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Promoting the Low-Carbon Transition of Power Construction Projects under MRV: An Evolutionary Game Analysis

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Abstract: The actual situation of carbon-emission reduction in China's power sector has not yet achieved the expected benefits. The rent-seeking behavior of participants in power construction projects (PCPs) hinders the realization of low-carbon benefits. It is necessary to explore the behavioral strategies of the various participants in the low-carbon transition of PCPs. This paper creatively constructs an evolutionary game model of PCPs' participants from the perspective of MRV (monitoring, reporting, and verification) and introduces the influence of the public to provide a comprehensive analysis of strategic equilibrium points. Through numerical simulations with MATLAB R2021a software, this paper explores the strategic choices of participants in different situations and gives relevant inferences and proofs. The results show that the grid company dominates at the initial stage and promotes participants to regulate behaviors. Under the premise of satisfying the system-stability requirements, setting the growth rate of the grid company's punishments to 100% can enhance the willingness for strict supervision, while the growth rate of the supervision costs to 200% significantly decreases the probability of strict supervision. With the integration of MRV and PCPs, participants spontaneously fulfill the carbon-emission-reduction tasks. Reasonable control of input costs can effectively avoid the occurrence of rent-seeking behavior. In addition, this paper sets the public-influence growth rate at 200% and finds that the public plays a greater role in driving participants to fulfill responsibilities. Based on the results, a low-carbon transition mechanism for PCPs under the MRV system is proposed by considering several dimensions, which provides suggestions for participants to fulfill carbon-reduction responsibilities.

Keywords: power construction projects; low-carbon transition; MRV; evolutionary game theory

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Citation: Li, L.; Zhu, R.; Song, K.; Zhang, O.; Jiang, X. Promoting the Low-Carbon Transition of Power Construction Projects under MRV: An Evolutionary Game Analysis. *Buildings* **2023**, *13*, 2874. https://doi.org/10.3390/buildings13112874

Academic Editor: Irem Dikmen

Received: 27 October 2023
Revised: 10 November 2023
Accepted: 14 November 2023
Published: 16 November 2023

1. Introduction

The power sector has been playing a non-negligible role in global climate change. Global carbon emission from the power sector amounted to as much as 13 billion tons, accounting for 38% of the total carbon emissions related to energy consumption, and in recent years there is still a growing trend [1,2]. With the acceleration of China's industrialization and urbanization, the power sector is developing rapidly, and the number of power construction projects (PCPs) is increasing dramatically [3,4]. China's power sector accounts for about 41% of the country's total carbon emissions and about 32% of the world's total carbon emissions [5]. In response to the dilemma, China is actively seeking low-carbon solutions. In the same way, it has also aroused heated discussions in the academic community, and most scholars are researching the low-carbon development of the power sector from the perspective of energy consumption, such as through wind power generation, photovoltaic power generation, etc. [6,7]. While these measures reduce the dependence of the power sector on fossil fuels, the practical application costs are large [8,9]. Some scholars have also addressed the problem by introducing carbon-neutral technologies, such as carbon capture and storage, which prevent the release of greenhouse gases into the atmosphere [10,11].

It is worth noting that, in recent years, the studies related to carbon emissions in various fields have shown that carbon-emission reduction not only depends on energy structure or technical support but also needs to be driven by the economic market and social policies [12]. However, there are fewer studies that integrate the behavioral strategies of the relevant participants with the low-carbon development of PCPs as the entry point for problem-solving. In addition, China's resource endowment determines that the types of (PCPs) are still dominated by traditional coal-fired power generation projects [13]. Based on the MRV (Monitoring, Reporting, Verification) system, the implementation of carbon verification is an effective way to promote the low-carbon development of PCPs, which has attracted wide attention from all circles at home and abroad [14,15].

Low-carbon transition of PCPs in China is a landmark step in the process of realizing carbon peak and carbon neutrality in the power sector, and carbon verification of PCPs based on the MRV system is the basis for the integration of the power sector into the carbon market [5,16]. However, the current low-carbon development of PCPs under China's MRV system still faces many problems [14]. Firstly, from the perspective of carbon monitoring and reporting, PCPs are characterized by large spans and long construction periods, as well as complexity and uncertainty of geographic location, which make it difficult to measure carbon-emission data related to PCPs and ensure the accuracy of carbon-emission monitoring and reporting [17]. Unlike ordinary construction projects, PCPs are mainly transmission and substation projects, and it is difficult to determine the relevant factors influencing the participants' fulfillment of the carbon-emission-reduction tasks, which also lead to a lack of reference for the participants in the process of formulating low-carbon development programs. Secondly, the implementation of low-carbon transition programs will undoubtedly lead to higher input costs in the short term and the benefits may not be obvious. Rent-seeking behaviors between carbon-emission third-party-verification agencies and construction units often occur under the drive of benefits, resulting in construction units that do not meet carbon-emission standards passing the inspection, generating more carbon emissions, and losing more resources in the long run. In addition, in the era of increasingly developed information networks, the public's assessment of the influence of the public has gradually increased. The generation of rent-seeking behaviors on the carbon verification work has caused a greater negative impact and seriously hindered the low-carbon transformation of PCPs under the MRV system. Although power grid companies have implemented management measures for participants' refusal and slacking of carbon-reduction responsibilities, the strength and methods of specific measures in the implementation process are still unclear [18]. It can be found that the promotion of the MRV system faces great challenges due to various uncertainties, resulting in unfavorable low-carbon development of PCPs. Therefore, it is necessary to comprehensively consider the behavioral strategies of participants under the MRV system in different situations and propose a more effective mechanism for the low-carbon transition of PCPs.

Based on the above analysis, this paper proposes the following research questions:

1. What are the factors that influence the behavioral strategies of each participant of PCPs under the MRV system, and what are the relationships among the participants as the evolutionary game system tends to stabilize?
2. In the process of low-carbon transition of PCPs under the MRV system, how can we ensure that the core benefits are not damaged while promoting participants to actively fulfill their responsibilities of carbon-emission reduction?
3. What is the low-carbon transition mechanism for PCPs under the MRV system, and what are its internal components?

In order to solve the above questions, this paper analyzes the behavioral-strategy choices of the grid company, construction units, and carbon-emission third-party-verification agencies in different situations, under the influence of public participation, and with the help of evolutionary game theory. Subsequently, the stability analysis of pure and mixed strategy equilibrium points of the replicated dynamic system is carried out, and the evolutionary stable strategy combinations under different conditions are deduced. Finally, numerical simulation using MATLAB R2021a software is carried out to analyze the influence of different parameters on the evolution of the system and verify the validity of the method. The main contributions of the paper are as follows:

1. This paper reveals the roles of participants in PCPs under the MRV system, describing the interaction mechanism among the participants.
2. The paper explores the changes in the behavioral strategies of each participant under different circumstances, confirming the influence of the main parameters.
3. This paper proposes a low-carbon transition mechanism for PCPs under the MRV system, which provides scientific and reasonable suggestions for participants to avoid the emergence of rent-seeking behavior.

2. Literature Review

2.1. The Low-Carbon Benefits of the MRV

The MRV system, derived from the Bali Action Plan agreed at the 13th Conference of the Parties to the United Nations Framework Convention on Climate Change (UNFCCC) in 2007, for developed countries to support developing country's parties in enhancing national action on the mitigation of climate change [19]. After the signing of the Kyoto Protocol, the MRV system, as a necessary means to achieve energy saving and emission reduction targets, has received widespread attention from countries around the world, leading to the further development of the MRV system [20].

In terms of how MRV systems contribute to low-carbon benefits, Smith et al. pointed out that a complete MRV system is the key to realizing soil carbon sequestration, and even more so to reducing the investment risk of investors [21]. Panagakos collected and calculated MRV indicators for a Danish shipping company in order to confirm the scientific validity and rationality of the MRV system introduced by the EU to reduce carbon emissions from the shipping industry [22]. Perosa et al. studied the application of the MRV system to achieve the low-carbon development of the Brazilian agricultural sector, suggesting that producers, as implementers of carbon monitoring and reporting, should be more active in the introduction of low-carbon technologies to obtain low-interest credits and economic incentives for investors [23]. Vargas et al. established a robust MRV system to improve forest management and increase carbon stocks, and the key to achieving the desired goals lies in the joint efforts of the behavioral strategies of landowners, regulators, investors, and other actors [24].

It can be found that in realizing the low-carbon benefits of projects, the MRV system mainly focuses on the active activities of the participating entities to provide accurate, consistent, and comparable data for carbon quantification of the project, and to judge the potential and space for carbon-emission reduction. Including the initiator of the carbon verification work, the regulator who receives the carbon verification work, and the implementer of carbon-emission monitoring and reporting. Therefore, it is essential to identify the key participants and their strategic choices.

2.2. The Key Participants in PCPs under the MRV

Key participants in the low-carbon transition of PCPs under the MRV system can be described as individuals, groups, or organizations that influence or are influenced by the decisions, activities, or outcomes of the project [25]. The construction units, as the subject of carbon monitoring and reporting, are often considered to have great potential to contribute to PCPs. The last link of the MRV system lies in carbon verification, where the grid company, as the leader of carbon verification, commissions the carbon third-party-verification agencies to verify the carbon-emission monitoring and reporting information submitted by construction units. In addition, the rewards and penalties of the grid company have positively driven the carbon third-party-verification agencies and the construction units [18]. Therefore, this paper identifies the construction units, carbon third-party-verification agencies, and grid company as the key participants.

The benefits of each participant in the low-carbon development of PCPs under the MRV system will have impacts on their behavioral-strategy choices. The construction units aim to maximize benefits in the progress of carbon monitoring and reporting, focusing more on the actual benefits they receive, such as incentives of the grid company, income from carbon verification, etc. [26]. The current high level of carbon monitoring and reporting programs are costly and difficult to implement, and the willingness of construction companies to do so is not strong. As a result, very few construction units emphasize and develop detailed carbon monitoring and reporting plans, and the phenomenon of low-level carbon monitoring or even neglected monitoring is more serious. Carbon third-party-verification agencies are commissioned by the grid company to verify the construction units' carbon-emission reports for profits [27]. However, it is difficult to eliminate the risk of rent seeking between the carbon third-party-verification agencies and the construction units, resulting in irregularities in verification behavior [28].

2.3. Evolutionary Game Theory

Considering the actual situation that the rationality of the construction units, grid company and carbon third-party-verification agencies in PCPs under the MRV system tends to be limited, each participant is a limited rational subject. And two important assumptions of traditional game theory lie in the fact that perfectly rational subjects and complete information will not apply to this paper [29]. Evolutionary game theory provides a mathematical foundation for the study of interactions among decision makers that not only takes into account the subject's state of limited rationality and incomplete information, but also incorporates changes in the subject's behavioral-strategy choices over time [30]. Thus, evolutionary game theory provides an effective approach for this paper.

In recent years, evolutionary game theory has been widely used to study the problem of the existence of rent-seeking behavior among the subjects of large-scale projects and their respective behavioral-strategy choices. In order to seek a low-carbon transition path in the context of carbon neutrality, Tian et al. [31] analyzed the complex relationship between producers, regulators, third-party-verification agencies, and consumers with the help of evolutionary game theory. Wang et al. [32] established a tripartite evolutionary game model of the government, the energy industry and the third-party clean-energy regulatory auditor, aiming to solve the dilemma of clean-energy-technology promotion in China and to enhance the subjects' resistance to rent-seeking behaviors. Jiang et al. [33] used evolutionary game theory to explore the interaction strategies between polluting firms, regulators, and central government planners in China and proposed redesigning incentive mechanisms to curb the impact of rent-seeking behavior. Xu et al. [34] based their approach on the tripartite evolutionary game perspective in order to analyze the rent-seeking problem between soil discharging enterprises and third-party management institutions, so as to solve the real dilemma of soil pollution. Li et al. [35] constructed a tripartite evolutionary game model of car companies, local regulators, and the central government in order to analyze the rent-seeking behaviors of car companies in the face of the gasoline-car sales-ban policy. Based on previous studies, it can be found that evolutionary game theory has a high degree of fit with the behavioral-strategy choices of inter-subjects and the solution of rent-seeking problems, but there is still a lack of knowledge in the application of evolutionary game theory to solve the practical problems of PCPs.

2.4. Research Gap

The literature review shows that scholars have studied the low-carbon benefits of MRV systems and the key participants in PCPs, providing an important theoretical foundation for this paper. However, the existing studies have the following shortcomings:

1. There is a research gap in the equilibrium state and corresponding conditions for MRV systems to realize the low-carbon benefits of PCPs, and the interactions among the behavioral strategies of key participants are unclear.

2. Existing studies have focused more on exploring the factors influencing the behavioral strategies of key participants in PCPs from the perspective of MRV, while neglecting the influence of public participation on the evolution of the whole system.
3. The use of evolutionary game theory to solve the problem of rent-seeking behavior can provide relevant suggestions for the participants. However, none of the existing studies have clearly indicated the implementation strength and scope of the relevant measures, and the effectiveness of the application cannot be guaranteed.

3. Tripartite Evolutionary Game Modeling

3.1. Application of Evolutionary Game

As the power grid company, construction units, and carbon-emission third-party-verification agencies have different benefits, and each participant cannot fully grasp the other side of the decision-making and conditions, this leads to conflict in the process of low-carbon transition of PCPs under the MRV system [25]. The evolutionary game theory provides a mathematical framework for this paper because of its unique advantage in analyzing the dynamic changes of behavioral strategies. The logical relationship diagram is shown in Figure 1, and carbon-emission monitoring, reporting, and verification are the main lines of the tripartite evolutionary game model.

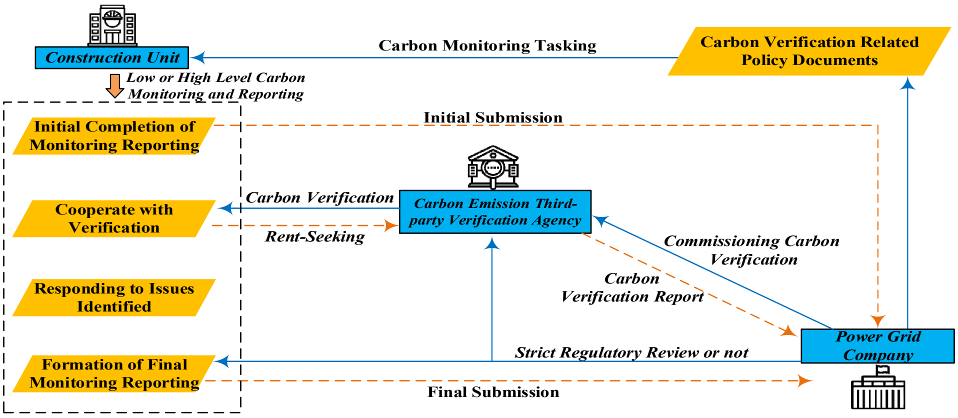


Figure 1. Tripartite evolutionary game model of PCPs under MRV system. Source: own creations.

The power grid company informs the carbon monitoring and reporting tasks by conveying the relevant policy documents of the higher regulatory authorities, and the construction unit clarifies the tasks and then initially completes the tasks and submits them. The power grid company entrusts the carbon-emission third-party-verification agency to carry out carbon verification of the construction unit. At this point, the construction unit actively cooperates with the carbon verification work and responds to the questions as required, forming the final carbon monitoring report to be submitted to the power grid company. Similarly, upon completion of the verification task, the carbon third-party-verification agency submits the carbon verification report and the results to the power grid company. In the face of the current dilemma of difficult and costly carbon monitoring for PCPs, profit-oriented construction units may adopt low-level carbon monitoring and reporting programs. In addition, driven by benefits, the carbon-emission third-party-verification agency will inevitably generate rent-seeking violations, resulting in doubts about the authenticity of the final carbon monitoring report and verification report. Based on this, the power grid company may adopt programs such as carbon review to avoid violations by other participants.

3.2. Model Assumptions

Based on the above analysis, this paper proposes the following assumptions:

Assumption 1. *The evolutionary game model includes the power grid company, construction units, and carbon-emission third-party-verification agencies. All three are limited rational participating subjects, that can make independent decisions, and their behavioral-strategy choices gradually evolve and stabilize in the optimal strategy over time.*

Assumption 2. *Construction units are primarily responsible for carbon monitoring and submitting reports. There is scope to implement high-level carbon monitoring and reporting programs and submit the report with a good level of credibility. It is also possible to have low-level carbon monitoring and reporting programs. The strategy space for construction units is* $\alpha = (\alpha_1, \alpha_2)$ = *(implementation of high-level carbon-emission monitoring and reporting programs, and implementation of low-level carbon-emission monitoring and reporting programs). The probability that the construction units will choose* α_1 *is* x $(0 \le x \le 1)$*, and the probability to choose* α_2 *is* $(1 - x)$*.*

Assumption 3. *Carbon-emission third-party-verification agencies are entrusted by the power grid company to carry out carbon verification of construction units. Carbon-emission third-party-verification agencies can either follow the regulations and standardize the verification, or may be driven by benefits to violate the verification, with the intention of rent seeking to obtain additional benefits. The strategic space for the carbon third-party-verification agencies is* $\beta = (\beta_1, \beta_2)$ = *(Standardized Verification, Irregularity Verification). The probability that carbon-emission third-party-verification agencies will choose* β_1 *is* y $(0 \le y \le 1)$*, and the probability to choose* β_2 *is* $(1 - y)$*.*

Assumption 4. *The power grid company has two behavioral-strategy choices. Strict supervision means that the power grid company will review the carbon monitoring report and verification report. Based on the results of the review, rewards and punishments can be imposed. Permissive supervision means that a carbon review will not be conducted. Due to the lack of information flow, no substantial rewards or punishments will be applied either. The strategic space for the power grid company is* $\gamma = (\gamma_1, \gamma_2)$ = *(Strict Supervision, Permissive Supervision), and chooses* γ_1 *with probability* z $(0 \le z \le 1)$ *and* γ_2 *with probability* $(1 - z)$*.*

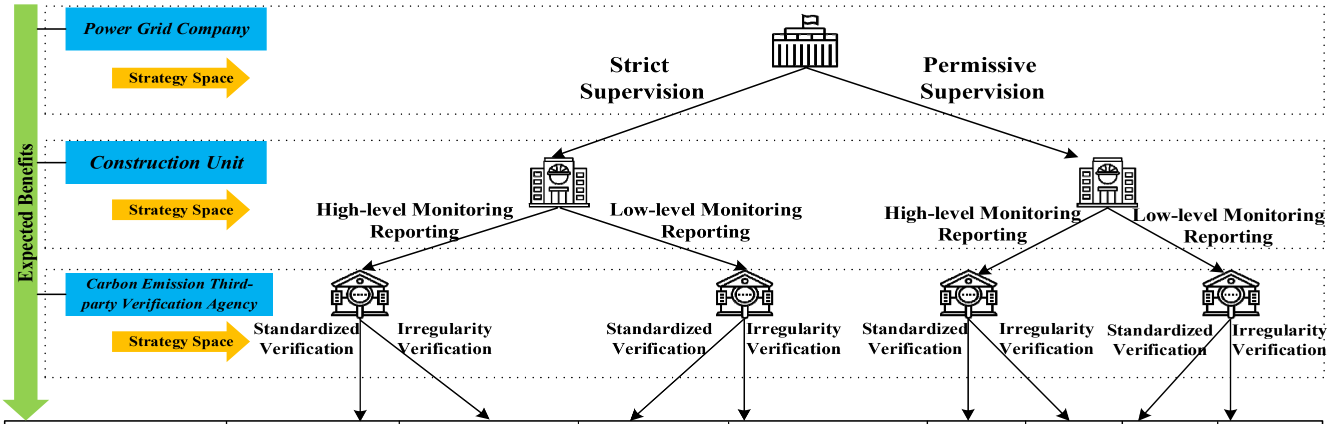
To explore the expected benefits and costs for each participant under the case of different behavioral-strategy choices, this paper is based on the literature analysis method to set the relevant parameters and descriptions as shown in Table 1.

Table 1. Descriptions of major parameters.

Parameters	Descriptions	References
I_t	Income obtained by the construction units through carbon verification.	[28,36–38]
I_v	Income from verification by carbon-emission third-party-verification agencies.	
C_h	Costs for construction units to implement high-level carbon-monitoring programs.	
C_l	Costs for construction units to implement low-level carbon-monitoring programs.	
C_r	Costs of applying for rent seeking by construction units to pass carbon verification.	
C_e	Extra costs incurred by carbon-emission third-party-verification agencies in the event of profit-driven violations in verification.	
C_S	Costs of inputs when strictly supervised by the power grid company.	
C_m	Costs of environmental governance required by the power grid company's negligent supervision, leading to substandard construction units passing verification.	
R_b	Construction units implement high-level carbon-emission monitoring and reporting programs, which are supported by the public and add value to the brand.	[17,39,40]
R_e	Construction units deliver environmental benefits to the power grid company.	
R_a	The power grid company rewards carbon-emission third-party-verification agencies for the standardized verification.	
R_c	The power grid company rewards construction units for implementing high-level carbon-emission monitoring and reporting programs.	
R_g	The power grid company receives a credibility boost from strict supervision.	
P_c	The power grid company punishes construction units for failing carbon verification.	[26,31,36]
P_a	The power grid company punishes carbon-emission third-party-verification agencies.	
L_r	Construction units' failure to meet carbon reduction leads to reputational damage.	
L_g	The grid company is being punished by higher regulators for loose supervision.	
L_c	Disclosure of irregularities in carbon-emission third-party-verification agencies leads to loss of credibility.	

Source: own creations.

Based on the above assumptions, the expected benefits of the power grid company, construction units, and carbon third-party-verification agencies under different strategy choices are presented in the decision tree, as shown in Figure 2.



Power Grid Company	$-C_s+R_g-R_c-R_a+R_e$	$-C_g+R_g-R_c+P_a+R_e$	$-C_s+R_g+P_c$-R_a	$-C_s+R_g+P_c+P_a-C_m$	R_e	R_e	0	$-C_m-L_g$
Construction Unit	$I_t-C_h+R_b+R_c$	$I_t-C_h+R_b+R_c$	$-C_l-C_r-L_r-P_c$	$-C_l-C_r-L_r-P_c+I_t$	$I_t-C_h+R_b$	$I_t-C_h+R_b$	$-C_l-C_r$	$I_t-C_l-C_r$
Carbon Emissions Third-party Verification Agency	I_v+R_a	$I_v-L_c-P_a-C_e$	I_v+R_a	$I_v+C_r-C_e-L_c-P_a$	I_v	I_v-C_e	I_v	$I_v-C_e+C_r$

Figure 2. Decision tree of the power grid company, construction unit, and carbon third-party-verification agency. Source: own creations.

3.3. Model Establishment

3.3.1. The Strategy Stability Analysis for Construction Units

Based on Figure 2, this paper calculates the expected benefits of the construction units choosing high- or low-carbon monitoring and reporting programs, denoted respectively as E_x and E_{1-x}. The average expected benefits are denoted as $\overline{E_x}$.

$$E_x = yz(I_t - C_h + R_b + R_c) + y(1-z)(I_t - C_h + R_b) + (1-y)z(I_t - C_h + R_b + R_c) + (1-y)(1-z)(I_t - C_h + R_b) = zR_p + I_t - C_h + R_b \tag{1}$$

$$\begin{aligned} E_{1-x} = {} & yz(-Cl - Cr - Lr - Pc) + y(1-z)(-Cl - Cr) + (1-y)z(It - Cl - Cr - Lr - Pc) + (1-y)(1-z)(It - Cl - Cr) \\ & = -yIt + z(-Lr - Pc) + It - Cl - Cr \end{aligned} \tag{2}$$

$$\overline{E_x} = xE_x + (1-x)E_{1-x} \tag{3}$$

According to Equations (1)–(3), the replicator dynamic equation for the construction units choosing high-level carbon monitoring and reporting programs can be obtained, denoted as $F(x)$.

$$F(x) = \frac{dx}{dt} = x(E_x - \overline{E_x}) = x(1-x)(yI_t + z(L_r + P_c + R_c) + C_l + C_r + R_b - C_h) \tag{4}$$

This paper proposes Inference 1 and Inference 2 for the strategy stability of the construction units implementing high-level carbon monitoring and reporting programs, and Proof 1 and Proof 2 are presented in Appendix A.

Inference 1. The probability of the construction units implementing high-level carbon monitoring and reporting programs is positively correlated with the income received through verification, the degree of public acceptance, the costs of low-level carbon monitoring and reporting programs, the costs of rent seeking, the loss of reputation caused by the adoption of low-level carbon-monitoring programs, and the degree of the power grid company rewards and punishments. Conversely, it is negatively related to the costs of implementing high-level carbon-monitoring programs.

Inference 2. As the probability of the power grid company implementing strict supervision increases or the probability of the carbon third-party-verification agencies rejecting rent seeking increases, the probability of construction units adopting high-level carbon monitoring and reporting programs will increase.

3.3.2. The Strategy Stability Analysis for Carbon-Emission Third-Party-Verification Agencies

Based on Figure 2, this paper calculates the expected benefits of the carbon-emission third-party-verification agencies for standardized or irregularity verification, denoted respectively as E_y and E_{1-y}. The average expected benefits are denoted as $\overline{E_y}$.

$$E_y = xz(I_v + R_a) + x(1 - z)I_v + (1 - x)z(I_v + R_a) + (1 - x)(1 - z)I_v = zR_a + I_v \tag{5}$$

$$\begin{aligned} E_{1-y} &= xz(I_v - L_c - P_a - C_e) + x(1 - z)(I_v - C_e) + (1 - x)z(I_v + C_r - L_c - P_a - C_e) + (1 - z)(1 - x)(I_v + C_r - C_e) \\ &= -xC_r + z(-L_c - P_a) + I_v + C_r - C_e \end{aligned} \tag{6}$$

$$\overline{E_y} = yE_y + (1 - y)E_{1-y} \tag{7}$$

Based on the above Equations (5)–(7), the replicator dynamic equation for the carbon third-party-verification agencies choosing standardized verification can be obtained, denoted as $F(y)$.

$$F(y) = \frac{dy}{dt} = y(E_y - \overline{E_y}) = y(1 - y)[xC_r + z(R_a + L_c + P_a) + C_e - C_r)] \tag{8}$$

This paper proposes Inference 3 and Inference 4 for the strategy stability of the carbon-emission third-party-verification agencies implementing standardized verification, and Proof 3 and Proof 4 are presented in Appendix B.

Inference 3. The probability that the carbon-emission third-party-verification agencies standardizing verification is positively correlated with the income gained from intentional rent seeking, the degree of rewards and punishments from the power grid company, and the degree of public distrust caused by the disclosure of verification violations. Conversely, the probability is negatively related to extra costs of intentional rent seeking.

Inference 4. As the probability of the power grid company implementing strict supervision increases or the probability of the construction units adopting high-level carbon monitoring and reporting programs increases, the probability of the carbon-emission third-party-verification agencies standardizing verification will increase.

3.3.3. The Strategy Stability Analysis for the Power Grid Company

Based on Figure 2, this paper calculates the expected benefits of the power grid company for strict or permissive supervision, denoted respectively as E_z and E_{1-z}. The average expected benefits are denoted as $\overline{E_z}$.

$$\begin{aligned} E_z = {} & xy(-C_s - R_c - R_a + R_g + R_e) + x(1 - y)(-C_s - R_c + R_g + P_a + R_e) \\ & + (1 - x)y(-C_s - R_a + R_g + P_c) + (1 - x)(1 - y)(-C_s - C_m + R_g + P_c + P_a) \\ = {} & -xyC_m + y(-R_c - P_c + R_e + C_m) + y(-R_a - P_a + C_m) - C_s + R_g + P_c + P_a - C_m \end{aligned} \tag{9}$$

$$E_{1-z} = xyR_e + x(1 - y)R_e + (1 - x)(1 - y)(-C_m - L_g) = x(R_e + C_m + L_g) + y(C_m + L_g) - xy(C_m + L_g) - C_m - L_g \tag{10}$$

$$\overline{E_z} = zE_z + (1 - z)E_{1-z} \tag{11}$$

Based on the above Equations (9)–(11), the replicator dynamic equation for the power grid company choosing strict supervision can be obtained, denoted as $F(z)$.

$$F(z) = \frac{dz}{dt} = z(E_z - \overline{E_z}) = z(1 - z)[xyL_g + x(-R_c - P_c - L_g) + y(-R_a - P_a - L_g) - C_s + R_g + P_c + P_a + L_g] \tag{12}$$

This paper proposes Inference 5 and Inference 6 for the strategy stability of the power grid company implementing strict supervision, and Proof 5 and Proof 6 are presented in Appendix C.

Inference 5. The probability that the power grid company choosing the strict regulation is positively related to the degree of public acceptance, the degree of punishments by the higher supervisory authority, and the punishments imposed on construction units and carbon third-party-verification agencies, and negatively related to the rewards imposed on both. In addition, the probability is negatively related to the costs of regulation.

Inference 6. As the probability of the construction units implementing high-level carbon monitoring and reporting programs increases or the probability of standardized verification by the carbon-emission third-party-verification agencies increases, the probability of the power grid company imposing strict supervision decreases.

Based on the above analysis, this paper combines Equations (4), (8) and (12) to construct a tripartite evolutionary game system as follows:

$$\begin{cases} F(x) = \frac{dx}{dt} = x(E_x - \overline{E_x}) = x(1 - x)\left(yI_t + z(L_r + P_c + R_c) + C_l + C_r + R_b - C_h\right) \\ F(y) = \frac{dy}{dt} = y(E_y - \overline{E_y}) = y(1 - y)[xC_r + z(R_a + L_c + P_a) + C_e - C_r)] \\ F(z) = \frac{dz}{dt} = z(E_z - \overline{E_z}) = z(1 - z)[xyL_g + x(-R_c - P_c - L_g) + y(-R_a - P_a - L_g) - C_s + R_g + P_c + P_a + L_g] \end{cases} \tag{13}$$

The eight pure strategy equilibrium points of the system can be obtained based on $F(x) = 0$, $F(y) = 0$, and $F(z) = 0$: $e_1(0,0,0)$, $e_2(0,0,1)$, $e_3(0,1,0)$, $e_4(1,0,0)$, $e_5(0,1,1)$, $e_6(1,0,1)$, $\mathrm{e}_7(1,1,0)$, $\mathrm{e}_8(1,1,1)$, and some mixed strategy equilibrium points $\mathrm{e}^*(\mathrm{x}^*,\mathrm{y}^*,\mathrm{z}^*)$, where x^*, y^*, $\mathrm{z}^* \in [0, 1]$. Therefore, $e_9((C_r - C_e)/C_r, (C_h - C_l - C_r - R_b)/I_t, 0)$, $e_{10}((-C_s + R_g + P_c + P_a + L_g)/(R_c + P_c + L_g), 0, (C_h - C_l - C_r - R_b)/L_r + P_c + R_c)$, $e_{11}(0, (R_g + P_c + P_a + L_g - C_s)/(R_a + P_a + L_g), (C_r - C_e)/(L_c + P_a + R_a))$, $e_{12}((C_r - C_e - L_c - P_a - R_a)/C_r, (C_h - C_l - C_r - R_b - L_r - R_c - P_c)/I_t, 1)$.

3.4. Analysis of Evolutionarily Stable Strategy

In this paper, the asymptotic stability of the equilibrium points is verified by analyzing the eigenvalues of the Jacobian matrix of the tripartite evolutionary game system according to Lyapunov's first method [41]. The rules are as follows: (1) When all eigenvalues $\lambda < 0$ of the Jacobian matrix, the equilibrium point is an ESS (Evolutionarily Stable Strategy). (2) When the Jacobian matrix has at least one positive eigenvalue, the equilibrium point is unstable.

$$\mathrm{J} = \begin{bmatrix} \frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} & \frac{\partial F(x)}{\partial z} \\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} & \frac{\partial F(y)}{\partial z} \\ \frac{\partial F(z)}{\partial x} & \frac{\partial F(z)}{\partial y} & \frac{\partial F(z)}{\partial z} \end{bmatrix} = \begin{bmatrix} J_{11} & J_{12} & J_{13} \\ J_{21} & J_{22} & J_{23} \\ J_{31} & J_{32} & J_{33} \end{bmatrix}$$

$J_{11} = (2x - 1)[-yI_\mathrm{t} - z(L_\mathrm{r} + P_\mathrm{c} + R_\mathrm{c}) - \mathrm{C_l} - \mathrm{C_r} - R_\mathrm{b} + \mathrm{C_h}]$, $J_{12} = x(1 - x)I_\mathrm{t}$, $J_{13} = x(1 - x)(L_\mathrm{r} + P_\mathrm{c} + R_\mathrm{c})$, $J_{21} = y(1 - y)\mathrm{C_r}$, $J_{22} = (2y - 1)[-x\mathrm{C_r} - z(R_\mathrm{a} + L_\mathrm{c} + P_\mathrm{a}) + \mathrm{C_r} - \mathrm{C_e}]$, $J_{23} = y(1 - y)(L_\mathrm{c} + P_\mathrm{a} + R_\mathrm{a})$, $J_{31} = z(1 - z)(yL_\mathrm{g} - R_\mathrm{c} - \mathrm{P_c} - L_\mathrm{g})$, $J_{32} = z(1 - z)(xL_\mathrm{g} - R_\mathrm{a} - P_\mathrm{a} - L_\mathrm{g})$, $J_{33} = (2z - 1)[-xyL_\mathrm{g} + x(R_\mathrm{c} + P_\mathrm{c} + L_\mathrm{g}) + y(R_\mathrm{a} + P_\mathrm{a} + L_\mathrm{g}) + \mathrm{C_s} - R_\mathrm{g} - P_\mathrm{c} - P_\mathrm{a} - L_\mathrm{g}]$. The eigenvalues of equilibrium points of each strategy and ESS condition are found as shown in Table 2.

Inference 7 . When $C_e - C_r + L_c + P_a + R_a < 0$ and $C_l - C_h + C_r + L_r + P_c + R_b + R_c < 0$, there are two equilibrium points e_2, e_7. At this time, the power grid company's rewards and punishments for construction units and carbon third-party-verification agencies are weak, and both are less affected by the public and the benefits of violation of the verification are higher. The evolution of the system tends to be (0, 0, 1), and (1, 1, 0).

Proof 7 is presented in Appendix D.

Inference 8. When $R_c + P_c > C_h - C_l - C_r - L_r - R_b > 0$, $R_a + P_a > C_r - C_e - L_c > 0$, and $P_a - R_c + R_g > C_s$, $P_c - R_a + R_g > C_s$, the system exists as only one ESS of e_7. At this time, the degree of effect of the power grid company on the rewards and punishments for construction units and carbon third-party-verification agencies is greater than the gains of both intentions to rent seeking, which can effectively avoid the emergence of the mixed strategy equilibrium points.

Proof 8 is presented in Appendix D.

Table 2. Eigenvalues and stability conditions for each equilibrium point.

Equilibrium Points	Eigenvalues λ_1 λ_2 λ_3	State		Conditions
$e_1(0, 0, 0)$	$C_e - C_r, C_l + C_r + R_b - C_h, L_g + P_a + P_c + R_g + C_s$	(−,−,+)	\	Unstable
$e_2(0, 0, 1)$	$C_e + L_c + P_a + R_a - C_r, C_s - L_g - P_a - P_c - R_g, C_l + C_r + L_r + P_c + R_b + R_c - C_h$	(−,−,−)	a	ESS
$e_3(0, 1, 0)$	$C_r - C_e, P_c + R_g - C_s - R_a, C_l + C_r + I_t + R_b - C_h$	(+,×,+)	\	Unstable
$e_4(1, 0, 0)$	$C_e, P_a + R_g - C_s - R_c, C_h - C_l - C_r - R_b$	(+,×,+)	\	Unstable
$e_5(0, 1, 1)$	$C_s + R_a - R_g - P_c, C_r - C_e - L_c - P_a - R_a, C_l + C_r + I_t + L_r + P_c + R_b + R_c - C_h$	(×,+,+)	\	Unstable
$e_6(1, 0, 1)$	$C_s + R_c - R_g - P_a, C_e + L_c + P_a + R_a, C_h - C_l - C_r - L_r - P_c - R_b - R_c$	(×,+,+)	\	Unstable
$e_7(1, 1, 0)$	$-C_e, R_g - R_a - R_c - C_s, C_h - C_l - C_r - I_t - R_b$	(−,−,−)	\	ESS
$e_8(1, 1, 1)$	$-C_e - L_c - P_a - R_a, C_s + R_a + R_c - R_g, C_h - C_l - C_r - I_t - L_r - P_c - R_b - R_c$	(×,+,+)	\	Unstable
$e_9(x_1, y_1, 0)$	$\lambda_1 = -\lambda_3, \lambda_2 = c_1$	(+,×,−)	b	Unstable
$e_{10}(x_2, 0, z_2)$	$\lambda_1 = -\lambda_2, \lambda_3 = c_2$	(+,−,×)	c	Unstable
$e_{11}(0, y_3, z_3)$	$\lambda_1 = c_3, \lambda_2 = -\lambda_3$	(×,+,−)	d	Unstable
$e_{12}(x_4, y_4, 1)$	$\lambda_1 = c_4, \lambda_2 = -\lambda_3$	(×,+,−)	a	Unstable

Notes: × denotes uncertainty in the sign of the eigenvalue. Conditions a, b, c, and d denote the conditions under which the equilibrium point realizes the current stability structure. When the condition is not satisfied, the equilibrium point is unstable or meaningless. \ Indicates that the equilibrium point is in the current state without conditions. a: $C_r > C_e + L_c + P_a + R_a$, $C_h > C_l + C_r + R_b + L_r + P_c + R_c$; b: $C_h > C_l + C_r + R_b$; c: $C_h < C_l + C_r + R_b + L_r + P_c + R_c$; and d: $C_r < C_e + L_c + P_a + R_a$. Source: own creations.

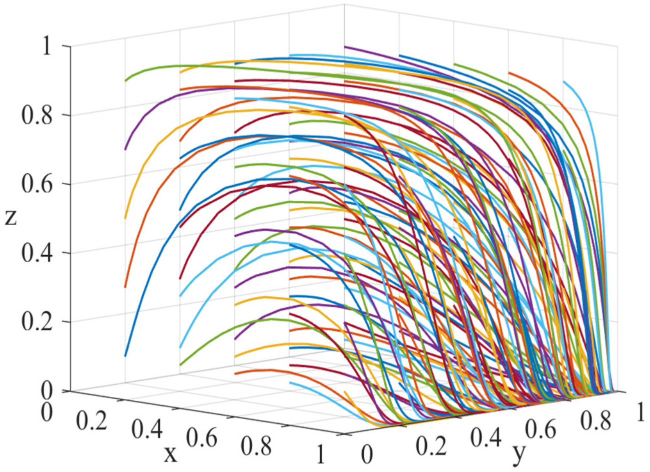
4. Numerical Simulations

4.1. Dynamic Evolutionary Results

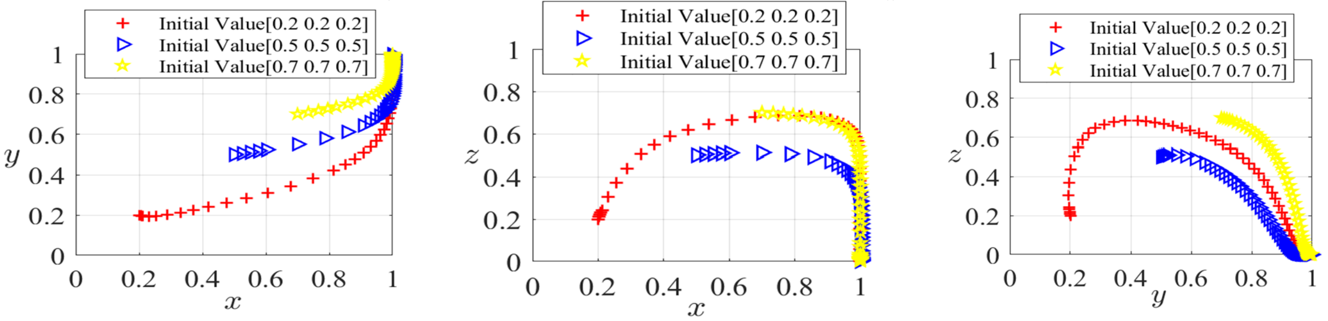
To intuitively observe the effect of different parameters on the evolutionary process in the low-carbon development evolutionary game system. MATLAB is a commercial mathematical software from MathWorks, Inc. used in the fields of data analysis, wireless communications, deep learning, image processing, and computer vision [42]. Therefore, MATLAB provides an effective tool to implement numerical simulation and analysis in this paper. This paper uses MATLAB R2021a for numerical simulation and sets the initial values of the parameters: $C_h = 100$, $C_l = 20$, $I_t = 200$, $C_r = 35$, $P_c = 40$, $R_c = 20$, $C_e = 10$, $P_a = 35$, $R_a = 15$, $C_s = 20$, $L_g = 15$, $R_g = 10$, $R_b = 5$, $L_c = 5$, $L_r = 10$, and (x, y, z)=(0.2,0.2,0.2). At this point, the initial values are set to satisfy the conditional requirements in Inference 8. The evolution of the system over time 100 times is shown in Figure 3a,b. It can be found that the system converges to (1,1,0). The three parties are grouped and given initial probabilities of 0.2, 0.5, 0.7, and all of them eventually reach the desired equilibrium state.

4.2. Sensitivity Analysis of Reward Parameters for the Power Grid Company

For exploring the evolution of the behavioral strategies of the subjects under different reward strengths of the power grid company. This paper assigns R_c = 0, 20, 40, R_a = 0, 15, 30, and numerical simulations are performed. The simulation results of the system evolving 100 times are shown in Figures 4 and 5. It can be found that in terms of the rewards of the power grid company to the construction units, with the increasing R_c, it accelerates the evolution speed of the probability of the construction units to implement high-level carbon monitoring and reporting stabilized at 1, while the probability of the power grid company's strict supervision decreases. Similarly, concerning the rewards to carbon third-party-verification agencies, as R_a increases, the probability of strict supervision decreases, and the probability of standardized verification by carbon third-party-verification agencies increases. Based on the above analysis, construction units and carbon third-party-verification agencies will be encouraged to regulate behaviors if they receive high rewards. However, high rewards will increase the burden on the power grid company, and the costs of strict supervision will reduce the willingness to implement strict supervision. Therefore, it is important to clarify the relationship between the rewards provided by the power grid company and the costs of strict regulation.



(**a**) Systematic three-dimensional evolutionary processes.



(**b**) Systematic two-dimensional evolutionary processes

Figure 3. Systematic evolutionary processes. Source: own creations.

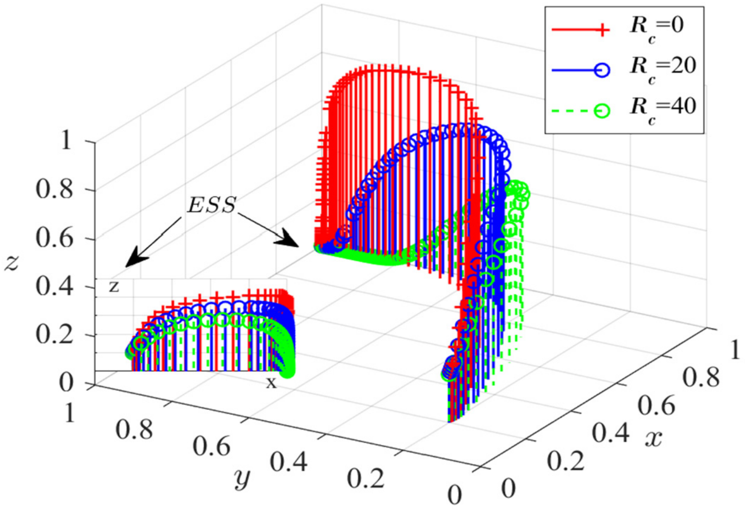


Figure 4. The effect of R_c on the evolutionary process of the system. Source: own creations.

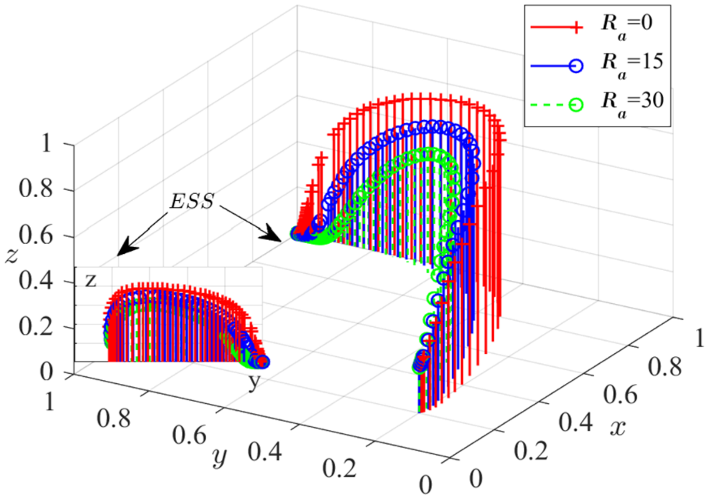


Figure 5. The effect of R_a on the evolutionary process of the system. Source: own creations.

4.3. Sensitivity Analysis of Punishment Parameters for the Power Grid Company

The paper assigns P_a = 0, 20, 40 and P_c = 0, 40, 80, and the system evolves 100 times as shown in Figures 6 and 7. When the power grid company makes no punishments, the probability that the construction units implementing low-level carbon monitoring and reporting programs and irregular verification by carbon-emission third-party-verification agencies increase slightly. As P_c keeps increasing, the evolution of construction units stabilizing to implement high-level carbon monitoring and reporting programs accelerates, and the probability of strict supervision by the power grid company increases. The probability of standardizing verification increases as P_a continues to increase. In addition, before the probability of standardizing verification evolution stabilizes at 1, the probability of strict supervision by the power grid company increases. Therefore, increasing the punishments for the construction units and carbon third-party-verification agencies can promote the probability of strict supervision by the power grid company, and effectively promote the advancement of the MRV system.

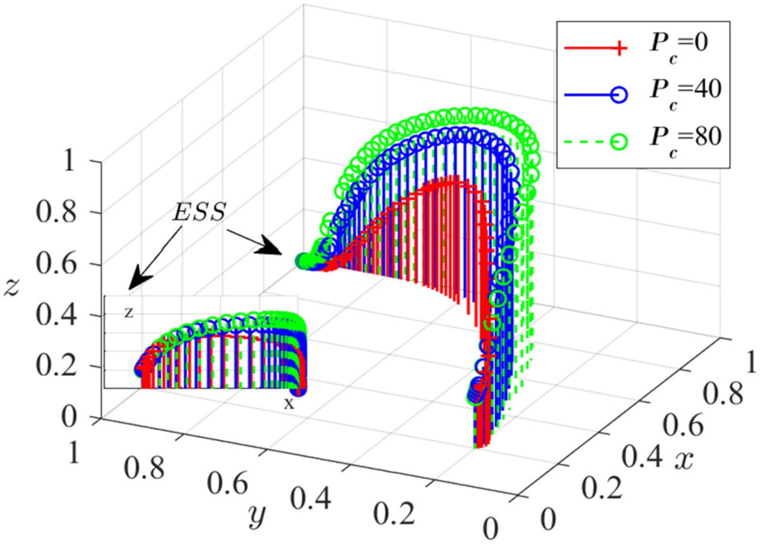


Figure 6. The effect of P_c on the evolutionary process of the system. Source: own creations.

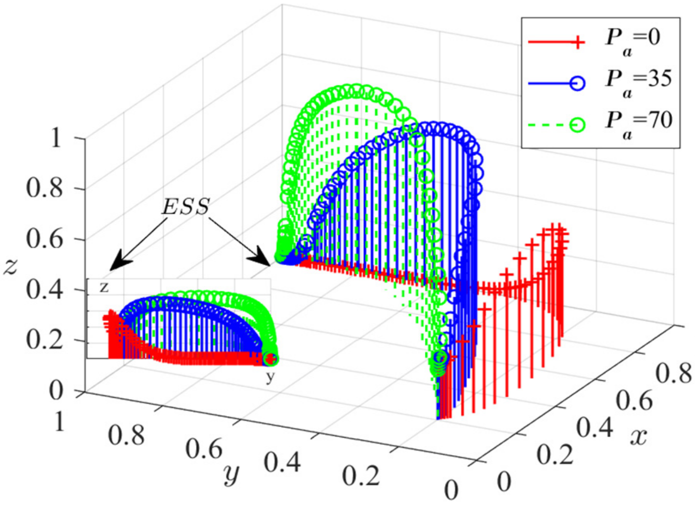


Figure 7. The effect of P_a on the evolutionary process of the system. Source: own creations.

4.4. Sensitivity Analysis of Other Parameters

It is essential to continue to analyze the costs of implementing strict supervision by the power grid company and the degree of public acceptance received, as well as the costs of high-level carbon monitoring and rent-seeking costs for construction units. This paper assigns C_s = 10, 20, 30, R_g = 5, 10, 15, C_r = 15, 35, 55, and C_h = 80, 100, 120, respectively, and the simulation results of the system evolving 100 times are shown in Figures 8–11. From Figures 8 and 9, it can be seen that the increase in the costs of strict supervision by the power grid company accelerates the evolution of the probability of construction units implementing high-level carbon monitoring and reporting programs to stabilize at 1, which means that the probability of strict supervision by the power grid company decreases. In contrast, the higher the degree of public recognition, the higher the probability of strict supervision. The public recognition of the power grid company invariably enhances its credibility. Therefore, promoting public participation in the development of PCPs under the MRV system can enhance the power grid company's willingness to adhere to strict supervision.

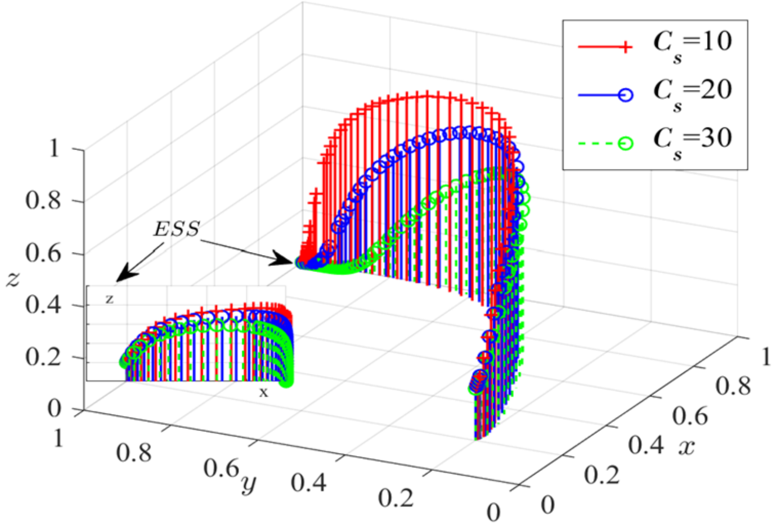


Figure 8. The effect of C_s on the evolutionary process of the system. Source: own creations.

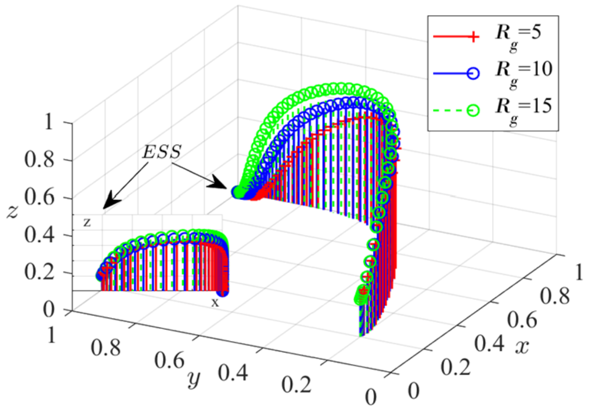


Figure 9. The effect of R_g on the evolutionary process of the system. Source: own creations.

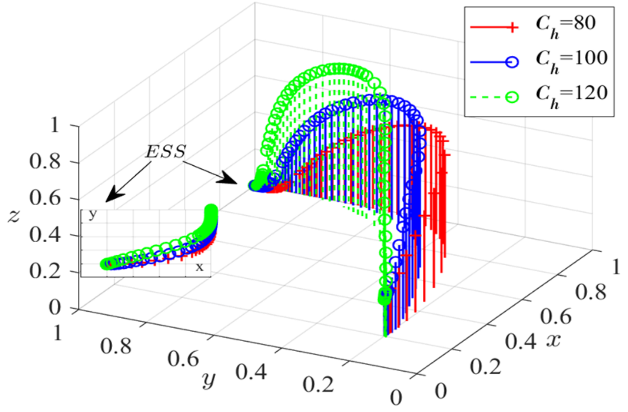


Figure 10. The effect of C_h on the evolutionary process of the system. Source: own creations.

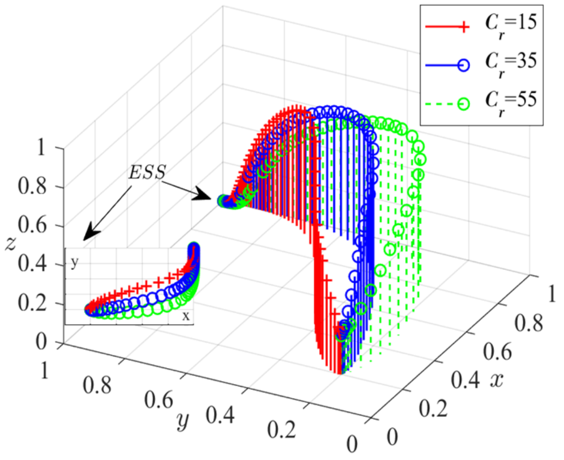


Figure 11. The effect of C_r on the evolutionary process of the system. Source: own creations.

According to Figures 10 and 11, it is clear that rent-seeking costs have a more significant impact on the behavioral-strategy choices of construction units and carbon-emission third-party-verification agencies. As C_r increases, the probability of construction units implementing high-level carbon monitoring and reporting programs increases, while the probability of carbon-emission third-party-verification agencies standardizing verification decreases. In addition, as the system evolves to the equilibrium point, the willingness of the construction units implementing high-level carbon monitoring and reporting programs decreases as C_h increases. Although the high-level carbon monitoring and reporting programs provide the guarantee for construction units through verification, the introduction of advanced carbon-monitoring equipment and technology puts cost pressure on the construction units. Therefore, it is important to balance the costs of implementing high-level carbon monitoring and reporting programs in combination with other parameters to promote the fulfillment of the carbon-monitoring tasks.

5. Discussion

Based on the above numerical simulation analysis, this paper proposes the low-carbon development mechanism for PCPs under the MRV system, as shown in Figure 12, consisting of the MRV Joint Rewards and Punishments Mechanism, the Input Costs Control Mechanism, and the Low Carbon Technology Introduction Mechanism. In addition, the operation of each of the constituent mechanisms is elaborated upon.

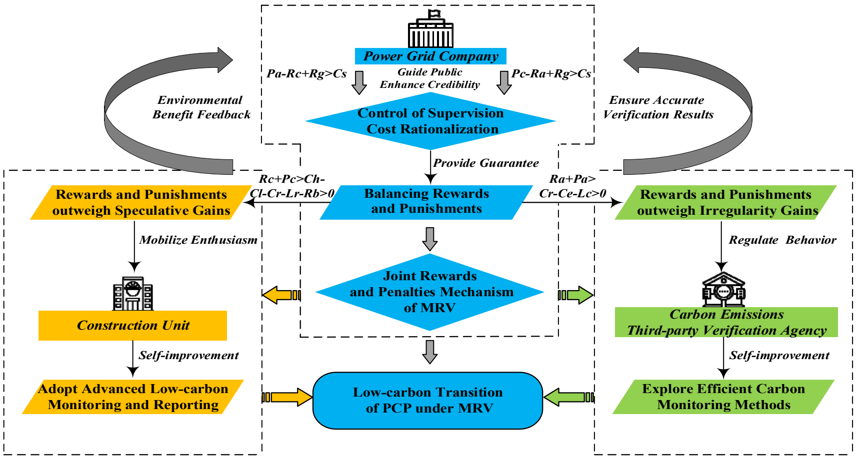


Figure 12. The low-carbon transition mechanism for PCPs under the MRV system. Source: own creations.

5.1. MRV Joint Rewards and Punishments Mechanism

From the perspective of rewards from the power grid company, the rewards from the power grid company to the construction units and carbon-emission verification agencies gradually increase, which will motivate high-level carbon-emission monitoring and reporting, and standardized verification. However, increased rewards might also place a greater financial burden on the power grid company, resulting in less interest in strict supervision. Stricter punishments for construction units and carbon third-party-verification agencies can promote the implementation of responsible behaviors. Lower punishments are not only detrimental to the power grid company's willingness to adopt strict supervision, but also make it difficult to standardize the responsibilities of construction units and carbon third-party-verification agencies. At the same time, this paper finds an interesting phenomenon when the power grid company does not make any rewards and punishments or a single rewards and punishments are implemented, the irresponsible behaviors of the construction units and the carbon third-party-verification agencies will seriously hinder the promotion of the MRV system, leading to the low-carbon development of the PCPs in a difficult situation. Therefore, the rewards and punishments of the power grid company are closely related and interrelated. Balancing the rewards and punishments of the power grid company and implementing joint rewards and punishments is the key to ensuring the stability of the whole evolutionary gaming system. Based on the numerical simulation analysis, it should be ensured that the system satisfies the conditions of Inference 8. Specifically, the power grid company should actively establish a joint MRV rewards and punishments mechanism, and the rewards and punishments for the construction units and the carbon-emission third-party-verification agencies should be higher than the speculative gains obtained from the implementation of low-level carbon-emission monitoring and reporting by both of them and the violation of the verification, to maximize the mobilization of their motivation and to promote the low-carbon development of PCPs in an orderly manner.

5.2. Input Costs Control Mechanism

The affordability of the power grid company for the cost of strict supervision is particularly critical and forms the basis of the MRV joint rewards and punishments mechanism. The study shows that the strict supervision of the power grid company has greatly improved the credibility of the company, which increases the recognition and popularity of the public and plays a positive role in the implementation of strict supervision. Moreover, under the strict supervision of the power grid company, the construction units and carbon-emission third-party-verification agencies are guaranteed to implement the standardized behavior. In addition, the standardized behavior of both not only reaps the rewards from the power grid company but also brings additional environmental benefits for the power grid company, realizing a triple win–win situation. However, when the cost of supervision is too high, the possibility of the power grid company implementing strict supervision will be greatly reduced, which will exacerbate the information mismatch between the subjects, and MRV joint rewards and punishments will no longer exist. Therefore, the grid company needs to control the cost of strict supervision within a reasonable range, to ensure that all parties standardize behavior to bring external benefits for the power grid company to ease the pressure. Combined with the results of the analysis, the power grid company also holds profits as the ultimate goal. Therefore, the power grid company should link the cost of strict supervision with the implementation of rewards and punishments to ensure that the cost of strict supervision is lower than the difference between the rewards and punishments for the construction units and the rewards and punishments for the carbon third-party-verification agencies, to realize the conditions in Inference 8 and to avoid the emergence of the equilibrium point of the mixed strategy. On the other hand, the power grid company should actively publicize low-carbon development to the public, promote public participation in low-carbon development of PCPs, and indirectly reduce the burden of strict supervision.

5.3. Low Carbon Technology Introduction Mechanism

The cost of implementing high-level carbon monitoring and reporting by construction units and the cost of rent seeking have a significant impact on the cooperative relationship between construction units and carbon third-party-verification agencies. The introduction of advanced carbon-monitoring technology and equipment by construction units will inevitably lead to a surge in cost, and the short-term benefits are not obvious. Also, there are still many deficiencies in the carbon-emission measurement methods of PCPs, which makes the work of carbon-emission third-party-verification agencies more difficult. At this time, both of them will reach a rent-seeking intention out of their benefits. When the rent-seeking cost is high, construction units are more inclined to implement the high-level carbon monitoring and reporting program, and carbon third-party-verification agencies naturally expect to reach a rent-seeking agreement with construction units. Regardless of whether the rent-seeking cost is high or low, the existence of rent-seeking behavior is a great obstacle to the low-carbon development of PCPs under the MRV system. Therefore, from a long-term perspective, construction units should take the implementation of a high-level carbon monitoring and reporting program as the entry point to solve the problem and increase the investment in high-level carbon monitoring technology and equipment, while carbon third-party-verification agencies should actively explore more effective carbon-emission measurement methods for PCPs, in conjunction with the power grid company and construction units. It is worth noting that for the construction units to increase low-carbon investment does not mean them blindly investing without regard to cost. According to the numerical analysis results, the construction units' inputs for high-level carbon-emission-reduction programs should be less than the sum of the incentives and penalties received and more than the sum of the inputs for low-level carbon-emission-reduction programs and the additional benefits they bring. For carbon-emission third-party agencies, the verification costs should be lower than the sum of rewards and punishments received, and higher than the sum of benefits and loss of public support for irregular verification.

6. Conclusions

Firstly, this paper establishes an evolutionary game model of PCPs based on the MRV perspective, and determines the influential parameters such as the cost of strict supervision, rewards, and punishments from monitoring, reporting, and verification levels. Through relevant inferences and proofs, it is found that at the initial stage of MRV system application, the power grid company is dominant and has a greater influence on the behavioral strategies of the other participants. With the gradual maturation of the MRV system, construction units and carbon-emission third-party-verification agencies spontaneously fulfill their carbon-emission-reduction tasks, thus realizing a stable and balanced system. Specifically, lower supervision costs and heavier penalties can help increase the likelihood of strict supervision by the power grid company and promote the implementation of regulated behaviors by other participants. It is worth noting that it is essential, to control the costs of strict supervision, to be lower than the difference between the rewards and punishments of the construction unit and those of the carbon-emission third-party-verification agency and to promote active participation by the public.

Secondly, in order to safeguard the benefits of the PCPs' participants and to facilitate the fulfillment of various carbon-reduction tasks, this paper finds, through numerical simulation, that all participants should reasonably control costs, and thus stimulate the willingness to reduce carbon emissions under the condition that the benefits are guaranteed. From the power-grid-company regulatory perspective, continually engaging the public in oversight and keeping the supervision costs below the difference between penalties and incentives for other participants is key to promoting system stability. From the point of view of the construction-unit carbon monitoring, the implementation of high-level carbon-emission-reduction programs should pay attention to the input costs lower than the incentives and penalties received, and higher than the implementation of low-level carbon-emission monitoring inputs and rent-seeking benefits. From the perspective of verification by the carbon-emission third-party-verification agency, the verification costs should be lower than the rewards and punishments received and higher than the sum of the additional inputs of rent-seeking behaviors and the losses suffered from the disclosure of rent-seeking behaviors.

Finally, the MRV joint rewards and punishments mechanism, the input costs control mechanism, and the low-carbon-technology introduction mechanism constitute the low-carbon transition mechanism of PCPs under the MRV system, which respectively deconstructs the complex internal relationships among the participants in the low-carbon transition process of PCPs from the macro, meso, and micro viewpoints. In particular, the MRV joint mechanism is the cornerstone of the tripartite win–win situation; the input costs control mechanism is the guarantee to activate the momentum of carbon-emission reduction; and the low-carbon technology introduction mechanism is an effective means to realize the low-carbon transformation of PCPs, which help to deeply understand the relationship between the MRV system and the behavioral decisions of each participant in PCPs.

This paper explores the decision-making behaviors and stable strategies of participants in the low-carbon transition of PCPs under different situations, based on the MRV perspective. The conclusions make up for the lack of research in the field of low-carbon development of PCPs and can effectively guide PCPs participants to fulfill their carbon-emission responsibilities. However, this paper still has some limitations. With the gradual maturation of low-carbon technologies, the influencing factors considered in this paper will change dynamically. Therefore, it is necessary for the future research to combine with actual cases, incorporate more influencing factors into the evolutionary game model, and conduct comparative analyses of cases that have achieved low-carbon transition to verify the feasibility of the research results.

Author Contributions: Conceptualization, L.L. and R.Z.; methodology, K.S.; software, R.Z.; validation, K.S., O.Z. and R.Z.; formal analysis, X.J.; investigation, L.L.; resources, K.S.; data curation, L.L.; writing—original draft preparation, L.L.; writing—review and editing, R.Z.; visualization, R.Z.; supervision, O.Z.; project administration, X.J.; and funding acquisition, L.L. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by a grant from Research on Carbon Emission Measurement Methods for State Grid Construction Projects of State Grid Liaoning Electric Power Company Limited Economic Research Institute (23-08-199).

Data Availability Statement: Data used can be shared by contacting the corresponding author. The data are not publicly available due to privacy.

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

Appendix A

Based on the stability of the differential equation, if the probability of the construction units implementing high-level carbon monitoring and reporting programs lies in a stable state, the conditions need to be fulfilled: $F(x) = 0$ and $\mathrm{d}(F(x))/\mathrm{d}x < 0$. Based on Equation (4), it is possible to calculate $\mathrm{d}(F(x))/\mathrm{d}x$ and set $J(y)$, as shown in Equations (A1) and (A2):

$$\frac{d(F(x))}{dx} = (2x - 1)(-yI_t + z(-L_r - P_c - R_c) - C_l - C_r - R_b + C_h) \tag{A1}$$

$$J(y) = -yI_t + z(-L_r - P_c - R_c) - C_l - C_r - R_b + C_h \tag{A2}$$

Since $\partial(J(y))/\partial y < 0$, $J(y)$ is a decreasing function concerning y. When $y = [(C_l + C_r + R_b - C_h) + z(L_r + R_c + P_c)]/(-I_t)$, $J(y) = 0$. At this point, $d(F(x))/dx \equiv 0$, and the stable state cannot be determined. When $y < [(C_l + C_r + R_b - C_h) + z(L_r + R_c + P_c)]/(-I_t)$, then $J(y) > 0$, $d(F(x))/dx\,|_{x=0} < 0$, and $x = 0$ is the equilibrium point. Conversely, $x = 1$ is the equilibrium point. Therefore, this paper assumes that the probability of the construction units implementing low- or high-level carbon monitoring and reporting programs is denoted as V_{1-x} and V_x, respectively, as follows:

$$V_{1-x} = \int_0^1 \int_0^1 \frac{C_l + C_r + R_b - C_h - z(L_r + R_c + P_c)}{-I_t} dzdx = \frac{2(C_h - C_l - R_b) - L_r - R_c - P_c}{2I_t} \tag{A3}$$

$$V_x = 1 - V_{1-x} = 1 - \frac{2(C_h - C_l - C_r - R_b) - L_r - R_c - P_c}{2I_t} \tag{A4}$$

Proof 1. Calculating the first-order partial derivatives of V_x with respect to the different variables shows that if the result is greater than 0, the variable increases and so does V_x, which means that the probability of the construction units implementing high-level carbon monitoring and reporting programs increases. It can be found that $\partial(V_x)/\partial(I_t) > 0$, $\partial(V_x)/\partial(R_b) > 0$, $\partial(V_x)/\partial(C_l) > 0$, $\partial(V_x)/\partial(C_r) > 0$, $\partial(V_x)/\partial(L_r) > 0$, $\partial(V_x)/\partial(R_c) > 0$, $\partial(V_x)/\partial(P_c) > 0$, $\partial(V_x)/\partial(C_h) < 0$. As I_t, R_b, C_l, C_r, L_r, R_c, P_c increase, V_x increases. Conversely, as C_h increases, V_x decreases. □

Proof 2. According to the stability analysis of the construction units' behavioral-strategy choices, it can be seen that when $y < [(C_l + C_r + R_b - C_h) + z(L_r + R_c + P_c)]/(-I_t)$ or $z < (yI_t + C_l + C_r + R_b - C_h)/(-L_r - P_c - R_c)$, $x = 0$ is the equilibrium point. Therefore, as y and z continue to increase until $y > [(C_l + C_r + R_b - C_h) + z(L_r + R_c + P_c)]/(-I_t)$ or $z > (yI_t + C_l + C_r + R_b - C_h)/(-L_r - P_c - R_c)$, the stable strategy of the construction units grows from $x = 0$ to $x = 1$. □

Appendix B

In the same way as Appendix A, this paper calculates d($F(y)$)/dy and sets $G(z)$ according to Equation (8), as shown in Equations (A5) and (A6):

$$\frac{d(F(y))}{dy} = (2y - 1)[-xC_r + z(-R_a - L_c - P_a) + C_r - C_e)] \tag{A5}$$

$$G(z) = -xC_r + z(-R_a - L_c - P_a) + C_r - C_e) \tag{A6}$$

Since $\partial(G(z))/\partial z < 0$, $G(z)$ is a decreasing function concerning z, when $z = [(x - 1)C_r + C_f]/(-L_c - P_a - R_a)$, $G(z) = 0$, $d(F(y))/dy \equiv 0$, then the stable state cannot be determined. When $z < [(x - 1)C_r + C_f]/(-L_c - P_a - R_a)$, $G(z) > 0$, $d(F(y))/dy\,|_{y=0} < 0$, then $y = 0$ is the equilibrium point. Conversely, $y = 1$ is the equilibrium point. Therefore, this paper assumes that the probability of the carbon-emission third-party-verification agencies implementing violation or standardized verification is denoted as V_{1-y} and V_y, respectively:

$$V_{1-y} = \int_0^1 \int_0^1 \frac{xC_r + C_e - C_r}{-L_c - P_a - R_a} dxdy = \frac{(C_r - C_e)^2}{2(L_c + P_a + R_a)C_r} \tag{A7}$$

$$V_y = 1 - V_{1-y} = 1 - \frac{(C_r - C_e)^2}{2(L_c + P_a + R_a)C_r} \tag{A8}$$

Proof 3. By calculating the first-order partial derivatives of the variables in V_y, it can be found that $\partial(V_y)/\partial(C_r) > 0$, $\partial(V_y)/\partial(R_a) > 0$, $\partial(V_y)/\partial(P_a) > 0$, $\partial(V_y)/\partial(L_c) > 0$, $\partial(V_y)/\partial(C_e) < 0$. With increasing C_r, R_a, P_a, L_c, V_y increases. Conversely, as C_e increases, V_y decreases. □

Proof 4. According to the stability analysis of the carbon-emission third-party-verification agencies' behavioral-strategy choices, it can be seen that when $z < [(x - 1)C_r + C_e]/(-L_c - P_a - R_a)$ or $x < [C_e - C_r + x(L_c + P_a + R_a)]/(-C_r)$, $y = 0$ is the equilibrium point. Therefore, as z and x continue to increase until $z > [(x - 1)C_r + C_e]/(-L_c - P_a - R_a)$ or $x > [C_e - C_r + x(L_c + P_a + R_a)]/(-C_r)$, the stable strategy of the carbon-emission third-party-verification agencies grows from $y = 0$ to $y = 1$. □

Appendix C

In the same way as Appendix A, this paper calculates d($F(z)$)/dz and sets $H(x)$ according to Equation (12), as shown in Equations (A9) and (A10):

$$\frac{d(F(z))}{dz} = (2z - 1)H(x) = (2z - 1)[-xyL_g + x(R_c + P_c + L_g) + y(R_a + P_a + L_g) + C_s - R_g - P_c - P_a - L_g] \tag{A9}$$

$$H(x) = -xyL_g + x(R_c + P_c + L_g) + y(R_a + P_a + L_g) + C_s - R_g - P_c - P_a - L_g \tag{A10}$$

Since $\partial(H(x))/\partial x > 0$, $H(x)$ is an increasing function concerning x. When $x = [-y(R_a + P_a + L_g) - C_s + R_g + P_c + P_a + L_g]/(-yL_g + R_c + P_c + L_g)$, $H(x) = 0$, $d(F(z))/dz \equiv 0$, then the stable state cannot be determined. When $x < [-y(R_a + P_a + L_g) - C_s + R_g + P_c + P_a + L_g]/(-yL_g + R_c + P_c + L_g)$, $H(x) < 0$, $d(F(z))/\mathrm{d}z\,|_{z=1} < 0$, then $z = 1$ is the equilibrium point. Conversely, $z = 0$ is the equilibrium point. Therefore, this paper assumes that the probability of the power grid company implementing strict or permissive supervision is denoted as V_z and V_{1-z}, respectively:

$$V_z = \int_0^1 \int_0^1 \frac{-y(R_a + P_a + L_g) - C_s + R_g + P_c + P_a + L_g}{-yL_g + R_c + P_c + L_g} dydx = \frac{R_a + P_a + L_g}{L_g} - ln\left(1 + \frac{L_g}{R_c + P_c}\right)\left[\frac{(R_a + P_a)(R_c + P_c) + (R_a + R_c + C_s - R_g)L_g}{L_g^2}\right] \tag{A11}$$

$$V_z = 1 - V_{1-z} \tag{A12}$$

Proof 5. By calculating the first-order partial derivatives of the variables in V_z, it can be found that $\partial(V_z)/\partial(R_g) > 0$, $\partial(V_z)/\partial(L_g) > 0$, $\partial(V_z)/\partial(P_a) > 0$, $\partial(V_z)/\partial(P_c) > 0$, $\partial(V_z)/\partial(R_a) < 0$, $\partial(V_z)/\partial(R_c) < 0$, $\partial(V_z)/\partial(C_s) < 0$. This means that as R_g, L_g, P_a, P_c increase, V_z increases. Conversely, as R_a, R_c, C_s increase, V_z decreases. □

Proof 6. According to the stability analysis of the behavioral-strategy choice of the power grid company, it can be seen that when $x < [-y(R_a + P_a + L_g) - C_s + R_g + P_c + P_a + L_g]/(-yL_g + R_c + P_c + L_g)$ or $y < [-x(R_c + P_c + L_g) - C_s + R_g + P_c + P_a + L_g]/(R_a + P_a + L_g - xL_g)$, $z = 1$ is the equilibrium point. Therefore, as x and y continue to increase until $x > [-y(R_a + P_a + L_g) - C_s + R_g + P_c + P_a + L_g]/(-yL_g + R_c + P_c + L_g)$ or $y > [-x(R_c + P_c + L_g) - C_s + R_g + P_c + P_a + L_g]/(R_a + P_a + L_g - xL_g)$, the stable strategy of the power grid company decreases from $z = 1$ to $z = 0$. □

Appendix D

Proof 7. According to the Jacobian matrix eigenvalues, it can be found that when $C_e - C_r + L_c + P_a + R_a < 0$, $C_l - C_h + C_r + L_r + P_c + R_b + R_c < 0$, condition a is satisfied, e_{12} is unstable, and the eigenvalues of e_2, e_7 are negative, so they are ESS. Condition b is also satisfied, e_9 is unstable. If conditions c and d cannot be satisfied, then e_{10} and e_{11} are meaningless. □

Proof 8. According to the Jacobian matrix eigenvalues, it can be found that when $R_c + P_c > C_h - C_l - C_r - L_r - R_b > 0$, $R_a + P_a > C_r - C_e - L_c > 0$, condition a is not satisfied, so e_2, e_{12} is meaningless. Condition b is satisfied, so e_9 is unstable. When additional conditions $P_a - R_c + R_g > C_s$, $P_c - R_a + R_g > C_s$, conditions c and d are satisfied, so e_{10} and e_{11} are meaningless. □

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