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Knowledge interaction analysis of cooperative digital green innovation of photovoltaic building materials enterprises based on reciprocity theory

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ABSTRACT

In the process of collaborative digital green innovation of photovoltaic building materials enterprises, knowledge sharing between photovoltaic building materials enterprises and academic and research institutions is conducive to the achievement of win-win goals of enterprises and academic and research institutions. However, due to the non-contractual relationship between cooperative subjects, it is difficult to observe the efforts of members, which is easy to cause poor information. Therefore, knowledge reciprocity incentive is particularly important. In this paper, the sequential reciprocity model is introduced to analyze the knowledge interaction between photovoltaic building materials enterprises, and academic and research institutions on cooperative green innovation. The results show that: (1) when the reciprocity sensitivity of academic and research institutions is large enough, academic and research institutions can feel the goodwill conveyed by the high effort level of knowledge sharing, and will reciprocate with friendly behavior. (2) When the reciprocity sensitivity of academic and research institutions is small, they will choose to pay a low level of effort in knowledge sharing. (3) When the reciprocity sensitivity of academic and research institutions is in the middle value, the higher effort level of the institutions will increase with the increase of reciprocity sensitivity of the institutions. In this paper, the sequential reciprocity model is introduced to study the reciprocity incentive effect of knowledge sharing in enterprise cooperative digital green innovation from the perspective of dynamic domain, in order to enrich the reciprocity theory and provide reference for the knowledge sharing incentive problem of enterprise cooperative digital green innovation.

Keywords: knowledge sharing incentive; photovoltaic building materials enterprises; digital green; sequential reciprocity model

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1. Introduction

The proposal of double carbon goal means that the sustainable development strategy of our country has entered a new stage, and the sustainable development of the new stage challenges the sustainable energy[1]. In the new stage of energy sustainability, we need to consider at least two aspects. First, we need to adhere to the long-term strategy of giving priority to energy conservation. Second, we need to accelerate the transformation of the energy mix and vigorously develop clean energy[2]. As a kind of clean energy, solar energy is also a kind of renewable energy. Solar energy has many advantages. It is not only safer and pollution-free than nuclear power, but also more abundant and stable than other clean energy sources such as wind and water[3]. The development of photovoltaic industry has realized the conversion of solar energy to electric energy. Vigorously developing the photovoltaic industry is an important link to speed up the transformation of energy structure. After decades of efforts, our photovoltaic industry has developed rapidly, and now has formed a complete industrial chain of photovoltaic, which not only has the conditions for large-scale power generation, but also has accumulated rich technical experience.

The Ministry of Industry and Information Technology and other four departments jointly issued the “carbon peak Implementation plan for Building Materials Industry” recently, to ensure that the building materials industry to achieve carbon peak before 2030[4]. The building materials industry is complete in product categories, the industrial chain is perfect, the production technology of kiln calcination is mature, unit energy consumption, pollutant emission has reached the international advanced level, but because of the large industrial scale, high process emission, the energy structure is partial to coal, the differences between industries are larger, the building materials industry does have a large total emission, the development is good and bad, the carbon peak work task is difficult[5].

In order to promote the building materials industry to reach the peak at a low level and reach the peak in a comprehensive way, the building materials industry needs to change the task of energy use structure, including increasing the proportion of alternative fuels, accelerating the application of clean and green energy, guiding enterprises to strengthen the fine management of energy, and improving the energy use efficiency of the building materials industry[6]. “Carbon Peak Implementation Plan for Building Materials Industry” clearly puts forward the key task of “accelerating the application of clean and green energy” and points out the important direction. It is imperative for building materials industry to vigorously develop clean energy. In 2020, coal will still account for 49% of China’s energy mix, but with the development of renewable energy, especially the definite growth of photovoltaic power generation is expected to surpass coal in 2030 and become the main energy source in 2060. The building materials industry clearly puts forward that accelerating the application of clean energy will help building materials enterprises install and use clean energy, and the economic characteristics of photovoltaic will also help improve the enthusiasm of building materials enterprises for energy conservation and emission reduction[7]. Photovoltaic and building materials two industries extend each other, photovoltaic building materials enterprise integration has become a high topic[8]. More and more photovoltaic enterprises choose to cooperate with building materials enterprises to give full play to each other’s advantages in technology research and development and channel installation. More and more photovoltaic building integration products gradually appear, and photovoltaic building materials manufacturing enterprises gradually develop[9].

Photovoltaic building materials manufacturing industry has become another green technology industry after IT and microelectronics[10]. Under the guidance of the goal of carbon neutrality, China’s photovoltaic building materials manufacturing enterprises will enter a period of rapid development. To achieve carbon neutrality in photovoltaic building materials industry is an extensive and profound green reform of industrial economy. It involves the adjustment of industrial structure and energy structure, the transformation of production mode and other practical issues, which requires the joint efforts of the whole society[11]. Building materials industry to change the energy-using structure, need many joint efforts to promote. By establishing a platform for communication and interaction between governments, enterprises, universities and other research institutes in the upstream and downstream of the photovoltaic building materials industry chain, the cooperation between the industry, the university and the research institute is guided, the knowledge sharing between the photovoltaic building materials manufacturing enterprises and the university and the research institute is strengthened, and the digital green innovation is promoted[12]. At the same time, it is necessary to consider the impact of various links on the environment from design, production, use to recycling, etc., and take photovoltaic application as the entry point to drive energy conservation and emission reduction of the building materials industry chain, so as to improve the green level of the whole life cycle[13].

Since the participants of digital green innovation come from different organizations, the cooperation between different participants is generally temporary and transient. There is no basis of non-contractual relationship, and it is not easy to observe the efforts of the members[14]. Therefore, the subjective willingness to cooperate among subject members is generally low, and each subject is more inclined to cooperate with subjects that have cooperated with each other before, which makes it difficult for different subjects to fully realize knowledge sharing as expected. The social laziness of subject members makes their willingness and effort level of knowledge sharing lower than they can actually achieve, which leads to the decrease of knowledge sharing value[15].

Existing researches on knowledge sharing mainly include: some scholars focus on knowledge sharing within organizations such as individuals and teams from a static perspective. Mir and Rafique believe that inclusive leadership has a significant positive impact on employees' knowledge sharing[16]. Yin and Yu pointed out in their study that at the project level, project manager empowerment leadership can significantly promote knowledge sharing within a project[17]. Mcgrath et al. provide a behavioural analysis focusing on opening play[18]. Xiao and Guo considered the influence of knowledge potential difference, built an evolutionary game model of knowledge sharing considering knowledge potential difference and solved the simulation, and analyzed that knowledge potential difference, knowledge sharing degree coefficient and collaborative income coefficient kept within a certain range in cross-organizational project cooperation would be conducive to knowledge sharing in cooperation[19]. Another part of scholars focus on external knowledge sharing from a dynamic perspective. Zhang et al. found that the higher the subsidy ratio, the higher the knowledge sharing level of universities, but it has no influence on the knowledge sharing strategy of enterprises[20]. Guo et al. found that in the industry-university-research collaborative innovation knowledge sharing system composed of universities and enterprises, there is a delayed effect when considering members' knowledge sharing strategies. The existence of delay time has a negative effect on knowledge sharing strategies of universities and enterprises, and when the delay time of knowledge sharing increases, enterprises will increase the subsidy ratio[21]. Li planned to establish a theoretical model of industrial agglomeration, knowledge sharing and innovation performance from the perspective of industrial agglomeration, and explored how to promote knowledge sharing and improve enterprise innovation performance through the correlation of industrial agglomeration[22]. Qi et al. explored the knowledge sharing behavior and influencing factors in the collaborative innovation network of advanced manufacturing enterprises, providing reference for different subjects to carry out knowledge sharing decision-making and improving the stability of the collaborative innovation system[23]. Liang and Zhao believed that the improvement of benefits brought by knowledge sharing, the enhancement of incentives for knowledge sharing behavior and the punishment for knowledge non-sharing behavior can strengthen the willingness of construction enterprises to share knowledge to a certain extent[24]. Hai-Wei and Shu-Yue found that in the process of green transformation, construction enterprises need to use a lot of knowledge and generate new knowledge. Therefore, the sharing of these knowledge is of great significance to promote the green transformation of the whole construction industry[25].

Existing research on green knowledge sharing mainly analyzes green knowledge sharing among supply chain nodal enterprises from the perspective of green supply chain. Cheng proposed a new research model to investigate the influencing factors of knowledge sharing and implementation in the nodal enterprise relationship of green supply chain. The findings provide useful insights into how green supply chain members can enhance their relationship benefits and relationship activities that will improve their value-based relationships in order to enhance environmental knowledge sharing in the green supply chain as a whole[26]. Lin et al. used descriptive statistics and CFA analysis to discuss the relationship between green knowledge sharing, green dynamic capability, green service innovation and green competitive advantage. Green knowledge sharing improves green dynamic capability[27], green service innovation[28] and green competitive advantage[29]. Absorbing and utilizing green knowledge shared among supply chain members to achieve excellent green innovation is the core issue faced by many Chinese manufacturing enterprises[30]. Song et al. tested and analyzed the samples of 247 Chinese manufacturing enterprises and suggested that Chinese manufacturing enterprises effectively develop absorptive capacity and realize the green innovation benefits of green knowledge sharing[31]. Some scholars quantitatively analyzed the influence of network conventions on heterogeneous knowledge sharing from multiple dimensions[32] and proposed[33] that the knowledge spillover and diffusion effects of agglomeration should be given full play. The green supply chain platform is embedded into industrial clusters, and the heterogeneous knowledge management mode of green supply chain under industrial agglomeration and integration is actively explored[34].

Existing researches on knowledge sharing incentive mainly focus on the knowledge sharing incentive within organizations such as individuals and teams based on the premise of rational human. Based on the reciprocity preference theory[35] and principal-agent theory[36] and the game analysis results, Wei concluded that the reciprocity effect among employees can improve the employees' efforts in knowledge sharing, and the reciprocity effect between enterprises and employees can improve the value of knowledge output of enterprises[37]. Azam et al. reviewed the research literature on incentives for knowledge sharing in recent ten years from three dimensions of inter-individual, intra-organization and inter-organization, as well as three aspects of influencing factors, mechanism design and effect evaluation, and considered the development trend and potential of the research on incentives for knowledge sharing in the future[38]. Choi et al. proposed that enterprises should develop a customer knowledge sharing evaluation mechanism and a benefit distribution mechanism based on the shared knowledge structure, and adjust the profit distribution coefficient according to the risk avoidance degree of customers[39], providing theoretical guidance for the formulation and implementation of enterprise knowledge sharing incentive mechanism[40]. He et al. used evolutionary game theory to analyze the strategy selection and evolutionary path of cloud manufacturing service integrators and suppliers in the incentive process of knowledge sharing, and put forward some countermeasures and suggestions to improve the performance of knowledge sharing in the cloud manufacturing innovation ecosystem, providing theoretical guidance for knowledge sharing among members of the cloud manufacturing innovation ecosystem[41].

First of all, previous studies on green knowledge mostly analyzed green knowledge sharing among supply chain nodes from the perspective of green supply chain, and there was a lack of research on green knowledge sharing between enterprises and academic and research institutions. Secondly, most of the researches on knowledge sharing incentive focus on the internal knowledge sharing incentive of individuals and groups from the static perspective, while there are few researches on knowledge sharing incentive of cooperative green innovation among different entities at the enterprise level in the dynamic strategy environment. Dufwenberg and Kirchsteiger constructed a sequential reciprocity game model with reciprocity motivation, extending reciprocity to a dynamic environment, which can explain the change of participants' beliefs and its impact on reciprocity behavior[42]. Based on this, this paper introduces the sequential reciprocity model to study the reciprocity incentive effect of knowledge sharing in collaborative digital green innovation of photovoltaic building materials enterprises from the perspective of dynamic domain, in order to enrich the reciprocity theory and provide reference for the knowledge sharing incentive problem of cooperative digital green innovation of enterprises.

The remaining research contents of this paper are as follows: The second part elaborates the theoretical basis; The third part establishes the game model and solves it. The fourth part analyzes the incentive effect of reciprocal preference knowledge sharing in academic and research institutions. The fifth part analyzes the incentive effect of reciprocal preference knowledge sharing in photovoltaic building materials enterprises. The sixth part summarizes the research results and analyzes the shortcomings of this study, and looks forward to the future research.

2. Theoretical basis

Many experimental studies have shown that people not only focus on material gains, but also consider the influence of altruistic fairness[43] and other factors when making decisions. Rabin proposed the concept of "reciprocity" in response to this phenomenon. He believed that when people are motivated by reciprocity, intention will play a crucial role, that is, when a person wants to be kind to those who are friendly to him or retaliate against those who are unfriendly to him, he must consider whether his action intention is friendly[44]. To this end, Rabin used the psychological game framework developed by Geanakoplos et al.[45], to incorporate reciprocity motivation into two-person game and build a two-person complete information static game model. Yin and Zhao built a multi-person complete information dynamic game model aiming at the limitations of the Rabin model, focusing on how strategy choice and reciprocity motivation change in sub-games, and requiring sequential rationality[46]. Chen et al. based on DK sequential reciprocal game model and generalized assumptions, constructed a two-stage sequential reciprocal model of cooperation behavior between suppliers and core enterprises in which core enterprises provide supply chain finance support[47]. The sequential reciprocal equilibrium between suppliers and core enterprises is derived under the assumption of supplier's complete rationality and reciprocity motivation. Based on DK sequential reciprocity model, this paper studies the reciprocity incentive effect of knowledge sharing in cooperative original innovation from the perspective of dynamic domain, in order to enrich the reciprocity theory and provide reference for the problem of knowledge sharing incentive in cooperative original innovation[48]. Ni and Paul argued that a person's friendliness depends on his intention to act, and intention depends on his belief in another person's intention to act, that is, the reciprocity motive depends on beliefs about faith. Ni and Paul. study finite multistage games[49]. It is also assumed that each player at any stage of the game (1) knows all the previous decisions; (2) only one action in each stage, and alternate actions; (3) the decision information of other participants in the current stage cannot be known. Since the research objects of this paper are two types of original innovation subjects: enterprises and academic and research institutions, it is assumed that the participants are i and j. The policy set of participant i is A_i. The belief set of participant i about the strategy of participant j is $B_{ij} = A_j$. The belief set of participant i about participant j's beliefs about participant i's strategies is $C_{iji} = B_{ji} = A_i$. Therefore, the belief of actor i about the strategy of actor j (first-order belief) is $b_{ij} \in B_{ij}$. The belief of participant i about participant j's belief about participant i's strategy (second-order belief) is $c_{iji} \in C_{iji}$.

The degree of goodwill of i to j is

$$\kappa_{ij}(a_i, b_{ij}) = \pi(a_i, b_{ij}) - \pi_j^{e_i}(b_{ij}) \tag{1}$$

where $\pi_j^{e_i}(b_{ij}) = \frac{[\max\{\pi_j(a_i,b_{ij})\}+\min\{\pi_j(a_i,b_{ij})\}]}{2}$ is the fair payment of j with respect to i, which means that when j's strategy b_{ij} is given, strategy a_i of i will bring j the average of the maximum and minimum returns; then, the degree of goodwill of i to j is described as the difference between the benefits that i 's choice will bring to j and the average benefits that i can bring to j.

In addition, since j's good will depends on j's belief, i cannot directly observe j's good will. However, i can infer j's good faith based on his beliefs about j's actions and beliefs. Therefore, the degree of goodwill that i perceives from j is

$$\lambda_{iji}(b_{ij}, c_{iji}) = \pi_i(b_{ij}, c_{iji}) - \pi_i^{e_j}(c_{iji}) \tag{2}$$

where $\pi_i^{e_j}(c_{iji}) = \frac{[\max\{\pi_i(b_{ij},c_{iji})\}+\min\{\pi_i(b_{ij},c_{iji})\}]}{2}$ is the fair payment of j by i. Then, the degree of goodwill perceived by j from j is described as the difference between the income j's choice will bring to i and the average income j can bring to i.

The utility of actor i is defined as

$$U_i(a_i, b_{ij}, c_{iji}) = \pi(a_i, b_{ij}) + \sum_{j \neq i} Y_{ij}\, \kappa_{ij}(a_i, b_{ij}) \lambda_{iji}(b_{ij}, c_{iji}) \tag{3}$$

The utility consists of two parts, the first part is i's material payment $\pi_j(a_i,b_{ij})$; The second part is the reciprocal payment of i to other players, where Y_{ij} is the reciprocal sensitivity of i to j, and $Y_{ij} > 0$, the subject with reciprocity motivation will decide the behavior he will take according to the intention of other players' behavior in the game, and the greater the reciprocity sensitivity, it is easier for i to make reciprocal response according to j's behavior, that is, i chooses "reciprocating kindness with kindness, the greater the motivation to reward unkindness with unkindness"; $\kappa_{ij}(a_i,b_{ij})$ is the degree of goodwill of i to j; $\lambda_{iji}(b_{ij}, c_{iji})$ is the degree to which i perceives goodwill from j.

3. Model

In the collaborative digital green innovation process of photovoltaic building materials enterprises, photovoltaic building materials enterprises focus on applied basic research on digital green innovation, while academic and research institutions focus on pure basic research on digital green innovation. The two types of digital green innovation subjects form an interactive mechanism through knowledge sharing[50]. Assume that in the collaborative digital green innovation process of photovoltaic building materials enterprises, the effort level of photovoltaic building materials enterprises' knowledge sharing is S_e and that of academic and research institutions' knowledge sharing is S_r. The strategy of photovoltaic building materials enterprises and academic and research institutions is to choose the high effort level of knowledge sharing and the low effort level of knowledge sharing, namely $S_e \in \{S_H, S_L\}$, $S_r \in \{S_h, S_l\}$, and $S_H > S_L$, $S_h > S_l$. Assume that the cost of knowledge sharing is a convex function of effort level[51], the cost of knowledge sharing in photovoltaic building materials enterprises is $C_e = \frac{1}{2} c_e S_e^2$, and the cost of knowledge sharing in academic and research institutions is $C_r = \frac{1}{2} c_r S_r^2$, where c_e and c_r are the cost coefficients of knowledge sharing between photovoltaic building materials enterprises and academic and research institutions, and $c_e > 0$, $c_r > 0$. Assume that the income generated by cooperative digital green innovation of photovoltaic building materials enterprises is π, and assume that the income is related to the effort level of knowledge sharing of both parties, namely $\pi = \theta S_e^{\alpha} S_r^{\beta}$, where θ is the income coefficient of cooperative digital green innovation between photovoltaic building materials enterprises and academic research institutions, and $\theta > 0$; α and β are the elastic coefficients of knowledge sharing efforts between photovoltaic building materials enterprises and academic and research institutions, and $0 < \alpha < 1$, $0 < \beta < 1$. It is assumed that the income is only distributed between two types of digital green innovation subjects: photovoltaic building materials enterprises and academic and research institutions. q is the proportion of income obtained by photovoltaic building materials enterprises, $1 - q$ is the proportion of income obtained by academic and research institutions, and $0 < q < 1$. The sequential game tree of knowledge sharing between photovoltaic building materials enterprises and research institutions is shown in **Figure 1**.

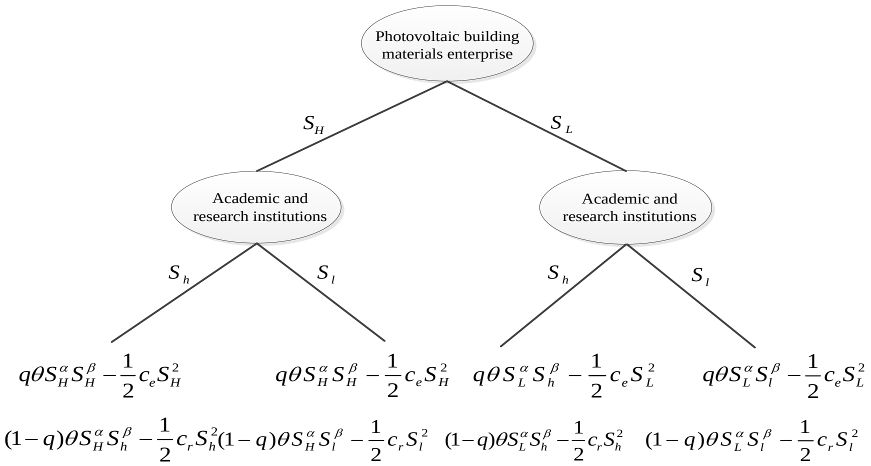

Figure 1. Sequential game tree of knowledge sharing between enterprise and universities and research institutions.

In addition, considering the Pareto improvement[52], which is also the embodiment of the significance of reciprocal behavior, it is assumed that the material payment obtained when both photovoltaic building materials enterprises and learning and research institutions choose to make high knowledge sharing effort is greater than the material payment obtained when both of them choose to make low knowledge sharing effort, namely $q\theta S_H^{\alpha} S_H^{\beta} - \frac{1}{2} c_e S_H^2 > q\theta S_L^{\alpha} S_h^{\beta} - \frac{1}{2} c_e S_L^2$.

Simplify to get $q\theta(S_H^{\alpha} S_h^{\beta} - S_L^{\alpha} S_l^{\beta}) > \frac{1}{2} c_e (S_H^2 - S_L^2)$;

$$(1-q)\theta S_H^{\alpha} S_l^{\beta} - \frac{1}{2} c_r S_l^2 > (1-q)\theta S_L^{\alpha} S_h^{\beta} - \frac{1}{2} c_r S_h^2 \tag{4}$$

Simplify to get

$$(1-q)\theta(S_H^{\alpha} S_h^{\beta} - S_L^{\alpha} S_l^{\beta}) \frac{1}{2} c_r S_h^2 > \frac{1}{2} c_r (S_h^2 - S_l^2) \tag{5}$$

It is assumed that when the learning and research institutions choose to pay a high level of knowledge sharing effort, the material payment obtained by the photovoltaic building materials enterprises when they choose to pay a high level of knowledge sharing effort is less than the material payment obtained when they choose to pay a low level of knowledge sharing effort, namely

$$(1-q)\theta S_H^{\alpha} S_h^{\beta} - \frac{1}{2} c_r {S_h}^2 < (1-q)\theta S_H^{\alpha} S_l^{\beta} - \frac{1}{2} c_r {S_l}^2,$$

Simplify to get

$$(1-q)\theta {S_H}^{\alpha}\left({S_h}^{\beta} - {S_l}^{\beta}\right) < \frac{1}{2} c_r \left({S_h}^2 - {S_l}^2\right) \tag{6}$$

It is assumed that when photovoltaic building materials enterprises choose to pay a low level of knowledge sharing effort, the material payment obtained by learning and research institutions when they choose to pay a high level of knowledge sharing effort is less than the material payment obtained when they choose to pay a low level of knowledge sharing effort, namely

$$(1-q)\theta S_H^{\alpha} S_h^{\beta} - \frac{1}{2} c_r {S_h}^2 < (1-q)\theta S_H^{\alpha} S_l^{\beta} - \frac{1}{2} c_r {S_l}^2,$$

$$(1-q)\theta {S_L}^{\alpha}\left({S_h}^{\beta} - {S_l}^{\beta}\right) < \frac{1}{2} c_r \left({S_h}^2 - {S_l}^2\right) \tag{7}$$

It is assumed that when the learning and research institutions choose to pay a high level of knowledge sharing effort, the material payment obtained by the photovoltaic building materials enterprises when they choose to pay a high level of knowledge sharing effort is less than the material payment obtained when they choose to pay a low level of knowledge sharing effort, namely

$$q\theta {S_H}^{\alpha} {S_h}^{\beta} - \frac{1}{2} c_e {S_H}^2 < q\theta {S_L}^{\alpha} {S_h}^{\beta} - \frac{1}{2} c_e {S_L}^2,$$

Simplify to get

$$q\theta {S_h}^{\beta} ({S_H}^{\alpha} - {S_L}^{\alpha}) < \frac{1}{2} c_e ({S_H}^{\alpha} - {S_L}^{\alpha}), \tag{8}$$

4. Analysis of the incentive effects of knowledge sharing based on reciprocal preferences of academic and research institutions

Proposition 1. *When a reciprocal preference motive is given to academic and research institutions, academic and research institutions will choose* S_l *if photovoltaic building materials enterprises choose* S_L*; if photovoltaic building materials enterprises choose* S_H*, the following sequential reciprocal equilibrium exists:*

(1) When $Y_r > \frac{2(1-q)\theta {S_H}^{\alpha}({S_l}^{\beta}-{S_h}^{\beta})+c_r({S_h}^2-{S_l}^2)}{q(1-q)\theta^2 {S_H}^{\alpha}({S_h}^{\beta}-{S_l}^{\beta}){S_h}^{\beta}({S_H}^{\alpha}-{S_L}^{\alpha})}$*, academic and research institutions will choose* S_h*;*

(2) When $Y_r < \frac{2(1-q)\theta {S_H}^{\alpha}({S_l}^{\beta}-{S_h}^{\beta})+c_r({S_h}^2-{S_l}^2)}{[q\theta {S_H}^{\alpha}({S_h}^{\beta}-{S_l}^{\beta})]\left[(1-q)\theta({S_H}^{\alpha}{S_l}^{\beta}-{S_h}^{\beta}{S_L}^{\alpha})+\frac{1}{2}c_r({S_h}^2-{S_l}^2)\right]}$*, academic and research institutions will choose* S_l*;*

(3) When $\frac{2(1-q)\theta {S_H}^{\alpha}({S_l}^{\beta}-{S_h}^{\beta})+c_r({S_h}^2-{S_l}^2)}{[q\theta {S_H}^{\alpha}({S_h}^{\beta}-{S_l}^{\beta})]\left[(1-q)\theta({S_H}^{\alpha}{S_l}^{\beta}-{S_h}^{\beta}{S_L}^{\alpha})+\frac{1}{2}c_r({S_h}^2-{S_l}^2)\right]} < Y_r < \frac{2(1-q)\theta {S_H}^{\alpha}({S_l}^{\beta}-{S_h}^{\beta})+c_r({S_h}^2-{S_l}^2)}{q(1-q)\theta^2 {S_H}^{\alpha}({S_h}^{\beta}-{S_l}^{\beta}){S_h}^{\beta}({S_H}^{\alpha}-{S_L}^{\alpha})}$*, academic and research institutions will choose* S_h *based on the probability of* p*.*

Among them, $p = 1 - \frac{2}{Y_r q\theta {S_H}^{\alpha}({S_h}^{\beta}-{S_l}^{\beta})} + \frac{(1-q)\theta {S_h}^{\beta}({S_H}^{\alpha}-{S_L}^{\alpha})}{\frac{1}{2}c_r({S_h}^2-{S_l}^2)-(1-q)\theta {S_H}^{\alpha}({S_h}^{\beta}-{S_l}^{\beta})}$.

Proof. From Dufwenberg and Kirchsteiger's[42] sequential reciprocity model, it is clear that when photovoltaic building materials enterprises choose academic and research institutions choose S_h to photovoltaic building materials enterprises goodwill for

$$\begin{gathered} K_{re}(S_h, S_H) = q\theta {S_H}^{\alpha} {S_h}^{\beta} - \frac{1}{2} c_e {S_H}^2 - \frac{1}{2}\left[\left(q\theta {S_H}^{\alpha} {S_h}^{\beta} - \frac{1}{2} c_e {S_H}^2\right) + \left(q\theta {S_H}^{\alpha} {S_l}^{\beta} - \frac{1}{2} c_e {S_H}^2\right)\right] \\ = \frac{1}{2} q\theta {S_H}^{\alpha} ({S_h}^{\beta} - {S_l}^{\beta}), \end{gathered} \tag{9}$$

Academic and research institutions to choose S_l for photovoltaic building materials enterprises goodwill for

$$\begin{gathered} K_{re}(S_l, S_H) = q\theta {S_H}^{\alpha} {S_l}^{\beta} - \frac{1}{2} c_e {S_H}^2 - \frac{1}{2}\left[\left(q\theta {S_H}^{\alpha} {S_h}^{\beta} - \frac{1}{2} c_e {S_H}^2\right) + \left(q\theta {S_H}^{\alpha} {S_l}^{\beta} - \frac{1}{2} c_e {S_H}^2\right)\right] \\ = \frac{1}{2} q\theta {S_H}^{\alpha} ({S_l}^{\beta} - {S_h}^{\beta}). \ \square \end{gathered} \tag{10}$$

Hypothesis academic and research institutions to choose S_h second-order belief for p, namely photovoltaic building materials enterprises and academic and research institutions believe that academic and research institutions choose S_h probability of p; then the maximum payment that academic and research institutions believe the choice of photovoltaic building materials enterprises will give them is $p\left[(1-q)\theta {S_H}^{\alpha} {S_h}^{\beta} - \frac{1}{2} c_r {S_h}^2\right] + (1-p)\left[(1-q)\theta {S_H}^{\alpha} {S_l}^{\beta} - \frac{1}{2} c_r {S_l}^2\right]$, the minimum payment is $(1-q)\theta {S_L}^{\alpha} {S_h}^{\beta} - \frac{1}{2} c_r {S_h}^2$; when photovoltaic building materials enterprises choose S_H, academic and research institutions perceive the goodwill from photovoltaic building materials enterprises as

$$\begin{gathered} \lambda_{rer}((pS_h, (1-p)S_l), S_H) = p\left[(1-q)\theta {S_H}^{\alpha} {S_h}^{\beta} - \frac{1}{2} c_r {S_h}^2\right] + (1-p)\left[(1-q)\theta {S_H}^{\alpha} {S_l}^{\beta} - \frac{1}{2} c_r {S_l}^2\right] - \\ \frac{1}{2}\left\{p\left[(1-q)\theta {S_H}^{\alpha} {S_h}^{\beta} - \frac{1}{2} c_r {S_h}^2\right] + (1-p)\left[(1-q)\theta {S_H}^{\alpha} {S_l}^{\beta} - \frac{1}{2} c_r {S_l}^2\right] + (1-q)\theta {S_L}^{\alpha} {S_h}^{\beta} - \right. \\ \left. \frac{1}{2} c_r {S_h}^2\right\} = \frac{1}{2}\left\{(1-q)\theta {S_h}^{\beta}({S_H}^{\alpha} - {S_L}^{\alpha}) + (1-p)\left[\frac{1}{2} c_r ({S_h}^2 - {S_l}^2) - (1-q)\theta {S_H}^{\alpha}({S_h}^{\beta} - {S_l}^{\beta})\right]\right\}, \end{gathered} \tag{11}$$

From the hypothesis and Equation (6), it is clear that Equation (11) is greater than 0, i.e., academic and research institutions perceive positive goodwill when photovoltaic building materials enterprises choose S_H.

When photovoltaic building materials enterprises choose S_L, academic and research institutions perceive the goodwill from photovoltaic building materials enterprises as

$$\lambda_{rer}\big((pS_h,(1-p)S_l),S_L\big) = p\left[(1-q)\theta {S_L}^{\alpha}{S_h}^{\beta} - \frac{1}{2}c_r{S_h}^2\right] + (1-p)\left[(1-q)\theta {S_L}^{\alpha}{S_l}^{\beta} - \frac{1}{2}c_r{S_l}^2\right] - \frac{1}{2}\left\{p\left[(1-q)\theta {S_L}^{\alpha}{S_h}^{\beta} - \frac{1}{2}c_r{S_h}^2\right] + (1-p)\left[(1-q)\theta {S_L}^{\alpha}{S_l}^{\beta} - \frac{1}{2}c_r{S_l}^2\right] + (1-q)\theta {S_H}^{\alpha}{S_h}^{\beta} - \frac{1}{2}c_r{S_h}^2\right\} \quad (12)$$
$$= \frac{1}{2}\left\{(1-q)\theta {S_h}^{\beta}({S_L}^{\alpha} - {S_H}^{\alpha}) + (1-p)\left[\frac{1}{2}c_r({S_h}^2 - {S_l}^2) - (1-q)\theta({S_H}^{\alpha}{S_h}^{\beta} - {S_L}^{\alpha}{S_l}^{\beta})\right]\right\},$$

From the hypothesis and Equations (5) and (12) is less than 0, i.e., when photovoltaic building materials enterprises choose S_L, academic and research institutions perceive a negative goodwill. Therefore, it can be inferred that when photovoltaic building materials enterprises choose S_L, academic and research institutions with reciprocal preference motives will choose S_l.

When photovoltaic building materials enterprises choose S_H, The utility of the choice of S_h for academic and research institutions is

$$U_r(S_h,S_H) = (1-q)\theta {S_H}^{\alpha}{S_h}^{\beta} - \frac{1}{2}c_r{S_h}^2 + \frac{1}{4}Y_r\left[q\theta {S_H}^{\alpha}({S_h}^{\beta} - {S_l}^{\beta})\right] \left\{(1-q)\theta {S_h}^{\beta}({S_H}^{\alpha} - {S_L}^{\alpha}) + (1-p)\left[\frac{1}{2}c_r({S_h}^2 - {S_l}^2) - (1-q)\theta {S_H}^{\alpha}({S_h}^{\beta} - {S_l}^{\beta})\right]\right\}, \quad (13)$$

The utility of the choice of S_l for academic and research institutions is

$$U_r(S_l,S_H) = (1-q)\theta {S_H}^{\alpha}{S_l}^{\beta} - \frac{1}{2}c_r{S_l}^2 + \frac{1}{4}Y_r\left[q\theta {S_H}^{\alpha}({S_l}^{\beta} - {S_h}^{\beta})\right] \left\{(1-q)\theta {S_h}^{\beta}({S_H}^{\alpha} - {S_L}^{\alpha}) + (1-p)\left[\frac{1}{2}c_r({S_h}^2 - {S_l}^2) - (1-q)\theta {S_H}^{\alpha}({S_h}^{\beta} - {S_l}^{\beta})\right]\right\}, \quad (14)$$

(1) When $U_r(S_h,S_H) > U_r(S_l,S_H)$, academic and research institutions will choose S_h, at this moment $p=1$. Substituting into Equations (13) and (14), we get that $Y_r > \frac{2(1-q)\theta {S_H}^{\alpha}({S_l}^{\beta} - {S_h}^{\beta}) + c_r({S_h}^2 - {S_l}^2)}{q(1-q)\theta^2 {S_H}^{\alpha}({S_h}^{\beta} - {S_l}^{\beta}){S_h}^{\beta}({S_H}^{\alpha} - {S_L}^{\alpha})}$. Therefore, when $Y_r > \frac{2(1-q)\theta {S_H}^{\alpha}({S_l}^{\beta} - {S_h}^{\beta}) + c_r({S_h}^2 - {S_l}^2)}{q(1-q)\theta^2 {S_H}^{\alpha}({S_h}^{\beta} - {S_l}^{\beta}){S_h}^{\beta}({S_H}^{\alpha} - {S_L}^{\alpha})}$, if photovoltaic building materials enterprises choose S_H, then academic and research institutions will choose S_h.

(2) When $U_r(S_h,S_H) < U_r(S_l,S_H)$, academic and research institutions will choose S_l, at this moment $p=0$. Substituting into Equations (13) and (14), we get that $Y_r < \frac{2(1-q)\theta {S_H}^{\alpha}({S_l}^{\beta} - {S_h}^{\beta}) + c_r({S_h}^2 - {S_l}^2)}{\left[q\theta {S_H}^{\alpha}({S_h}^{\beta} - {S_l}^{\beta})\right]\left[(1-q)\theta({S_H}^{\alpha}{S_l}^{\beta} - {S_h}^{\beta}{S_L}^{\alpha}) + \frac{1}{2}c_r({S_h}^2 - {S_l}^2)\right]}$.

Therefore, when $Y_r < \frac{2(1-q)\theta {S_H}^{\alpha}({S_l}^{\beta} - {S_h}^{\beta}) + c_r({S_h}^2 - {S_l}^2)}{\left[q\theta {S_H}^{\alpha}({S_h}^{\beta} - {S_l}^{\beta})\right]\left[(1-q)\theta({S_H}^{\alpha}{S_l}^{\beta} - {S_h}^{\beta}{S_L}^{\alpha}) + \frac{1}{2}c_r({S_h}^2 - {S_l}^2)\right]}$, if photovoltaic building materials enterprises choose S_H, then academic and research institutions will choose S_l.

(3) When $U_r(S_h,S_H) = U_r(S_l,S_H)$, simplifying to get $p = 1 - \frac{2}{Y_r q\theta {S_H}^{\alpha}({S_h}^{\beta} - {S_l}^{\beta})} + \frac{(1-q)\theta {S_h}^{\beta}({S_H}^{\alpha} - {S_L}^{\alpha})}{\frac{1}{2}c_r({S_h}^2 - {S_l}^2) - (1-q)\theta {S_H}^{\alpha}({S_h}^{\beta} - {S_l}^{\beta})}$. From $0 < p < 1$, it follows that $\frac{2(1-q)\theta {S_H}^{\alpha}({S_l}^{\beta} - {S_h}^{\beta}) + c_r({S_h}^2 - {S_l}^2)}{\left[q\theta {S_H}^{\alpha}({S_h}^{\beta} - {S_l}^{\beta})\right]\left[(1-q)\theta({S_H}^{\alpha}{S_l}^{\beta} - {S_h}^{\beta}{S_L}^{\alpha}) + \frac{1}{2}c_r({S_h}^2 - {S_l}^2)\right]} < Y_r < \frac{2(1-q)\theta {S_H}^{\alpha}({S_l}^{\beta} - {S_h}^{\beta}) + c_r({S_h}^2 - {S_l}^2)}{q(1-q)\theta^2 {S_H}^{\alpha}({S_h}^{\beta} - {S_l}^{\beta}){S_h}^{\beta}({S_H}^{\alpha} - {S_L}^{\alpha})}$, certificating of completion.

From Proposition 1, it follows that in the collaborative digital green innovation knowledge sharing process of photovoltaic building materials enterprises, when the reciprocal sensitivity of academic and research institutions is large enough, i.e., when $Y_r > \frac{2(1-q)\theta {S_H}^{\alpha}({S_l}^{\beta} - {S_h}^{\beta}) + c_r({S_h}^2 - {S_l}^2)}{q(1-q)\theta^2 {S_H}^{\alpha}({S_h}^{\beta} - {S_l}^{\beta}){S_h}^{\beta}({S_H}^{\alpha} - {S_L}^{\alpha})}$, academic and research institutions, sensing the goodwill conveyed by photovoltaic building materials enterprises choosing to pay a high level of knowledge sharing effort, will reciprocate with friendly behaviour, i.e., also choosing to pay a high level of knowledge sharing effort. Although this option reduces the material payments of academic and research institutions, their reciprocal payments increase more than the material payments are lost. When the reciprocity sensitivity of academic and research institutions is low, the institutions will not repay the goodwill of photovoltaic building materials enterprises for choosing to pay a high level of knowledge sharing effort, because the increased reciprocal payment for choosing to pay a high level of knowledge sharing effort is not enough to compensate for the material payment it loses, and choosing to pay a low level of knowledge sharing effort is the equilibrium choice for it. When the reciprocity sensitivity of research institutions is in the middle, the institutions will choose to pay a high level of knowledge sharing effort with a certain probability p. The probability increases as the reciprocity sensitivity of the institution increases. When photovoltaic building materials enterprises choose to pay a low level of knowledge sharing effort, academic and research institutions feel the unfriendliness of photovoltaic building materials enterprises, and will choose to pay a low level of knowledge sharing effort in retaliation under the dual effect of material payment and reciprocal payment.

The above analysis shows that when the inherent reciprocal motivation of academic and research institutions is large enough, photovoltaic building materials enterprises should improve their own knowledge sharing efforts to stimulate the reciprocal preference of academic and research institutions, which will be more conducive to the sharing and absorption of explicit and tacit knowledge, enabling a more tacit and positive interaction between photovoltaic building materials enterprises and academic and research institutions, promoting the development of collaborative digital green innovation activities of photovoltaic building materials enterprises, and thus increasing the benefits generated by collaborative digital green innovation of photovoltaic building materials enterprises.

5. Analysis of the incentive effect of knowledge sharing based on reciprocal preferences of photovoltaic building materials enterprises

Proposition 2. *If* $Y_r < \frac{2(1-q)\theta S_H{}^{\alpha}(S_l{}^{\beta}-S_h{}^{\beta})+c_r(S_h{}^2-S_l{}^2)}{[q\theta S_H{}^{\alpha}(S_h{}^{\beta}-S_l{}^{\beta})]\left[(1-q)\theta(S_H{}^{\alpha}S_l{}^{\beta}-S_h{}^{\beta}S_L{}^{\alpha})+\frac{1}{2}c_r(S_h{}^2-S_l{}^2)\right]}$, *then photovoltaic building materials enterprises will choose* S_L.

If the reciprocity sensitivity of academic and research institutions is low, then they will choose to pay a low level of knowledge sharing effort. A strategy that is unfriendly to photovoltaic building materials enterprises, which will end up choosing to pay a low level of knowledge sharing effort based on inferences about the behaviour and beliefs of academic and research institutions, based on both material payment and reciprocal payment. This suggests that increasing the reciprocity motivation of academic and research institutions is a prerequisite for changing the choice of photovoltaic building materials enterprises to pay low levels of knowledge sharing effort when the reciprocity sensitivity of academic and research institutions is low.

Proposition 3. *If* $Y_r > \frac{2(1-q)\theta S_H{}^{\alpha}(S_l{}^{\beta}-S_h{}^{\beta})+c_r(S_h{}^2-S_l{}^2)}{q(1-q)\theta^2 S_H{}^{\alpha}(S_h{}^{\beta}-S_l{}^{\beta})S_h{}^{\beta}(S_H{}^{\alpha}-S_L{}^{\alpha})}$, *then there are three possibilities for the equilibrium behaviour of photovoltaic building material enterprises:*

(1) Regardless of the value of Y_e, *photovoltaic building material enterprises will choose* S_H;

(2) When $Y_e > \frac{2\left[\left(q\theta S_H{}^{\alpha}S_h{}^{\beta}-\frac{1}{2}c_e S_H{}^2\right)-\left(q\theta S_L{}^{\alpha}S_l{}^{\beta}-\frac{1}{2}c_e S_L{}^2\right)\right]}{\left[(1-q)\theta(S_H{}^{\alpha}S_h{}^{\beta}-S_L{}^{\alpha}S_l{}^{\beta})-\frac{1}{2}c_r(S_h{}^2-S_l{}^2)\right][q\theta S_L{}^{\alpha}(S_h{}^{\beta}-S_l{}^{\beta})]}$, *then photovoltaic building materials enterprises will choose*S_L;

(3) When $Y_e > \frac{2\left[\left(q\theta S_H{}^{\alpha}S_h{}^{\beta}-\frac{1}{2}c_e S_H{}^2\right)-\left(q\theta S_L{}^{\alpha}S_l{}^{\beta}-\frac{1}{2}c_e S_L{}^2\right)\right]}{\left[(1-q)\theta(S_H{}^{\alpha}S_h{}^{\beta}-S_L{}^{\alpha}S_l{}^{\beta})-\frac{1}{2}c_r(S_h{}^2-S_l{}^2)\right][q\theta S_L{}^{\alpha}(S_h{}^{\beta}-S_l{}^{\beta})]}$, *the probability that photovoltaic building material enterprises will choose* S_H *is*

$$p' = \frac{2\left[\left(q\theta S_L{}^{\alpha} S_l{}^{\beta} - \frac{1}{2}c_e S_L{}^2\right) - \left(q\theta S_H{}^{\alpha} S_h{}^{\beta} - \frac{1}{2}c_e S_H{}^2\right)\right]}{Y_e\left[(1-q)\theta\left(S_H{}^{\alpha} S_h{}^{\beta} - S_L{}^{\alpha} S_l{}^{\beta}\right) - \frac{1}{2}c_r\left(S_h{}^2 - S_l{}^2\right)\right]\left[q\theta\left(S_H{}^{\alpha} S_h{}^{\beta} - S_H{}^{\alpha} S_l{}^{\beta} + S_L{}^{\alpha} S_h{}^{\beta} - S_L{}^{\alpha} S_l{}^{\beta}\right)\right]} + \frac{S_L{}^{\alpha} S_h{}^{\beta} - S_L{}^{\alpha} S_l{}^{\beta}}{S_H{}^{\alpha} S_h{}^{\beta} - S_H{}^{\alpha} S_l{}^{\beta} + S_L{}^{\alpha} S_h{}^{\beta} - S_L{}^{\alpha} S_l{}^{\beta}}.$$

Proof.□It follows from Proposition 1 that if $Y_r > \frac{2(1-q)\theta S_H{}^{\alpha}\left(S_l{}^{\beta} - S_h{}^{\beta}\right) + c_r\left(S_h{}^2 - S_l{}^2\right)}{q(1-q)\theta^2 S_H{}^{\alpha}\left(S_h{}^{\beta} - S_l{}^{\beta}\right) S_h{}^{\beta}\left(S_H{}^{\alpha} - S_L{}^{\alpha}\right)}$, when photovoltaic building materials enterprises choose S_H, academic and research institutions will choose S_h; when photovoltaic building materials enterprises choose S_L, academic and research institutions will choose S_l.

Fair payment from academic and research institutions on photovoltaic building materials enterprises for

$$\pi_r{}^{e_e}(b_{er}) = \frac{1}{2}\left[(1-q)\theta S_H{}^{\alpha} S_h{}^{\beta} - \frac{1}{2}c_r S_h{}^2 + (1-q)\theta S_L{}^{\alpha} S_l{}^{\beta} - \frac{1}{2}c_r S_l{}^2\right] = \frac{1}{2}\left[(1-q)\theta\left(S_H{}^{\alpha} S_h{}^{\beta} + S_L{}^{\alpha} S_l{}^{\beta}\right) - \frac{1}{2}c_r\left(S_h{}^2 + S_l{}^2\right)\right]. \square \quad (15)$$

From Dufwenberg and Kirchsteiger's sequential reciprocity model, it is clear that when photovoltaic building materials enterprises choose S_H, the goodwill towards academic and research institutions is

$$\begin{aligned} K_{\mathrm{er}}(S_H, b_{er}) &= (1-q)\theta S_H{}^{\alpha} S_h{}^{\beta} - \frac{1}{2}c_r S_h{}^2 - \pi_r{}^{e_e}(b_{er}) \\ &= \frac{1}{2}\left[(1-q)\theta\left(S_H{}^{\alpha} S_h{}^{\beta} - S_L{}^{\alpha} S_l{}^{\beta}\right) - \frac{1}{2}c_r\left(S_h{}^2 - S_l{}^2\right)\right] \end{aligned} \quad (16)$$

When photovoltaic building materials enterprises choose S_L, the goodwill towards academic and research institutions is

$$\begin{aligned} K_{\mathrm{er}}(S_L, b_{er}) &= (1-q)\theta S_L{}^{\alpha} S_l{}^{\beta} - \frac{1}{2}c_r S_l{}^2 - \pi_r{}^{e_e}(b_{er}) \\ &= \frac{1}{2}\left[(1-q)\theta\left(S_L{}^{\alpha} S_l{}^{\beta} - S_H{}^{\alpha} S_h{}^{\beta}\right) - \frac{1}{2}c_r\left(S_l{}^2 - S_h{}^2\right)\right] \end{aligned} \quad (17)$$

Assume that the second-order belief that photovoltaic building materials enterprises choose S_H is p', i.e., the probability that photovoltaic building materials enterprises believe that academic and research institutions believe that photovoltaic building materials enterprises choose S_H is p'; then the benefit that photovoltaic building materials enterprises believe that academic and research institution's choice will give photovoltaic building materials enterprises is

$$\pi_e(b_{er}, c_{ere}) = p'\left(q\theta S_H{}^{\alpha} S_h{}^{\beta} - \frac{1}{2}c_e S_H{}^2\right) + (1-p')\left(q\theta S_L{}^{\alpha} S_l{}^{\beta} - \frac{1}{2}c_e S_L{}^2\right) \quad (18)$$

If academic and research institutions consistently choose to S_h give photovoltaic building materials enterprises the benefit of

$$\pi_e(a_e, S_h) = p'\left(q\theta S_H{}^{\alpha} S_h{}^{\beta} - \frac{1}{2}c_e S_H{}^2\right) + (1-p')\left(q\theta S_L{}^{\alpha} S_h{}^{\beta} - \frac{1}{2}c_e S_L{}^2\right) \quad (19)$$

If academic and research institutions consistently choose to S_l give photovoltaic building materials enterprises the benefit of

$$\pi_e(a_e, S_l) = p'\left(q\theta S_H{}^{\alpha} S_l{}^{\beta} - \frac{1}{2}c_e S_H{}^2\right) + (1-p')\left(q\theta S_L{}^{\alpha} S_l{}^{\beta} - \frac{1}{2}c_e S_L{}^2\right) \quad (20)$$

Photovoltaic building materials enterprises perceive the arrival of self-learning and academic and research institutions with good intentions for

$$\begin{aligned} \lambda_{ere}(b_{er}, c_{ere}) &= \pi_e(b_{er}, c_{ere}) - \pi_e{}^{e_r}(c_{ere}) \\ &= p'\left(q\theta S_H{}^{\alpha} S_h{}^{\beta} - \frac{1}{2}c_e S_H{}^2\right) + (1-p')\left(q\theta S_L{}^{\alpha} S_l{}^{\beta} - \frac{1}{2}c_e S_L{}^2\right) \\ &- \frac{1}{2}\left[\pi_e(a_e, S_h) + \pi_e(a_e, S_l)\right] = \frac{1}{2}\left[p' q\theta S_H{}^{\alpha}\left(S_h{}^{\beta} - S_l{}^{\beta}\right) - (1-p') q\theta S_L{}^{\alpha}\left(S_h{}^{\beta} - S_l{}^{\beta}\right)\right] \end{aligned} \quad (21)$$

If $Y_r > \frac{2(1-q)\theta S_H{}^{\alpha}\left(S_l{}^{\beta} - S_h{}^{\beta}\right) + c_r\left(S_h{}^2 - S_l{}^2\right)}{q(1-q)\theta^2 S_H{}^{\alpha}\left(S_h{}^{\beta} - S_l{}^{\beta}\right) S_h{}^{\beta}\left(S_H{}^{\alpha} - S_L{}^{\alpha}\right)}$, the utility of the photovoltaic building material enterprises' choice of S_H is

$$
\begin{aligned}
U_e(S_H, b_{er}, c_{ere}) &= \pi_e(S_H, S_h) + Y_e K_{\mathrm{er}}(S_H, S_h)\lambda_{ere}(b_{er}, c_{ere}) \\
&= q\theta {S_H}^{\alpha} {S_h}^{\beta} - \frac{1}{2} c_e {S_H}^2 \\
&+ \frac{1}{4} Y_e \left[(1-q)\theta\left({S_H}^{\alpha}{S_h}^{\beta} - {S_L}^{\alpha}{S_l}^{\beta}\right) - \frac{1}{2} c_r \left({S_h}^2 - {S_l}^2\right)\right] \left[p' q\theta {S_H}^{\alpha}\left({S_h}^{\beta} - {S_l}^{\beta}\right)\right. \\
&\left. - (1-p') q\theta {S_L}^{\alpha}\left({S_h}^{\beta} - {S_l}^{\beta}\right)\right]
\end{aligned} \tag{22}
$$

The utility of the photovoltaic building material enterprises' choice of S_L is

$$
\begin{aligned}
U_e(S_L, b_{er}, c_{ere}) &= \pi_e(S_L, S_l) + Y_e K_{\mathrm{er}}(S_L, S_l)\lambda_{ere}(b_{er}, c_{ere}) \\
&= q\theta {S_L}^{\alpha} {S_l}^{\beta} - \frac{1}{2} c_e {S_L}^2 \\
&+ \frac{1}{4} Y_e \left[(1-q)\theta\left({S_L}^{\alpha}{S_l}^{\beta} - {S_H}^{\alpha}{S_h}^{\beta}\right) - \frac{1}{2} c_r \left({S_l}^2 - {S_h}^2\right)\right] \left[p' q\theta {S_H}^{\alpha}\left({S_h}^{\beta} - {S_l}^{\beta}\right)\right. \\
&\left. - (1-p') q\theta {S_L}^{\alpha}\left({S_h}^{\beta} - {S_l}^{\beta}\right)\right]
\end{aligned} \tag{23}
$$

(1) When $U_e(S_H, b_{er}, c_{ere}) > U_e(S_L, b_{er}, c_{ere})$, photovoltaic building material enterprises will choose S_H, at this moment $p' = 1$. Substituting into Equations (22) and (23), we get that

$$
Y_e > \frac{2\left[\left(q\theta {S_L}^{\alpha}{S_l}^{\beta} - \frac{1}{2} c_e {S_L}^2\right) - \left(q\theta {S_H}^{\alpha}{S_h}^{\beta} - \frac{1}{2} c_e {S_H}^2\right)\right]}{\left[(1-q)\theta\left({S_H}^{\alpha}{S_h}^{\beta} - {S_L}^{\alpha}{S_l}^{\beta}\right) - \frac{1}{2} c_r\left({S_h}^2 - {S_l}^2\right)\right]\left[q\theta {S_H}^{\alpha}\left({S_h}^{\beta} - {S_l}^{\beta}\right)\right]}.
$$

From Equations (4) and (5), the right-hand side of the inequality is less than 0. Therefore, the inequality always holds.

(2) When $U_e(S_H, b_{er}, c_{ere}) < U_e(S_L, b_{er}, c_{ere})$, photovoltaic building material enterprises will choose S_L, at this moment $p' = 0$. Substituting into Equations (22) and (23), we get that

$$
Y_e > \frac{2\left[\left(q\theta {S_H}^{\alpha}{S_h}^{\beta} - \frac{1}{2} c_e {S_H}^2\right) - \left(q\theta {S_L}^{\alpha}{S_l}^{\beta} - \frac{1}{2} c_e {S_L}^2\right)\right]}{\left[(1-q)\theta\left({S_H}^{\alpha}{S_h}^{\beta} - {S_L}^{\alpha}{S_l}^{\beta}\right) - \frac{1}{2} c_r\left({S_h}^2 - {S_l}^2\right)\right]\left[q\theta {S_L}^{\alpha}\left({S_h}^{\beta} - {S_l}^{\beta}\right)\right]}.
$$

(3) When $U_e(S_H, b_{er}, c_{ere}) = U_e(S_L, b_{er}, c_{ere})$, simplifying to get

$$
\begin{aligned}
p' = &\frac{2\left[\left(q\theta {S_L}^{\alpha}{S_l}^{\beta} - \frac{1}{2} c_e {S_L}^2\right) - \left(q\theta {S_H}^{\alpha}{S_h}^{\beta} - \frac{1}{2} c_e {S_H}^2\right)\right]}{Y_e\left[(1-q)\theta\left({S_H}^{\alpha}{S_h}^{\beta} - {S_L}^{\alpha}{S_l}^{\beta}\right) - \frac{1}{2} c_r\left({S_h}^2 - {S_l}^2\right)\right]\left[q\theta\left({S_H}^{\alpha}{S_h}^{\beta} - {S_H}^{\alpha}{S_l}^{\beta} + {S_L}^{\alpha}{S_h}^{\beta} - {S_L}^{\alpha}{S_l}^{\beta}\right)\right]} \\
&+ \frac{{S_L}^{\alpha}{S_h}^{\beta} - {S_L}^{\alpha}{S_l}^{\beta}}{{S_H}^{\alpha}{S_h}^{\beta} - {S_H}^{\alpha}{S_l}^{\beta} + {S_L}^{\alpha}{S_h}^{\beta} - {S_L}^{\alpha}{S_l}^{\beta}}
\end{aligned}
$$

From $0 < p' < 1$ we have $Y_e > \frac{2\left[\left(q\theta {S_H}^{\alpha}{S_h}^{\beta} - \frac{1}{2} c_e {S_H}^2\right) - \left(q\theta {S_L}^{\alpha}{S_l}^{\beta} - \frac{1}{2} c_e {S_L}^2\right)\right]}{\left[(1-q)\theta\left({S_H}^{\alpha}{S_h}^{\beta} - {S_L}^{\alpha}{S_l}^{\beta}\right) - \frac{1}{2} c_r\left({S_h}^2 - {S_l}^2\right)\right]\left[q\theta {S_L}^{\alpha}\left({S_h}^{\beta} - {S_l}^{\beta}\right)\right]}$. Certificate of completion.

Proposition 4. *Considers the equilibrium behaviour of photovoltaic building material enterprises when the reciprocal sensitivity of academic and research institutions is sufficiently high in the collaborative digital green innovation knowledge sharing process of photovoltaic building material enterprises. Where (1) is the most plausible equilibrium, photovoltaic building material enterprises will choose to pay a high level of knowledge sharing effort when the reciprocal sensitivity of academic and research institutions is sufficiently high, given the combination of material and reciprocal payments. However, there are other kinds of equilibria, where if photovoltaic building material enterprises believe that academic and research institutions believe that photovoltaic building material enterprises will choose to pay a low level of knowledge sharing effort, and academic and research institutions will choose to pay a low level of knowledge sharing effort in such cases, then photovoltaic building material enterprises will perceive academic and research institutions as being unfriendly and therefore will cause photovoltaic building material enterprises to choose to pay a low level of knowledge sharing effort. This equilibrium will only occur if photovoltaic building material enterprises is sufficiently motivated by reciprocity. The other equilibrium is that photovoltaic building material enterprises* *will choose to pay a high level of knowledge sharing effort with probability p', leading academic and research institutions to choose to pay a high level of knowledge sharing effort as well.*

Proposition 5. *If*

$$\frac{2(1-q)\theta {S_H}^{\alpha}\left({S_l}^{\beta}-{S_h}^{\beta}\right)+c_r\left({S_h}^2-{S_l}^2\right)}{\left[q\theta {S_H}^{\alpha}\left({S_h}^{\beta}-{S_l}^{\beta}\right)\right]\left[(1-q)\theta\left({S_H}^{\alpha}{S_l}^{\beta}-{S_h}^{\beta}{S_L}^{\alpha}\right)+\frac{1}{2}c_r\left({S_h}^2-{S_l}^2\right)\right]}<Y_r < \frac{2(1-q)\theta {S_H}^{\alpha}\left({S_l}^{\beta}-{S_h}^{\beta}\right)+c_r\left({S_h}^2-{S_l}^2\right)}{\left[q(1-q)\theta^2 {S_H}^{\alpha}\left({S_h}^{\beta}-{S_l}^{\beta}\right){S_h}^{\beta}({S_H}^{\alpha}-{S_L}^{\alpha})\right]}$$

Then there are three possibilities for the equilibrium behaviour of photovoltaic building material enterprises:

(1) When $Y_r > \frac{4\left[\frac{1}{2}c_r\left({S_h}^2-{S_l}^2\right)-(1-q)\theta {S_H}^{\alpha}\left({S_h}^{\beta}-{S_l}^{\beta}\right)\right]}{q\theta {S_H}^{\alpha}\left({S_h}^{\beta}-{S_l}^{\beta}\right)\left[\frac{1}{2}c_r\left({S_h}^2-{S_l}^2\right)+(1-q)\theta\left({S_H}^{\alpha}{S_h}^{\beta}+{S_H}^{\alpha}{S_l}^{\beta}-2{S_L}^{\alpha}{S_h}^{\beta}\right)\right]}$, *photovoltaic building material enterprises will choose S_H.*

(2) When

$$Y_e < \frac{2\left[q\theta\left({S_H}^{\alpha}{S_h}^{\beta}-{S_L}^{\alpha}{S_l}^{\beta}\right)-\frac{1}{2}c_e\left({S_H}^2-{S_L}^2\right)\right]-\frac{4}{Y_r}+\frac{2\left[(1-q)q\theta^2{S_h}^{\beta}({S_H}^{\alpha}-{S_L}^{\alpha}){S_H}^{\alpha}\left({S_h}^{\beta}-{S_l}^{\beta}\right)\right]}{\frac{1}{2}c_r\left({S_h}^2-{S_l}^2\right)-(1-q)\theta {S_H}^{\alpha}\left({S_h}^{\beta}-{S_l}^{\beta}\right)}}{\frac{2{S_L}^{\alpha}\left[(1-q)\theta {S_H}^{\alpha}\left({S_h}^{\beta}-{S_l}^{\beta}\right)-\frac{1}{2}c_r\left({S_h}^2-{S_l}^2\right)\right]}{Y_r{S_H}^{\alpha}}-\left[(1-q)\theta {S_L}^{\alpha}\left({S_h}^{\beta}-{S_l}^{\beta}\right)-\frac{1}{2}c_r\left({S_h}^2-{S_l}^2\right)\right]\left[q\theta {S_L}^{\alpha}\left({S_h}^{\beta}-{S_l}^{\beta}\right)\right]}$$

, photovoltaic building material enterprises will choose S_L.

(3) When $Y_r > \frac{4\left[\frac{1}{2}c_r\left({S_h}^2-{S_l}^2\right)-(1-q)\theta {S_H}^{\alpha}\left({S_h}^{\beta}-{S_l}^{\beta}\right)\right]}{q\theta {S_H}^{\alpha}\left({S_h}^{\beta}-{S_l}^{\beta}\right)\left[\frac{1}{2}c_r\left({S_h}^2-{S_l}^2\right)+(1-q)\theta\left({S_H}^{\alpha}{S_h}^{\beta}+{S_H}^{\alpha}{S_l}^{\beta}-2{S_L}^{\alpha}{S_h}^{\beta}\right)\right]}$ *or*

$$Y_e < \frac{2\left[q\theta\left({S_H}^{\alpha}{S_h}^{\beta}-{S_L}^{\alpha}{S_l}^{\beta}\right)-\frac{1}{2}c_e\left({S_H}^2-{S_L}^2\right)\right]-\frac{4}{Y_r}+\frac{2\left[(1-q)q\theta^2{S_h}^{\beta}({S_H}^{\alpha}-{S_L}^{\alpha}){S_H}^{\alpha}\left({S_h}^{\beta}-{S_l}^{\beta}\right)\right]}{\frac{1}{2}c_r\left({S_h}^2-{S_l}^2\right)-(1-q)\theta {S_H}^{\alpha}\left({S_h}^{\beta}-{S_l}^{\beta}\right)}}{\frac{2{S_L}^{\alpha}\left[(1-q)\theta {S_H}^{\alpha}\left({S_h}^{\beta}-{S_l}^{\beta}\right)-\frac{1}{2}c_r\left({S_h}^2-{S_l}^2\right)\right]}{Y_r{S_H}^{\alpha}}-\left[(1-q)\theta {S_L}^{\alpha}\left({S_h}^{\beta}-{S_l}^{\beta}\right)-\frac{1}{2}c_r\left({S_h}^2-{S_l}^2\right)\right]\left[q\theta {S_L}^{\alpha}\left({S_h}^{\beta}-{S_l}^{\beta}\right)\right]}$$

, the probability that photovoltaic building material enterprises will choose S_H is

$$p' = \frac{\dfrac{\left[q\theta\left({S_H}^{\alpha}{S_h}^{\beta}-{S_L}^{\alpha}{S_l}^{\beta}\right)-\frac{1}{2}c_e\left({S_H}^2-{S_L}^2\right)\right]-\frac{2}{Y_r}+\dfrac{\left[(1-q)q\theta^2{S_h}^{\beta}({S_H}^{\alpha}-{S_L}^{\alpha}){S_H}^{\alpha}\left({S_h}^{\beta}-{S_l}^{\beta}\right)\right]}{\frac{1}{2}c_r\left({S_h}^2-{S_l}^2\right)-(1-q)\theta {S_H}^{\alpha}\left({S_h}^{\beta}-{S_l}^{\beta}\right)}}{Y_e\left\{\dfrac{2(1-q)}{Y_r q}-\dfrac{c_r\left({S_h}^2-{S_l}^2\right)}{Y_r q\theta {S_H}^{\alpha}\left({S_h}^{\beta}-{S_l}^{\beta}\right)}-\left[(1-q)\theta {S_L}^{\alpha}\left({S_h}^{\beta}-{S_l}^{\beta}\right)-\frac{1}{2}c_r\left({S_h}^2-{S_l}^2\right)\right]\right\}}+\frac{1}{2}q\theta {S_L}^{\alpha}\left({S_h}^{\beta}-{S_l}^{\beta}\right)}{\frac{1}{2}q\theta({S_H}^{\alpha}+{S_L}^{\alpha})\left({S_h}^{\beta}-{S_l}^{\beta}\right)-\frac{2}{Y_r}+\dfrac{\left[(1-q)q\theta^2{S_h}^{\beta}({S_H}^{\alpha}-{S_L}^{\alpha}){S_H}^{\alpha}\left({S_h}^{\beta}-{S_l}^{\beta}\right)\right]}{\frac{1}{2}c_r\left({S_h}^2-{S_l}^2\right)-(1-q)\theta {S_H}^{\alpha}\left({S_h}^{\beta}-{S_l}^{\beta}\right)}}$$

Proof. It follows from Proposition 1 that if

$$\frac{2(1-q)\theta {S_H}^{\alpha}\left({S_l}^{\beta}-{S_h}^{\beta}\right)+c_r\left({S_h}^2-{S_l}^2\right)}{\left[q\theta {S_H}^{\alpha}\left({S_h}^{\beta}-{S_l}^{\beta}\right)\right]\left[(1-q)\theta\left({S_H}^{\alpha}{S_l}^{\beta}-{S_h}^{\beta}{S_L}^{\alpha}\right)+\frac{1}{2}c_r\left({S_h}^2-{S_l}^2\right)\right]}<Y_r<\frac{2(1-q)\theta {S_H}^{\alpha}\left({S_l}^{\beta}-{S_h}^{\beta}\right)+c_r\left({S_h}^2-{S_l}^2\right)}{q(1-q)\theta^2 {S_H}^{\alpha}\left({S_h}^{\beta}-{S_l}^{\beta}\right){S_h}^{\beta}({S_H}^{\alpha}-{S_L}^{\alpha})}.$$

When photovoltaic building material enterprises choose S_H, academic and research institutions will choose S_h with probability p. When photovoltaic building material enterprises choose S_L, academic and research institutions will choose S_l. Fair payment from academic and research institutions on photovoltaic building material enterprises for

$$\pi_r{}^{e_e}(b_{er})=\frac{1}{2}\left\{p\left[(1-q)\theta {S_H}^{\alpha}{S_h}^{\beta}-\frac{1}{2}c_r{S_h}^2\right]+(1-p)\left[(1-q)\theta {S_H}^{\alpha}{S_l}^{\beta}-\frac{1}{2}c_r{S_l}^2\right]+\left((1-q)\theta {S_L}^{\alpha}{S_l}^{\beta}-\frac{1}{2}c_r{S_l}^2\right)\right\} \tag{24}$$

When photovoltaic building material enterprises choose S_H, the goodwill towards academic and research institutions is

$$K_{\mathrm{er}}(S_H, b_{er}) = p\left[(1-q)\theta {S_H}^{\alpha} {S_h}^{\beta} - \frac{1}{2} c_r {S_h}^2\right] + (1-p)\left[(1-q)\theta {S_H}^{\alpha} {S_l}^{\beta} - \frac{1}{2} c_r {S_l}^2\right] - {\pi_r}^{e_e}(b_{er}) \tag{25}$$

When photovoltaic building material enterprises choose S_L, the goodwill towards academic and research institutions is

$$K_{\mathrm{er}}(S_L, b_{er}) = (1-q)\theta {S_L}^{\alpha} {S_l}^{\beta} - \frac{1}{2} c_r {S_l}^2 - {\pi_r}^{e_e}(b_{er}) \tag{26}$$

Assume that the second-order belief that photovoltaic building materials enterprises choose S_H is p', i.e., the probability that photovoltaic building materials enterprises believe that academic and research institutions believe that photovoltaic building materials enterprises choose S_H is p'; then the benefit that the photovoltaic building materials enterprises believe that academic and research institution's choice will give photovoltaic building materials enterprises is

$$\begin{aligned}\pi_e(b_{er}, c_{ere}) = {} & p'\left[p\left(q\theta {S_H}^{\alpha} {S_h}^{\beta} - \frac{1}{2} c_e {S_H}^2\right) + (1-p)\left(q\theta {S_H}^{\alpha} {S_l}^{\beta} - \frac{1}{2} c_e {S_H}^2\right)\right] \\ & + (1-p')\left(q\theta {S_L}^{\alpha} {S_l}^{\beta} - \frac{1}{2} c_e {S_L}^2\right)\end{aligned} \tag{27}$$

If academic and research institutions consistently choose to S_h give photovoltaic building materials enterprises the benefit of

$$\pi_e(a_e, S_h) = p'\left(q\theta {S_H}^{\alpha} {S_h}^{\beta} - \frac{1}{2} c_e {S_H}^2\right) + (1-p')\left(q\theta {S_L}^{\alpha} {S_h}^{\beta} - \frac{1}{2} c_e {S_L}^2\right) \tag{28}$$

If academic and research institutions consistently choose to S_l give photovoltaic building materials enterprises the benefit of

$$\pi_e(a_e, S_l) = p'\left(q\theta {S_H}^{\alpha} {S_l}^{\beta} - \frac{1}{2} c_e {S_H}^2\right) + (1-p')\left(q\theta {S_L}^{\alpha} {S_l}^{\beta} - \frac{1}{2} c_e {S_L}^2\right) \tag{29}$$

Photovoltaic building materials enterprises perceive the arrival of self-learning and academic and research institutions with good intentions for

$$\begin{aligned}\lambda_{ere}(b_{er}, c_{ere}) &= \pi_e(b_{er}, c_{ere}) - {\pi_e}^{e_r}(c_{ere}) \\ &= p'\left(p - \frac{1}{2}\right)\left[q\theta {S_H}^{\alpha}\left({S_h}^{\beta} - {S_l}^{\beta}\right)\right] - \frac{1}{2}(1-p')\left[q\theta {S_L}^{\alpha}\left({S_h}^{\beta} - {S_l}^{\beta}\right)\right]\end{aligned} \tag{30}$$

The utility of choice S_H for photovoltaic building materials enterprises is

$$\begin{aligned}& U_e(S_H, b_{er}, c_{ere}) \\ & \quad = p\left(q\theta {S_H}^{\alpha} {S_h}^{\beta} - \frac{1}{2} c_e {S_H}^2\right) + (1-p)\left(q\theta {S_H}^{\alpha} {S_l}^{\beta} - \frac{1}{2} c_e {S_H}^2\right) \\ & \quad + Y_e K_{\mathrm{er}}(S_H, b_{er}) \lambda_{ere}(b_{er}, c_{ere})\end{aligned} \tag{31}$$

The utility of choice S_L for photovoltaic building materials enterprises is

$$U_e(S_L, b_{er}, c_{ere}) = q\theta {S_L}^{\alpha} {S_l}^{\beta} - \frac{1}{2} c_e {S_L}^2 + Y_e K_{\mathrm{er}}(S_L, b_{er}) \lambda_{ere}(b_{er}, c_{ere}) \tag{32}$$

(1) When $U_e(S_H, b_{er}, c_{ere}) > U_e(S_L, b_{er}, c_{ere})$, photovoltaic building materials enterprises will choose S_H, at this moment $p' = 1$. This only occurs when $p > 1/2$, as it is necessary to ensure that $\lambda_{ere}(b_{er}, c_{ere}) > 0$. Substituting and simplifying gives

$$Y_r > \frac{4\left[\frac{1}{2} c_r\left({S_h}^2 - {S_l}^2\right) - (1-q)\theta {S_H}^{\alpha}\left({S_h}^{\beta} - {S_l}^{\beta}\right)\right]}{q\theta {S_H}^{\alpha}\left({S_h}^{\beta} - {S_l}^{\beta}\right)\left[\frac{1}{2} c_r\left({S_h}^2 - {S_l}^2\right) + (1-q)\theta\left({S_H}^{\alpha} {S_h}^{\beta} + {S_H}^{\alpha} {S_l}^{\beta} - 2{S_L}^{\alpha} {S_h}^{\beta}\right)\right]}.$$

(2) When $U_e(S_H, b_{er}, c_{ere}) < U_e(S_L, b_{er}, c_{ere})$, photovoltaic building materials enterprises will choose S_L, at this moment $p' = 0$. Substituting p' and p into Equations (31) and (32) gives

$$Y_e < \frac{2\left[q\theta\left({S_H}^{\alpha} {S_h}^{\beta} - {S_L}^{\alpha} {S_l}^{\beta}\right) - \frac{1}{2} c_e\left({S_H}^2 - {S_L}^2\right)\right] - \frac{4}{Y_r} + \frac{2\left[(1-q)q\theta^2 {S_h}^{\beta}\left({S_H}^{\alpha} - {S_L}^{\alpha}\right){S_H}^{\alpha}\left({S_h}^{\beta} - {S_l}^{\beta}\right)\right]}{\frac{1}{2} c_r\left({S_h}^2 - {S_l}^2\right) - (1-q)\theta {S_H}^{\alpha}\left({S_h}^{\beta} - {S_l}^{\beta}\right)}}{\frac{2{S_L}^{\alpha}\left[(1-q)\theta {S_H}^{\alpha}\left({S_h}^{\beta} - {S_l}^{\beta}\right) - \frac{1}{2} c_r\left({S_h}^2 - {S_l}^2\right)\right]}{Y_r {S_H}^{\alpha}} - \left[(1-q)\theta {S_L}^{\alpha}\left({S_h}^{\beta} - {S_l}^{\beta}\right) - \frac{1}{2} c_r\left({S_h}^2 - {S_l}^2\right)\right]\left[q\theta {S_L}^{\alpha}\left({S_h}^{\beta} - {S_l}^{\beta}\right)\right]}.$$

(3) When $U_e(S_H, b_{er}, c_{ere}) = U_e(S_L, b_{er}, c_{ere})$, simplifying to get

$$p' = \frac{\dfrac{\left[q\theta\left({S_H}^{\alpha}{S_h}^{\beta}-{S_L}^{\alpha}{S_l}^{\beta}\right)-\frac{1}{2}ce\left({S_H}^2-{S_L}^2\right)\right]-\frac{2}{Y_r}+\frac{\left[(1-q)q\theta^2{S_h}^{\beta}({S_H}^{\alpha}-{S_L}^{\alpha}){S_H}^{\alpha}\left({S_h}^{\beta}-{S_l}^{\beta}\right)\right]}{\frac{1}{2}cr\left({S_h}^2-{S_l}^2\right)-(1-q)\theta {S_H}^{\alpha}\left({S_h}^{\beta}-{S_l}^{\beta}\right)}}{Y_e\left\{\frac{2(1-q)}{Y_r q}-\frac{cr\left({S_h}^2-{S_l}^2\right)}{Y_r q\theta {S_H}^{\alpha}\left({S_h}^{\beta}-{S_l}^{\beta}\right)}-\left[(1-q)\theta {S_L}^{\alpha}\left({S_h}^{\beta}-{S_l}^{\beta}\right)-\frac{1}{2}cr\left({S_h}^2-{S_l}^2\right)\right]\right\}}+\frac{1}{2}q\theta {S_L}^{\alpha}\left({S_h}^{\beta}-{S_l}^{\beta}\right)}{\frac{1}{2}q\theta({S_H}^{\alpha}+{S_L}^{\alpha})\left({S_h}^{\beta}-{S_l}^{\beta}\right)-\frac{2}{Y_r}+\frac{\left[(1-q)q\theta^2{S_h}^{\beta}({S_H}^{\alpha}-{S_L}^{\alpha}){S_H}^{\alpha}\left({S_h}^{\beta}-{S_l}^{\beta}\right)\right]}{\frac{1}{2}cr\left({S_h}^2-{S_l}^2\right)-(1-q)\theta {S_H}^{\alpha}\left({S_h}^{\beta}-{S_l}^{\beta}\right)}}.$$

Certificate of completion. □

Proposition 4 considers the equilibrium behaviour of photovoltaic building materials enterprises when the reciprocity sensitivity of academic and research institutions is at an intermediate value in the collaborative digital green innovation knowledge sharing process of photovoltaic building materials enterprises. The first type of equilibrium is that photovoltaic building materials enterprises choose to pay a high level of knowledge sharing effort when the likelihood that academic and research institutions choose to pay a high level of knowledge sharing effort is high, given the dual effect of material payment and reciprocal payment. However, there are other types of equilibrium, where if photovoltaic building materials enterprises believes that academic and research institutions believes that photovoltaic building materials enterprises will choose to pay a low level of knowledge sharing effort, and that academic and research institutions will choose to pay a low level of knowledge sharing effort in retaliation in such a case, then photovoltaic building materials enterprises will consider academic and research institutions to be unfriendly. This can therefore lead to photovoltaic building materials enterprises choosing to pay a low level of knowledge sharing effort. Another equilibrium is that material payments by photovoltaic building materials enterprises and the friendly behaviour of academic and research institutions cause photovoltaic building materials enterprises to choose to pay a high level of knowledge sharing effort with a certain probability p'.

6. Conclusions and perspectives

Research conclusions: This paper investigates the reciprocal effect of knowledge sharing in collaborative digital green innovation in photovoltaic building materials enterprises from a dynamic domain perspective by introducing a sequential reciprocity model, and the following conclusions are obtained:

In the collaborative digital green innovation knowledge sharing process of photovoltaic building materials enterprises, when the reciprocal sensitivity of the academic and research institutions is large enough, academic and research institutions can sense the goodwill conveyed by photovoltaic building materials enterprises enterprises choosing to pay a high level of knowledge sharing effort and will reciprocate with friendly behaviour, i.e., also choosing to pay a high level of knowledge sharing effort.

When the reciprocal sensitivity of academic and research institutions is low, academic and research institutions will choose to pay a low level of knowledge sharing effort to photovoltaic building materials enterprises.

When the reciprocity sensitivity of academic and research institutions is in the middle, academic and research institutions will choose to pay a high level of knowledge sharing effort with a certain probability, and the probability increases as the reciprocity sensitivity of academic and research institutions increases. When photovoltaic building materials enterprises chooses to pay a low level of knowledge sharing effort, academic and research institutions, sensing the company's unfriendliness, will choose to pay a low level of knowledge sharing effort in retaliation under the dual effect of material payment and reciprocal payment.

Theoretical contributions: Existing studies on knowledge sharing incentives has mainly focused on knowledge sharing incentives within organisations such as consortia and teams from a static perspective, and there are fewer studies on the reciprocal incentive effects of collaborative digital green innovation between different actors at the firm level in a dynamic strategic environment. As knowledge resources are the most important factors of production and core capital for enterprises in the knowledge economy, and the key to technological innovation and core competitiveness, it is particularly important for enterprises to strengthen knowledge sharing with academic and research institutions. In particular, major innovation projects in the field of basic research and high technology require more knowledge sharing of digital green innovation subjects with distributed knowledge. In the process of cooperation, photovoltaic building materials enterprises take corresponding measures in order to stimulate collaborative digital green innovation knowledge sharing. However, relatively little research has been conducted on the incentive of knowledge sharing between enterprises and academic and research institutions. In addition, few studies have been conducted using the sequential reciprocity model. This paper introduces a sequential reciprocity model to study the incentive effects of knowledge reciprocity in collaborative digital green innovation from a dynamic domain perspective, in the hope of enriching the theory of reciprocity and providing a reference for knowledge sharing in collaborative digital green innovation.

Practical insights: Knowledge sharing is a key element of knowledge management throughout organisational collaboration. A collaborative knowledge sharing mechanism is a prerequisite for effective work. Knowledge sharing is a common choice between enterprises and academic and research institutions for digital green innovation, reflecting the overall attitude of enterprises and academic and research institutions towards innovation. Strengthening knowledge sharing between enterprises and academic and research institutions facilitates dynamic knowledge flow, promotes knowledge transfer, and is more beneficial to the generation of new knowledge. However, as the members of innovation subjects come from different organisations, cooperation between different subjects is generally characterised by temporary and transient nature, resulting in both parties not understanding the level of knowledge sharing efforts of different subjects, thus creating an information gap. Therefore, enterprises need to take appropriate measures to stimulate collaborative digital green innovation knowledge sharing.

Firstly, when the intrinsic reciprocal motivation of academic and research institutions is large enough, photovoltaic building materials enterprises should improve their own knowledge sharing efforts to stimulate the reciprocal preference of academic and research institutions, which will be more conducive to the sharing and absorption of explicit and tacit knowledge, enabling a more tacit and benign interaction between photovoltaic building materials enterprises and academic and research institutions, promoting the development of collaborative digital green innovation activities of enterprises, and thus increasing the benefits generated by collaborative digital green innovation of photovoltaic building materials enterprises.

Secondly, where the reciprocity sensitivity of academic and research institutions is low, increasing the motivation of academic and research institutions to reciprocate is a prerequisite for changing the low level of knowledge sharing effort that photovoltaic building materials enterprises choose to pay.

Shortcomings and future research perspectives: In this study, the sequential reciprocity model is used to investigate the mechanism of forming a collaborative digital green innovation climate in photovoltaic building materials enterprises. This paper lacks a suitable case study, and future research could combine case studies to reveal the reciprocal mechanism of collaborative digital green innovation.

In addition, this paper mainly analyses the internal elements in the process of collaborative digital green innovation of enterprises, without considering the influence of factors such as government policy orientation in the external environment on collaborative digital green innovation of enterprises, which can be further explored in future research.

Finally, this paper uses the sequential reciprocity model to establish an evolutionary game model of knowledge sharing incentives between photovoltaic building materials enterprises and academic and research institutions, and draws conclusions through the analytical solution of the model, lacking the inclusion of numerical simulation models. In the future, the inclusion of numerical simulation and the combination of relevant cases can be studied to make the research conclusions more constructive and feasible.

Author contributions

Conceptualization, YS and SY; methodology, YS and YZ (Yingying Zhang); software, YS and SY; validation, YD (Yudan Zhao) and SY; writing—original draft preparation, YZ (Yingying Zhang) and YS; writing—review and editing, CH, SY and YZ (Yingying Zhang). All authors have read and agreed to the published version of the manuscript.

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Data availability statement

No underlying data was collected or produced in this study.

Conflicts of interest

The authors declare no conflict of interest.

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