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A Study on Inter-Regional Cooperation Patterns and Evolution Mechanism of Traditional and Renewable Energy Sources

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Abstract: To obtain the early realization of carbon peak and carbon neutrality in China, this study explores the cooperative relationship of inter-regional energy power-generation substitution between regions dominated by traditional thermal power and renewable energy sources (RES). By taking a regional government as the decision-making subject, focused on interest and environmental factors, an evolutionary game model of inter-regional energy cooperation is structured, and a simulation platform of the two different power-generation replacement cooperative patterns/strategies is constructed by using system dynamics. Then, the influences of the sensitive parameters on the cooperative evolutionary path under symmetric and asymmetric sharing cost cases have been discussed based on practical example in the regions of China. The results imply that agents can only select the favorable cooperative strategies unilaterally, by choosing a strategy of sharing the environmental revenues rather than the cooperative costs. When the failure cost of the opportunity revenues is less than or equal to the RES power-generation cost, a traditional thermal power regional government adopts a cooperative no-sharing strategy, while an RES regional government selects the opposite strategy. However, under the optimized dynamic proportional allocation schema, it is more likely that the traditional thermal power regional government will prefer cooperative sharing strategies, which can promote the social value of RES. This study provides beneficial inspiration for the Chinese government to further improve its RPS policy. The RES consumption fulfilled by direct or indirect trans-regional energy cooperation can be included in the RPS index framework assigned to traditional thermal power energy regions, and the added environmental value should be regarded as being as crucial as the economic and energy factors are in the cooperative process. In addition, RES regions that contribute more to clean energy absorption should raise the weight of the RPS rewards.

Keywords: traditional thermal power energy; RES power generation; regional government; cooperative patterns; strategic selection; evolutionary game; system dynamics

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Citation: Shang, B.; Jiang, T.; Bao, Z. A Study on Inter-Regional Cooperation Patterns and Evolution Mechanism of Traditional and Renewable Energy Sources. *Sustainability* **2022**, *14*, 16022. https://doi.org/10.3390/su142316022

Academic Editors: Kittisak Jermsittiparsert and Thanaporn Sriyakul

Received: 29 October 2022
Accepted: 28 November 2022
Published: 30 November 2022

1. Introduction

A regiment of enormous challenges such as energy utilization efficiency [1,2], incremental environment stress [3–6], security of the energy supply [7,8], and so on have been witnessed in the process of China's energy development. From 2000 to 2012, the share of fossil fuel energy in primary energy consumption decreased by 5.98% [9], among which oil accounted for 5.19% and coal for 0.79% [9]. Meanwhile, the proportion of renewable energy sources (RES) in primary energy consumption increased by 3.08% [9], among which water energy accounted for 1.99% and non-water RES for 1.09% [9]. Although the Chinese government plans to nearly double the share of RES in the overall energy structure from 8% in 2006 to 15% by 2020 [10], RES consumption is still wanting of momentum. In 2016, 56% of China's power demand stemmed from RES, with hydropower accounting for 28%, wind for 22%, biomass for 5%, and photovoltaic for 1% [11]. However, China's abandonment rate peaked from 2015 to 2016, which typically reflects the country's power system inability to integrate and accommodate RES [12]. To further expedite the pace of RES production and consumption, the Chinese government promulgated in 2019 the "Notice on the Establishment and Improvement of the RES Power Consumption Guarantee Mechanism", stipulating the RES development phase of the mandatory planning objectives in different provincial administrative regions, which aimed at fortifying the market share of RES to cast off the conundrum of RES consumption by introducing Renewable Portfolio Standards (RPS) [13,14]. It is also a vital strategic move for China to achieve carbon peaking by 2030 and carbon neutrality by 2060.

China's RES is chiefly concentrated in the northwest and southwest regions and has great economic potential. It is necessary to strengthen energy cooperation among regions to manifest the social value of RES and remove the restrictive effect of a region being isolated on the development of China's RES market. Should the advantages of RES sources in the western region be taken fully, partially replacing traditional thermal power generation, they might bring many preponderances such as the curtailment of economic dependence on coal-fired resources, the abatement of carbon emissions pollution, and the high-efficiency improvement of RES usage. Nevertheless, it is necessary to establish alternative energy power-generation cooperation between thermal power and RES regions on the basis of mutual benefit and reciprocity. This alternative cooperation can not only fulfill the RPS quota for the traditional thermal power regions but also avert the actual limitations of an individual region to pursue its own interests. In particular, from a regional view, the integration of sophisticated interests inclusive of the transfer of cooperative benefits, cost sharing, environmental value sharing, etc., is extraordinarily pivotal for inter-regional power-generation energy replacement cooperation.

In terms of inter-regional power market transactions, the power grid transmission system is the intermediary bridge connecting regional energy trading cooperation, which encompasses physical and economic attributes [15]. Physical properties is a major field that scholars currently pay close attention to. On the one hand, it is mainly reflected in the analysis of the characteristics and development direction of the power grid distribution in China's regions as a whole, and the leading role of government policies in power grid planning stands out [16,17]. On the other hand, it is embodied in the coordination of scheduling the strategic optimization of energy systems, i.e., the coordination of a wind–solar–hydro–thermal power system in single or multiple region(s) such as seasonal periodic scheduling [18], load and emission scheduling technology from the aspect of cost [19,20], an optimization scheme for a power-generation compensation mechanism [21], economic and environmental scheduling [22,23], etc. The common purpose of these strategic scheduling optimizations is to ensure the coordination of the energy power supply system, improve the power quality of RES, and lessen carbon emission pollution and ecological damage, although the physical attributes of the trans-regional power grid are not an important topic to be considered in this study [24]. It is necessary to make a statement at first, because trans-regional power transmission is taken as a significant strategic move to equilibrate the allocation of national resources and satisfy the long-term interests of each region, and it is also the basis for conciliating the contradiction between RES intensive regions and areas with large power demands [25]. The focus of this article is the problem of economic attributes in the realm of cross-regional transactions.

Inter-regional energy power-generation replacement is one of the important channels to improve the consumption capacity of RES. It is not only a new energy cooperation manner formed among regions but also an important measure of large-scale market-oriented resource allocation [26]. However, there are plentiful uncertainties in regional transactions [27]: (1) Some immature matters exist such as an imperfect pricing formation mechanism, a lower degree of marketization, and the non-standardization of trading behavior among regions, which become the prerequisites for successful regional market trading. (2) The layout of the power grid among regions is not very reasonable. Some of the planning construction is in a state of controversy, and the network channel involved in power transmission has the nature of a partial monopoly. (3) Due to the sufficient transmission capacity that the power market's design requires [28], the increase in different stakeholders in the process of inter-regional power transmission causes more intricate interest games among agents. Since local governments generally refuse to receive outside-zone RES power sources, owing to the protection of traditional thermal power generation [29], energy power generators are confronted with colossal risks by participating in competitive inter-regional power market transactions directly [26], but this new energy cooperative manner requires a regional government to take the lead in guiding market participants by a scientific energy development strategy to avoid a failure of the trading market [30]. When the trading conditions are gradually mature, the power generators participating in the market's bidding transactions will integrate into the market's trading environment easily [31]. Sun et al. analyzed the benefits of trans-regional power trading from the perspective of the amount of coal-fired energy saved, the amount of the economic earnings, and the reduction in pollution [32], which promoted the grid connection of RES such as hydropower and wind power [33]. The aforementioned research evaluation is static. As a matter of fact, the cooperation benefits of power-generation replacement will be reallocated according to the traders' interest demands; hence, the behavior selection of cooperators is not solely dynamic, but changes willfully. However, a plethora of works show few signs of these behavior selection characteristics. The role of government and/or RPS policy in energy power-generation replacement has not shed light on inter-regional power trading. Additionally, although RES has the feasibility of cost competition in partially replacing traditional thermal power scale, it must have a certain regional-scale effect [34].

Previous studies have focused on issues such as the technical strategy scheduling of different energy generations [1,11,16–23,25,27] and regional environmental and energy efficiency evaluations [2,6,7,24,35]. In terms of generation right replacement (regional or non-regional level) [26,31–34,36], existing studies chiefly concentrate on the benefit change and energy-development efficiency under a static game, but the region as the lead decision-making subject and the dynamic change process of the cooperative strategy/mode in power-generation replacement have been given insufficient attention. Peculiarly, few studies have included RPS policy into the game framework between traditional thermal power and RES energy [30]. Inspired by the abovementioned research findings, we will take into account power grid companies' long-term dominant position in the power trading market and the differences between grid operation areas in China. Also, we should attach importance to the media role of regional governments for inter-regional energy cooperation and the local RPS quota's objectives. Already, all these previous studies have failed to consider any further economic behavior attributes. Therefore, we investigate the cooperative behavior of power-generation replacement between thermal power energy and RES by regional governments, synchronously, paying close attention to the dynamic behavior selection of cooperative patterns built on costs, which is the most notable otherness from the existing literature. Consequently, the following critical questions posed in our study will be addressed:

(1) How do we define the cooperative power-generation substitution benefits of thermal power energy and RES by regional governments? How does power-generation substitution affect their behavior choice considering their RPS policy role?

(2) What are the cooperative patterns of inter-regional energy power-generation replacement? How do we define these cooperative patterns constituting the agents' behavior strategies?

(3) Since the reduction in traditional thermal power-generation plans can result in the loss of other opportunity gains, how do we discuss the cooperative strategies' evolutionary path when it is difficult to accurately estimate the actual loss value?

(4) How do we construct an effective dynamic proportional allocation schema of benefit sharing and cost sharing? What is the basis for optimizing such a schema? This optimization can highlight the social value of RES-generation alternatives as much as possible.

Surmounting the aforementioned pivotal issues will generate a rewarding significance in realizing green low-carbon economic development, establishing long-term energy cooperation mechanism among regions, and improving inter-regional power trading. To hunt for these answers, a theoretical framework constructed by an evolutionary game approach using system dynamics has been designed to explore the selection of regional energy power-generation cooperative patterns. Several contributions to the existing literature have been made in this study: (i) We focused on the changing process of cooperative patterns/strategies between traditional thermal power and RES at the regional level, and regional governments act as the main subject of decision making, owing to the current regional energy market-trading mechanism not being mature enough in China. (ii) RPS policy is incorporated into the evolutionary game framework of inter-regional energy cooperation, and the effect of the incentive weight of RPS on regional energy cooperation is also investigated, which contains the policy information for improving the RPS system. (iii) Simultaneously, the coordination of energy, environmental, and economic factors is detected when a traditional thermal power region participates in the cooperation process, which has a favorable influence on the consideration of multi-objective balanced development and further adjustment of inter-regional energy cooperation relations.

The rest of the part of this work is scheduled in the following order. Section 2 analyzes the theoretical framework of the evolutionary game. Section 3 constructs a model of the evolutionary game based on the system dynamics between regional governments for thermal power and RES generation. Section 4 further puts forth the stable conditions of the evolutionary game strategy. Section 5 firstly describes the base case for the model and then discusses the evolutionary results. Section 6 concludes the work and research prospects.

2. Materials and Methodology

Evolutionary game application idea is that groups achieve the equilibrium state through continuous trial and error. Different from traditional game theory, the group participants of evolutionary game are not completely rational, i.e., bounded rationality, which is determined by the complexity of the objective environment. However, the individuals' game is the basis of the evolution mechanism of group behavior, which determines that the group is a dynamic system that constantly adapts to the environment based on their bounded rationality. Maynard put forth the idea that evolutionary stability strategy is an extremely important concept in evolutionary game theory [37]. On account of the individual's bounded rationality, the evolution strategy of the group has the characteristics of diversity, complexity, and mutation in the dynamic game process but it is more than difficult for game agents to seek an equilibrium state of evolutionary stable strategy given the dynamic change from the continuous boost in the number of agents in evolutionary game and the disturbance by random elements such as individual finite rationality, incomplete information of game, and external environment. Usually, these complex evolutionary behaviors can be revealed by nonlinear differential equations [38]. But, sometimes it is difficult to solve the equilibrium solution of these nonlinear systems, while system dynamics (SD) provides a way to solve complex system problems [39].

The SD modeling methodology inquiring into a complicated system covers scores of disparate social fields such as power industry [40], management of RES sources [41], greenhouse gas emissions reduction [35], etc. The method is a sound tool of integrating qualitative and quantitative methods to carry out the comprehensive deductive process. Qualitative analytical method is meant to depict principally causal circuit diagrams (CLDs) on the strength of causal and nonlinear relationships among all sorts of variables for diverse properties, which brings the pivotal variable types together to boost gradual formation of dynamic system in a feedback fashion [42]; such information feedback loops imply the endogenous characteristics of the system structure and determine the system behavior [43]. Quantitative analytical method is likewise tempted to identify and classify systematic variable types on the basis of CLDs, establish mathematical function relations among these variables, and analyze the dynamic connections of systematic structure, function, and behavior over time span with the help of computer simulation [44]. SD model analysis consists of two phases. The first is to perform a sensitivity analysis by carrying out computer simulations, that is, an analysis of the reason why the system model induces this behavior and the dynamic changes in the behavior over time; the second is to perform a policy analysis by carrying out computer simulations, in other words, to analyze the extent to which effective policy instruments can be introduced for decision makers [45].

The issue of inter-regional energy power-generation replacement cooperation belongs to the field of energy management. Therefore, the SD method will be adopted in this study to settle the dynamic evolutionary process of subjects' behavior. Due to the visualization effect of SD approach, especially when the unbalanced strategy appears in the evolutionary game system, the optimized mathematical expression can be displayed in the SD model in a remarkable form. This is an important reason for choosing this method in this paper. To be specific, firstly, it can describe the system functional structure diagram among these regional energy cooperative decision-making variables. Moreover, it is also able to capture details for the information feedback of behaviors on account of the SD evolutionary game's variable attributes. Secondly, it can control the optimization strategy stability behavior when there exists chaotic process affected by external factors' interference, which is vital for us to discover feasible paths for inter-regional energy cooperation in accordance with our expectations. Of course, it has other advantages such as solving the intricate problem of equilibrium in multi-stakeholder evolutionary games with more participants. As this article deals with two decision-making subjects, this merit is not given detailed description.

3. Construction of Evolutionary Game System Model

3.1. Description of Evolutionary Game Nexus

For power generators, inter-regional energy power-generation replacement is a new energy cooperative pattern [36]; in other words, the traditional thermal power region entrusts the RES energy region to complete the generating capacity schedule to replace the coal-fired power energy partly based on the contract signed for a transaction according to the market operation rules. Given the immature market-trading mechanism of energy power generation in China's different regions, the government as the trading-rules maker plays a vital role in the establishment of the inter-regional energy market framework. The regional government can also be regarded as a trader in the economic market in the initial stage due to comprehensively balancing each region's social welfare, which gives the impetus to form and standardize the transaction mode, rules, etc., and enhance the matching of supply and demand in the energy market through inter-regional governments' preliminary cooperation.

In practice, the regional government that is supporting traditional thermal power energy will also decide whether to conduct inter-regional energy cooperation with regions rich in RES in view of integrated elements such as the local RPS quota's volume, coal-fired supply and demand, carbon emission of the power industry, and the regional economy. If power-generation replacement can capture the high added value of social welfare for a traditional thermal power energy region, then its cooperative willingness will increase. However, due to the influence of the regional energy endowment difference of the social welfare utility in disparate regions, and the effect of imperfect information such as trade preferences, motivation, etc., both trading parties give priority to their own economic interests in an uncertain market environment, which determines whether they can come to a consensus in terms of the benefits and cost sharing. If a partial reduction in traditional energy power should bring further benefits, a traditional thermal power regional government, as a bounded rational entity, would be more willing to share the opportunity gains lost by reducing thermal power generation and pay the extra RES power-generation cost. While the inter-regional energy cooperation in which an RES regional government participates in power generation generates higher transmission costs, the strategy of sharing power-generation costs is an RES regional government's best option. What's more, RES power generation brings a regional environmental value, so a consensus can be reached on sharing the environmental benefits. However, both governments have adopted different cooperative strategies to seek maximum social welfare for themselves in the context of the uncertainty of the opportunity cost and the determination of the RES power-generation cost.

If both sides in the cooperation do not select the cost-sharing pattern, the cooperative pattern is a no-sharing cooperation; otherwise, it is a sharing cooperation, which constitutes the strategic choice space of cooperative stakeholders. For a rational traditional thermal power energy regional government, if the failure cost of the opportunity gains is less than the RES power-generation cost, the traditional thermal power regional government is reluctant to bear the higher RES power-generation cost under the no-sharing cooperative pattern. But, for the other way around, the traditional thermal power regional government may choose cost sharing or the no-sharing strategy with greater randomness, when the strategic selections lean toward choosing a higher or lower social welfare payoff; in other words, this kind of strategic behavior selection is characterized by mutation and changes ceaselessly in the process of trial and error, adjustment, and improvement. Eventually, cooperative strategies with affluent social welfare benefits are reserved with the steady state achieved after dynamic evolution, which coincides with the basic idea of the evolutionary game characterizing the diversity, mutability, and complicacy of stakeholders.

The logical framework for the formation and evolution of the energy power-generation replacement between traditional thermal power and RES regions is shown in Figure 1.

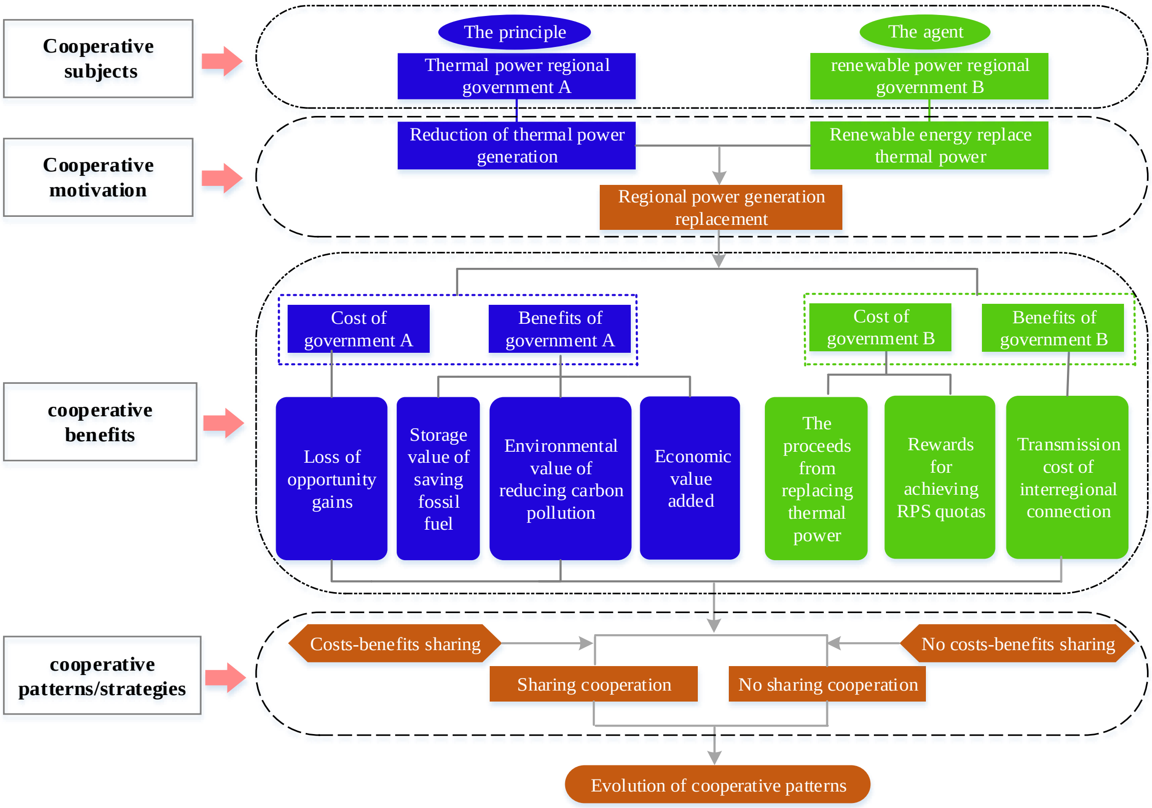


Figure 1. Evolutionary logic of regional energy power-generation replacement process.

3.2. Modeling Assumptions

The following assumptions can be presented to illustrate the interest relations:

◆ Cooperative agents. A traditional thermal power-generation regional government (government/region A) and an RES power-generation regional government (government/region B) are the main agents of inter-regional energy cooperation. The motivation for cooperation lies in the fact that government A intends to alleviate the contradiction between the supply and demand of coal-fired energy, control carbon emission intensity, and fulfill RPS obligations. Energy cooperation is based on strong power supervision, connected transmission network, advanced dispatching, and operational technology.

◆ Cooperative strategies. The strategies for governments A and B are sharing cooperation and no-sharing cooperation; both sides game together dynamically, considering the affluent social welfare in their respective regions. The probability that government A selects sharing cooperative strategy at moment t is $x(t)$, and the probability that government B selects sharing cooperative strategy at moment t is $y(t)$, where $0 \le x(t), y(t) \le 1$.

◆ Profit components. If the governments cooperate in power generation, government A will pay a certain expense for the RES power generation, denoted as e, and the power price shall be negotiated by them. Suppose the storage value of saving coal-fired energy is r_1, and the influence of coefficient r_1 is ℓ ($\ell > 0$), then the storage value of saving coal-fired energy can be written as ℓr_1. Owing to the carbon emissions abatement in region A, the environmental value of carbon abatement can be denoted as r_2. Meanwhile, let region A's added economic value be r_3, and the influence coefficient r_3 be λ ($\lambda > 0$), then the added economic value is λr_3.

◆ The effect of RPS on profit components. Given that the RPS volume δ completed by region B can be expressed as the ratio of the RES power-generation capacity to the social power consumption of coal-fired regions, r_2 can be denoted as δr_2. In line with the national government's stipulation that the RPS excitation of regional governments increases by 10% based on the RPS constraint proportion, let δ be the RPS constraint proportion, and then government B is awarded by the national government, which can be written as ρe, where $\rho = (\delta + 0.1)$ is the excitation coefficient.

◆ The case of no-sharing benefits and costs. If both sides do not share the environmental benefits, the failure cost of opportunity gains π will be undertaken by government A, and power-generation cost c will be undertaken by government B. Then, the two governments select the strategy of no-sharing cooperation. Therefore, the benefits of no-sharing cooperative strategies between governments A and B are $\ell r_1 + \delta r_2 + \lambda r_3 - e - \pi$ and $e + \rho e - c$, respectively.

◆ The case of sharing benefits and costs. When the revenues are shared, government A's allocated proportion of environmental benefits is α ($0 < \alpha < 1$). If the environmental benefits of government A are $\alpha\delta r_2$ and the environmental benefits of government B are $(1-\alpha)\delta r_2$ when the costs are shared, the sum of the failure cost of opportunity gains π, and the RES power-generation cost c is expressed as the sharing costs between governments A and B, i.e., $\pi + c$. If the allocated proportion of the cost of government A is θ ($0 < \theta < 1$), the cost allocation borne by government A is $\theta(\pi + c)$, and the cost allocation borne by government B is $(1-\theta)(\pi + c)$. At this moment, governments A and B will select the strategy of sharing cooperation. Then, the benefits of sharing cooperative strategies between governments A and B are $\ell r_1 + \alpha\delta r_2 + \lambda r_3 - e - \theta(\pi + c)$ and $e + (1-\alpha)\delta r_2 + (\delta + 0.1)e - (1-\theta)(\pi + c)$, respectively.

◆ The case of sharing benefits but no-sharing costs. If government A chooses the sharing cooperative strategy and government B adopts the no-sharing cooperative strategy and vice versa, i.e., $(x,\ 1-y)$ or $(1-x,\ y)$, the meaning is that both the trading parties are willing to share the incremental environment benefits rather than share the cooperative costs.

In a nutshell, the game payoff matrix between governments A and B under different cooperative strategies is shown in Table 1 based on the modeling assumptions.

Table 1. Game payoff matrix between governments A and B under different cooperative strategies.

Government A	**Government B**	
	Sharing Cooperation (y)	**No−Sharing Cooperation ($1-y$)**
Sharing cooperation (x)	$\begin{pmatrix} \ell r_1 + \alpha\delta r_2 + \lambda r_3 - e - \theta(\pi + c) \\ e + (1-\alpha)\delta r_2 + (\delta + 0.1)e - (1-\theta)(\pi + c) \end{pmatrix}$	$\begin{pmatrix} \ell r_1 + \alpha\delta r_2 + \lambda r_3 - e - \pi \\ e + (\delta + 0.1)e - c \end{pmatrix}$
No-sharing cooperation ($1-x$)	$\begin{pmatrix} \ell r_1 + \delta r_2 + \lambda r_3 - e - \pi \\ e + (1-\alpha)\delta r_2 + (\delta + 0.1)e - c \end{pmatrix}$	$\begin{pmatrix} \ell r_1 + \delta r_2 + \lambda r_3 - e - \pi \\ e + (\delta + 0.1)e - c \end{pmatrix}$

3.3. Payoff Analysis of Different Cooperative Strategies

In light of the payoff matrix, the expected return of the probability of government A selecting the sharing cooperative strategy and that of the no-sharing cooperative strategy gain are u_1 and u_2, respectively, and the total average expected return of government A $\overline{u}$ are written, respectively, as follows:

$$u_1 = y[\ell r_1 + \alpha\delta r_2 + \lambda r_3 - e - \theta(\pi + c)] + (1-y)[\ell r_1 + \alpha\delta r_2 + \lambda r_3 - e - \pi] \tag{1}$$

$$u_2 = y(\ell r_1 + \delta r_2 + \lambda r_3 - e - \pi) + (1-y)(\ell r_1 + \delta r_2 + \lambda r_3 - e - \pi) \tag{2}$$

$$\overline{u} = x u_1 + (1-x) u_2 \tag{3}$$

Similarly, the expected return of the probability of government B choosing the sharing cooperative strategy and that of the no-sharing cooperative strategy are v_1 and v_2, respectively, and the total average expected return of government B $\overline{v}$ are written, respectively, as follows:

$$v_1 = x[e + (1-\alpha)\delta r_2 + (\delta + 0.1)e - (1-\theta)(\pi + c)] + (1-x)[e + (1-\alpha)\delta r_2 + (\delta + 0.1)e - c] \tag{4}$$

$$v_2 = x[e + (\delta + 0.1)e - c] + (1-x)[e + (\delta + 0.1)e - c] \tag{5}$$

$$\overline{v} = y v_1 + (1-y) v_2 \tag{6}$$

3.4. System Dynamics Model of Evolutionary Game

Now, the system dynamic flow diagram of the evolution of cooperative strategies between governments A and B is depicted, showing the causality of diverse variables, as shown in Figure 2. The evolutionary game based on the SD model covers four status variables, i.e., x, $1-x$, y, $1-y$; two rate variables, i.e., the change rates of government A and B's strategies; eight auxiliary variables, i.e., x, u_1, u_2, $u_1 - u_2$, y, v_1, v_2, $v_1 - v_2$; and other variables that are all external variables, where the functional nexus of the rate and the auxiliary and external variables mainly rests with the payoff structure and replicator dynamic equations, as shown in Equation (8).

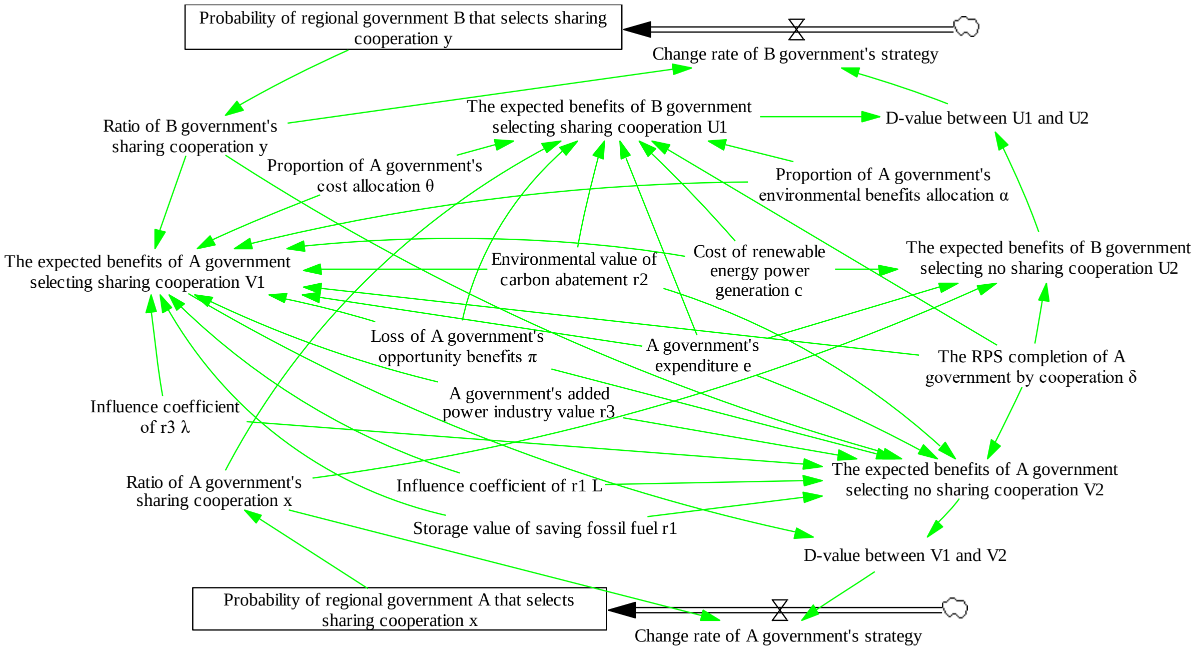


Figure 2. The SD flow diagram of the evolution of cooperative strategies between governments A and B.

As shown in Figure 2, it can be clearly seen that the probability of region A choosing strategy x and region B choosing strategy y is chiefly affected by the change rates of their respective strategies. However, in the final analysis, the difference of the expected return brought by the adoption of the sharing cooperative strategy and no-sharing cooperative strategy determines the change rate of the regional governments' strategy selection. Hence, the SD that causes the tree of the respective expected return u_1, u_2 and v_1, v_2 has been analyzed, which shows that the determinants and relations of region A's expected return are more complicated than region B's. For instance, the variables α, π, c, δ, e, ℓ, λ, θ, r_1, r_2, r_3, y determine the structure of the expected return u_1 and u_2, and the structure of the expected return v_1 and v_2 is from part of the variables, α, c, δ, e, π, θ, x. This means that region A will select strategy x out of intense economic purpose, which acts on the change rate of region B's strategy choice by the expected revenue v_1 and v_2. It follows that the two regions affect the changes of their own behavior selection in the interest interaction, and the SD dynamic flow diagram provides an intuitive flow of the benefits and economic behavior connection to illustrate this complex evolutionary process.

4. Stable Conditions of Evolutionary Game Strategy

4.1. Acquisition of Equilibrium Points

According to the idea of Malthusian's equation, each group represents a specific group type, so they constantly try new strategies to make the group find the best adaptive strategy and use the long-term strategy. Hence, the growth rate $\dot{x}$ of the sharing cooperative strategy x chosen by government A conforms to the following replicator dynamic, as shown by Equation (7):

$$\dot{x} = x(u_1 - \overline{u}) = x(1-x)(u_1 - u_2) = x(1-x)[y(\pi - \theta\pi - \theta c) + (\alpha - 1)\delta r_2] \tag{7}$$

Similarly, the replicator dynamic equation of government B selecting its sharing cooperative strategy can also be acquired. As a result, the two-dimensional evolutionary game system (I) between regional governments A and B can be written in the following way:

$$\begin{cases} \dot{x} = x(1-x)(u_1 - u_2) = x(1-x)[y(\pi - \theta\pi - \theta c) + (\alpha - 1)\delta r_2] \\ \dot{y} = y(1-y)(v_1 - v_2) = y(1-y)[xc - x(1-\theta)(\pi + c) + (1-\alpha)\delta r_2] \end{cases} \tag{8}$$

At this point, let Equation (8) equal zero simultaneously, i.e., $\dot{x} = 0$, $\dot{y} = 0$, and all the definite solutions can be calculated accurately in the plane $S = \{(x,y) | 0 \le x \le 1,\ 0 \le y \le 1\}$; that is, four pure strategic equilibrium points, (0, 0), (0, 1), (1, 0), and (1, 1), and one blended strategic equilibrium point, $X_5(\widetilde{x},\ \widetilde{y})$, where $\widetilde{x} = \frac{(1-\alpha)\delta r_2}{(1-\theta)(\pi+c)-c}$, $\widetilde{y} = \frac{(1-\alpha)\delta r_2}{\pi - \theta(\pi+c)}$, and $0 < \widetilde{x}, \widetilde{y} < 1$.

4.2. Stable Conditions of Equilibrium Points

Nevertheless, it is not necessarily stable to solve all equilibrium points by the replicator dynamic equation of the evolutionary game; other steady states also exist. Therefore, we need to further infer whether the equilibrium points obtained are stable or not. According to Lyapunov stability theory, the asymptotic stability at the equilibrium point of the system (I) can be determined by computing the eigenvalues of the Jacobian matrix; specifically, the real roots or plural real parts of the eigenvalues are both negative. Thus, the Jacobian matrix $J(I)$ of the evolutionary game system (I) is

$$J(I) = \begin{pmatrix} (1-2x)[y(\pi - \theta\pi - \theta c) + (\alpha - 1)\delta r_2] & x(1-x)(\pi - \theta\pi - \theta c) \\ y(1-y)[c - (1-\theta)(\pi + c)] & (1-2y)[xc - x(1-\theta)(\pi + c) + (1-\alpha)\delta r_2] \end{pmatrix} \tag{9}$$

Take the stability analysis of equilibrium point $X_1(0,\ 0)$ as an example. The equilibrium point $X_1(0,\ 0)$ in system (I) can be expressed as $J(X_1)$. Then, the matrix $J(X_1)$'s eigenvalues are $\lambda_1 = (\alpha - 1)\delta r_2$ and $\lambda_2 = (1-\alpha)\delta r_2$, respectively, because $0 < \alpha < 1$, so $\lambda_1 < 0$ and $\lambda_2 > 0$. As we can see, the equilibrium point $X_1(0,\ 0)$ is not an evolutionary stability strategy. Therefore, let us analyze the stability of equilibrium point $X_3(0,\ 1)$. The matrix $J(X_3)$'s eigenvalues are $\lambda_1 = (\alpha-1)\delta r_2 < 0$ and $\lambda_2 = \pi - \theta\pi - \theta c + (\alpha-1)\delta r_2$, respectively. If condition ① is satisfied, the equilibrium point $X_3(0,\ 1)$ will be the stable point of the evolutionary strategy.

$$J(X_3) = \begin{pmatrix} \pi-\theta(\pi+c)+(\alpha-1)\delta r_2 & 0 \\ 0 & (\alpha-1)\delta r_2 \end{pmatrix} \tag{10}$$

$$\pi-\theta(\pi+c)+(\alpha-1)\delta r_2 < 0 \tag{11}$$

The judgment results of the stability of the other two pure strategic equilibrium points can be seen in Tables 2 and 3, while the Jacobian matrix $J(X_5)$ corresponding to equilibrium point $X_5(\widetilde{x},\ \widetilde{y})$ in system (I) can be expressed by Equation (11).

$$J(X_5) = \begin{pmatrix} 0 & \left(1-\frac{(1-\alpha)\delta r_2}{(1-\theta)(\pi+c)-c}\right)\frac{[\pi-\theta(\pi+c)](1-\alpha)\delta r_2}{(1-\theta)(\pi+c)-c} \\ \frac{[c-(1-\theta)(\pi+c)](1-\alpha)\delta r_2}{\pi-\theta(\pi+c)}\left(1-\frac{(1-\alpha)\delta r_2}{\pi-\theta(\pi+c)}\right) & 0 \end{pmatrix} \tag{12}$$

and the eigenvalues of the matrix $J(X_5)$ are given as follows:

$$\widetilde{\lambda}_1 = \left(1-\frac{(1-\alpha)\delta r_2}{(1-\theta)(\pi+c)-c}\right)\frac{[\pi-\theta(\pi+c)](1-\alpha)\delta r_2}{(1-\theta)(\pi+c)-c} \tag{13}$$

$$\widetilde{\lambda}_2 = \frac{[c-(1-\theta)(\pi+c)](1-\alpha)\delta r_2}{\pi-\theta(\pi+c)}\left(1-\frac{(1-\alpha)\delta r_2}{\pi-\theta(\pi+c)}\right) \tag{14}$$

Table 2. The stability of equilibrium points $X_1 \sim X_5$.

Equilibrium Points	Eigenvalues		Asymptotic Stability
	λ_1	λ_2	
$X_1(0,\ 0)$	$(\alpha-1)\delta r_2$	$(1-\alpha)\delta r_2$	Instability
$X_2(1,\ 0)$	$(1-\alpha)\delta r_2$	$c-(1-\theta)(\pi+c)+(1-\alpha)\delta r_2$	Instability
$X_3(0,\ 1)$	$(\alpha-1)\delta r_2$	$\pi-\theta(\pi+c)+(\alpha-1)\delta r_2$	Condition (11)
$X_4(1,\ 1)$	$(1-\alpha)\delta r_2-\pi+\theta(\pi+c)$	$(\alpha-1)\delta r_2-c+(1-\theta)(\pi+c)$	Condition (15)
$X_5(\widetilde{x},\ \widetilde{y})$	$\widetilde{\lambda}_1$	$\widetilde{\lambda}_2$	Condition (16)

Table 3. The condition of equilibrium stable points.

Stable Points	Condition of Stable Points	ID
$X_3(0,\ 1)$	$\pi-\theta(\pi+c)+(\alpha-1)\delta r_2 < 0$	(11)
$X_4(1,\ 1)$	$(1-\alpha)\delta r_2-\pi+\theta(\pi+c) < 0,$ $(\alpha-1)\delta r_2-c+(1-\theta)(\pi+c) < 0$	(15)
$X_5(\widetilde{x},\ \widetilde{y})$	$\widetilde{\lambda}_1 < 0, \widetilde{\lambda}_2 < 0$	(16)

5. Discussion of Evolutionary Results

5.1. Case Basis

To discuss the evolutionary process of the regional governments' cooperative strategies in detail, we select a practical case in the development of China's "West-East electricity transmission project". "Water and Fire Energy Replacement in Yunnan-Guizhou", carried out by the China Southern Power Grid and abbreviated "WFERYG", enhances the practical interpretation of the theoretical model.

The business area of the China Southern Power Grid includes Yunnan, Guizhou, Guangdong, Guangxi, and Hainan Provinces. With the aid of this platform, the "WFERYG" project has been implemented successfully. Yunnan Province is an RES base based on hydropower energy, and Guizhou Province is a traditional energy base based on fossil fuel, which are the power-supply terminals from west to east, while Guangdong Province with its high power demand is the consumption terminal of the power supply.

The cooperative mechanism of "WFERYG" is to transfer the capacity plan of traditional thermal power generation from Guizhou Province to hydropower generation in Yunnan Province with compensation, instead of Guizhou thermal power, Yunnan hydropower is directly transported to Guangdong and serves as the planned task for Guizhou to complete the transmission from west to east. The two regions are the main cooperative subjects, and each regional power grid acts as the agent of its own hydropower and thermal power energy to carry out power-generation replacement. Therefore, it is reasonable to take "WFERYG" as a case for our model analysis. In this study, Guizhou Province is recorded as a traditional thermal power-generation region, and Yunnan province is recorded as an RES power-generation region. Both the regions' decision makers are represented by their provincial governments.

"WFERYG" is generally concentrated in the hydropower flood season in Yunnan, considering there is an enormous gap between the supply and demand of coal-fired energy in Guizhou. For example, between July and September of a certain year, Guizhou Province's average social power consumption was about 23.55 TWh. Yunnan replaces Guizhou's traditional thermal power with 4.32 TWh in cumulative generating capacity, with an intermediate cost of RMB 0.2 per KWh. When the two sides sign a cooperative deal, the electricity price is RMB 0.157 per KWh. Then, the cooperative return gained by Yunnan is RMB 6.7824×10^8, with a total cost of RMB 8.64×10^8.

Accordingly, about 2.4×10^6 tons of coal-fired energy consumption and 4.9×10^5 tons of carbon dioxide emissions will be reduced. If the average coal-fired price in the Guizhou market is RMB 600 per ton and the carbon trading price is RMB 42.58 per ton, the added storage value of saving coal-fired energy and the environmental value in Guizhou are RMB 14.4×10^8 and RMB 0.208642×10^8, respectively, and the added value of the power industry is approximately RMB 47.87224×10^8. In October, the growth rates of coal and power industries were 5.7% and 10.4%, respectively. Assuming that this is due to the corresponding influence coefficient, in line with our hypothesis, we can estimate the RPS quota's completion for the Guizhou provincial government by "WFERYG" cooperation, i.e., 18.434%. What's more, considering that it is difficult to evaluate the failure cost of the opportunity benefits, owing to reducing the traditional thermal power generation in Guizhou, for convenience, let the failure cost of the opportunity benefits equal the power-generation cost of the Yunnan area.

Consequently, the initial value of the parameters can be formulated on the basis of the above analysis, as shown in Table 4.

Table 4. Initial value of model parameters.

Symbol	Definition	Initial Value	Units
r_1	Storage value of saving coal-fired energy	14.4	10^8 RMB
r_2	Environmental value of carbon abatement	0.208642	10^8 RMB
r_3	Government A's added economic value	47.87224	10^8 RMB
e	Government A's expense for RES alternative	6.7824	10^8 RMB
c	RES power-generation cost	8.64	10^8 RMB
π	Failure cost of opportunity gains	8.64	10^8 RMB
ℓ	Influence coefficient of r_1	5.7	%
λ	Influence coefficient of r_3	10.4	%
δ	RPS volume completed by government B	18.434	%
θ	Government A's cost's allocated proportion	50	%
α	Government A's environmental benefits' allocated proportion	50	%

5.2. Effect of Sensitive Parameters on the Cooperative Strategy's Evolutionary Path

If the parameters are in an initial state, $x = y = 0.5$, and the failure cost of the opportunity gains is equal to the RES power-generation cost, i.e., $\pi = c$, according to Tables 2 and 3, the stable results of all equilibrium points can be deduced. To be specific, $X_3(0,\ 1)$ is the evolutionary stabilization strategy (ESS), $X_1(0,\ 0)$ and $X_4(1,\ 1)$ are the saddle points, and $X_2(1,\ 0)$ is an unstable point, but there is no mixed strategic equilibrium point $X_5(\widetilde{x},\ \widetilde{y})$, as shown in Table 5. The results indicate that both regional governments A and B have adopted a pure strategy for a long time; that is, the strategic evolution of government A tends to be a no-sharing cooperative pattern with dynamic time changes, while the strategic evolution of government B is apt to choose a sharing cooperative pattern.

Table 5. Equilibrium stability in an initial state.

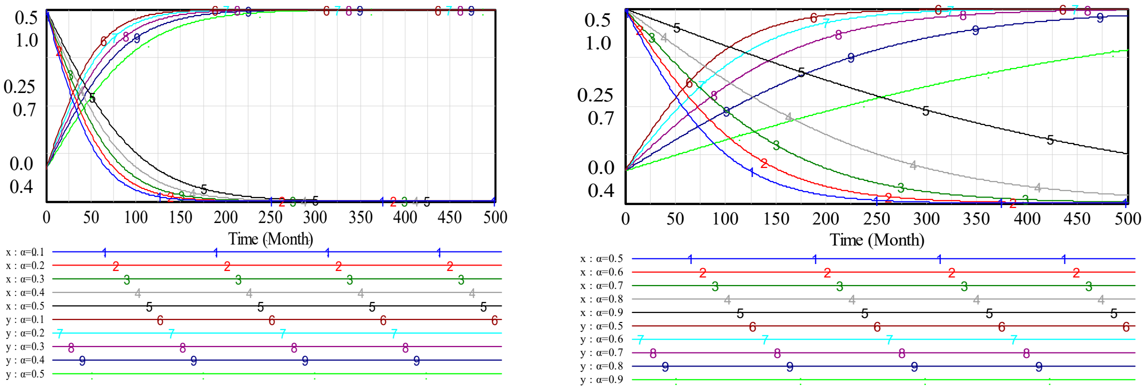
Equilibrium Points	Eigenvalues		Stability
	λ_1	λ_2	
$X_1(0,\ 0)$	−0.019231	0.019231	Saddle point
$X_2(1,\ 0)$	0.019231	0.019231	Unstable point
$X_3(0,\ 1)$	−0.019231	−0.019231	ESS
$X_4(1,\ 1)$	0.019231	−0.019231	Saddle point
$X_5(\widetilde{x},\ \widetilde{y})$	/	/	/

At this point, some findings can be drawn after analyzing the SD model. To put it another way, six sensitive parameters exist in the initial state that derive significant implications for the cooperative evolution path, which are summarized as four sharing cooperative parameters and two sharing cost parameters in this model. Among others, the sharing cooperative parameters cover α, r_2, δ, and θ; the sharing cost parameters include π and c. When π and c are equal, there will be a unique pure strategic equilibrium point $X_3(0,\ 1)$, but other equilibrium points may also exist if the sharing cost parameters are uneven.

In order to make the discussion practical, the sharing cost parameters π and c are divided into symmetric (i.e., $\pi = c$) and asymmetric (i.e., $\pi \neq c$) scenarios, and the influence of the sharing cooperative parameters on the evolutionary path of the cooperative strategies is based on the two scenarios.

5.2.1. Sensitivity Analysis of Sharing Cooperative Parameters When Sharing Cost Is Symmetric

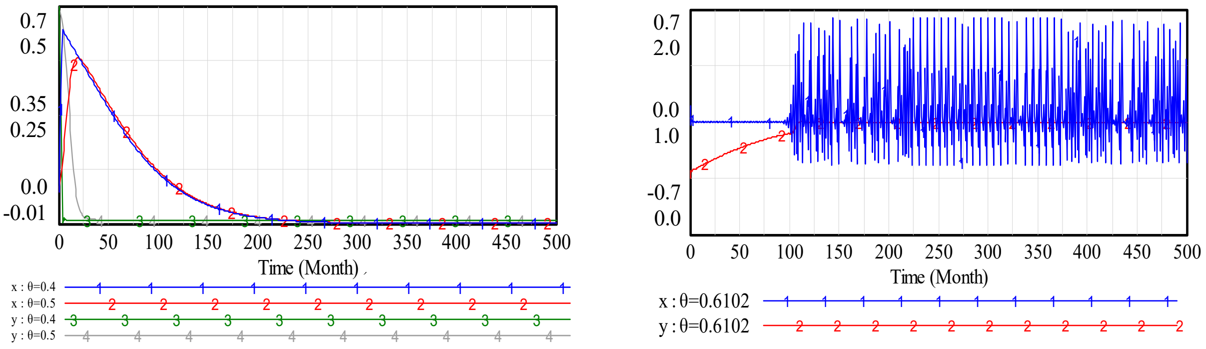
Keep the other initial parameters' value unchanged and analyze the sensitivity of α. Figure 3a shows that parameter α decelerates successively at the interval of 0.1, and the convergence speed of probability $x = 0$ ascends continuously when $\alpha < 0.5$. It can be found that a shrinking α means increasing government B's environmental benefits allocated proportion, and the probability y tends toward one at a synchronous convergence rate. When $\alpha > 0.5$, the amplitude of government A's strategic selection, deviating from probability $x = 0$, is much larger than when $\alpha < 0.5$. Although the possibility of selecting the sharing cooperative strategy proliferates for government A, it greatly decelerates the fierce willingness of government B to share the cooperative strategy, as shown in Figure 3b. The evolutionary results imply that simply increasing or decreasing proportion α cannot prevent governments A and B from having to choose to share the cooperative strategy simultaneously. Both sides invariably have opposite points of interest.



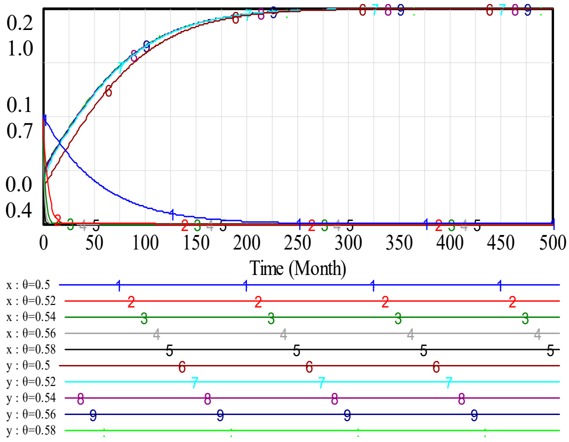
(**a**) $\alpha < 0.5$ (**b**) $\alpha > 0.5$

Figure 3. The evolutionary path of $X_3^{ESS}(0,\ 1)$ in different α value ranges.

Keep the other initial parameters' values unchanged and analyze the sensitivity of θ. The cost allocation proportion θ between governments A and B is within the reasonable range of 50–60% under a symmetric sharing cost, and $X_3(0,\ 1)$ is the *ESS*, as shown in Figure 4c. Otherwise, both sides cannot achieve long-term cooperation, because government A sharing less than 50% of the cooperative cost will cause the evolutionary trend of the probability y to become negative, as shown in Figure 4a. However, more than 60% of proportion θ will chronically turn government B's strategic choice into a state of chaos, as shown in Figure 4b. Consequently, in order to cultivate stable cooperative relations, the increasing extent of θ must be limited to an acceptable scope within the range of 10%.



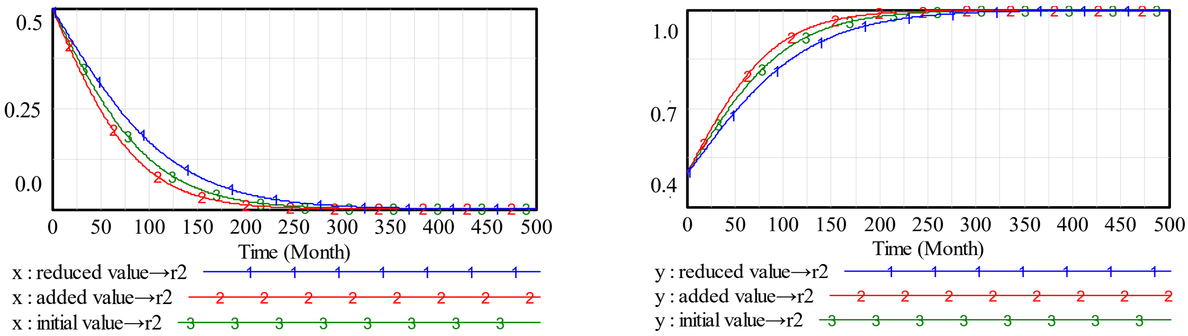
(**a**) $\alpha < 0.5$ (**b**) $\theta > 0.6$



(**c**) $\theta \in [0.5, 0.6)$

Figure 4. The effect of θ on evolutionary path of $X_3^{ESS}(0,\ 1)$.

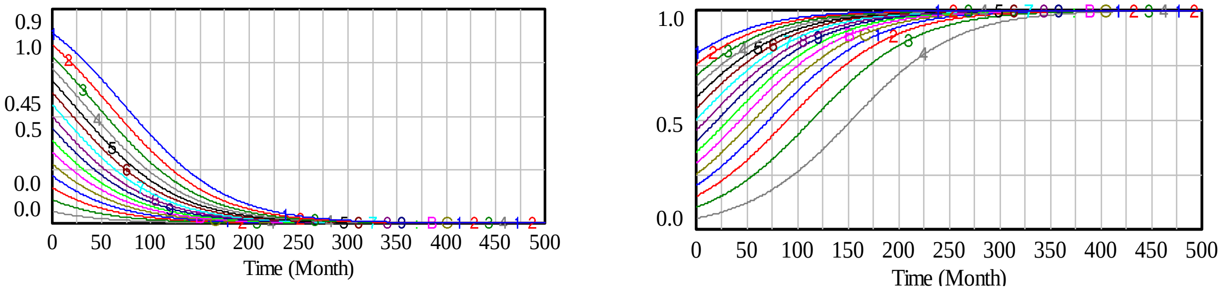
Keep the other initial parameters' values unchanged and analyze the sensitivity of r_2. In line with Section 5.1, the environmental value r_2 hinges on the carbon emission abatement and carbon trading price in region A. Let us assume that the carbon emission abatement is constant and that the carbon trading price is mutative. If the market carbon trading price drops from 42.58 to 35.26, the r_2 will change from the initial value to 0.172774. If the market carbon trading price climbs from 42.58 to 49.15, the r_2 will change from the initial value to 0.240835. Subsequently, the impact of the initial, reduced, and added r_2 on cooperative strategy $X_3(0,\ 1)$ is shown in Figure 5a,b. The results manifest that the convergence rates of the no-sharing and sharing cooperative probabilities selected by governments A and B severally are in direct proportion to the added r_2 and in inverse proportion to the reduced r_2, which prolongs the period of evolutionary stability.



(**a**) Strategy *x* (**b**) Strategy *y*

Figure 5. The evolutionary path of strategy $(x,\ y)$ under changed value r_2.

Keep the other initial parameters' values unchanged and analyze the sensitivity of δ. The parameter δ has double implications. For one thing, it represents the basic RPS volume completed by government A through RES power-generation replacement. For another, it serves as the incentive reference for government B gaining from the central government due to absorbing the surplus RES. The analog graph of the two aspects is consistent, so this study analyzes the latter. Figure 6a reveals that the probabilistic curve x is uniform and compact, while that of the probabilistic curve y is relatively sparse, as shown in Figure 6b. Apparently, the effect of excitation coefficient ρ on strategy x is weaker than that on strategy y, which demonstrates that the RPS policy implemented by the Chinese government has shown the initial effects of absorbing the surplus RES.



(**a**) Strategy *x* (**b**) Strategy *y*

Figure 6. The impact of ρ on evolutionary path of strategy $(x,\ y)$.

5.2.2. Sensitivity Analysis of Sharing Cooperative Parameters When Sharing Cost Is Asymmetric

Case 1. The failure cost of the opportunity gains is less than the RES power-generation cost $(\pi < c)$.

When $\pi < c$, let $\pi = 6.64$ and c remain unchanged. According to Tables 2 and 3, we deduce that $X_3(0,\ 1)$ is ESS, $X_1(0,\ 0)$, $X_4(1,\ 1)$, and $X_5(\tilde{x},\ \tilde{y})$ are saddle points, and

$X_2(1,\ 0)$ is an unstable point, as shown in Table 6. The stability of the other four equilibrium points is identical with the stability of the initial state ($\pi = c$), except that mixed strategy $X_5(\widetilde{x},\ \widetilde{y})$ is the saddle point.

Table 6. Equilibrium stability in Case 1.

Equilibrium Points	Eigenvalues		Stability
	λ_1	λ_2	
$X_1(0,\ 0)$	-0.019231	0.019231	Saddle point
$X_2(1,\ 0)$	0.019231	1.019231	Unstable point
$X_3(0,\ 1)$	-0.019231	-1.019231	*ESS*
$X_4(1,\ 1)$	1.019231	-1.019231	Saddle point
$X_5(\widetilde{x},\ \widetilde{y})$	0.019601	-0.019601	Saddle point

Keep the other initial parameters' values unchanged and analyze the sensitivity of α. When $\alpha < 0.4$, there exists a minimum marginal value (i.e., 0.4) for α; otherwise, the evolutionary trend of probability x is negative. When $\alpha > 0.4$, the evolutionary trend of strategy x converges on probability zero ahead of schedule at time $t = 2$, as shown in Figure 7, which illustrates the truth that if the failure cost of the opportunity gains is lower than the RES power-generation cost, be it for the short or long term, a rational government A will always be reluctant to take the sharing cooperative strategy. The size of α just derives the implications of government B's selection of the sharing cooperative patterns.

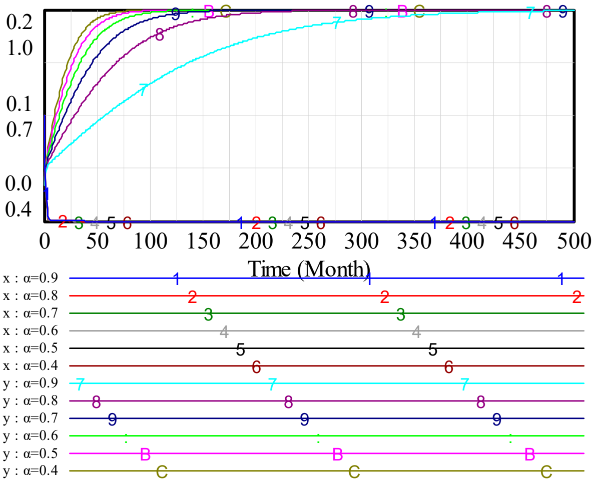
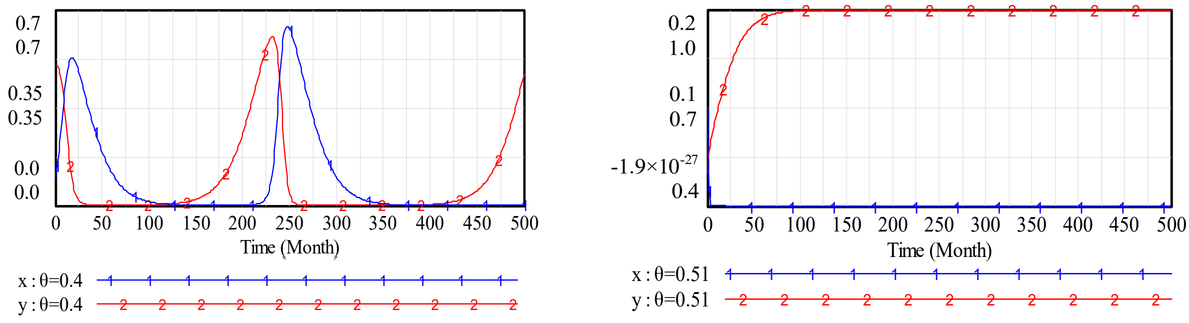


Figure 7. The evolutionary path of $X_3^{ESS}(0,\ 1)$ when $\alpha > 0.4$.

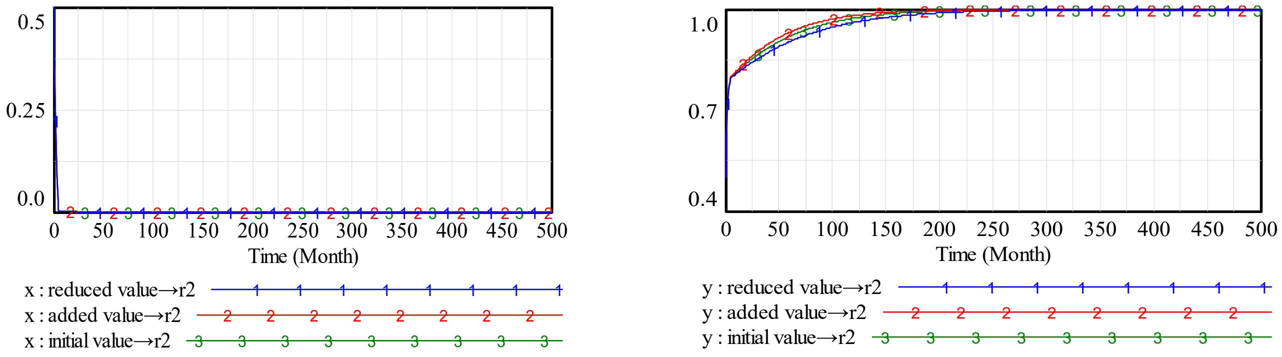
Keep the other initial parameters' values unchanged and analyze the sensitivity of θ. When $\theta = 0.4$, the choice of the governments' cooperative strategies reflects an oscillating trend with the increase in time, which is due to the fact that government B is reluctant to share 60% of the inter-region RES power-generation cost. However, by contrast, the failure cost of opportunity gains is relatively temperate. If government A shares 51% of the total cost, the evolutionary result of probability x is negative, and a rational regional government A is reluctant to establish an energy power-generation replacement cooperation. The *ESS* of $X_3(0,\ 1)$ exists in an evolutionary game system only if both sides contribute 50% of the total cost, as illustrated in Figure 8a,b.



(**a**) $\theta = 0.4$ (**b**) $\theta = 0.51$

Figure 8. The evolutionary path of strategy $(x,\ y)$ for different θ values.

Keep the other initial parameters' values unchanged and analyze the sensitivity of r_2. According to the sensitivity analysis of r_2 under the symmetric sharing cost, the value and analysis of parameter r_2 here are consistent with the previous ones in Section 5.2.1. Figure 9a,b show the impact of the change in r_2 on the cooperative strategies of both parties. The results in Figures 7 and 9a signify that government A selects the same strategies, and the change of environmental value r_2 has a mild positive impact on government A's selection of the sharing cooperative strategy. Analogously, excitation coefficient ρ has a feeble positive effect on government B's selection of the sharing cooperative strategy, as shown in Figure 10.



(**a**) Strategy x (**b**) Strategy y

Figure 9. The evolutionary path of strategy $(x,\ y)$ under changed value r_2.

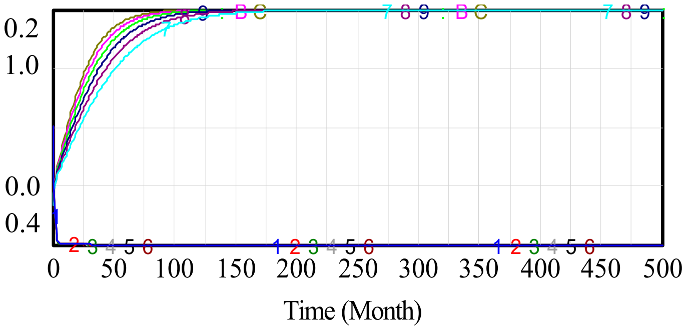


Figure 10. The impact of ρ on evolutionary path on strategy $(x,\ y)$.

Case 2. The failure cost of the opportunity gains is far more than the RES power-generation cost ($\pi > c$).

When $\pi > c$, let $\pi = 6.64$ and c remain unchanged. According to Tables 2 and 3, we deduce that $X_1(0,\ 0)$, $X_2(1,\ 0)$, $X_3(0,\ 1)$, $X_4(1,\ 1)$, and $X_5(\widetilde{x},\ \widetilde{y})$ are all saddle points. Thus, it can be seen that there is no ESS in the SD evolutionary system (I) in the asymmetric case of $\pi > c$, as shown in Table 7 and Figure 11.

Table 7. Equilibrium stability in Case 2.

Equilibrium Points	Eigenvalues		Stability
	λ_1	λ_2	
$X_1(0,\ 0)$	−0.019231	0.019231	Saddle point
$X_2(1,\ 0)$	0.019231	−0.480769	Saddle point
$X_3(0,\ 1)$	−0.019231	0.480769	Saddle point
$X_4(1,\ 1)$	−0.480769	0.480769	Saddle point
$X_5(\widetilde{x},\ \widetilde{y})$	0.018491	−0.018491	Saddle point

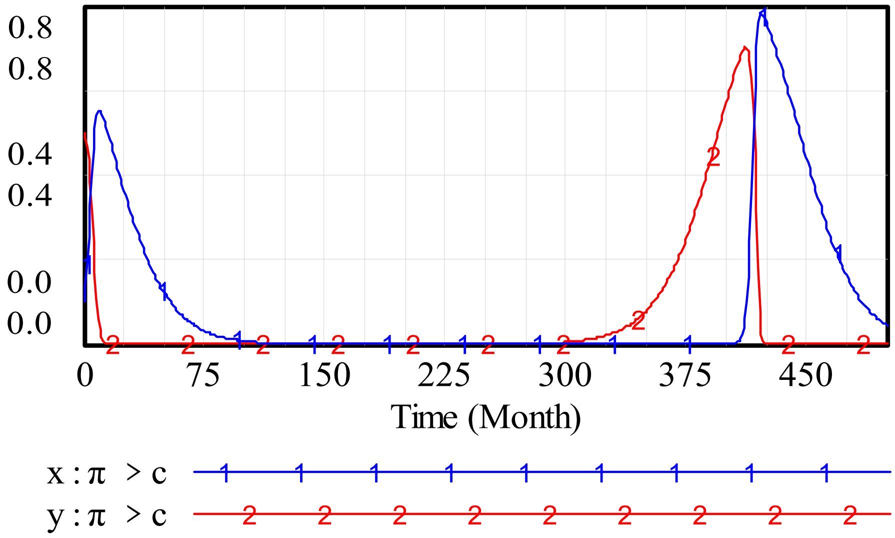


Figure 11. The equilibrium point $(x,\ y)$ is the saddle evolutionary trend when $\pi > c$.

As a result, aiming at the deficiencies of the static determination of the allocation proportion of α and θ, this study constructs an optimized and improved dynamic proportional allocation schema of revenue and cost sharing. Among others, (i) the expression of dynamic revenue sharing proportional allocation can be structured as $\alpha = 1 - y\delta r_2$, which is determined by the product of the probability y and environmental value δr_2. The basis for optimization lies in the fact that the simulation results in Figures 6a, 9a, and 10 do not significantly denote the indicator that the completion of the RPS quota's volume and environmental value enhance the selection of government A's sharing cooperative pattern. (ii) And the expression of the dynamic cost sharing proportional allocation can be arranged as $\theta = x/(\pi - c - \delta)$. The structure is the ratio of probability x to the difference among the opportunity gains' loss, RES power-generation cost, and the completion of the RPS quota's volume.

Therefore, the optimized SD evolutionary game model of cooperative strategies between regional governments A and B under the dynamic proportional allocation schema is shown in Figure 12, where the causal relationship represented by the dotted line in purple rests with the aforementioned expression of the dynamic proportional allocation.

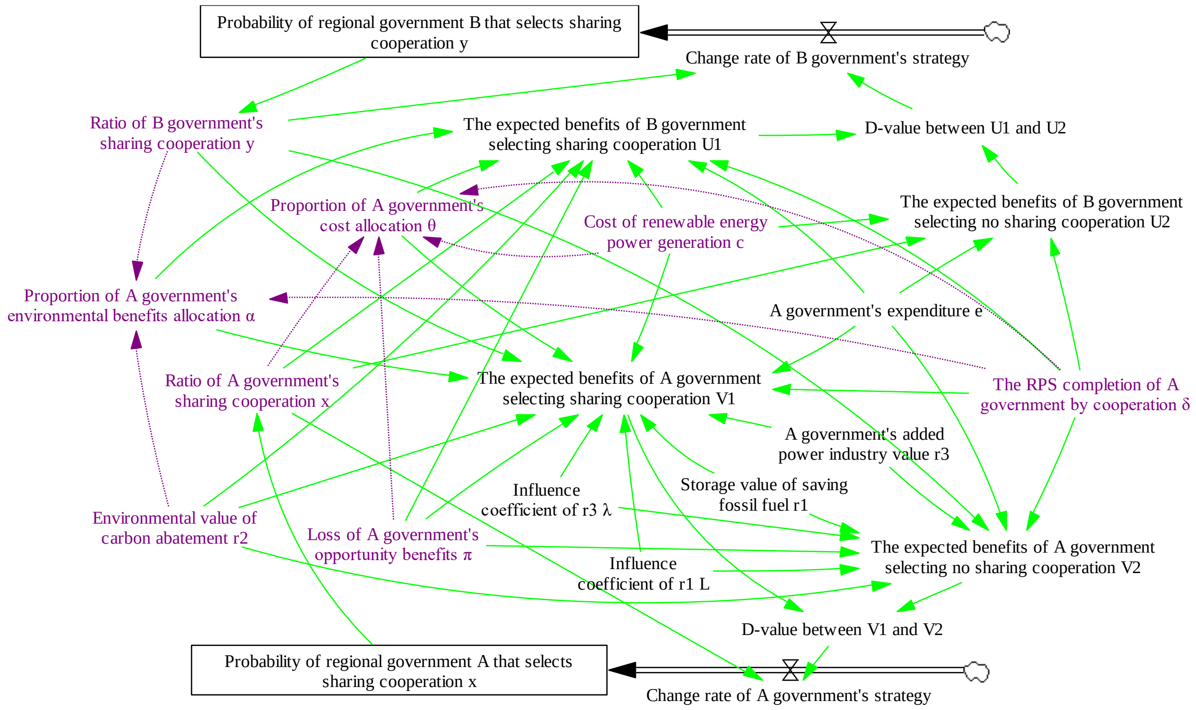


Figure 12. The optimized SD evolutionary game model under dynamic proportional allocation schema.

Under the circumstances of the dynamic proportional allocation schema, keep the conditions of parameters in Case 2 unchanged and let the initial probability value satisfy $(x,\ y) \to (0.1,\ 0.5)$. Then, the simulation result of the optimization and improvement is shown in Figure 13. There exists a mixed strategy equilibrium $(x^*,\ y^*)$ in the optimal dynamic evolutionary process, which converges to stable probability interval $(0.43,\ 0.32)$, approximately. Therefore, it can be inferred that $(0.43,\ 0.32)$ is the equilibrium point of the evolutionary strategy's stability. And the theoretical proof has been provided in the Appendix A. What's more, although *ESS* exists in the SD evolutionary game model under the dynamic proportional allocation schema, the mixed strategy $(x^*,\ y^*)$ evolves from the *ESS* equilibrium point $(0.43,\ 0.32)$ to $(1,\ 0)$ with the increase in the asymmetric cost gap, as shown in Figure 14. The optimized results imply that government A is more willing to select the sharing cooperative pattern, which demonstrates the social value of RES in the inter-regional substitution for traditional thermal power generation.

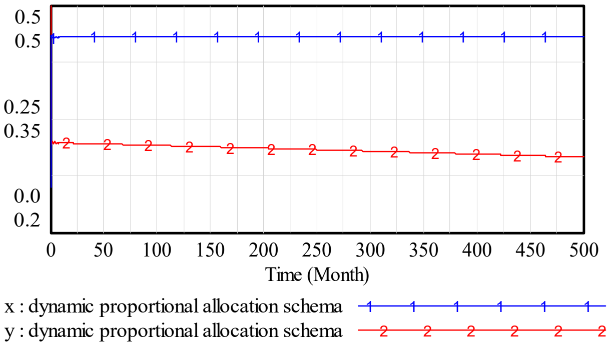


Figure 13. Evolutionary result of mixed strategy $X_5^*(x^*,\ y^*)$ under dynamic proportional allocation schema.

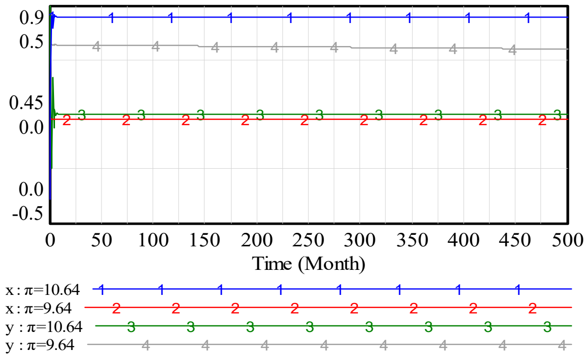


Figure 14. Evolutionary result of mixed strategy $X_5^*(x^*, y^*)$ with the increase in π value.

6. Conclusions

6.1. Research Conclusions

In view of the development status of curbing fossil-fuel energy consumption to relieve carbon emissions and completely improving the consumption capacity of the RES market in China currently, combined with the disparity of energy endowment in western China, this article explores the establishment of inter-regional power-generation substitution cooperation, which is dominated by traditional thermal power and RES power generation and has a real and academic significance. By taking the regional government as the decision-making subject, an SD evolutionary game model of inter-regional energy power-generation replacement cooperation between traditional thermal power and RES is structured. The influences of the sensitive parameters of sharing cooperation on the evolutionary path of cooperative strategies under symmetric and asymmetric sharing cost cases have been discussed, based on the actual example of "WFERYG". And an optimized dynamic proportional allocation schema of revenue and cost sharing is presented for the asymmetric situation where the failure cost is higher than the generation cost. Some noticeable conclusions in this study can be drawn as follows.

In trans-regional energy cooperation, the relationship between the opportunity income lost by region A and the RES power-generation cost in region B determines their choice of cooperation pattern. If the opportunity gains' loss is less than or equal to the RES-generation cost, region A will always select the no-sharing cooperative pattern, which means that it is willing to bear its own opportunity benefit loss in exchange for energy replacement. Region B always selects the sharing cooperation pattern. The reason why region B bears the expensive power-generation cost is that the RES power replacement can obtain some RPS incentive subsidies from the central government, which is a premise of this study.

According to the parameter data, the environmental benefits ($\alpha\delta r_2 \approx 0.01923$) earned by region A via an RES replacement amount to complete the RPS index cannot even fully compensate for the opportunity benefits' loss ($\pi = 6.64$) or the expense for an RES alternative ($e = 6.7824$). This is the reason why region A wants to share the environmental benefits and bear the opportunity gains' loss. As the simulation result shows, singularly increasing or decreasing the proportion of the environmental benefits' distribution does not determine region A's selection of the sharing cooperative pattern; that is, the environmental benefits caused by power-generation replacement are not the primary factor determining the implementation of inter-regional energy cooperation in region A, but the RES replacement volume may be one of the important ways for region A to complete the overall RPS target. Moreover, RES power-generation replacement plays a more significant role in promoting the economic development of region A ($r_3 = 47.87224$), which fully covers the expense for an RES power alternative in region A. The RPS incentive subsidy ($\rho e \approx 1.9385$) received by region B is also rather small compared to the RES power-generation cost, not fully covering the total power-generation cost (8.64). However, almost all the simulation results show that energy cooperation has a positive social impact on region B.

For the situation where the opportunity gains' loss is higher than the RES power-generation cost, dynamic benefit distribution is a pivotal path to promote region A to take the initiative to carry out cooperative pattern of benefits and cost sharing. Especially with an increase in the opportunity gains' loss or a decrease in the RES power-generation cost, this can encourage region A to share the cost of energy cooperation and strengthen its cooperative willingness.

6.2. Limitations and Suggestions

The implementation of the RPS policy in China can promote an RES region's willingness to participate in inter-regional energy cooperation. In this study, although a higher RES power-generation cost is generated in the process of inter-regional energy power-generation replacement, the partial rewards an RES region receives from the RPS policy can make up for the corresponding power-generation cost loss, to a certain extent. On the other hand, the replacement volume of RES power generation can also be regarded as the local RPS overall indicator plan completed by a traditional thermal power energy region, which is beneficial to both regions, in a certain sense. This is also in line with relying on vigorous policies to promote the rapid development of renewable energy sources in China.

However, if the predominant role of regional governments in trans-regional energy cooperation is ignored, and an immature market mechanism is the existing basis for cooperation, can they still realize the possibility of free trade in energy across regions? At least, the sign of this research indirectly manifests that a traditional thermal power energy region does not show very high enthusiasm or initiative in trans-regional energy cooperation. What's more, this paper builds an optimization path that makes an SD evolutionary game model have a mixed equilibrium strategy, which is not necessarily the best but at least can increase the possibility of region A choosing sharing cooperation. However, how to continue to promote region A to actively participate in energy cooperation through specific measures is not discussed in detail in this study. These are the shortcomings of the present analysis in this study. Future studies need to focus on the latter phenomenon, which is conducive not only to further perfecting the existing RPS system in China from the marketization level but also to building the potential market mechanism to accelerate the development of renewable energy sources, to realize the market allocation of regional resources.

In addition, the result also indicates that the cooperative motivation of a traditional thermal power region mainly depends on economic factors and RPS system factors, instead of environmental factors. Among them, the RPS system is the institutional factor by which local governments obey the national allocation of the RES weight, the compulsion of RPS is the external driving force to promote traditional thermal power region cooperation and complete the task of the national quotas in China, which can indeed be a sound suggestion. It is also necessary to coordinate the equilibrium relationship among energy, the environment, and the economy, which is critical to promote the development of regional RES from the government to a market-trading process. This research will be carried out as the next step.

Author Contributions: B.S. and T.J. were responsible for the construction of the research ideas and writing the first draft; Z.B. was responsible for the revision of the content and language. All authors have read and agreed to the published version of the manuscript.

Funding: This work presented in this article has been financially supported by the National Social Science Fund of China (Grant No. 22CJY026).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The datasets analyzed during this study are available form our practical energy field survey.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

By analyzing the sensitivity of the sharing cooperative parameters under the condition of the asymmetric sharing cost (i.e., $\pi > c$), we find that all local equilibrium points in the game system (I) are saddle points. In the absence of *ESS* in system (I), a dynamic proportional allocation schema for revenue sharing and cost sharing has been proposed in this article. And the blended strategy $X_5(\widetilde{x},\ \widetilde{y})$ converges stably to the equilibrium point $(0.43,\ 0.32)$. In doing so, we will verify $X_5(\widetilde{x},\ \widetilde{y})$ is the only *ESS* in the optimized SD evolutionary game model.

First of all, by putting $\alpha = 1 - y\delta r_2$ and $\theta = x/(\pi - c - \delta)$ into Equation (A1), we can obtain evolutionary game system (II), as shown in Equation (A1):

$$\begin{cases} \dot{x} = x(1-x)\{[y(\pi - \frac{x(\pi+c)}{(\pi-c-\delta)}) - y\delta^2 r_2^2]\} \\ \dot{y} = y(1-y)\left[y\delta^2 r_2^2 + xc - \frac{(\pi-c-\delta)(\pi+c)x - x^2(\pi+c)}{(\pi-c-\delta)}\right] \end{cases} \tag{A1}$$

Substitute the initial values of different variables into Equation (A1), respectively, and simplify the formula, and then the exact replicated dynamic Equations (II) under the dynamic proportional allocation schema can be calculated as follows:

$$\begin{cases} M(x,y) = \dot{x} = x(1-x)(9.638521y - 22.4113xy) \\ N(x,y) = \dot{y} = y(1-y)(0.001479y - 9.64x - 22.4113x^2) \end{cases} \tag{A2}$$

Suppose $\Gamma = (M(x,y),\ N(x,y))^T = 0$ and meets $0 \le x \le 1$ and $0 \le y \le 1$. Then, all the equilibrium points of the replicated dynamic equations in Equation (A2) can be gained, as shown in Table A1. However, it is also needed to count the Jacobian matrix $J(II)$ of Equation (A2) and judge whether the characteristic root of $J(II)$ is less than zero according to Friedman's theory [46]. In this case, the matrix $J(II)$ of Equation (A2) is given in Equation (A3):

$$J(II) = \begin{pmatrix} \begin{pmatrix} (1-2x)(9.638521y - 22.4113xy) \\ -22.4113xy(1-x) \end{pmatrix} & x(1-x)(9.638521 - 22.4113x) \\ y(1-y)(-9.64 - 44.8226x) & \begin{pmatrix} (1-2y)(0.001479y - 9.64x - 22.4113x^2) \\ +0.001479y(1-x) \end{pmatrix} \end{pmatrix} \tag{A3}$$

In the same way, it is not difficult to observe from Table A1 that the eigenvalues of Jacobian matrix $J(X_5^*(0.43,\ 0.32))$ corresponding to the mixed equilibrium point $X_5^*(0.43,\ 0.32)$ are all negative, as applied in [47]. Therefore, the mixed equilibrium point $X_5^*(0.43,\ 0.32)$ is the *ESS*, and the mathematical proof is consistent with the simulation results $X_5(\widetilde{x},\ \widetilde{y}) \rightarrow (0.43,\ 0.32)$ of the optimized SD evolutionary game model, which demonstrates the rationality of the optimization procedure.

Table A1. Stability of equilibrium points under dynamic proportional allocation schema.

Equilibrium Points	**Eigenvalues**		**Stability**
	λ_1^*	λ_2^*	
$X_1^*(0,\ 0)$	0	0	Unstable point
$X_2^*(1,\ 0)$	0	0	Unstable point
$X_3^*(0,\ 1)$	0	9.6385	Unstable point
$X_4^*(1,\ 1)$	12.7728	32.0498	Unstable point
$X_5^*(0.43,\ 0.32)$	−1.7580	−2.9834	*ESS*

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