Evolutionary Game Study on Technical Cooperation Innovation of Photovoltaic Enterprises with Multi-agent Participation

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Abstract. The paper establishes a tripartite cooperative technology innovation game among photovoltaic enterprises, universities and governments, and analyzes the influence of government subsidies, distribution coefficient and other factors on the cooperative technology innovation game; this paper links the innovation cost with government subsidies and preferential policies, and puts forward the factors of innovation investment and policy support into the game model, which is based on the key influencing factors Based on the game payment matrix of three-party cooperation innovation of prime, the equilibrium solution of industry university research cooperation innovation is obtained by evolutionary game method, and the influence of innovation input, policy support, government subsidy and other factors on cooperation technology innovation is explored by numerical and case analysis. The results show that the appropriate subsidies of the government can effectively promote the technological innovation of cooperation between photovoltaic enterprises and universities; enterprises can improve the willingness of cooperation and innovation by properly increasing their investment in innovation; photovoltaic enterprises and universities are sensitive to the allocation ratio of cooperative income and penalties.

1. Introduction

It is difficult for a single enterprise to make significant breakthroughs in technological innovation by relying on its own strength. Enterprises seek to cooperate with universities or scientific research institutions in technological innovation[1]. There are many factors affecting cooperative innovation. It is of practical significance to clarify the main factors and their influencing mechanisms for improving the technological innovation capability of enterprises.

Scholars at home and abroad have studied the effect of government subsidies on photovoltaic enterprises. Literature mainly focuses on the promotion of government subsidies on R&D investment of photovoltaic enterprises and the role of government policies in reducing R&D costs of enterprises. Yang Guijin [2] analyzed the motivation of the development of government and photovoltaic enterprises, the mechanism of government subsidy, and the relationship between R&D investment and utilization subsidy. GuoBenhai and others believe that the effective incentives of the government can reduce the cost of photovoltaic enterprises cooperating with equipment manufacturers. Fan Bin [4] believes that increasing investment in research and development of photovoltaic technology is the key to reducing the production cost of photovoltaic products and enhance the competitiveness of the photovoltaic industry. Mansfield and others believe that financial subsidies can stimulate and promote enterprises to expand R&D investment. Fuyi [6] analyzed the specific manifestations of several
prominent problems in the financial subsidy policy of photovoltaic industry in China, such as pre-subsidy, one-size-fits-all, lack of innovation incentives and lack of post-supervision. Luigi et al. [7] through studying the policies of photovoltaic industry in Eastern European countries, put forward excessive incentive policies which are not conducive to the healthy development of photovoltaic industry. Zhou Dequn et al. [8] introduced the learning curve method to analyze the impact of changes in the game equilibrium strategy between photovoltaic enterprises and the government.

This paper constructs the payment matrix of evolutionary cooperative innovation game between photovoltaic enterprises, universities and the government, considers the influence of government subsidies, preferential policies, innovation input and policy support on innovation revenue and cost, and obtains the equilibrium solution of the three-party cooperative technology innovation game, and studies it through simulation and case study. The impact of different changes in government subsidies, innovation investment and policy support on technological innovation of photovoltaic enterprises, universities and government cooperation.

2. Model Construction and Solution

2.1. Hypothesis Conditions and Payment Matrix

Hypothesis 1: $x$, $y$ and $z$ are used to express the probability of photovoltaic enterprises, universities and governments choosing "cooperation" and "subsidy" strategies in the initial state of the game. Then the probability of photovoltaic enterprises choosing "non-cooperation" strategy is $1-x$, the probability of universities choosing "non-cooperation" strategy is $1-y$, and the probability of government choosing "non-subsidy" strategy is $1-z$, of which $x, y, z \in [0,1]$.

Hypothesis 2: $\alpha$ is used to represent the proportion of income allocation of photovoltaic enterprises, and $1-\alpha$ is used to represent the proportion of income allocation of colleges and universities, of which $0<\alpha<1$ is used.

Hypothesis 3: Income. $\pi_1$ and $\pi_2$ are used to express the profit of photovoltaic enterprises before they cooperate with universities. $k$ is used to express the profit of photovoltaic enterprises and university colleagues when choosing "cooperation" strategy. Then photovoltaic enterprises choose the profit of cooperative innovation as $\alpha k$, and universities choose the profit of cooperative innovation as $(1-\alpha)k$. $b$ indicates that the proportion of the government's revenue from the non-subsidy strategy is the proportion of the government's revenue from the subsidy strategy, while the government's revenue from the non-subsidy strategy is $bR$, of which $0<b<1$.

Hypothesis 4: The innovation investment of photovoltaic enterprises is expressed by $\theta$, and $0<\theta<1$.

Hypothesis 5: Use $\beta$ to express the government's policy support, of which $0<\beta<1$. At the same time, when the government chooses the "subsidy" strategy, the government will provide corresponding financial support to photovoltaic enterprises, using $G$ to express the government's financial subsidies to photovoltaic enterprises.

Hypothesis 6: the cost of cooperative innovation invested by photovoltaic enterprises is expressed by $(1-\beta)^{\frac{1}{\theta}}C_1$, and the cost of cooperative innovation invested by universities is expressed by $(1-\beta)C_2$.

Hypothesis 7: Use $H$ to denote the penalty paid to the other party by either party in photovoltaic enterprises or universities for breach of contract.

The payment matrix of industrial technical cooperation innovation under the participation of photovoltaic enterprises, universities and the government is shown in Table 1.
Table 1 Revenue Matrix of Photovoltaic Enterprises, Universities and Governments under Different Strategies Combination

| strategy                              | Photovoltaic Enterprises (E) | universities (S) | government (A) |
|---------------------------------------|-------------------------------|-----------------|---------------|
| (Cooperation, Cooperation, Subsidies) | $\pi_1 + \alpha k + G - (1 - \beta)^2 C_i$ | $\pi_2 + (1 - \alpha)k - (1 - \beta)C_2$ | $R - G$       |
| (Cooperation, cooperation, non-subsidy) | $\pi_1 - \alpha k - C_i$    | $\pi_2 + (1 - \alpha)k - C_2$ | $hR$          |
| (Cooperation, non-cooperation, subsidies) | $\pi_1 + H + G - (1 - \beta)^2 C_i$ | $\pi_2 - H$    | $-G$          |
| (Cooperation, non-cooperation, non-subsidy) | $\pi_1 + H - C_i$    | $\pi_2 - H$    | $0$           |
| (Non-cooperation, cooperation and subsidies) | $\pi_1 + G - H$    | $\pi_2 + H - (1 - \beta)C_2$ | $-G$          |
| (Non-cooperation, non-cooperation, subsidies) | $\pi_1 + G$    | $\pi_2$        | $-G$          |
| (Non-cooperation, non-cooperation and non-subsidy) | $\pi_1$    | $\pi_2$        | $0$           |

2.2. Evolutionary Game Model Solution

According to the income payment matrix under the strategic combination of photovoltaic enterprises, universities and governments in Table 1, the average expected income of photovoltaic enterprises $U_E$ is $U_E = xU_{E1} + (1 - x)U_{E2}$.

The $U_S$ of universities choosing "cooperation" strategy and "non-cooperation" strategy are respectively: $U_S = yU_{S1} + (1 - y)U_{S2}$.

Similarly, the average expected return $U_A$ can be obtained respectively: $U_A = zU_{A1} + (1 - z)U_{A2}$.

According to the average expected return obtained, the replication dynamic equation of photovoltaic enterprises choosing "cooperation" strategy is obtained as follows:

$$F(x) = \frac{dx}{dt} = x(U_{E1} - U_E) = x(1 - x)[z(C_i - (1 - \beta)^2 C_i) + y\alpha k + H - C_i]$$  \hspace{1cm} (1)

The replication dynamic equation of university choosing "cooperation" strategy is as follows:

$$F(y) = \frac{dy}{dt} = y(U_{S1} - U_S) = y(1 - y)[z\beta C_i + x(1 - \alpha)k + H - C_i]$$  \hspace{1cm} (2)

The replication dynamic equation of government's choice of "subsidy" strategy is as follows:

$$F(z) = \frac{dz}{dt} = z(U_{A1} - U_A) = z(1 - z)[xy(R - bR) - G]$$  \hspace{1cm} (3)

According to formula (1, 2, 3), eight local equilibrium points can be obtained: (0, 0, 0), (1, 0, 0), (0, 1, 0), (0, 0, 1), (1, 1, 0), (1, 0, 1), (1, 0, 1), (0, 1, 1), and (1, 1, 1).

The stability of differential equation system can be obtained by Jacobian matrix of the system. The Jacobian matrix can be obtained by the above formula as follows:

$$J = \begin{bmatrix}
(1 - 2x)[z(C_i - (1 - \beta)^2 C_i) + y\alpha k + H - C_i] & x(1 - x)\alpha k & x(1 - x)(C_i - (1 - \beta)^2 C_i) \\
y(1 - y)(1 - \alpha)k & (1 - 2y)[z\beta C_i + x(1 - \alpha)k + H - C_i] & y(1 - y)\beta C_i \\
z(1 - z)y(R - bR) & z(1 - z)x(R - bR) & (1 - 2z)[xy(R - bR) - G]
\end{bmatrix}$$
2.3. Evolutionary Game Model Analysis

According to the above evolutionary game model, the eigenvalues of other equilibrium points can be obtained as shown in Table 2.

| Equilibrium Point | characteristic value | characteristic value | characteristic value |
|-------------------|----------------------|----------------------|----------------------|
| (0, 0, 0)         | $H - C_1$            | $H - C_1$            | $-G$                 |
| (1, 0, 0)         | $-H + C_1$           | $(1-\alpha)k + H - C_2$ | $-G$                 |
| (0, 1, 0)         | $ak + H - C_1$       | $-H + C_2$           | $-G$                 |
| (0, 0, 1)         | $-(1-\beta)^2 C_1 + H$ | $\beta C_2 + H - C_2$ | $G$                  |
| (1, 1, 0)         | $-ak - H + C_1$      | $-(1-\alpha)k - H + C_2$ | $R - bR + G$         |
| (1, 0, 1)         | $(1-\beta)^2 C_1 - H$ | $\beta C_2 + (1-\alpha)k + H - C_2$ | $G$                  |
| (0, 1, 1)         | $-(1-\beta)^2 C_1 + ak + H$ | $-\beta C_1 - H + C_2$ | $G$                  |
| (1, 1, 1)         | $(1-\beta)^2 C_1 - ak - H$ | $-\beta C_2 - (1-\alpha)k - H + C_2$ | $R + bR + G$         |

Because there are many parameters in the model, the default cooperative technology innovation income $k$ is much larger than the cost $C_1$ and $C_2$, and the net income of government subsidies is much larger than that of non-subsidies, that is, $R > bR + G$. The stability of technological innovation in photovoltaic enterprises, universities and governments can be discussed in two ways. The specific results are shown in Table 3.

In case one, when a photovoltaic enterprise or university defaults and does not participate in cooperative innovation, the penalty provided is less than the cost of participating in cooperation, that is $H < C_1, H < C_2$. At this time, as can be seen from Table 3, the eigenvalues corresponding to equilibrium points (0, 0, 0) and points (1, 1, 1) are not positive, which is the evolutionary stability point. In this case, the corresponding evolutionary strategies are (non-cooperation, non-subsidy), (cooperation, cooperation, subsidy).

Second, when a photovoltaic enterprise or university defaults and does not participate in cooperative innovation, the penalty provided is greater than the cost of its participation in cooperation, that is $H > C_1, H > C_2$. At this time, it can be seen from Table 3 that the eigenvalues of equilibrium points (1, 1, 1) are not positive, and they are evolutionary stable points. In this case, the corresponding evolutionary strategies are (cooperation, subsidies), and the other equilibrium points are unstable points or saddle points.
Table 3 Stability Table of Equilibrium Point of Technological Innovation Game between Photovoltaic Enterprises, Universities and Governments

| Equilibrium Point | Situation I |       |       | Situation II |       |       |
|-------------------|-------------|-------|-------|--------------|-------|-------|
|                   | \( \lambda_1 \) | \( \lambda_2 \) | \( \lambda_3 \) | stability   | \( \lambda_1 \) | \( \lambda_2 \) | \( \lambda_3 \) | stability   |
| (0, 0, 0)         | -           | -     | -     | ESS         | +     | +     | -     | Unstable point |
| (1, 0, 0)         | +           | +     | -     | Unstable point | -     | +     | -     | Unstable point |
| (0, 1, 0)         | +           | +     | -     | Unstable point | +     | -     | -     | Unstable point |
| (0, 0, 1)         | +           | -     | +     | saddle point | +     | +     | +     | saddle point |
| (1, 1, 0)         | -           | -     | +     | Unstable point | -     | -     | +     | Unstable point |
| (1, 0, 1)         | +           | -     | +     | saddle point | -     | +     | +     | Unstable point |
| (0, 1, 1)         | +           | +     | -     | saddle point | +     | -     | +     | Unstable point |
| (1, 1, 1)         | -           | -     | -     | ESS         | -     | -     | -     | ESS         |

3. numerical simulation
In order to more intuitively reflect the evolution process and law of the cooperation technology innovation of photovoltaic enterprises, universities and the government, this paper uses MATLAB software to simulate and analyze the cooperation technology innovation process. On the basis of considering the realistic cooperative innovation, the parameters in the model are initially assigned. Specific parameter assignments are shown in the following table:

| parameter | \( \alpha \) | \( R \) | \( b \) | \( \theta \) | \( \beta \) |
|-----------|-------------|-------|-------|-------------|-------|
| assignment| 0.6         | 200   | 0.5   | 0.6         | 0.3   |

3.1. Impact of Policy Support on Technological Innovation of Photovoltaic Enterprises

Fig. 1 Evolution of Tripartite Cooperative Technological Innovation under the Change of Policy Support

Fig. 1 is a simulation of the impact of changes in government policy support on the technological innovation of tripartite cooperation under the condition where other parameters remain unchanged. From Figure 1, we can see that the critical value of policy support is between 0.2 and 0.3. When the...
policy support is less than the critical value, the cooperation willingness of photovoltaic enterprises will increase slightly because of the higher initial cooperation willingness of universities, but eventually tend to (0, 0, 0). At this time, with the gradual increase of government policy support strength, the cooperation willingness of photovoltaic enterprises will increase slightly. The speed of convergence of photovoltaic enterprises, universities and the government to (0, 0, 0) slows down with the increase of the government's support.

3.2. The impact of the change of enterprise innovation investment on the innovation of photovoltaic enterprises' cooperative technology

Fig. 2 Evolution of Tripartite Cooperative Technological Innovation with the Change of Enterprise Innovation Input

Fig. 2 is a simulation of the impact of the change of enterprise innovation investment on the technological innovation of the tripartite cooperation subject under the condition where other parameters remain unchanged. Fig. 2 shows that the critical value of enterprise innovation investment is between 0.8 and 0.9. When enterprise innovation investment is less than that critical value, photovoltaic enterprises and universities finally converge to (1, 1, 1). With the increase of enterprise innovation investment, the speed of photovoltaic enterprises and universities convergence to (1, 1, 1) slows down. When the investment intensity of industry innovation is greater than the threshold value, the cooperation willingness of photovoltaic enterprises will increase slightly at the beginning, but will eventually tend to (0, 0, 0). At this time, with the increase of the investment intensity of enterprise innovation, photovoltaic enterprises and universities converge to (0, 0, 0) speed.

4. Conclusion

The equilibrium solution of technological innovation is analyzed. The stable conditions of equilibrium solution are analyzed. The influence of the changes of innovation investment, policy support and government subsidy on cooperative technological innovation is emphatically analyzed. The following conclusions and enlightenments are obtained:

(1) Appropriate government subsidies can effectively promote technological innovation between photovoltaic enterprises and universities. Government subsidy is reflected in policy support and financial support. The enhancement of government policy support is conducive to promoting the cooperative innovation willingness of photovoltaic enterprises and universities; and direct financial support should be controlled in an appropriate range.

(2) Appropriate promotion of innovation investment by enterprises is conducive to enhancing the willingness of both sides to cooperate and innovate. Government financial subsidy is conducive to guiding photovoltaic enterprises to increase investment in technological innovation, but excessive investment in innovation will increase the asset burden of enterprises, and diminishing marginal benefits will reduce the willingness of photovoltaic enterprises to participate in cooperative innovation.
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