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# Evolutionary Game and Simulation Analysis of Power Plant and Government Behavior Strategies in the Coupled Power Generation Industry of Agricultural and Forestry Biomass and Coal

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**Abstract:** Under the background of "dual carbon", the coupled power generation of agricultural and forestry biomass (AFB) and coal, as a new path of coal-power transformation, is key to achieving energy conservation and reducing emissions in the power sector. Timely and effective government subsidies as well as regulation policies will play important roles in the development of the coupled power generation industry. Previous studies usually assumed government policy as singular and static, rarely considering the dynamic changes in government policies. In this study, evolutionary game theory and systematic dynamics research methods were combined. The game relationship and the dynamic evolution process of the behavioral strategies of both sides are analyzed through the construction of a mixed-strategies game model of the government and power plants. A system dynamics model is built for simulations based on the results of the dynamic game evolution, and the influence paths of key factors on the behavioral strategies of the government and power plants were further demonstrated. The results indicated the following: (1) The behavioral strategies of the government and power plants were not stable for a long period of time, but fluctuated during their mutual influence. The dynamic policies and measures formulated by the government according to changes in the behavioral strategies of power plants will promote industrial development more effectively. (2) Increasing subsidization and the strengthening of supervision caused by government policy can increase the enthusiasm of power plants to choose the coupled power generation of AFB and coal. (3) If the government improves the benefits or reduces the transformation costs caused by coupled power generation the industry will be fundamentally improved. The results clearly show the interactions as well as adjustment processes of the behavioral strategies of power plants and the government in the coupled power generation industry of AFB and coal, and the specific effects of key factors on the behavioral strategies of power plants and the government were investigated. This study can provide a theoretical basis for the government to formulate reasonable industrial policies and measures for the coupled power generation of AFB and coal, in addition to being a valuable reference for other countries to develop a coupled power generation industry.

**Keywords:** agricultural and forestry biomass; coupled power generation; evolutionary game; system dynamics; behavioral strategy

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## 1. Introduction

China has been committed to reducing international carbon emissions, and has actively promoted as well as fulfilled its climate change commitments. At the UN General Assembly in 2020, China proposed the goal of "carbon peaking and carbon neutrality", that is, carbon emissions will peak before 2030 and achieve carbon neutrality around 2060 [1]. As a major contributor to global energy consumption and $CO_2$ emissions, and the largest industrial source of greenhouse gas emissions in China, the transformation of the energy utilization structure in the power sector is key to achieving the “dual carbon” goal [2]. The Intergovernmental Panel on Climate Change (IPCC) has noted that energy use is closely related to increased greenhouse gas emissions; the use of renewable energy can help to break this correlation and thus contribute to sustainable development [3]. As a kind of renewable energy, the $CO_2$ absorbed by biomass energy in the growth process can offset the $CO_2$ released in combustion, and it has the characteristic of “zero carbon emissions”. It can replace fossil energy in the field of power supply and heating, and has great potential for carbon emission reduction [4]. Biomass energy includes multiple forms, such as forest biomass energy, agricultural biomass energy, animal feces, food residue, and municipal solid waste. Among them, agricultural and forestry biomass energy usually refers to agricultural residues (cereal straw, maize stover, rapeseed straw, etc.) and forestry residues (shrub residues, branches, sawdust, etc.) [5].

Biomass energy technologies have been widely used in the field of power generation, including direct combustion, gasification, and coupled power generation technologies [6], among which the coupled power generation of biomass and coal is regarded as one of the economic, effective, and executable ways of reducing carbon emissions in thermal power plants [7]. The coupled power generation of agricultural and forestry biomass (AFB) and coal uses the mixed combustion of AFB raw materials and coal to generate electricity, which is a comprehensive utilization method of traditional and renewable energy [8]. On the one hand, this power generation technology reduces the usage costs of AFB raw materials, enabling them to be fully utilized and avoiding the air pollution caused by direct combustion (such as straw incineration returning to the field) [9]. On the other hand, by replacing a certain proportion of coal for power generation, AFB can not only ensure better combustion calorific value and efficiency in the power generation process but also greatly reduce $CO_2$ emissions [10]; however, the policies and measures for the agricultural and forestry biomass and coal coupling power generation industry are not consistent in China. In 2016, the National Energy Administration proposed promoting the coupled power generation technology of biomass and coal during the 13th Five-Year Plan period [11]. In 2017, the Ministry of Ecology and Environmental issued the Notice on Carrying out the Technical Transformation Pilot Work of Coal-Biomass Co-firing Power generation, aiming at developing the technical transformation project of the coupled power generation of AFB and coal [12]; however, in 2018 this technology project was officially removed from the national subsidy catalog [13]. In 2019, the Guidance Catalogue of Industrial Structure Adjustment 2019, issued by the National Development and Reform Commission, once again listed coal–biomass co-firing power generation as an industry to be encouraged [14]; however, in 2020 the National Development and Reform Commission issued a supplementary notice on matters related to “Several Opinions on Promoting the Healthy Development of Non-Water Renewable Energy Power Generation”, which made it clear that biomass-related power generation projects will not be eligible for subsidies if they run for 15 years or if the number of reasonable utilization hours in the whole life cycle reaches 82,500 h [15]. The instability of these industrial policies leads to the failure of the steady development of the coupled power generation industry of AFB and coal; therefore, it is very important for the formulation of industrial policies to systematically analyze the behavioral strategies of the government and the mutual influence paths between the behavioral strategies of the government and power plants.

In the existing literature, the research on China’s coupled power generation industry of AFB and coal mainly focuses on technological research as well as development [16–21] and the evaluation of economic and environmental benefits [22–28], while the research on industrial policy [29–32] is relatively lacking. In some of the literature scholars focused on the macro-level to study the effect of industrial policies on the development of the coupled power generation industry of AFB and coal. It is generally believed that reasonable policies can promote industrial development, but there are few studies on how to formulate the rationality of policies and how policies affect the development of enterprises. Some studies have pointed out that the behavioral strategies between government and enterprises are mutually driven and influenced [33]. Studies have also confirmed that enterprises will change their strategies according to the policies and measures of the government, and the design as well as choice of policies by the government play important roles in guiding and demonstrating the behavioral strategies of enterprises [34,35]; sustainable and stable industrial policies can better promote industrial development [36].

Many scholars have also studied the relevant subjects in the field of biomass energy utilization, which aimed to figure out the influence of the changes in the behavioral strategies of various stakeholders to better improve the government's policies and measures. The specific research can be divided into two aspects: (1) As for the study of the influence on behavior strategies of enterprises and inter-enterprises, Nasiri and Zaccour [37] built a static game model among power plants, brokers, and farmers to study the behavior strategies of stakeholders and pointed out that the quantity of biomass raw materials supplied by farmers was affected by the purchase price of brokers and power plants. Tan et al. [38] and Zhang et al. [39] argued that the behavioral strategy of farmers to supply quantities of biomass raw materials would be affected by the type and quantity of participants in the supply chain. (2) As for the influence of behavioral strategies between the government and enterprises, Zhai et al. [40] constructed a game model among the government, power plants, and farmers, and concluded that government subsidy strategies would improve the income as well as participation enthusiasm of all of participants, and the level of a subsidy policy was positively correlated with the income as well as enthusiasm of the participants. Luo and Miller [41] analyzed the influence of government policies on the development of the AFB market with game theory, and believed that appropriate incentive policies could improve the supply quantity of biomass raw materials in addition to the benefits of relevant participants.

By reviewing and summarizing the literature, we found that the existing literature has enriched our understanding of the research on the influence of game theory on industrial policy formulation and the strategies of players, in addition to laying the foundation for this study; however, there are still some shortcomings. For instance, the aforementioned research on industrial policies usually assumed that government policies are singular or static, but policies are not eternal; however, research on how dynamic changes in policies affect enterprise behavior and strategies are rare. In order to remedy these defects, the research methods of evolutionary game theory and system dynamics are used in this study. Evolutionary game theory is often used to study the existence of players' behavior strategies and dynamic evolutionary stability [42], while system dynamics (SD) can explore the causal feedback relationship between various factors in the model [43]. Based on this, the specific objectives of this study are as follows: (1) to establish an evolutionary game model between the government and power plants under the condition of fully considering the externalities of the coupled power generation of AFB and coal, as well as to clarify the dynamic evolution process of the game relationship and behavioral strategies of both sides; (2) based on the results of the evolutionary game model, an SD model of the government and power plants is constructed to analyze the influence path of key factors on the behavior strategies of the government and power plants. This study will provide a theoretical basis and scientific reference for the government to formulate reasonable policy measures, promoting more enterprises to choose the coupled power generation of AFB and coal.

## 2. Evolutionary Game Model

### *2.1. Applicability of Evolutionary Game Theory*

In the coupled power generation industry of AFB and coal, the government is the policy maker in regard to subsidies and regulation, whilst enterprise is the practitioner of policy measures; the government mainly considers subsidies and regulatory costs, while enterprises pay attention to the actual gains and losses in subsidies and regulatory policies. In the process of strategy selection, two players will constantly adjust their strategies according to the behaviors of the other side, eventually evolving into a stable strategy, which is in line with the basic characteristics of an evolutionary game [44].

Evolutionary game theory is a combination of biological evolutionary theory and game theory. It believes that game players are bounded, rational, and will constantly adjust their strategies according to changes in a situation through trial and error to finally reach a state of dynamic equilibrium [45]. This method abandons the assumption of complete rationality and focuses on the analysis of dynamic adjustment processes, which makes up for the deficiencies in rational as well as static perspectives and can better deal with some management problems; it is suitable for the study of repeated game processes between two groups in dynamic processes [46,47]. Therefore, it is reasonable and feasible to use evolutionary game theory to study the behavior policies of the government and power plants in the coupled power generation industry of AFB and coal.

### *2.2. Game Players*

In this study, power plants and government are the game players in the dynamic evolutionary game model.

A power plant refers to a factory using traditional coal burning technology to generate electricity that can be transformed into a power plant using AFB and coal for coupled power generation. Power plant behavior strategies can be divided into "choose the coupled power generation of AFB and coal" and "do not choose the coupled power generation of AFB and coal".

For the consideration of environmental benefits, the government has taken corresponding policy measures to encourage more power plants to reduce carbon emissions and develop the coupled power generation of AFB and coal. The government's behavioral strategies are divided into "regulate and subsidize" and "not regulate and not subsidize". To "regulate and subsidize" the power plants that choose coupled power generation technology can be regarded as the government's investment in and management of the environment. The purpose is to reduce the carbon emissions of the power generation industry and achieve the coordinated development of economic and environmental benefits.

### *2.3. Model Hypotheses*

**Hypothesis 1.** *Due to the information asymmetry between the two sides of the game, both the government and power plants adopt bounded rational behaviors and play repeated games under the condition of asymmetric information* [45].

**Hypothesis 2.** $x \in (0,1)$ *represents the behavior strategies of power plants.* $x = 0$ *means that a power plant does not choose the "coupled power generation" strategy and* $x = 1$ *means that a power plant chooses the "coupled power generation" strategy. When* $y \in (0,1)$ *represents the government's behavior strategies,* $y = 0$ *means that the government chooses the "not regulation and not subsidy" strategy for power plants whilst* $y = 1$ *means that the government chooses the "regulation and subsidy" strategy for power plants.*

**Hypothesis 3.** *When the government chooses the subsidy and regulation strategy it will subsidize power plants that choose coupled power generation technology and take punitive measures for power plants that do not choose the technology. Power plants need to pay certain carbon emission fees to the government.*

**Hypothesis 4.** *When the government chooses the strategy of non-subsidy and non-regulation, it will not subsidize power plants that choose coupled power generation technology, nor will it punish power plants that do not choose the technology.*

**Hypothesis 5.** *When power plants choose the coupled power generation strategy the government will obtain certain environmental benefits regardless of whether the government chooses the subsidy and regulation strategy* [48].

### 2.4. Model Construction

Based on the above analysis of the applicability of the evolutionary game model, the game players, and the hypothesis of the model, an evolutionary game model with power plants and the government as the main players in the coupled power generation industry is constructed. The payoff matrix of the government and power plants is shown in Table 1.

**Table 1.** The payoff matrix for power plants and the government.

| Strategies of Power Plants | Strategies of the Government | |
|---|---|---|
| | Regulation and Subsidy $(y)$ | No Regulation and No Subsidy $(1-y)$ |
| Coupled power generation is chosen $(x)$ | $EC_b + S + B - C,\ EN_b - S - M$ | $EC_b + B - C,\ EN_b$ |
| Coupled power generation is not chosen $(1-x)$ | $EC_c - F,\ F - M - G$ | $EC_c, -G$ |

$EC_b$ represents the economic benefits generated when power plants choose coupled power generation. $EC_c$ represents the economic benefits generated by using traditional coal-fired power generation. Due to the high collection cost of AFB, the economic benefits generated by coupled power generation are smaller than those generated by coal-fired power generation [49], that is, $EC_b < EC_c$. $EN_b$ represents the environmental benefits obtained by the government when power plants choose coupled power generation [48]. S represents the policy subsidy amount given by the government when power plants choose coupled power generation. B represents the indirect benefits obtained when power plants choose coupled power generation, such as preferential power generation, full integration into power grid policy, sales of by-products, etc. [41,50]. C represents the transformation cost required for power plants to choose coupled power generation [51]. M is the regulatory cost that the government has to pay to regulate power plants. F is the carbon emission charge that power plants need to pay by burning coal when the government regulates power plants. G is the amount of money the government has to pay to clean up the environment when the power plant only uses coal to generate electricity.

According to the payoff matrix, the expected benefits when the power plant chooses the coupled power generation strategy are as follows:

$$U_{11} = y(EC_b + S + B - C) + (1 - y)(EC_b + B - C) \tag{1}$$

When the power plant does not choose the coupled power generation strategy the expected benefit is as follows:

$$U_{12} = y(EC_c - F) + (1 - y)(EC_c) \tag{2}$$

The average benefit of the power plant is as follows:

$$\overline{U_1} = xU_{11} + (1 - x)U_{12} \tag{3}$$

Similarly, the expected benefits of the government choosing the strategies of "regulation and subsidy" and "not regulation and not subsidy", as well as the average benefit of the government, are shown as follows, respectively:

$$U_{21} = x(EN_b - S - M) + (1 - x)(F - M - G) \tag{4}$$

$$U_{22} = xEN_b + (1 - x)(-G) \tag{5}$$

$$\overline{U_2} = yU_{21} + (1 - y)U_{22} \tag{6}$$

According to the definition of the replicator dynamics equation in evolutionary game theory [42], if the probability of a decision maker choosing a strategy at time t is x, then the rate of change of x at the next time will be related to the probability, x, at the previous time and the difference between the game player's corresponding strategy benefits and the expected average benefits at this time, which can be expressed as follows:

$$F(x) = \frac{dx}{dt} = x\left(U_{11} - \overline{U_1}\right) = x(1-x)[y(S+F) + EC_b + B - C - EC_c] \quad (7)$$

In the same way:

$$F(y) = \frac{dy}{dt} = y\left(U_{21} - \overline{U_2}\right) = y(1-y)[-(S+F)x + F - M] \quad (8)$$

### *2.5. Analysis of the Evolutionary Game Results*

#### 2.5.1. Unilateral Strategy Analysis of Power Plants

According to the replicator dynamics, Equation (7), of power plant strategies, when $y = \frac{EC_c+C-EC_b-B}{S+F}$, $F(x) = 0$, then the game is stable at any value of x;

when $y \neq \frac{EC_c+C-EC_b-B}{S+F}$, if $F(x) = 0$, it can be obtained that $x = 0$, $x = 1$ are two stable points of the replicator dynamics equation of power plant strategies. According to evolutionary game theory, when $F\prime(x) < 0$ or $F\prime(y) < 0$ the system will have an equilibrium point, such that it can be divided into two cases for discussion:

(a) When $0 < y < \frac{EC_c+C-EC_b-B}{S+F}$, then $F\prime(x) = (1-2x)[y(S+F) + EC_b + B - C - EC_c]$, $F\prime(0) < 0$, $F\prime(1) > 0$, so '$x = 0\prime$ is the equilibrium point. At this time, the power plant strategy is not to choose coupled power generation technology;

(b) When $\frac{EC_c+C-EC_b-B}{S+F} < y < 1$, $F\prime(0) > 0$, $F\prime(1) < 0$, so $x = 1$ is the equilibrium point. At this time, the power plant strategy is to choose coupled power generation technology.

Therefore, the unilateral strategies of power plants depend on the probability value of the government's strategies, and the dynamic evolution trend is shown in Figure 1. When the probability that the government adopts the regulation and subsidy strategy is greater than a certain value, ($\frac{EC_c+C-EC_b-B}{S+F}$), power plants will adopt the coupled power generation strategy. When the probability that the government will adopt the subsidy and supervision strategy is less than a certain value, ($\frac{EC_c+C-EC_b-B}{S+F}$), power plants will adopt the strategy of not using coupled power generation technology.

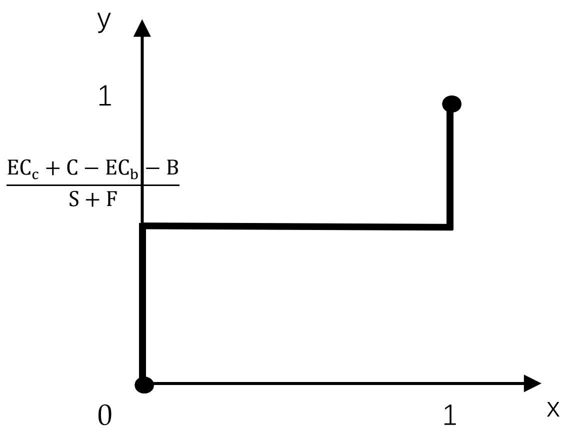



**Figure 1.** Dynamic evolution trend in the unilateral strategies of power plants.

#### 2.5.2. Unilateral Strategy Analysis of the Government

According to the replicator dynamics, Equation (8), of the government's strategies, when $x = \frac{F-M}{S+F}$, $F(y) = 0$, the game is stable at any value of y;

when $x \neq \frac{F-M}{S+F}$, if $F(y) = 0$, it can be obtained that $y = 0$, $y = 1$ are two stable points of the replicator dynamics equation of the government's strategies. It can also be divided into two cases for discussion:

(c) When $0 < x < \frac{F-M}{S+F}$, $F\prime(y) = (1-2y)[-(S+F)x + F - M]$, $F\prime(0) > 0$, $F\prime(1) < 0$, so $y = 1$ is the equilibrium point, the government will regulate and subsidize power plants;

(d) When $\frac{F-M}{S+F} < x < 1$, $F\prime(0)(0, F'(1))0$, so $y = 0$ is the equilibrium point. At this time, the government's strategy is not to regulate and subsidize power plants.

Similarly, the dynamic evolution trend in the government's unilateral strategies is shown in Figure 2. The choice of strategy depends on the probability value of power plants to adopt a strategy. When the probability of power plants choosing the coupled power generation strategy is less than a certain value, ($\frac{F-M}{S+F}$), the government will adopt the "subsidize and regulate" strategy. When the probability of power plants choosing the coupled power generation strategy is greater than a certain value, ($\frac{F-M}{S+F}$), the government will no longer regulate and subsidize power plants.

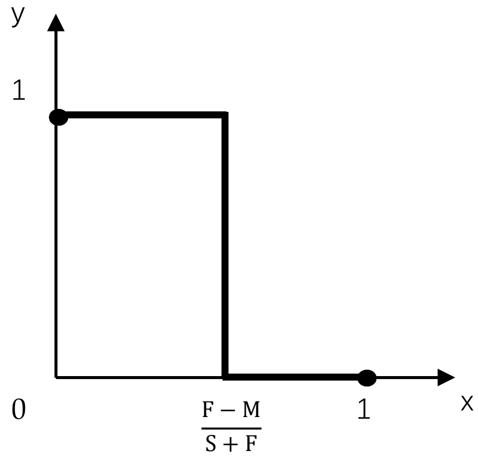



**Figure 2.** Dynamic evolution trend in the unilateral strategies of the government.

#### 2.5.3. Equilibrium Strategy Analysis of Mixed Evolutionary Game Model of Power Plants and the Government

According to the replicator dynamics equation of power plants and the government, $F(x) = 0$, $F(y) = 0$, five equilibrium points of the system can be obtained, namely $(0, 0)$, $(1, 0)$, $(0, 1)$, $(1, 1)$, and $(x^*, y^*)$, where $x^* = \frac{F-M}{S+F}$, $y^* = \frac{EC_c + C - EC_b - B}{S+F}$.

According to the analytical method proposed by Friedman [42], the stability of equilibrium points in evolutionary games can be judged by the local stability of the Jacobian matrix of the system. The Jacobian matrix, J, of the game system of power plants and the government is as follows:

$$J = \begin{bmatrix} \frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} \\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} \end{bmatrix} = \begin{bmatrix} (1-2x)[y(S+F) + EC_b + B - C - EC_c] & x(1-x)(S+F) \\ y(1-y)(-S-F) & (1-2y)[-(S+F)x + F - M] \end{bmatrix} \quad (9)$$

The determinant, $\det(J)$, of the Jacobian matrix, J, is as follows:

$$\det(J) = \begin{vmatrix} (1-2x)[y(S+F) + EC_b + B - C - EC_c] & x(1-x)(S+F) \\ y(1-y)(-S-F) & (1-2y)[-(S+F)x + F - M] \end{vmatrix} = (1-2x)[y(S+F) + EC_b + B - C - EC_c] \cdot (1-2y)[-(S+F)x + F - M] - x(1-x)(S+F) \cdot y(1-y)(-S-F) \quad (10)$$

The trace, $tr(J)$, of the Jacobian matrix, J, is as follows:

$$tr(J) = (1-2x)[y(S+F) + EC_b + B - C - EC_c] + (1-2y)[-(S+F)x + F - M] \quad (11)$$

When $\det(J) > 0$ and $tr(J) < 0$, the system equilibrium for the ESS can be determined, and the system is stable. The stability analysis of the above five equilibrium points is shown in Table 2.

**Table 2.** Stability analysis of five equilibrium points in the system.

| Local Equilibrium Point | det(J) | tr(J) | Nature |
|---|---|---|---|
| (0, 0) | − | ± | Instability |
| (0, 0) | − | ± | Instability |
| (0, 0) | − | ± | Instability |
| (0, 0) | − | ± | Instability |
| $(x^*, y^*)$ | − | 0 | Saddle point |

According to the above discussion on the unilateral strategies of power plants and the government (Sections 2.5.1 and 2.5.2), it can be seen that the characteristic roots corresponding to the point $(x^*, y^*) = \left(\frac{F-M}{S+F}, \frac{EC_c+C-EC_b-B}{S+F}\right)$ are a pair of pure virtual roots. According to the relevant literature [52], $(x^*, y^*)$ is the saddle point. That is to say, the mixed evolutionary game matrix of power plants and the government has no stable equilibrium point, and the game strategies of power plants and the government cannot be stable, always changing according to the strategies of the other side.

## 3. System Dynamics Model Construction and Simulation Analysis Based on an Evolutionary Game

System dynamics is a scientific method used to analyze and study the dynamic and dialectical relationships among information feedback systems, the core of which is to explore the causal feedback relationships among various factors in a model [53]. In consideration of the fact that the evolutionary game is limited to the explanatory description of the process and equilibrium results, it cannot describe the decision-making evolution paths of the government and power plants. In order to more profoundly explain and verify the model structure and changes in the players' behavior strategies, as well as explore the influence paths of different factors in the model on the behavior strategies of power plants and the government, the method of combining game theory and system dynamics is used to model and simulate the strategies of power plants and the government based on the results of the evolutionary game model.

### *3.1. System Dynamics Model Construction*

In this study, the system dynamics simulation software VENSIM PLE 7.3.5 is used to model and simulate the game behavior strategies of power plants and the government, the dynamic processes of the decision changes of both sides, and to build the stock and flow diagram of a system dynamics model of the behavior strategies, as shown in Figure 3. The model includes two level variables, two rate variables, four auxiliary variables, and nine constants. The two level variables are the probability that power plants choose coupled power generation and the probability that the government subsidizes and regulates, respectively. The two rate variables are the rate of change in the probability that power plants choose coupled power generation and the rate of change in the probability that the government subsidizes and regulates, respectively. The four auxiliary variables are the expected benefits of power plants choosing coupled power generation, the expected benefits of power plants not choosing coupled power generation, the expected benefits of the government subsidizing and regulating, and the expected benefits of the government not subsidizing and regulating. The nine constants are the economic benefit of coupled power generation technology, the environmental benefits of coupled power generation, the indirect benefits of coupled power generation, the transformation cost of coupled power generation, the government subsidy amount, the government regulation cost, the government environmental treatment cost, the economic benefits of coal-fired power generation, and the carbon emission charge of coal-fired power generation.

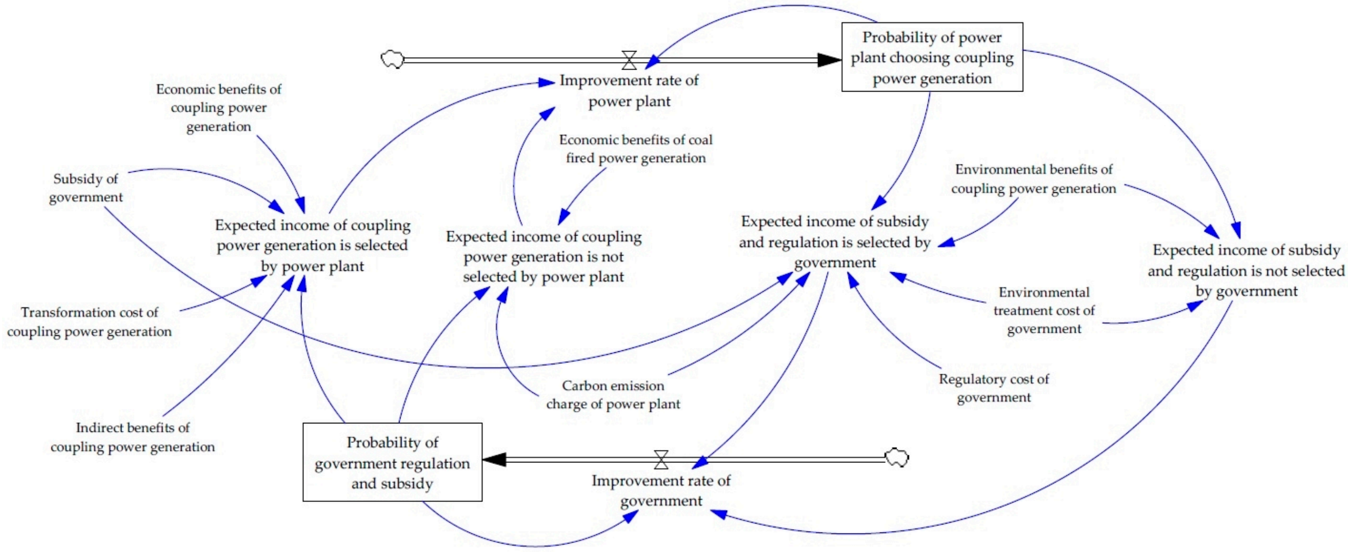



**Figure 3.** The stock and flow diagram of a system dynamics model of the government and power plants.

### 3.2. Analysis of Simulation Results

The initial parameters of the model are set as INITIAL TIME = 0, FINAL TIME = 100, and TIME STEP = 1. Based on existing research [26,28,54,55] and field survey data, the following values were assigned to relevant variables: $EC_c = 10$, $EC_b = 8$, $EN_b = 2$, $C = 4$, $B = 2$, $F = 5$, $S = 2$, $M = 3$, and $G = 2$.

#### 3.2.1. Initial Simulation Results

The initial value of the probability, x, of power plants choosing the coupled power generation strategy is set as 0.5, and the initial value of the probability, y, for the government to choose the regulation and subsidy strategy is also set as 0.5. The simulation results are shown in Figure 4.

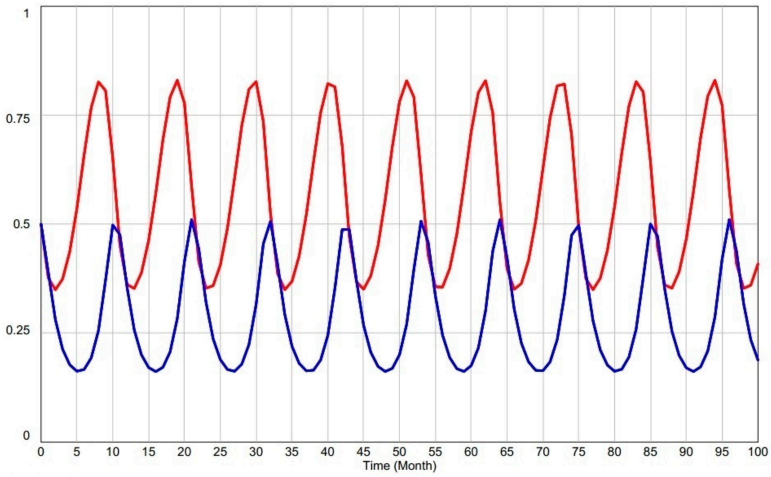



**Figure 4.** Initial simulation results of an evolutionary game model of power plants and the government.

As shown in Figure 4, the probability value, x, of power plants choosing the coupled power generation strategy fluctuates between [0.15, 0.55], while the probability value, y, of the government choosing the regulation and subsidy strategy fluctuates between [0.35, 0.85]. The strategies of power plants and the government cannot tend to a certain stable strategy, but change their own strategies according to each other in the long run. When the probability of power plants choosing coupled power generation is lower than a certain value, the government will increase the probability of regulating and subsidizing power plant. With the increase in the probability of government regulation and subsidization, power plants will increase their probability of choosing coupled power generation; however, when the probability of power plants choosing coupled power generation increases to a certain extent the government will reduce the probability of regulating and subsidizing power plants, after which the probability of power plants choosing coupled power generation will decrease, and the change trend in the strategies of power plants and the government is recurrent fluctuation in the long term.

3.2.2. The Influence of a Government Subsidy, S, on the Behavioral Strategies of the Players

The initial values of the system simulation remain unchanged and only the values of S are changed, which are set as S = 1 and S = 3. The influences of a reduction (S = 1) and increase (S = 3) in a subsidy on the behavior strategies of power plants and the government are analyzed successively. The simulation results are shown in Figure 5. When the subsidy amount is reduced, the probability value, x, of power plants choosing the coupled power generation strategy fluctuates between [0.2, 0.6], and the probability value, y, of the government choosing the regulation and subsidy strategy fluctuates between [0.4, 0.9]. When the subsidy amount increases, the probability value, x, of power plants choosing the coupled power generation strategy fluctuates between [0.1, 0.5], while the probability value, y, of the government choosing the regulation and subsidy strategy fluctuates between [0.25, 0.8].

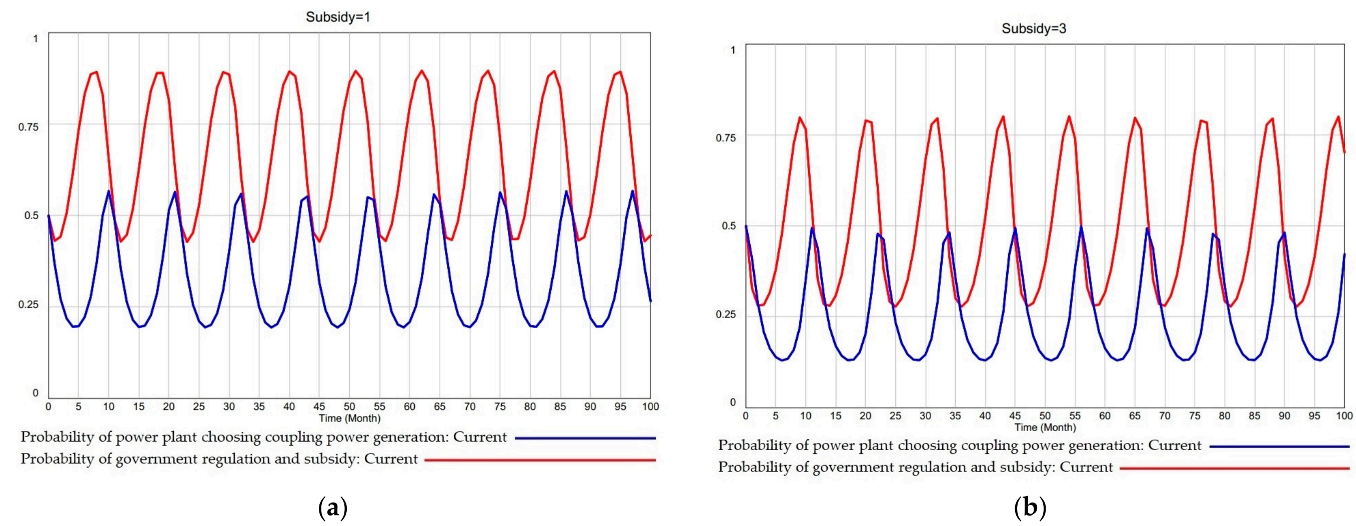
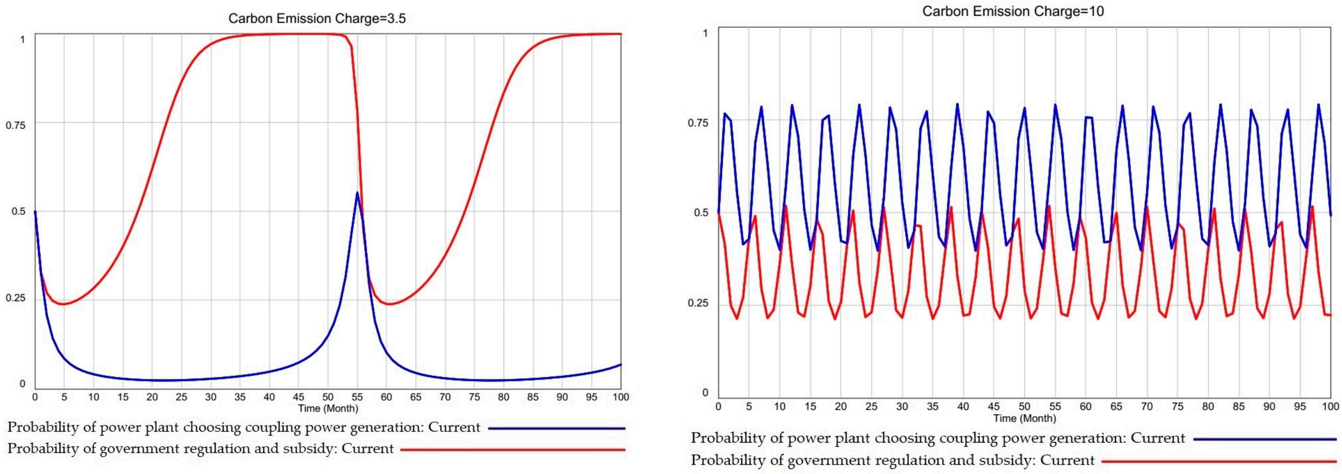



**Figure 5.** Simulation results of a change in the government subsidy amount, S. (**a**) Government subsidy amount equals 1; (**b**) government subsidy amount equals 3.

By comparing Figures 4 and 5, it can be seen that when the government subsidy amount decreases (S = 1) the probability of the government choosing the regulation and subsidy strategy increases, which further affects the probability of power plants choosing the coupled power generation strategy. On the contrary, when the government subsidy amount increases (S = 3), the probability of the government choosing the regulation and subsidy strategy for power plant decreases, resulting in a decrease in the probability of power plants choosing the coupled power generation strategy. Meanwhile, as can be seen from the change trend in power plants' strategies in Figure 5, when the government subsidy amount, S, decreases, the change in the power plant strategy curve slows down, while when the subsidy amount, S, increases, the change in the power plant strategy curve intensifies. This indicates that a change in the government subsidy amount can not only change the probability of power plants' and the government's strategy selection, but also improve or reduce the degree of influence of the government's strategies on the strategies of power plants. Therefore, if the government wants to promote the development of the coupled power generation industry in a relatively short period of time and improve the probability of power plants choosing coupled power generation technology, it should increase the probability and amounts of subsidies to power plants.

#### 3.2.3. The Influence of the Carbon Emission Charge, F, Paid by Power Plants on the Behavioral Strategies of the Players

The initial value of the system simulation remains unchanged, and only the value of F is changed, that is, the carbon emission charge (i.e., penalty amount) that power plants need to pay for coal-fired power generation under government regulation. The F is set as F = 3.5 and F = 10. The influence of reducing (F = 3.5) and increasing (F = 10) the penalty amount on the behavior strategies of power plants and the government is analyzed successively. The simulation results are shown in Figure 6. When the carbon emission charge to be paid by the power plant is reduced, the probability value, x, of power plants choosing the coupled power generation strategy fluctuates between [0.02, 0.55], while the probability value, y, of the government choosing the regulation and subsidy strategy fluctuates between [0.2, 1]. When the carbon emission charge to be paid by power plants increases the probability value, x, of power plants choosing the coupled power generation strategy fluctuates between [0.4, 0.8], while the probability value, y, of the government choosing the regulation and subsidy strategy fluctuates between [0.2, 0.55].



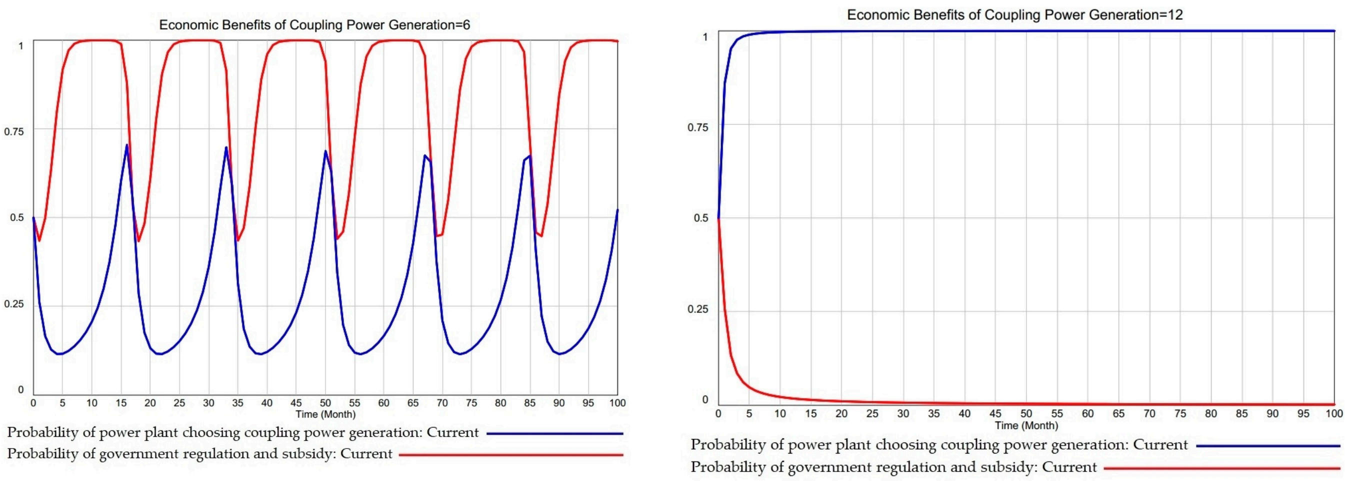

(**a**) (**b**)

**Figure 6.** Simulation results of a change in the carbon emission charge, F. (**a**) Carbon emission charge equals 3.5; (**b**) carbon emission charge equals 10.

By comparing Figures 4 and 6, it can be seen that when the carbon emission charge of power plants is reduced under government regulation (F = 3.5) power plants are very reluctant to choose coupled power generation due to the lax government supervision. Only when power plants notice that the government will definitely choose the strategy of supervision and subsidy (i.e., the probability of government supervision and subsidy is 1), will they improve the probability of choosing the coupled power generation strategy. When the carbon emission charge to be paid by power plants increases (F = 10), since the fee is very high once it is regulated by the government, power plants are reluctant to take risks and prefer to choose the coupled power generation strategy. As long as the government slightly increases the probability of choosing regulation and subsidies, the probability of choosing coupled power generation for the power plant will increase. Therefore, the government will increase the carbon emission charge paid by coal-fired power plants, which will encourage more power plants to choose coupled power generation.

3.2.4. The Influence of the Economic Benefits, $EC_b$, of Coupled Power Generation on the Behavior Strategies of the Players

The initial simulation values of the system remained unchanged, and only the values of the economic benefits, $EC_b$, of the coupled power generation of AFB and coal are changed, which are set as $EC_b = 6$ and $EC_b = 12$, respectively, so as to analyze the influence of a reduction ($EC_b = 6$) and increase ($EC_b = 12$) in economic benefits on the behavior strategies of power plants and the government. The simulation results are shown in Figure 7. When the economic benefits of coupled power generation decrease, the probability value, x, of power plants choosing the coupled power generation strategy fluctuates between [0.1, 0.7], while the probability value, y, of the government choosing the regulation and subsidy strategy fluctuates between [0.4, 1]. When the economic benefits of coupled power generation increase, the initial value of the probability, x, of power plants choosing the coupled power generation strategy is between [0.85, 1] and soon becomes stable at 1, while the initial value of the probability, y, of the government choosing the regulation and subsidy strategy is between [0, 0.3] and soon becomes stable at 0.



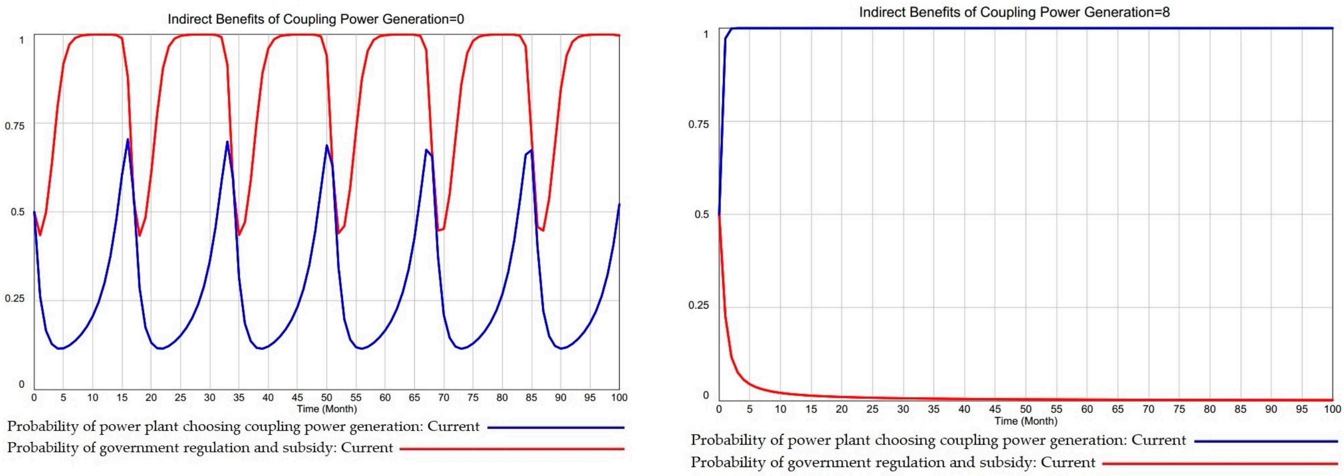

(**a**) (**b**)

**Figure 7.** Simulation results of a change in the economic benefits of coupling power generation, $EC_b$. (**a**) Economic benefits of coupling power generation equal 6; (**b**) economic benefits of coupling power generation equal 12.

By comparing Figures 4 and 7, it can be seen that when the economic benefits of the coupled power generation of AFB and coal decrease ($EC_b = 6$) the probability of power plants choosing the coupled power generation strategy decreased, and the probability of choosing the coupled power generation strategy will be increased only after ensuring that the government will implement regulatory and subsidy policies for power plants (i.e., the probability of government regulation and subsidies is 1). By comparing Figures 4 and 7, it can be seen that when the economic benefits of coupled power generation decrease ($EC_b = 6$) the main reason for this is that the economic benefits generated by coal-fired power generation are far greater than those obtained by coupled power generation. Without strong government regulatory and subsidy policies, power plants will not actively choose coupled power generation. On the contrary, when the economic benefits of coupled power generation increase ($EC_b = 12$) the economic benefits of power plants choosing the coupled power generation of AFB and coal are greater than those of coal-fired power generation. Power plants will actively choose the coupled power generation strategy to obtain larger economic benefits, and the government will no longer supervise and subsidize power plants.

### 3.2.5. The Influence of the Indirect Benefits, B, of Coupled Power Generation on the Behavior Strategies of the Players

The initial numerical value of the system simulation remains unchanged, and only the indirect benefits, B, generated by the coupled power generation of AFB and coal are changed, which are set as B = 0 and B = 8, respectively, so as to analyze the influence of a reduction (B = 0) and increase (B = 8) in the indirect benefits of coupled power generation on the behavior strategies of power plants and the government. The simulation results are shown in Figure 8. When the indirect benefits of coupled power generation decrease, the probability value, x, of power plants choosing the coupled power generation strategy fluctuates between [0.1, 0.7], and the probability value, y, of the government choosing the regulation and subsidy strategy fluctuates between [0.4, 1]. When the indirect benefits of coupled power generation increase, the initial value of the probability, x, of power plants choosing the coupled power generation strategy is between [0.95, 1] and soon becomes stable at 1, while the initial value of the probability, y, of the government choosing the subsidy and regulation strategy is between [0, 0.25] and soon becomes stable at 0.




(**a**) (**b**)

**Figure 8.** Simulation results of changes in the indirect benefits of coupled power generation, B. (**a**) Indirect benefits of coupled power generation equal 0; (**b**) indirect benefits of coupled power generation equal 8.

By comparing Figures 4 and 8, it can be seen that the influence of changes in the indirect benefits on the behavioral strategies of the government and power plant is similar to that of changes in the economic benefits. When the indirect benefits generated by the coupled power generation of AFB and coal are reduced (B = 0) the overall economic benefits will also be reduced, and the probability of power plants choosing the coupled power generation strategy will be reduced. Similarly, the probability of choosing the coupled power generation strategy is increased only after ensuring that the government will implement regulatory and subsidy policies for power plants (i.e., the probability of the government adopting regulation and subsidies is 1); however, when the indirect benefits of the coupled power generation of AFB and coal increase (B = 8), if the total economic benefits generated by the coupled power generation of power plants exceed coal-fired power generation, power plants will actively choose coupled power generation and the government will no longer regulate and subsidize power plants.

### 3.2.6. The Influence of the Transformation Cost, C, of Coupled Power Generation on the Behavior Strategies of the Players

The initial values of system simulation remain unchanged, and only the value of the coupled power generation transformation cost, C, is changed, which is set as C = 0 and C = 6, so as to analyze the influence of a reduction (C = 0) and increase (C = 6) in the transformation cost on the behavior strategies of power plants and the government. The simulation results are shown in Figure 9. When the coupled power generation transformation cost is reduced, the initial value of the probability, x, of power plants choosing the coupled power generation strategy is between [0.85, 1] and soon becomes stable at 1, while the initial value of the probability, y, of the government choosing the subsidy and supervision strategy is between [0, 0.3] and soon becomes stable at 0. When the coupled power generation transformation cost increases, the probability value, x, of power plants choosing the coupled power generation strategy fluctuates between [0.1 and 0.7], and the probability value, y, of the government choosing the regulation and subsidy strategy fluctuates between [0.4, 1].

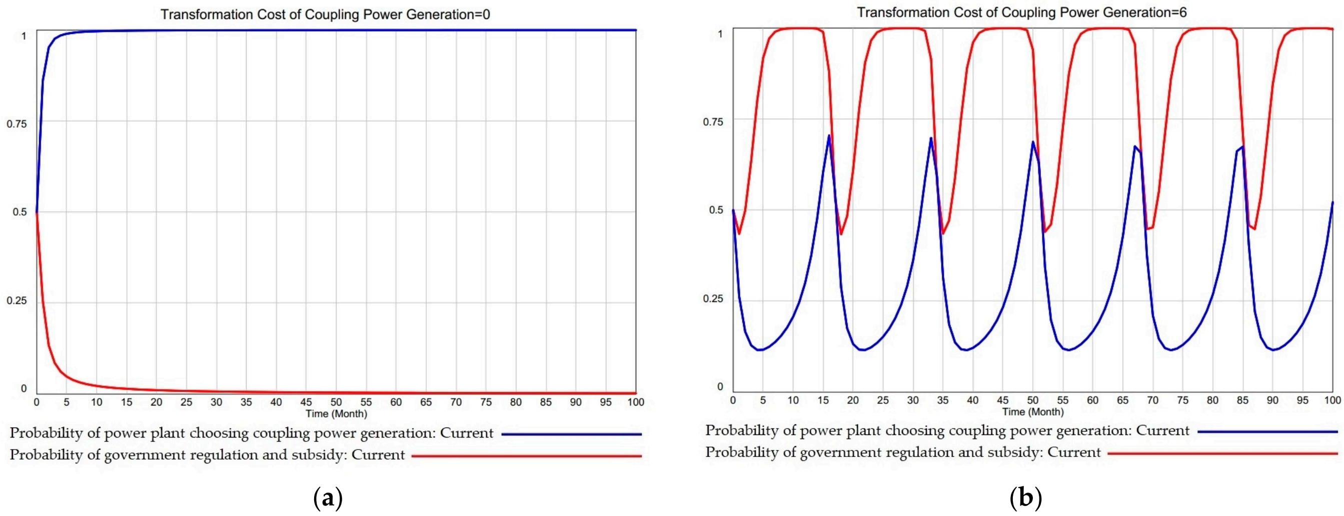



**Figure 9.** Simulation results of a change in the coupled power generation transformation cost, C. (**a**) Transformation cost of coupled power generation equals 0; (**b**) transformation cost of coupled power generation equals 6.

By comparing Figures 4 and 9, it can be seen that the influence of the coupled power generation transformation cost on the behavior strategies of the government and power plants is exactly the opposite of the influence of the coupled power generation economic benefits and indirect benefits. When there is no transformation cost (C = 0) power plants are very willing to choose the coupled power generation strategy, and the government will no longer regulate and subsidize power plants. When the transformation cost increases (C = 6), power plants need to pay a higher cost to choose the coupled power generation strategy, and the probability of choosing this strategy will decrease, while the government's regulatory and subsidy policies are needed to improve the probability of power plants choosing coupled power generation.

## 4. Discussion

In order to make up for the lack of consideration of the dynamic changes in government policies in previous research, this study explores the dynamic evolution process of the government and power plants' behavior strategies in the long term by constructing an evolutionary game model and system dynamics game. The influence paths of key factors on the government and power plants' behavior strategies are demonstrated to better formulate policies and measures to promote the development of the coupled power generation of AFB and coal industry. At the same time, this study can provide some references for other countries in the development of the coupled power generation of AFB and coal.

With regard to the results in this study, they can be discussed from three perspectives:

The first is a unilateral behavior strategy analysis of power plants and the government. When the influence of the other side's behavior strategies is not considered, the unilateral behavior strategies of power plants and the government are very stable. For power plants, as long as the government provides sufficient financial subsidies and implements regulatory measures for the coupled power generation of AFB and coal, they will choose coupled power generation. For the government, the essential purpose of subsidies for and the regulation of power plants is to reduce carbon emissions and improve environmental benefits. When many power plants do not adopt coupled power generation technology the government will increase subsidies and regulation to encourage more power plants to choose it.

The second is to study the dynamic evolution processes of power plants and the government's behavior strategies. According to the results of the evolutionary game model, the behavioral strategies of power plants and the government interact with and influence each other from a long-term development perspective, and the behavioral strategies of both sides cannot be stabilized but fluctuate. This is consistent with the research results of Li et al. [56] as well as Gao and Xi [57], that is, it is difficult for fixed policies and measures to effectively promote industrial development, and policies as well as measures should be constantly adjusted to adapt to the changes in enterprise behavior and strategy. When the probability of power plants choosing coupled power generation is lower than a certain value the government will increase the probability of subsidies for and the regulation of power plants. With the increase in the probability of government subsidies and regulation, power plants will increase the probability of choosing coupled power generation; however, when the probability of power plants choosing coupled power generation increases to a certain extent the government will reduce the probability of subsidies and regulation, after which the probability of power plants choosing coupled power generation decreases.

The third is an analysis of the influence paths of the key factors on the government and power plants' behavior strategies. This study selects key factors, such as the government subsidy amount, the carbon emissions charge paid by power plants, the economic benefits of coupled power generation, the indirect benefits of coupled power generation, and the transformation cost of coupled power generation, and analyzes how changes in these factors affect the behavior strategies of the government and power plants. When the government increases the subsidy amount for selected coupled power plants, power plants will be motivated to choose the coupled power generation strategy, which is also in line with the research expectations of Zhai et al. [40] as well as Luo and Miller [41], that is, an increase in the government subsidy amount improves an enterprise's participation enthusiasm, but an increase in the subsidy amount only increases the probability of choosing coupled power generation. The reason for this is that the subsidy amount is an external factors for power plants to choose coupled power generation. Once the external factors disappear, the probability of power plants choosing coupled power generation will be greatly reduced. At present, China has not formulated specific subsidy policies in the field of the coupled power generation industry of AFB and coal; however, there are related subsidy policies for biomass power generation, such as an electricity price subsidy policy. In 2010, the notice issued by the National Energy Administration of China was that the electricity generated by biomass energy was all incorporated into the national grid at a price of RMB 0.75. The price was the sum of the benchmark price and the subsidy price for renewable energy. The benchmark price was RMB 0.3068 and the subsidy price was RMB 0.4432 [58]. This electricity price subsidy has greatly promoted the development of the biomass power generation industry. This is consistent with the conclusion of this study, that subsidy policies can promote the development of the coupled power generation industry of AFB and coal. Similarly, when the carbon emission charge paid by power plants increases, enterprises face a very large risk of being punished with an increase in the probability of government regulation. In order to reduce the risk and cost, enterprises are more willing to choose the coupled power generation strategy. The carbon emission charge is also an external factor. When the carbon emission charge is reduced, enterprises are reluctant to choose coupled power generation because coal-fired power generation can bring more benefits.

However, changes in the economic benefits, indirect benefits, and transformation cost of the coupled power generation of AFB and coal will essentially change the behavioral strategies of power plants and the government. When the economic and indirect benefits generated by coupled power generation exceed the benefits obtained by coal-fired power generation, power plants will independently choose coupled power generation and the government will no longer need to formulate corresponding subsidy policies and regulatory measures. Similarly, when the transformation cost of coupled power generation is zero power plants are very willing to choose the coupled power generation strategy, and the government will no longer subsidize and regulate power plants; however, when the transformation cost is very high, far exceeding the benefits brought by coupled power generation, few power plants are willing to choose it. In this case, the government needs to formulate very high policy subsidies and strict regulatory measures. It can be seen that improving the economic and indirect benefits of coupled power generation in addition to reducing the transformation cost will encourage more power plants to choose it.

Despite the in-depth research in this study, some shortcomings must be admitted. First of all, the relevant subjects involved in this study are the government and power plants, and the subjects in the coupled power generation of AFB and coal also include raw material suppliers, brokers, logistics, and so on. It is hoped that more research subjects can be added in future research. Secondly, the selection of key factors affecting the subjects' strategies is limited in this study, most of which focus on benefits and costs. It is hoped that the selection scope of key factors can be expanded in future studies to bring research closer to reality.

## 5. Conclusions and Policy Recommendations

This study analyzes and simulates the behavior strategies of power plants and the government in the coupled power generation of AFB and coal, aiming at developing effective policies and measures to promote the development of the coupled power generation industry. In summary, we figured out the interactions and adjustment processes of the behavioral strategies of the government and power plants, and the specific effects of key factors on the behavioral strategies of the government and power plants were clarified. The conclusion is consistent with the hypothesis. The main research conclusions are as follows:

(1) In the process of the development of the coupled power generation of AFB and coal, the behavioral strategies of power plants and the government dynamically influence each other. The government's subsidy strategies and regulatory measures for the coupled power generation industry will drive more power plants to choose it.

(2) The government will increase the amount of policy subsidies and strengthen the punishment of coal-fired power plants, which will encourage more power plants to choose the coupled power generation of AFB and coal. Meanwhile, improving the economic benefits, increasing the indirect benefits, and reducing the transformation cost of coupled power generation can encourage more power plants to choose coupled coal power generation.

(3) The government's corresponding policy regulatory and subsidy measures can only change the enthusiasm of power plants to choose the coupled power generation of AFB and coal. In order to fundamentally enable power plants to independently choose it, it is necessary to increase the income obtained by the choice or reduce the transformation cost of coupled power generation.

According to the above research conclusions, corresponding suggestions are further proposed as follows: (1) Improving the timeliness of industrial policy measures. Since the behavioral strategies of power plants and the government can influence each other, the government should adjust and feed back the behavioral strategies of power plants quickly and accurately when formulating industrial policies, so as to ensure the timeliness of policy measures. (2) Improve the standards of industrial subsidy and punishment mechanisms. The government should subsidize and reward power plants that adopt the coupled power generation of AFB and coal, punish coal-fired power plants, and formulate as well as improve the levels and standards of the corresponding subsidy and punishment mechanisms, which will effectively encourage more power plants to choose coupled power generation. (3) Deepen technological research as well as development and improve the raw material supply system. Increasing the research on as well as innovation of the coupled power generation technology of AFB and coal, in addition to improving the supply systems of AFB raw materials, can reduce the economic cost of coupled power generation and further promote the development of this industry.

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