [42])
Power-selling companies	q_L	Total power sales in low-quota area	1.552*1011 kW h	National Energy Administration [38]
	q_H	Total power sales in high-quota area	2.785*1011 kW h	National Energy Administration [38]
	θ_L	RE target for low- quota area	56.5 %	National Energy Administration [48]
	θ_H	RE target for high-quota area	17.5 %	National Energy Administration [48]
	p	TGC price	0.22RMB/kW·h	Zhao et al. (2014) [4]
	v_C	Net value of conventional energy power (v_C)	0.05 RMB/kW·h	BJX Net (2019) [49]
	v_R	Net value of RE power (v_R)	0.05 RMB/kW·h	BJX Net (2019) [49]

regulatory authorities improves the performance of the local governments, the excess part α can help them receive certain excess and reward subsidies from the governments, while the insufficient part β requires them to pay a penalty to the governments, so we set the excess subsidy coefficient as s_g, the reward subsidy coefficient as s_a, and the penalty coefficient as ω_g. Due to the need for regulatory authorities to organize specialized agencies for monitoring and evaluation during the regulatory period, the total cost of strict regulation is C_2.

Hypothesis 4: Power-selling enterprises can make profits by selling conventional energy electricity and RE electricity, the unit net profits of which are denoted as v_C and v_R, respectively. The satisfaction of quota requirements is closely related to the enthusiasm of power-selling enterprises, so we propose a dynamic subsidy and penalty mechanism, and the income obtained by regulatory authorities and power-selling enterprises from the excess part of electricity and the expenditure of the penalty incurred due to the insufficient part is proportional to the TGC price (p). For power-selling enterprises, the excess part can not only warrant a certain subsidy from regulatory authorities but also be transferred to other enterprises, while the insufficient part is penalized by regulatory authorities, thus we set the subsidy coefficient as s_r, the transfer coefficient as t, and the penalty coefficient as ω_r. Considering the policy objectives of the RPS, we assume that the transfer coefficient is larger than the subsidy coefficient, while the profit of transfer and subsidy earning would not be lower than that of conventional power sales revenue, which can encourage power-selling enterprises to achieve the quota target. In addition, we assume that the power demand growth rate and growth rate of the quota of power-selling enterprises are immutable. The major variables' initial values are listed in Table 1.

2.3. Game model development

Based on the assumptions above, we can deduce the payoff matrix of the tripartite game, as shown in Table 2. In evolutionary game theory, the strategic choice of each player mainly depends on its competitive advantage in the long-term [50].

The payoff of players can be calculated by the probability of the strategy and the corresponding expected return. According to Tables 2 and it is assumed that the expected return of local governments choosing SS (x) is E_{G1} and the expected return of NSS(1-x) is E_{G2}, and when regulatory authorities and power-selling enterprises choose different strategy probabilities (y/(1-y) and (z/(1-z)) we have the following formula (1):

$$\begin{cases} E_{G1} = yz\pi_1^{SRF} + (1-y)z\pi_1^{SNF} + y(1-z)\pi_1^{SRN} + (1-y)(1-z)\pi_1^{SNN} \\ E_{G2} = yz\pi_1^{NRF} + (1-y)z\pi_1^{NNF} + y(1-z)\pi_1^{NRN} + (1-y)(1-z)\pi_1^{NNN} \end{cases} \tag{1}$$

The average income of the local governments is the expected return E_{G1} when choosing SS (x) and the expected return E_{G2} when choosing NSS (1-x) and the average expected return E_G as the following formula (2):

$$E_G = xE_{G1} + (1-x)E_{G2} \tag{2}$$

Similarly, we can calculate the expected return E_{R1} when the regulatory authorities choosing RS (y) and expected return E_{R2} when choosing NRS (1-y) and average expected return E_R as the following formula (3) and (4) :

$$\begin{cases} E_{R1} = xz\pi_2^{SRF} + (1-x)z\pi_2^{NRF} + x(1-z)\pi_2^{SRN} + (1-x)(1-z)\pi_2^{NRN} \\ E_{R2} = xz\pi_2^{SNF} + (1-x)z\pi_2^{NNF} + x(1-z)\pi_2^{SNN} + (1-x)(1-z)\pi_2^{NNN} \end{cases} \tag{3}$$

$$E_R = yE_{R1} + (1-y)E_{R2} \tag{4}$$

Then we calculate the expected return E_{E1} of power-selling enterprises when choosing FS (z), expected return E_{E2} when choosing NFS(1-z) and average expected return E_E are as follows formula (5) and (6) :

$$\begin{cases} E_{E1} = xy\pi_3^{SRF} + (1-x)y\pi_3^{SNF} + x(1-y)\pi_3^{NRF} + (1-x)(1-y)\pi_3^{NNF} \\ E_{F2} = xy\pi_3^{SRN} + (1-x)y\pi_3^{SNN} + x(1-y)\pi_3^{NRN} + (1-x)(1-y)\pi_3^{NNF} \end{cases} \tag{5}$$

$$E_E = yE_{E1} + (1-y)E_{E2} \tag{6}$$

Table 2
Payoff matrix for the tripartite game.

Players	Strategies	Regulatory authorities		Enterprises
		RS	NRS	
Governments	SS	$\pi_1^{SRF}, \pi_2^{SRF}, \pi_3^{SRF}$	$\pi_1^{SNF}, \pi_2^{SNF}, \pi_3^{SNF}$	FS
	NSS	$\pi_1^{NRF}, \pi_2^{NRF}, \pi_3^{NRF}$	$\pi_1^{NNF}, \pi_2^{NNF}, \pi_3^{NNF}$	
	SS	$\pi_1^{SRN}, \pi_2^{SRN}, \pi_3^{SRN}$	$\pi_1^{SNN}, \pi_2^{SNN}, \pi_3^{SNN}$	NFS
	NSS	$\pi_1^{NRN}, \pi_2^{NRN}, \pi_3^{NRN}$	$\pi_1^{NNN}, \pi_2^{NNN}, \pi_3^{NNN}$	

2.4. Income analysis

As mentioned above three players each have two optional strategies, so there are eight different strategy combinations (SRF, SNF, NRF, NNF, SRN, SNN, NRN and NNN), then we deduce the income function of each entity under different strategy combinations as shown in Table 3. We take the strategy combination (SS(x), RS(y), FS(z)) in Table 3 as an example, when the governments, regulatory authorities and electricity retailers choose this strategy combination, the game benefits of the three players are as shown:

$$\begin{cases} \pi_1^{SRF} = b(\theta+\alpha)q - \alpha\left(s_g+s_a\right)pq - C_1 \\ \pi_2^{SRF} = \alpha\left(s_g+s_a-s_r\right)pq - C_2 \\ \pi_3^{SRF} = v_c(1-\theta-\alpha)q + v_r\theta q + \alpha(s_r+t)pq \end{cases} \tag{7}$$

In formula (7), the governments' revenue π_1^{SRF} is expressed as the social welfare $b(\theta+\alpha)q$ of the increase in renewable electricity sales, deducting the excess subsidy $\alpha s_g pq$ and the incentive subsidy $\alpha s_a pq$ to the regulatory authorities, then deducting the total cost of the review and assessment C_1. The revenue of the regulatory authorities π_2^{SRF} is expressed as the governments' excess subsidy $\alpha s_g pq$ and incentive subsidy $\alpha s_a pq$, deducting the excess subsidy $\alpha s_r pq$ to the electricity selling enterprises, and deducting the regulatory cost C_2. The revenue of the electricity selling enterprises π_3^{SRF} is expressed as the traditional energy sales income $v_c(1-\theta-\alpha)q$ and the renewable energy sales income $v_r\theta q$, plus the excess part of the subsidy income $\alpha s_r pq$ and the resale income αtpq. Similarly, in the same way, the other seven strategy combinations in Table 3 can be derived, since the limited space we don't repeat explanation.

Then we derive the corresponding replication dynamic equations as follows formula (8)-(10):

$$F(x) = x(1-x)(E_{G1}-E_{G2}) = x(1-x)\left(C_3 - C_1 - z\alpha s_g pq - yz\alpha s_a pq\right) \tag{8}$$

$$F(y) = y(1-y)(E_{R1}-E_{R2}) = y(1-y)[\beta\omega_r pq - C_2 - z\beta\omega_r pq + xz\alpha s_a pq] \tag{9}$$

$$F(z) = z(1-z)(-v_c(\alpha+\beta)q + v_r\beta q + \alpha tpq + x\alpha s_r pq + y\beta\omega_r pq \tag{10}$$

The above model contains several equilibrium points, such as (0, 0, 0), (0, 0, 1), and (0, 1, 0), which can be analyzed by the eigenvalue of the system Jacobian matrix generally, however, as the Jacobian matrix of the tripartite system is too complex to determine the stability of the equilibrium point we analyze the stability of the above model with the help of system dynamic (SD) simulation.

3. SD modeling and simulation

3.1. Construction of the SD model and parameter settings

Based on the payoff matrix and evolutionary game replication dynamic equation, we build a SD model with Vensim to further reveal the dynamic evolutionary process of the internal game structure and interest relationship among local governments, regulatory authorities, and power-selling enterprises under RPS as shown in Fig. 2. The game system studied by SD can not only explain its internal microstructure behavior through information feedback between the internal factors of the system [47] but also pass the SD simulation diagram to characterize the stability of complex equilibrium points.SD is a method that can be used to analyze complex economic systems, and system simulation can help us study the impact of key parameters on the behavior of stakeholders, judge the evolutionary path and stability of a dynamic system and provide practical decision-making guidance. The SD model of three agents' behavioral evolution includes six state variables, namely the proportion of local governments choosing SS and NSS, the proportion of regulatory authorities choosing RS and NRS, and the proportion of power-selling enterprises choosing FS and NFS; the three rate

Table 3
Specific payoff matrix for the tripartite game.

Players	Strategies	Regulatory authorities		Enterprises
		RS(y)	NRS(y)	
Governments	SS(x)	$b(\theta+\alpha)q-\alpha(s_g+s_a)pq-C_1$ $\alpha(s_g+s_a-s_r)pq-C_2$ $v_c(1-\theta-\alpha)q+v_r\theta q+\alpha(s_r+t)pq$	$b(\theta+\alpha)q-\alpha s_g pq-C_1$ $\alpha(s_g-s_r)pq$ $v_c(1-\theta-\alpha)q+v_r\theta q+\alpha(s_r+t)pq$	FS(z)
	NSS(1-x)	$b(\theta+\alpha)q-C_3$ $-C_2$ $v_c(1-\theta-\alpha)q+v_r\theta q+\alpha tpq$	$b(\theta+\alpha)q-C_3$ 0 $v_c(1-\theta-\alpha)q+v_r\theta q+\alpha tpq$	
	SS(x)	$b(\theta-\beta)q+\beta\omega_g pq-C_1$ $\beta(\omega_r-\omega_g)pq-C_2$ $v_c(1-\theta+\beta)q+v_r(\theta-\beta)-\beta\omega_r pq$	$b(\theta-\beta)q+\beta\omega_g pq-C_1$ $-\beta\omega_g pq$ $v_c(1-\theta+\beta)q+v_r(\theta-\beta)q$	NFS(1-z)
	NSS(1-x)	$b(\theta-\beta)q+\beta\omega_g pq-C_1$ $\beta(\omega_r-\omega_g)pq-C_2$ $v_c(1-\theta+\beta)q+v_r(\theta-\beta)-\beta\omega_r pq$	$b(\theta-\beta)q+\beta\omega_g pq-C_1$ $-\beta\omega_g pq$ $v_c(1-\theta+\beta)q+v_r(\theta-\beta)q$	

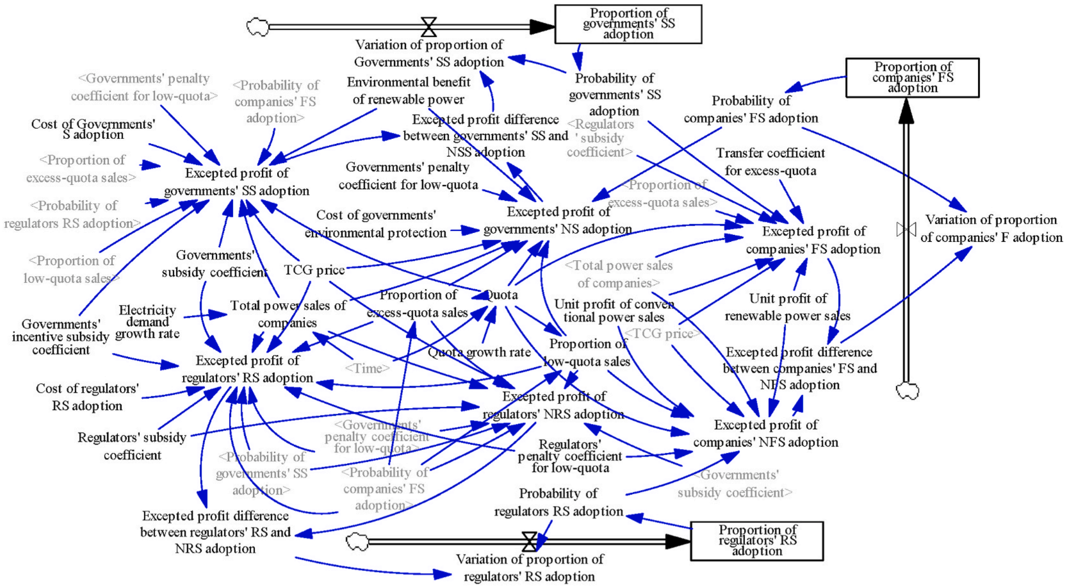

Fig. 2. The SD model for governments, regulatory authorities, and power sales enterprises.

variables are the change rate of the SS proportion, RS proportion and FS proportion; the twelve auxiliary variables include four auxiliary variables of governments, namely the SS probability, the expected return of the SS, the expected return of the NSS and the difference between the expected return of the SS and NSS; the four auxiliary variables of regulatory authorities are the probability of the RS, the expected return of the RS, the expected return of the NRS and the difference between the expected return of the RS and NRS; the four auxiliary variables of power-selling enterprises are the probability of FS, the expected return of FS, the expected return of NFS and the difference between the expected return of FS and NFS; the other variables are external and shadow variables or constants and mainly involve the income and cost parameters of the three players.

In the context of China's RE industry, we collect key parameter values from official statistics and previous research results, according to the "Report", the total electricity consumption amount of Hunan Province and Anhui Province were $1.552*10^{11}$ and $2.785*10^{11}$ kWh, and the corresponding quota was 56.5 % and 17.5 %, respectively; therefore, power-selling enterprises in Hunan and Anhui are positioned as high (H) and low (L) quota area, respectively. Since we assume that the transfer coefficient is greater than the subsidy coefficient, we set the award coefficient (s_a) as 0.05, the subsidy coefficient (s_g,s_r) as 0.2, and transfer coefficient (t) as 0.5, and the expenditures on energy conservation and environmental protection of governments when subsidy (C_1) as $2*10^8$ RMB and non-subsidy (C_2) as $4*10^8$ RMB, the regulation cost of regulatory authorities (C_3) as $5*10^8$ RMB according to the "Report". Referring to Zhao et al. (2014) [4] and BJX Net (2018) [43] we set the price of TGC as 0.22 RMB/kW·h and the net value of conventional energy power (v_C) and RE power (v_R) as 0.05 RMB/kW·h.

According to the above SD model, we carry out a simulation analysis from 2020 to 2032: initial time = 0, final time = 144 month, time step = 1 month. To verify the matching degree between the model and the real situation, we test the model for structural and behavioral validity. The results show that there are no consistency errors in the model.

Behavioral validity is the key to SD model validation, which indicates the extent to which the model is consistent with the behavior of the real system [51]. In this paper, behavioral validity of the model is proven by the Monte-Carlo sensitivity test in Vensim DSS, which can be used to check the behaviors of the selected output variables and calculate the confidence boundary through repeated simulations [52]. There are seven types of uncertain parameters for the SD model, including the TGC unit price, the net profit of conventional and renewable power selling, the incentive subsidy coefficient, the subsidy coefficient of governments, and the subsidy coefficient and penalty coefficient of regulatory authorities. We assume that each parameter follows a normal distribution. The parameters are listed in Table .4, and the number of simulations is set to 200.

Table 4
Parameters in sensitive test.

Parameters	Mean	Variance	Range(Normal)
TGC price	0.22	0.1	[0.1,0.45]
Unit value of power sales	0.05	0.01	[0.01,0.1]
Award coefficient of governments	0.05	0.01	[0.01,0.1]
Subsidy coefficient	0.2	0.02	[0.02,0.3]
Transfer coefficient	0.5	0.05	[0.1,1]
Penalty coefficient	2	0.2	[0.2,4]

The confidence bounds for the probability of SS adoption (x), RS adoption(y) and FS adoption (z) in low and high quota area are shown in Fig. 3(a–c) and Fig. 4(a–c), respectively. In this part, we use test cases to build the confidence bounds and test the behavioral validity. As we can see in the figures, for the SD model all test cases of players' strategy selection focus on the green area when the confidence level is 75 %, similarly, all test cases are located in the blue area when the confidence level is 95 %.

In summary, a SD model of the tripartite evolutionary game is verified to be effective for the strategy simulation of governments, regulatory authorities, and power-selling companies under RPS. In addition, it is effective in investigating the impact of key factors of stakeholders' behaviors.

3.2. SD simulation results

To clarify the impact of the initial strategies on the stable evolution, we simulated three scenarios namely (x_0, y_0, z_0) = (0.2,0.2,0.2), (0.5,0.5,0.5) and (0.8,0.8,0.8), and the results show that the strategies of the three players have different evolutionary processes. Fig. 5 (a) shows that different quota levels lead to different evolutionary trends of the governments: the proportion of governments choosing subsidy strategy (SS) in high quota area shows a downward trend, while that in low quota area shows an upward trend; however, when the initial subsidy ratio is not high, the subsidy ratio in high quota area will increase first in the early stage. Fig. 5 (b) shows that regardless of how the initial rate is combined, regulatory authorities eventually choose non-regulation strategy (NRS, y = 0), and the only difference is that if the initial probability is low, the proportion of strict supervision increases first, especially in the high-quota area, where it increases to 0.5 in the 28th month and then gradually reaches NRS and remains stable. Fig. 5(c) shows that power-selling enterprises eventually stabilize in the fulfillment strategy (z = 1), while the probability in the high quota area reaches the stable state before that in the low quota area. Furthermore, approximately 5 % of power-selling enterprises in the low area cannot stabilize in fulfillment strategy. It is evident that regulatory authorities are not as sensitive to the differences as local governments and power-selling enterprises in the initial stage, and that governments cannot reach a stable state regardless of the initial probability; therefore, such a system cannot be stable. To determine how the key parameters related to RPS policy affect the behavior of the three players, we continue by simulating and analyzing key parameters in the next section. Considering that we are in the early stage of policy implementation, we set the initial probability of tripartite strategy selection to 0.2, and the simulation results of the initial value are used as a benchmark to be compared and analyzed with other results in each scenario.

3.2.1. TGC price impact analysis

First, we discuss the impact of the TGC unit price on the strategic choice of local governments. We set the TGC unit price as 0.22,

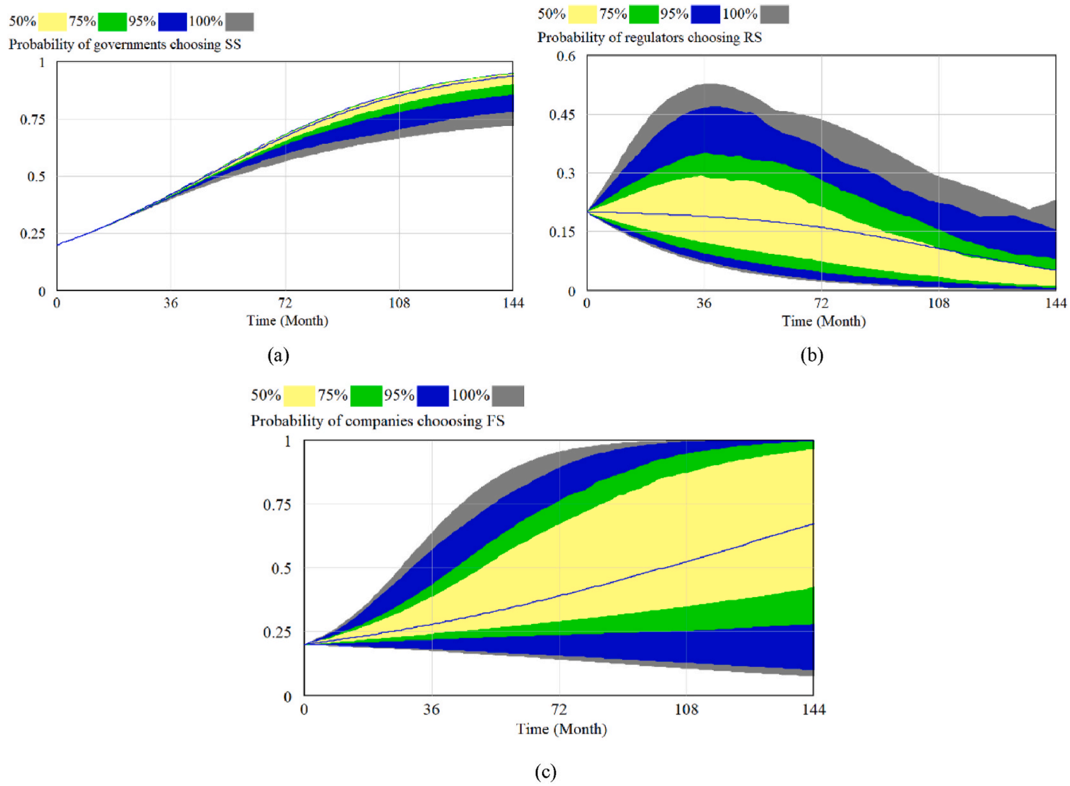

Fig. 3. Sensitivity analysis of players' strategy adoption in low quota area.

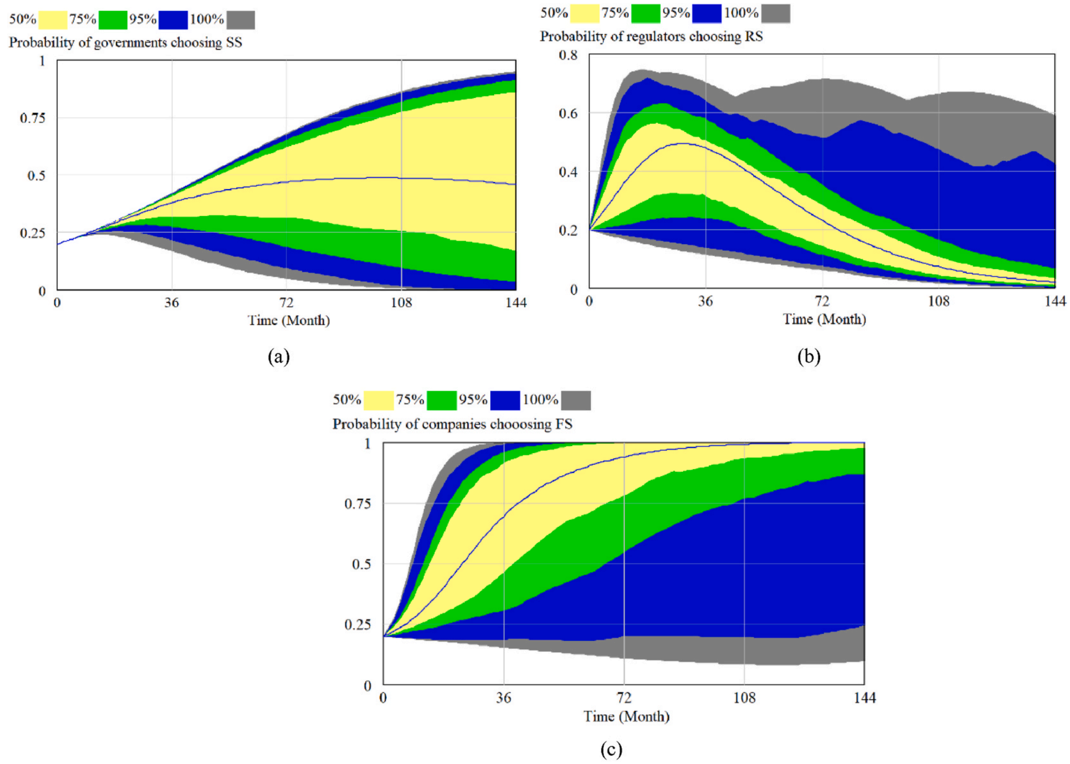

Fig. 4. Sensitivity analysis of players' strategy adoption in high quota area.

0.05 and 0.8, corresponding to medium, low, and high levels, respectively. As shown in Fig. 6 (a), we find that the reduction or increase in the TGC unit price help local governments reach a stable state, and the effect of such promotion by reducing the unit price at the low-quota area is more significant, while that of increasing the unit price at the high-quota area is most significant. Fig. 6 (b) shows that increasing the TGC unit price can quickly increase the proportion of regulation by local governments in the short term, but effect does not last long, between approximately 8 and 16 months, which is more obvious in high quota area than in low quota area, while reducing the TGC unit price steadily reduces the proportion of regulation by local governments conversely, especially in low quota area. Fig. 6 (c) shows that a high TGC unit price help power-selling enterprises stabilize quickly, and the companies in high quota area take approximately 24 months lesser than the low quota area to reach a stable state, while the low TGC unit price greatly reduces the enthusiasm of power-selling enterprises to meet the quota. Additionally, the proportion of such enterprises choosing fulfillment strategy in the low quota area almost stagnates during the simulation period.

3.2.2. Impact analysis of net profit from power sales

Based on the practice of RPS policy implementation, power-selling enterprises can make profits by selling traditional energy power and RE power, and these two commercial activities bring about two types of profits, namely, revenues from traditional energy power and from RE power, which are also important factors. In this part, we consider two different scenarios. In scenario 1, the net profit of traditional energy power (v_C) is lower than that of RE power (v_R), and in scenario 2, the situation is exactly the opposite; specifically, we set the net profit to 0.05, 0.01 and 0.4, corresponding to medium, low, and high profit levels, respectively. Scenario 1: As shown in Fig. 7 (a), neither a low net value of traditional energy power nor a high net value of RE power affects the evolutionary path of the strategy choice of power-selling enterprises, but both accelerate power-selling enterprises in reaching a stable state. For both low and high quota areas, power-selling enterprises are more sensitive to the change in the net value of RE power than to the change in the net value of conventional energy power, and the greater the difference between the net value of conventional energy power and RE power is, the faster they reach a stable state. The reason for this may be that when enterprises can obtain greater profits from selling RE power, their motivation to increase the proportion of such power will increase as well, thus making it faster for them to stabilize, but enterprises in the low quota area need more time to reach a stable state than enterprises in the high quota area. Under the condition of medium profit, however, approximately 3 % of enterprises still cannot reach the quota for either type. Scenario 2: As shown in Fig. 7 (b), when the net value of conventional energy power is consistent, a low net value of RE power encourages enterprises to accelerate to reach the stable state to fulfill the quota, which indicates that the probability of the FS in the high quota area is more sensitive to the change in the net value of RE power for enterprises in the low quota area. In contrast, a high net profit of traditional energy power reduces the enthusiasm of enterprises to meet the quota in the early stage and then gradually rises; specifically, enterprises in the highv quota area begin to rise in the 16th month, while enterprises in low quota area tend to stabilize and then rise in the 32nd-64th months.

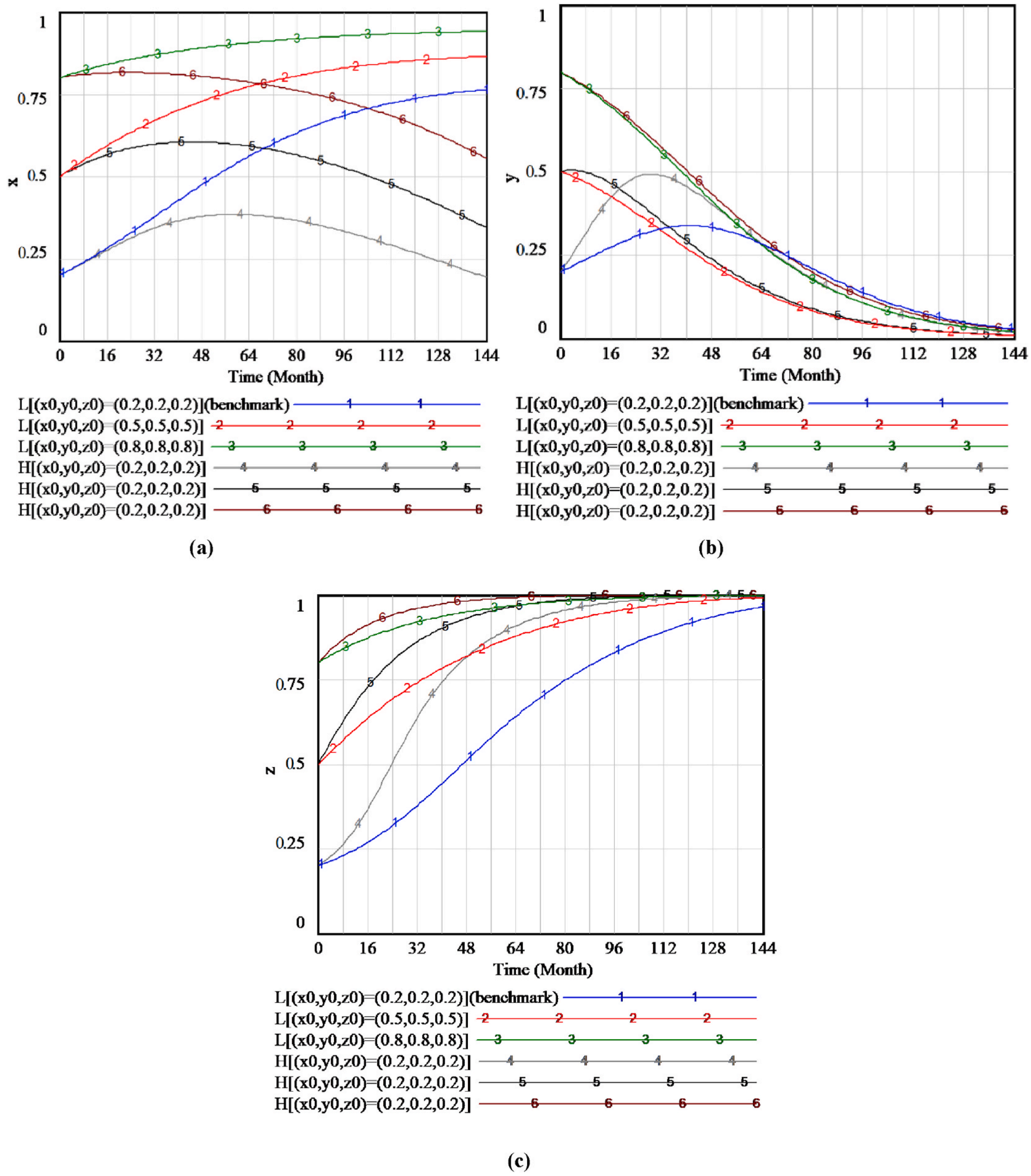

Fig. 5. Impact of different initial probabilities on players' strategy selection in low (L) and high (H) quota target areas.

Even so, most enterprises (72 % in the high quota area and 80 % in the low quota area) still relinquish fulfillment strategy. In addition, the greater the difference between the net profit of the two powers is, the faster the system reaches a stable state.

3.2.3. Analysis of subsidy and penalty effects

(1) Impact of reward subsidy on the choices of governments and regulatory authorities

To study the impact of incentive subsidies on governments and regulatory authorities, we set the subsidy coefficients to 0.05, 0.01 and 1, corresponding to medium-, low-, and high-incentive subsidy coefficients, respectively. Similarly, the reward subsidy coefficient for regulatory authorities is set to 0.01, 0.2 and 1. As shown in Fig. 8. (a), under the medium and low reward subsidy scenarios, the probability of governments subsidy in the low quota area increases steadily, while the effects of those governments in the high quota area show a trend of first increasing and then decreasing; In addition, we can see that almost all governments in high quota area choose the NSS under the high reward subsidy coefficient. Fig. 8 (b) shows that the government reward subsidy coefficient plays a certain incentive role for regulatory authorities in the early stage of evolution; however, in the long run, in the long run, in low quota areas, a

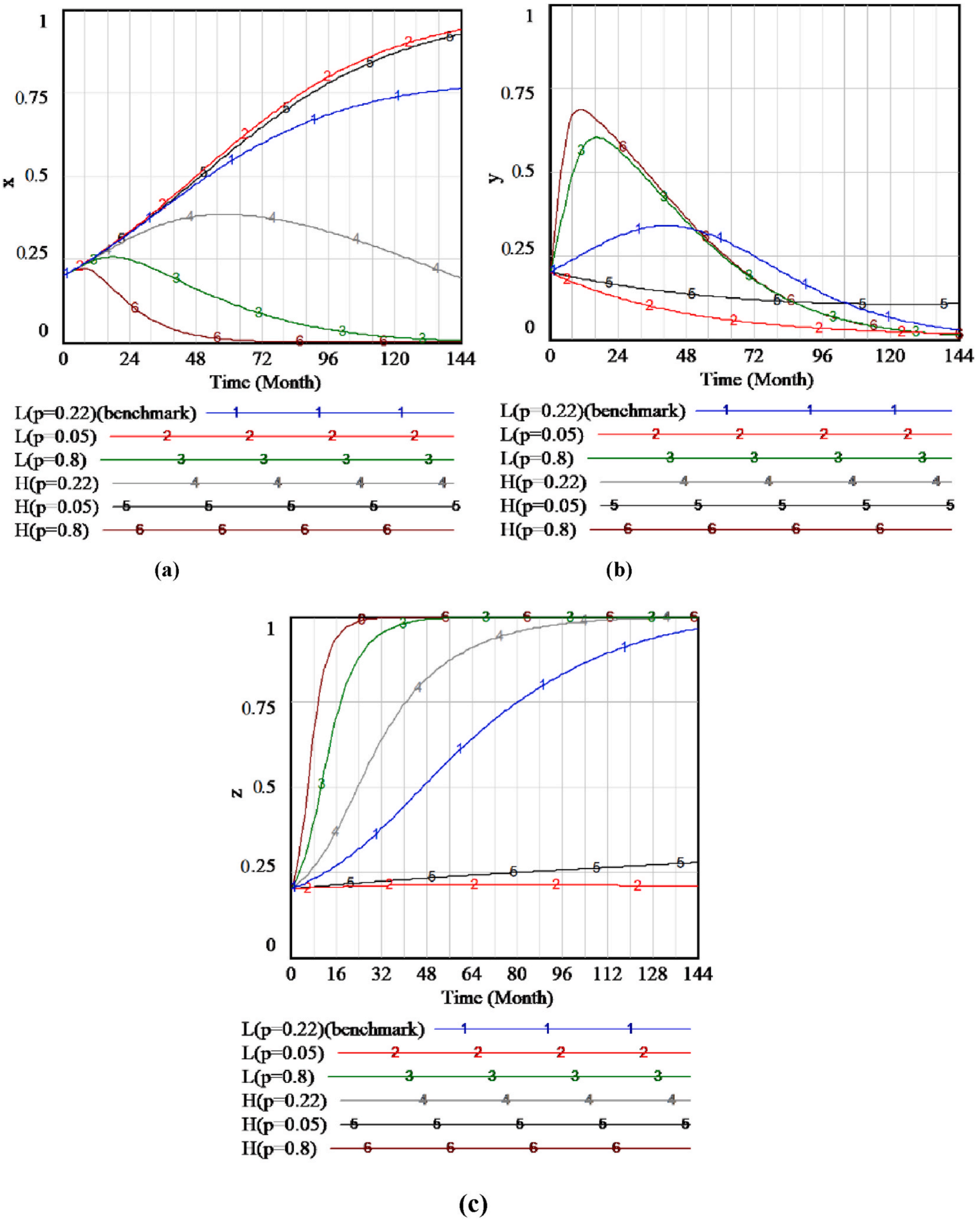

Fig. 6. The probability of players' adoption responses to different values of TGC price (p).

high reward subsidy coefficient can only ensure 25 % of the regulatory strategy of regulatory authorities, indicating that the impact of reward subsidies on regulatory authorities is not significant.

(2) Impact of the subsidy and transfer coefficient on the choice of power-selling enterprises

To study the impact of incentives on the behavior of power-selling enterprises, we set the subsidy coefficients of regulatory authorities to 0.2, 0.02 and 1, corresponding to medium, low, and high subsidy coefficients, respectively; Similarly, the transfer coefficients are set to 0.5, 0.05 and 1. We discussed two cases: in the first case, the subsidy coefficient is less than the transfer coefficient, and the second case is exactly the opposite. As shown in Fig. 9 (a), in the initial state 3 % of enterprises in the low quota area are unable to meet the quota, when the subsidy coefficient is low, 8 % of enterprises in the low-quota area are still unable to fulfill the quota, and

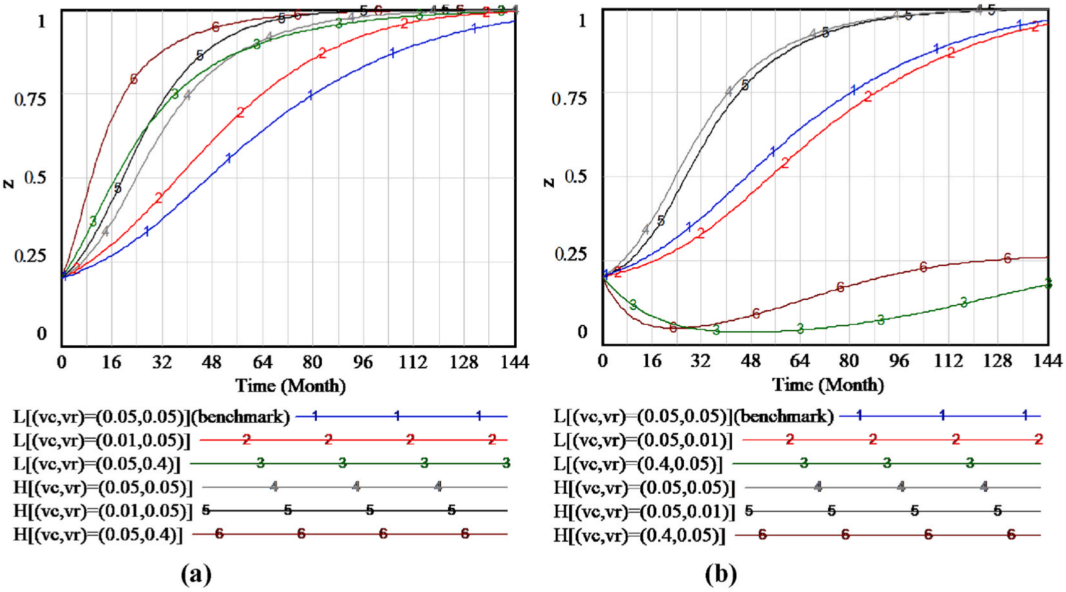

Fig. 7. The probability of players' adoption response to net profit of conventional energy power (vc) and RE power (vr).

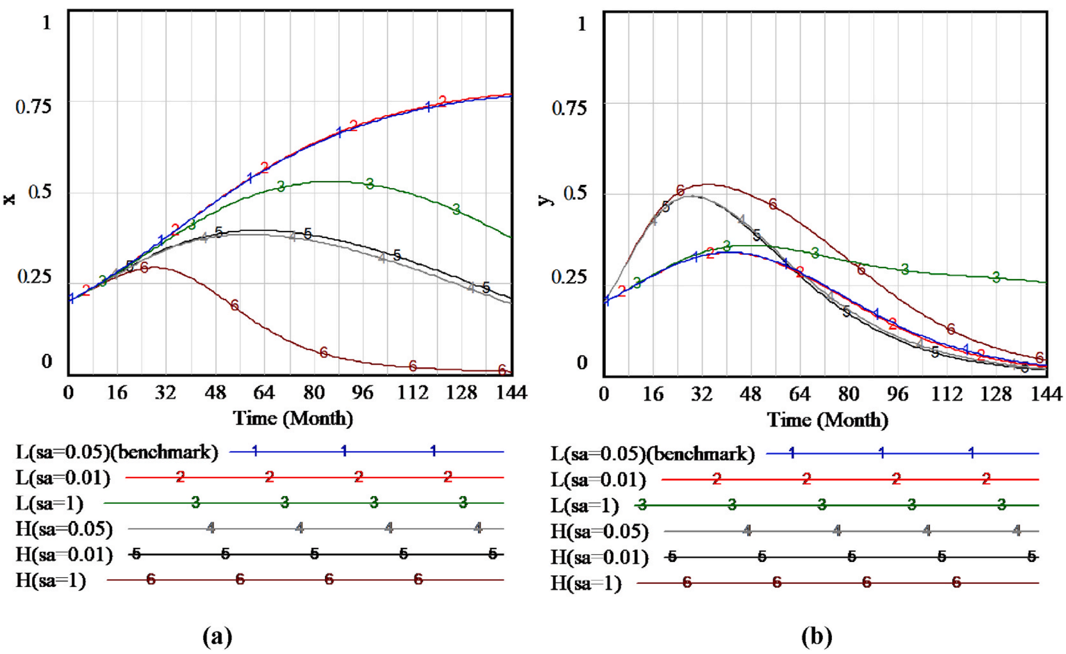

Fig. 8. The probability of players' adoption responses to different values of the reward subsidy coefficient (s_a).

changes in the transfer coefficient do not affect the enthusiasm of power-selling enterprises to fulfill the quota. Power-selling enterprises in the high-quota area can reach a stable state within 72 months; however, the increase in the transfer coefficient is more sensitive than the decrease in the subsidy situation, which means that the increase in the subsidy coefficient can increase the enthusiasm of power-selling enterprises. As shown in Fig. 9 (b), the decrease in the subsidy coefficient reduces the enthusiasm of power-selling enterprises to fulfill the quota, and approximately 25 % of enterprises in high or low quota areas are always unable to fulfill the quota. In contrast, an increase in the subsidy coefficient increases the enthusiasm of enterprises in meeting the quota, and the reaction time of enterprises in high quota area is shorter than that of those in low quota area (84 months). Compared with the change in the subsidy coefficient, the increase in the transfer coefficient can improve the enthusiasm of power-selling enterprises to fulfill the quota, and the sensitivity of the high quota is higher, of which we should make full use.

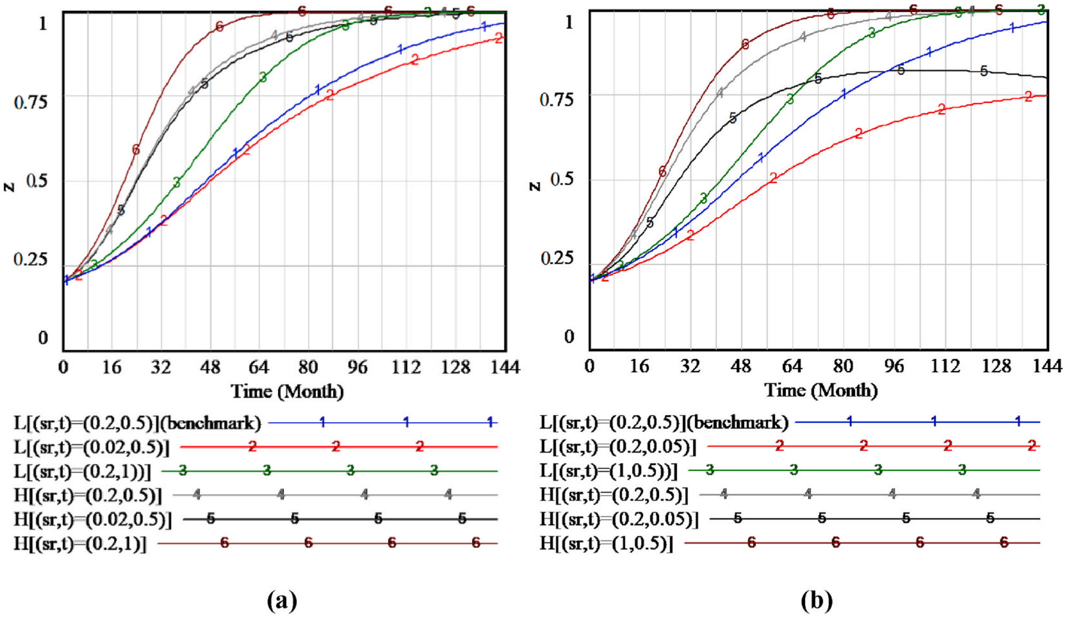

Fig. 9. The probability of players' adoption responses to different values of the subsidy (s_r) and transfer coefficient (t).

(3) Influence of subsidy and penalty on the strategic choices of power-selling enterprises

The subsidies and penalties of regulatory authorities affect the choice of strategies of power-selling enterprises; therefore, we set the subsidy coefficients to 0.2, 0.02 and 1, which correspond to medium, low, and high subsidy coefficients, respectively. Similarly, we set the penalty coefficients to 2, 0.5 and 6. As shown in Fig. 10 (a), when the subsidy coefficient is low, the change in the penalty coefficient significantly changes the probability of power-selling enterprises meeting the quota. Specifically, when the penalty coefficient decreases from 2 to 0.5 while the subsidy coefficient is medium or the subsidy coefficient is low, more than 50 % of the power-selling enterprises in the low-quota area cannot meet the quota, and 15 % of the power-selling enterprises in the high-quota area cannot meet the quota. When the penalty coefficient increases from 2 to 6, power-selling enterprises in the high quota area can reach a stable state

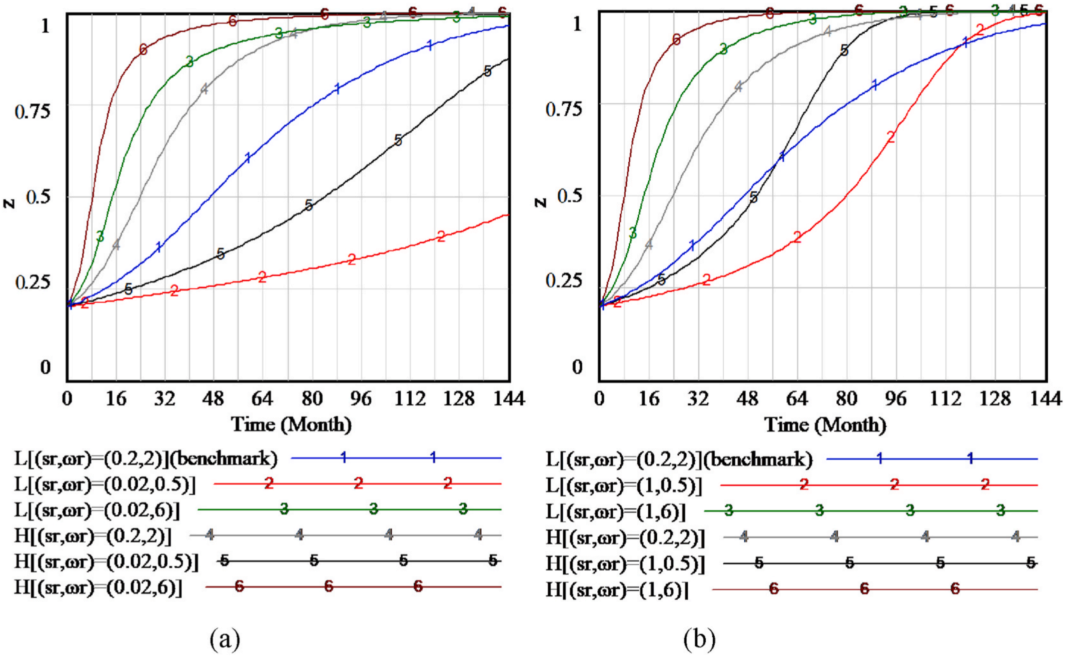

Fig. 10. The probability of enterprises' adoption responses to different values of subsidy (s_r) and penalty coefficient (w_r).

in the 80th month, while those in low-quota area can also ultimately meet the quota in the evolution period.Meanwhile, as shown in Fig. 10 (b), when the subsidy coefficient for power-selling enterprises is high, these enterprises in both high and low quota areas can fulfill the quota, indicating that the change in the penalty coefficient affects the enthusiasm of power-selling enterprises to meet the quota. When the penalty coefficient decresaes from 6 to 0.5, the enthusiasm of power-selling enterprises to fulfill the quota increases rapidly in the medium term, ultimately fulfilling the quota, which indicates that the ideal penalty rule for power-selling enterprises is not "the heavier, the better". Therefore, regulatory authorities need to make a tradeoff between a low completion probability and a high penalty coefficient. In summary, regulatory authorities do not need to stimulate power-selling enterprises through high subsidies and severe penalties at the same time, and unilateral high subsidies or appropriate penalties can promote the implementation of the RPS policy.

4. Discussion

The implementation of RPS is difficult due to the interests of multiple stakeholders, including power generation companies, power-selling enterprises, and local governments [53]. With the opening of the electricity-selling side, research on the effects of RE policies on the this side has achieved certain results [54,55]. However, there is little research on the multiagent dynamic game process of the electricity retail market considering the governments' subsidies and regulators' regulation under RPS. To explore the factors influencing the evolutionary game process of players in power retail market under the condition of limited rationality, in this paper we use SD model to simulate the game process of the evolution of the power-selling companies' strategies under governments' subsidies and regulators' regulation in two types of areas: H-(high) area and L-(low) area.

TGC is a supportive policy tool of RPS. This study indicates that the differences in the impact of TGC price changes on the government are reflected in the mid to late stages of evolution, while the differences in the impact on regulatory authorities are more pronounced in the initial stage of evolution. At the same time, we found that regulatory authorities and power selling companies are not sensitive to the low TGC unit price of government subsidies. This finding indicates that in the case of low TGC unit prices, regulatory authorities and power selling enterprises hold a "wait-and-see attitude" towards RPS policies, and the impact of TGC prices on policy implementation is not significant, which is not conducive to the promotion of policies and the withdrawal of government subsidies during this period. With the increase in the unit price of TGC, the portion exceeding the quota can receive higher transfer income, while the insufficient portion will be further punished, resulting in most power selling enterprises reaching the quota. However, enterprises in high quota area are more sensitive to quotas, and the corresponding probability of government subsidies is reduced. For regulatory authorities, companies that choose NFS in the early stage can charge high fines, and in the later stage, as the probability of quota fulfillment increases, unnecessary regulation can be avoided. Therefore, the probability of adjustment increases first and then decreases. The above explanation indicates that a higher TGC price helps power selling companies complete quotas, allowing the government to withdraw subsidies.

The net profit of conventional energy power (v_C) and RE power (v_R) are two important factors in the strategic choice of power-selling enterprises. When the net profit of RE power is slightly less than that of conventional energy power, all power-selling enterprises in the high quota area choose the FS, and approximately 98 % of power-selling enterprises in the low quota area adopt the FS; thus, the probability of power-selling enterprises fulfilling the quota increases. When the net profit of conventional energy power (v_C) is much larger than the that of RE power (v_R), 26 % of power-selling enterprises in the high quota area choose the FS, while fewer enterprises in low quota (approximately 18 %) choose the FS, which indicates that a high net profit of conventional energy power (v_C) has a certain blocking effect on the implementation of the RPS policy. The main reason for this may be that when power-selling enterprises obtain high profits from traditional energy power, they have no motivation to overfulfill, nor worry about facing the fines if they fail to meet the quota, and lack enthusiasm to change their current state. However, when the net profit of conventional energy power (v_C) is only slightly larger than that of RE power (v_R), subsidies, transfer income or penalties could increase the enthusiasm of power-selling enterprises, which leads to an increase in the probability of enterprises fulfilling the quota. When the net profit of conventional energy power (v_C) is less than the that of RE power (v_R), all power-selling enterprises can meet the quota, which is consistent with the situation in which the net profit of RE power (v_R) is slightly less than the net profit of conventional energy power (v_C), as rational economic entities completing the quota help enterprises achieve profit maximization. In summary, we conclude that a high net value of RE power is conducive to implementing RPS. The main reason for this may be that when the net profit per unit of RE power is greater than that of traditional energy power, any rational economic entity increases the proportion of RE power to maximize its profit. Therefore, if we want to achieve the expected RPS target, then we should keep the net profit of RE power higher than the that of conventional energy power.

In this study, government subsidies for regulatory authorities are classified as reward and excess subsidies. With the in reward subsidies and the excess subsidies coefficient increase, the probability of governments subsidies decreases, and the probability of subsidies in the high quota area is lower than that in the low quota area, indicating that the subsidy intensity changes inversely with the subsidy period; that is, the stronger the subsidy intensity is, the shorter the subsidy period, and vice versa. Moreover, enterprises in the low quota area need more subsidies from regulatory authorities, owing mainly to the fact that it is more difficult for the enterprises in these regions to increase the proportion of RE power due to natural factors compared to those in high quota area, which also shows the rationality of heterogeneity in quota setting. The reward subsidy has a certain incentive effect on regulatory authorities in the early stage, but this effect is not obvious in the long run. The main reason may be that regulatory authorities do not need to carry out strict supervision but can obtain a subsidy when power-selling enterprises fulfill their quotas. The excess portion from some power-selling enterprises can be transferred to other power-selling enterprises, which can also receive subsidies from regulatory authorities. Higher transfer income can increase the enthusiasm of power-selling enterprises to meet the quota, but the impact of higher subsidy income on the decision-making of power-selling enterprises is not significant. Therefore, against the background of the market economy, compared with the subsidies obtained by regulatory authorities, power-selling enterprises have greater motivation for market transactions, and the positive impact of the share advantages in high quota area is more significant. However, with the increase in the penalties, the promotion effect of subsidy income is significantly improved, but the rule regarding the ideal penalty is not "the heavier, the better"; therefore, it is particularly important to identify an appropriate penalty.

4.1. Outlook and future insights

To study the behavioral decisions of local governments, regulatory authorities, and power-selling enterprises with low and high quota targets under RPS, we established a SD model of a tripartite evolutionary game and analyzed the interactions among stakeholders by simulating the evolutionary process of strategy under scenarios with different parameters. In summary, we draw the following conclusions: First, under the RPS policy, power retail companies in low quota area need more government subsidies than those in high quota area, indicating a certain bottleneck period in the initial stage of RE development and confirms the necessity of government guidance. Regulatory authorities do not need comprehensive and strict regulation, and power-selling enterprises can meet their quotas, which indicates that the RPS policy can improve the enthusiasm of power-selling enterprises to sell a certain amount of RE power extent to promote RE development. Second, a high TGC price helps power-selling enterprises fulfill their quotas and governments withdraw subsidies; in contrast, regulatory authorities and power-selling enterprises are not sensitive to low TGC unit prices, and the subsidy probability increases when the TGC unit price is low. Third, the difference between the net profit of conventional energy power and that of RE power can easily affects the strategic choice of power-selling enterprises. With a high net profit of conventional energy power and a low the net profit of RE power, the proportion of power-selling enterprises in low quota area that complete the quota is less than 20 %, and the proportion in high quota area is less than 30 %. However, with a high the net profit of RE power and a low the net profit of conventional energy power, all power-selling enterprises in the high quota area choose to fulfill the quota, and 3 % of power-selling enterprises in the low quota level choose not to fulfill the quota, which shows that to promote the development of RE, the net profit of RE power should not be less than that of conventional energy power. Finally, for power-selling enterprises that meet the quota, the incentive effect of resale income is stronger than that of subsidy income; however, in the case of penalties and rewards, the incentive effect of subsidy is more obvious, but the penalty is not as severe as the better, which also proves the accuracy of the differential distribution of quotas.

Combining evolutionary game theory and SD model, we study the impact of RPS on China's retail power market, and the results can help relevant decision makers clarify their ideas. However, the research in this paper still needs to be supplemented, since the power demand growth rate and quota growth rate may be different at different stages of policy development, and the government's assessment of electricity quota obligations needs to be combined with necessary incentive measures [56]. In addition to gaining additional insights, future studies can further analyze the policy effect of the quota system based on the heterogeneity of the growth rate, propose more comprehensive policy suggestions for finding the optimal incentive method, and help each subject make better long-term decisions.

5. Conclusions

To promote the transformation of the RE share from a low to a high level and promote the development and transformation of RE, Chinese government officially implemented RPS in 2020. With the opening of the power sales side in China, it has become particularly important to consider the effect of RE policy on the power sales side. To simulate the strategies of local governments, regulatory authorities, and power-selling enterprises both in high and low quota areas, we expand a SD model of a tripartite evolutionary game by Vensim DSS which passes behavioral validity, then simulate the strategy evolution process of the three players by setting different initial probabilities; analysis the impact paths of TGC unit price, unit net profit of conventional and renewable power, governments' incentive subsidy coefficient and renewable power subsidy coefficients, and regulators' subsidy coefficient and penalty coefficient on model stability through model simulation, and draw the following conclusions: First, simulation results obtained with different initial probabilities show that the RPS can effectively drive the RE industry through the initial bottleneck period, and the governments can provide a certain proportion of subsidies, which play a more significant role than does the strict supervision of regulatory authorities; Second, by the simulation results obtained with different TGC price, it can be seen that higher TGC price will help power-selling enterprises meet the quota and avoid relying of governmental subsidies; Third, by the simulation results obtained with different unit electricity-selling profit, it can be seen that when the profit from the sales of RE power is higher than that of the sale of traditional energy, the enthusiasm of power-selling enterprises to fulfill the quota will be stimulated; Finally, by the simulation results obtained by different coefficient, it can be seen that transfer income can stimulate the enthusiasm of power-selling enterprises more than subsidies, but moderate penalties significantly improve the effect of subsidies. The above conclusions can provide participants in the electricity retail market with renewable portfolios a theoretical basis for specific directions in decision-making.

The key to the effective implementation of RPS on the electricity-selling side lies in the governments' appropriate subsidies and avoidance of excessive subsidies, as well as regulatory agencies increasing the intensity of constraints on electricity-selling enterprises through reward and punishment mechanisms. The political significance of this article is mainly reflected in the following two aspects: (1) In terms of the necessity of setting quotas differently, after weighing factors such as local socioeconomic development and resource endowment, the quota ratio should be assessed according to the actual situation. For example, RE resource in the western region is very abundant, after the western region achieved the excessive consumption of RE, governments should appropriately increase the quota proportion based on regional differences; On the other hand, the regulatory agencies may relax regulation due to high quota indicators but lack of incentives, therefore, the setting of quota ratios should also be considered based on the efforts made by regulatory authorities when choosing regulation. (2) Regulatory agencies need to establish a punishment mechanism under RPS to constrain the completion of quotas for power-selling enterprises and enhance the authority of regulatory enforcement through institutionalized construction. Although the incentive effect of subsidies is significant, the excessive financial pressure caused by dependence on subsidies should be considered, and the regulators could motivate the power selling enterprises to undertake RE quota task by increasing the price of TGC or the net profit obtained from selling renewable power.

Author contribution statement

Chun Fu; Yanfang Li: Conceived and designed the experiments; Performed the experiments; Wrote the paper. Abdulmoseen Segun Giwa; Siwei Luo: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

Data availability statement

Data included in article/supp. Material/referenced in article.

Declaration of competing interest

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

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