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*Research article*

# Enhancing building energy efficiency: Formation of a cooperative digital green innovation atmosphere of photovoltaic building materials based on reciprocal incentives

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**Abstract:** A good innovation atmosphere between photovoltaic building materials manufacturing enterprises and universities and scientific research institutions is conducive to the effective development of a cooperative digital green innovation process. This paper establishes an evolutionary game model for the formation of a cooperative digital green innovation atmosphere in photovoltaic building materials manufacturing enterprises under two mechanisms: direct and indirect reciprocity. The results show that both direct and indirect reciprocity mechanisms are conducive to the formation of a cooperative digital green innovation atmosphere for photovoltaic building materials manufacturing enterprises. This study provides theoretical guidance for photovoltaic building materials manufacturing enterprises to cultivate a cooperative digital green innovation atmosphere.

**Keywords:** innovation atmosphere; photovoltaic building materials manufacturing enterprises; reciprocity behavior

## 1. Introduction

The proposed two-carbon target means that many fields need to be transformed, among which energy transformation is the most important. The first task to reduce carbon emissions and achieve carbon neutrality is to achieve clean substitution at the end of power generation [1]. Solar energy is not only the primary energy form but also renewable energy. Solar energy has many advantages, such as being safer and pollution-free than nuclear power and being more abundant and stable than other clean energy sources, such as wind and water [2]. At present, there are many mature technologies for storing solar energy, including battery [3], hydrogen, and superconducting energy [4] storages. In theory, solar energy can release enough energy to meet a country's various energy needs for a long time. Solar energy has many advantages, such as sufficient amounts, environmental protection, and safety. It has become a new focus of energy development and utilization in many countries, which has also driven the rapid development of the photovoltaic industry in recent years [5].

The building materials industry is an important basic industry for national economic and social development, as well as a key industry for energy consumption and carbon emissions in the industrial field. The photovoltaic building materials manufacturing industry has become another green technology industry after IT and microelectronics. Under the guidance of the goal of carbon neutrality, China's photovoltaic building materials manufacturing industry is entering a period of rapid development [6]. The post-COVID-19 international market environment supports the co-existence of crises and opportunities. With the explosive growth of global photovoltaic building materials manufacturing enterprises, competition is becoming increasingly fierce [7]. Therefore, it is of great significance to study the formation mechanisms of the digital green innovation atmosphere of photovoltaic building materials manufacturing enterprises to realize the goal of "double carbon". The "double carbon" goal refers to China's goal of peaking carbon dioxide emissions by 2030 and achieving carbon neutrality by 2060.

Photovoltaic building materials manufacturing enterprises are currently in the early stages of development, with huge development potential, and they are expected to maintain a stable and high growth rate until 2030 or even longer. Photovoltaic building materials manufacturing enterprises have broad prospects, bringing huge space for photovoltaic technology innovation and industrial development [8]. However, the development of the enterprises also faces many challenges. Although China's photovoltaic building materials manufacturing enterprises have developed rapidly and their photovoltaic capacity has expanded rapidly due to their insufficient digital green innovation ability and lack of core technology [9], the product costs and market prices remain high, which hinders the improvement of the competitiveness of the industry and restricts the promotion of photovoltaic building materials in the market [10].

Digital green innovation is key to the survival and development of an enterprise and industry [11]. Only by achieving the lowest cost, the most advanced technology, the highest management efficiency, and the highest operational efficiency in the entire industry can enterprises have a foundation and achieve sustainable development [12]. In the innovation system of photovoltaic building materials manufacturing enterprises, there is a lot of industry–academic cooperation, including technology development project cooperation, personnel exchange joint training, co-construction of laboratories, etc. [13]. A good innovation atmosphere among photovoltaic building materials manufacturing enterprises, universities, and research institutes is conducive to the effective development of collaborative digital green innovation [14]. Therefore, whether a cooperative digital green innovation atmosphere can be formed between these entities is a key issue for the development of China's photovoltaic building materials manufacturing enterprises.

In this paper, the cooperative digital green innovation atmosphere of photovoltaic building materials manufacturing enterprises refers to the common perceptions of photovoltaic building materials manufacturing enterprises, universities, and scientific research institutions on the cooperative digital green innovation status. With regard to the photovoltaic building materials manufacturing industry, a cooperative digital green innovation atmosphere not only reflects the attitude of the two digital green innovation subjects (i.e., the enterprises and the universities and scientific research institutions) toward cooperative digital green innovation but also affects the behavior choice of the two types of digital green innovation subjects in the process of cooperative digital green innovation [15]. A cooperative digital green innovation atmosphere creates a good innovation environment, affects the value orientation of researchers, and stimulates the innovative spirit of researchers [16].

In the collaborative digital green innovation process of photovoltaic building materials manufacturing enterprises, since major breakthroughs in the forefront of science and technology mostly come from cross-disciplines and marginal disciplines, it is necessary to create conditions for researchers in different fields to discuss and inspire each other to develop innovative ideas [17]. In addition, a collaborative atmosphere influences the value orientation of the main members of digital green innovation, encourages researchers to take risks, innovate constantly, and gradually internalizes the psychological identity of the digital green innovation atmosphere into the main culture. Such a cultural transformation can foster the overall goal of pursuing cooperative digital green innovation of photovoltaic building materials manufacturing enterprises into the conscious behaviors of each entity in the cooperation, resulting in more collaborative efforts [18].

Existing studies on innovation climate originated from research on organizational climate by scholars in the 1990s, which mainly focused on the field of organizational behavior in three aspects. A first stream of this research addresses the influence of innovation climate on employees' innovation behavior and its process mechanism. For example, Gu pointed out that an innovation atmosphere is significantly positively correlated with employees' innovation behavior and that innovation self-efficacy plays an intermediary role between the two [19]. Wang revealed the mediating role of internal and external work motivation between different dimensions of the organizational innovation climate and employee innovation behavior [20]. Yan studied the mediating role of perceived organizational support and organizational commitment and the moderating role of performance pay and perceived innovation self-efficacy [21]. The second research stream explores the relationship between the innovation climate and innovation performance. For example, Xie indicated that a collaborative innovation atmosphere has a positive impact on innovation performance [22]. Shanker et al. pointed out that employees' innovative work behaviors play an intermediary role in the relationship between the organizational innovation climate and organizational performance [23]. Dang conducted an empirical study on the mediating effect of the innovation climate of network organizations on the leadership styles of different types of core enterprises and network innovation performance [24].

This review of the previous literature further reveals that the existing research on the innovation climate mainly focuses on the individual and team levels within the organization, with a few studies on the innovation climate between organizations. A notable gap is the paucity of studies on the formation of a digital green innovation atmosphere between enterprises and universities and scientific research institutions. Further, most current studies used questionnaires and structural equation models to study the antecedent variables, outcome variables, and measurement scales of innovation atmosphere, with a few studies on the formation of a cooperative digital green innovation atmosphere in photovoltaic building materials manufacturing enterprises based on the perspective of reciprocity mechanism and evolutionary game method.

To address the gaps in the existing research on the innovation atmosphere, this study analyzes the formation mechanism of the cooperative digital green innovation atmosphere of photovoltaic building materials manufacturing enterprises based on reciprocity theory, constructs the evolutionary game model of the digital green innovation atmosphere of photovoltaic building materials manufacturing enterprises under the two mechanisms of direct reciprocity and indirect reciprocity, and analyzes its stability. It provides important theoretical guidance for photovoltaic building materials manufacturing enterprises to cultivate a cooperative digital green innovation atmosphere.

The remainder of this paper is as follows. Section 2 elaborates on the theoretical basis and puts forward the basic hypothesis. Section 3 establishes the game model and provides a solution. Section 4 summarizes the research results, presents the limitations of the study, and offers suggestions for future research.

## 2. Theoretical basis and basic assumptions

### *2.1. Theoretical basis*

In the photovoltaic building materials manufacturing industry, collaborative digital green innovation requires cooperation between two digital green innovation subjects, a relationship that does not only possess the general characteristics of cooperation but also has the particularity of digital green innovation [25]. To elucidate the formation mechanisms of the cooperative digital green innovation atmosphere of photovoltaic building materials manufacturing enterprises under the reciprocal mechanism, the motivation behind the cooperative innovation behavior of the two types of digital green innovation subjects needs to be further investigated. Huang and Wei summarized the two main lines of the definition of "cooperation" through a review of the relevant literature on cooperation. The first is the definition based on "behavior", which regards cooperation as conscious or deliberate cooperative behavior. The second describes cooperation based on the "economy" of behavior and regards cooperation as a kind of joint action, which can bring mutual benefits to all cooperative subjects.

Huang and Wei also believed that cooperation has two basic characteristics. First, cooperation is the result of voluntary choice, and the basic premise of cooperative behavior is freedom. Second, the most essential feature of cooperation is the unity of self-interest and mutual benefits. Although certain cooperative behaviors may not make some cooperative subjects gain benefits in the short-term, concessions can result in gaining more considerable benefits in the long run [26]. This suggests that cooperative digital green innovation of the photovoltaic building materials manufacturing industry is a process of conscious and continuous interaction between the enterprises and universities and scientific research institutions to achieve their respective interests and purposes [27].

Reciprocity, as one of the mechanisms of the evolution of cooperative behavior, is the premise of the stable and sustainable cooperative innovation of the two types of digital green innovation subjects [28]. Given that the results of digital green innovation are often major discoveries and inventions, they open up new innovation cycles and climax them, as well as catalyze multiple fields. However, innovation subjects may not be able to obtain all the benefits and social value of digital green innovation results [29]. Therefore, digital green innovation has the characteristics of public goods, which may cause non-cooperation between the enterprises and universities and scientific research institutions and thus lead to the interruption of cooperative digital green innovation [30].

The cooperative digital green innovation atmosphere of photovoltaic building materials manufacturing is not only the cause but also the result of the cooperative innovation behavior between enterprises and universities and scientific research institutions [31]. The perceptions of researchers in the two types of digital green innovation subjects affect their choice of cooperative innovation behavior, which is the key to the formation of a cooperative digital green innovation atmosphere in photovoltaic building materials manufacturing enterprises [32]. Reciprocal behavior among the two types of digital green innovation subjects is the premise of a stable and sustainable cooperative innovation atmosphere. The subjects' cooperative innovation behavior will not only affect their respective returns and the overall returns but also determine the degree of reciprocity in the cooperative digital green innovation process of the enterprises [33]. Further, the reciprocal behavior between the subjects is also the premise for the formation of a good cooperative digital green innovation atmosphere. A digital green innovation atmosphere can promote the emergence of reciprocal behavior between the subjects [34]. Figure 1 summarizes the formation mechanism of a cooperative digital green innovation atmosphere for photovoltaic building materials manufacturing enterprises.

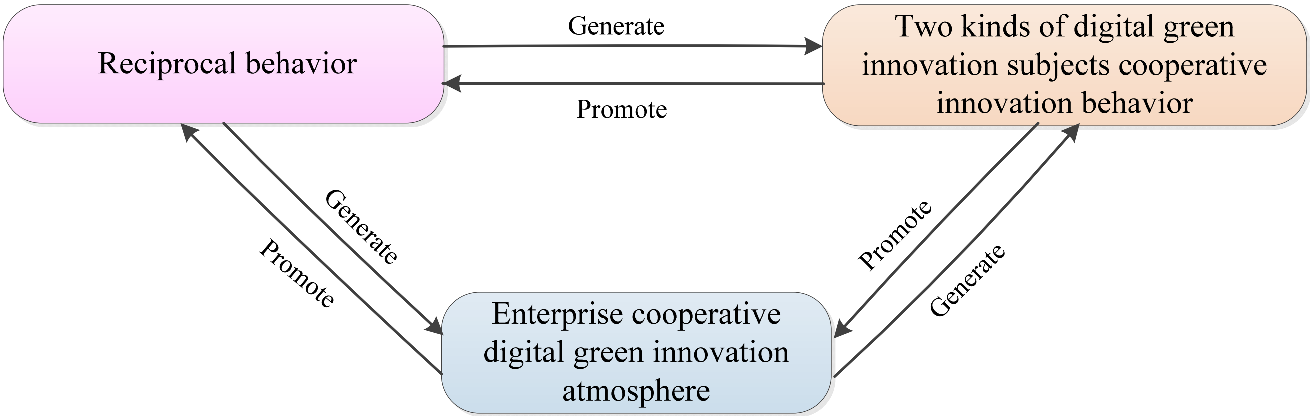


**Figure 1.** Formation mechanism of cooperative digital green innovation atmosphere in photovoltaic building materials manufacturing enterprises.

Many experimental game studies have shown that reciprocity is an important mechanism for promoting the evolution of cooperation. Reciprocity behavior includes two forms: direct reciprocity and indirect reciprocity [35]. The basic condition for direct reciprocity to work is the possibility of repeated encounters between cooperators. Only in this way can a single game be transformed into a repeated game, hence avoiding the "prisoner's dilemma". This indicates that direct reciprocity is more suitable for explaining the cooperative behavior of smaller groups [36]. Indirect reciprocity does not require repeated encounters between cooperators, and both parties can obtain rewards from a third party, which is more suitable for explaining large-scale group cooperative behaviors [37]. Reputation is the key for indirect reciprocity to work, and individual reputation information must be diffused in the group [38]. In the process of collaborative digital green innovation of photovoltaic building materials manufacturing enterprises, these two mechanisms usually exist simultaneously. Therefore, this study explores the evolution of the formation of a cooperative digital green innovation atmosphere in the photovoltaic building materials manufacturing industry from the perspectives of direct reciprocity behavior and indirect reciprocity behavior.

### *2.2. Basic assumptions and parameter settings*

(1) It is assumed that the photovoltaic building materials manufacturing enterprises and researchers in universities and scientific research institutions participating in the game are bounded rational. In other words, cooperative digital green innovation is not achieved overnight. It is a process in which each participant continuously adjusts and improves their own strategy and behavior mode through learning, trial and error, etc., to find a better strategy. This assumption cannot be relaxed and should be strictly enforced.

(2) It is assumed that collaborative innovation between photovoltaic building materials manufacturing enterprises and researchers in universities and scientific research institutions is carried out through random pairing. The basic premise of the stable and sustainable cooperative innovation of the two types of digital green innovation agents is that all partners believe that the cooperation process is mutually beneficial. This assumption cannot be relaxed and should be strictly enforced.

(3) It is assumed that the difference in the personal attributes of the two types of digital green innovation subjects participating in the game is not considered. The difference in their payment in the game is determined by their different behavior strategies and has nothing to do with their own attributes. This assumption cannot be relaxed and should be strictly enforced.

(4) It is assumed that according to the attitude toward collaborative innovation behavior, the strategies of the two types of digital green innovation subjects include non-cooperation and discrimination cooperation. Researchers who do not cooperate tend to use the innovation strategy of getting something for nothing, and researchers who cooperate tend to use the cooperative innovation strategy, which is manifested as strategy switching through learning and trial and error in the game process. The proportion of researchers who employ cooperative and non-cooperative strategies in the two types of digital green innovation subjects is denoted by $x$ and $1-x$, respectively.

The two types of digital green innovation agents are connected in the form of social interaction, and then form a social network of digital green innovation. This network is also the knowledge spillovers area when they interact [39]. Regardless of whether knowledge spillovers are conscious or unconscious, both types of digital green innovation agents may obtain positive externalities, enjoy each other's knowledge at a very low cost, and thus enhance their own knowledge base [40]. Therefore, researchers who choose the strategy of non-cooperation have the opportunity to obtain the knowledge shared by others in the knowledge spillover area at a very low cost while hiding their own knowledge from divulging to others [41]. Researchers who choose to employ cooperative strategies will collect and analyze information about each other before each round of the game for the accuracy of decision-making. However, due to the asymmetry of information, there are certain errors when researchers make judgments about the type of the other party based on the collected information [42]. This assumption cannot be relaxed and should be strictly enforced.

(5) Assume that the cost of collecting and analyzing the information of the opponent before each round of the game is $c'$, $c'>0$. The probability that the researcher made the correct judgment about the person's type based on the information gathered was $\omega$, $0<\omega\le 1$. This assumption cannot be relaxed and should be strictly enforced. Due to the limited research time, follow-up data verification will be the future research direction.

## 3. Evolutionary game analysis of digital green innovation climate formation under direct reciprocity behavior

### *3.1. Model assumptions and construction*

The basic condition for direct reciprocity to work is the possibility of repeated encounters between partners. This makes individuals not only focus on short-term gains, but also need to consider long-term gains [43]. In game theory, direct reciprocity behavior is represented by repeated games between individuals. The number of repeated games and the completeness of information are the main factors that affect the equilibrium outcome of repeated games [44].

It is assumed that each researcher sticks to his or her original strategy until he or she reflects on his or her strategy, that is, whether to change his or her strategy type [45]. In each reflection stage, the probability of the next round of cooperative innovation occurring is $\tau$, $0 \le \tau < 1$, then the expected number of rounds of cooperative innovation occurring in each reflection stage is $\frac{1}{(1-\tau)}$. In each round of the game, if researchers choose the cooperative innovation strategy, the cost paid is $c$, the cooperative innovation reward given by the two types of digital green innovation subjects is $b_1$, and the intrinsic incentive is $b_2$. If the non-cooperative innovation strategy is chosen, the gain of obtaining the other party's knowledge is $b_3$. If both of them choose the non-cooperative innovation strategy, the loss is $d$. Table 1 is Nomenclature.

**Table 1.** Nomenclature.

| | | | |
|---|---|---|---|
| $x$ | Select the proportion of cooperation strategies among the two types of digital green innovation subjects | $1-x$ | The proportion of researchers in the two types of digital green innovation subjects who choose non-cooperative strategies |
| $c'$ | The cost of collecting and analyzing each other's information before each round of the game | $\omega$ | The probability that the scientist will make a correct judgment about the type of the other person based on the information collected |
| $\tau$ | The probability of the next round of digital green collaborative innovation occurring in each reflection stage | $1/(1-\tau)$ | Expected number of rounds of digital green collaborative innovation occurring in each reflection stage |
| $c$ | The cost that researchers pay if they choose the digital green cooperative innovation strategy | $b_1$ | Digital green cooperation is rewarded by two types of digital green innovation subjects |
| $b_2$ | The cooperation is intrinsically stimulated by two types of digital green innovation subjects | $b_3$ | Choose not to digital green cooperative innovation strategy, get the benefits of each other's knowledge |
| $d$ | Both have chosen not to suffer from digital green collaborative innovation strategies | | |

**Table 2.** Game payoff matrix between two types of main scientific researchers in collaborative digital green innovation of photovoltaic building materials manufacturing enterprises under direct reciprocity behavior.

| Researchers of photovoltaic building materials manufacturing enterprises | Researchers in universities and research institutions: Identifying cooperation | Noncooperation |
|---|---|---|
| Identifying cooperation | $(\frac{(b_1+b_2-c)\omega^2-c}{1-\tau},\frac{(b_1+b_2-c)\omega^2-c}{1-\tau})$ | $((b_1+b_2-c)(1-\omega)-\frac{c'}{1-\tau},b_3(1-\omega))$ |
| Noncooperation | $(b_3(1-\omega),(b_1+b_2-c)(1-\omega)-\frac{c'}{1-\tau})$ | $(-\frac{d}{1-\tau},-\frac{d}{1-\tau})$ |

Suppose that each round of the game only needs to pay the cost of collecting and analyzing the information of the opponent, $c'$, to identify the unsuitable author and stop playing with him, and $c'$ is inversely related to the probability $\omega$ of making a correct judgment. When two researchers who choose the discrimination cooperation strategy play the game, they will get payment $b_1+b_2-c$ with probability $\omega^2$ in each round, and pay the information collection and analysis cost $c'$ of each other, so the total payment obtained in each round is $(b_1+b_2-c)\omega^2-c'$, and the final total payment obtained in each reflection stage is $\frac{(b_1+b_2-c)\omega^2-c'}{(1-\tau)}$. The other three payments are similar. Table 2 shows the game payoff matrix between the two types of main scientific researchers of collaborative digital green innovation of photovoltaic building materials manufacturing enterprises under direct reciprocity behavior.

The fitness of the researchers of the photovoltaic building materials manufacturing enterprise to choose the discrimination cooperation strategy is $eAP^T$ , where $e=(1,0)$ is the unit vector, $P=(x,1-x)$ is the mixed strategy of the researchers, and the corresponding payment matrix is

$$A=\begin{pmatrix} \dfrac{(b_1+b_2-c)\omega^2-c'}{1-\tau} & (b_1+b_2-c)(1-\omega)-\dfrac{c'}{1-\tau} \\ b_3(1-\omega) & -\dfrac{d}{1-\tau} \end{pmatrix} \tag{1}$$

The average fitness of researchers in photovoltaic building materials manufacturing enterprises is PAPT; then, the replication dynamic equation is

$$x=\frac{dx}{dt}=x(eAP^T-PAP^T)=x(1-x)\left\{\begin{matrix}\left[\dfrac{(b_1+b_2-c)\omega^2-d}{1-\tau}-(1-\omega)(b_3+b_1+b_2-c)\right] \\ +(b_1+b_2-c)(1-\omega)-\dfrac{c'-d}{1-\tau}\end{matrix}\right\} \tag{2}$$

*3.2. Stability analysis of cooperative digital green innovation atmosphere of photovoltaic building materials manufacturing enterprises*

Let $\dot{x}=0$, the possible evolutionary stable strategy of Eq (2) can be obtained as

$$x_2^*=1,\ x_1^*=0,\ x_3^*=1-\frac{c'+(1-\tau)(1-\omega)b_3-(b_1+b_2-c)\omega^2}{(1-\tau)(1-\omega)(b_3+b_1+b_2-c)+d-(b_1+b_2-c)\omega^2} \tag{3}$$

$x_1^*=0$ indicates that the researcher chooses the non-cooperative strategy, and $x_2^*=1$ indicates that the researcher chooses the discriminative cooperative strategy.

How to form the cooperative digital green innovation atmosphere of photovoltaic building materials manufacturing enterprises is to study under what circumstances the cooperative innovation behavior of the two types of digital green innovation subjects and researchers is stable and sustainable, that is, to analyze the evolution and stability of $x_1^*$, $x_2^*$ and $x_3^*$.

Proposition 1: When $\dfrac{c'}{1-\tau}>\dfrac{d}{1-\tau}+(1-\omega)(b_1+b_2-c)$, $x_1^*=0$ is an evolutionarily stable strategy.

Proof: When $\dfrac{c'}{1-\tau}>\dfrac{d}{1-\tau}+(1-\omega)(b_1+b_2-c)$, $x_3^*<0$ can be obtained, because it is contradictory with $0\le x\le 1$, so it is discarded. In this case, $\dot{x}'\big|_{x=x_1^*}<0, \dot{x}'\big|_{x=x_2^*}>0$ , according to the qualitative theory of differential equations, $x_1^*=0$ is an evolutionary stable strategy. Certificate completed.

Proposition 1 shows that after $\dfrac{1}{(1-\tau)}$ round of the game, when the researchers of the two types of digital green innovation subjects pay the cost $\dfrac{c'}{1-\tau}$ of collecting and analyzing each other's information is greater than the sum of the expected profit $(1-\omega)(b_1+b_2-c)$ and the loss $\frac{d}{1-\tau}$ suffered by the researchers who choose not to cooperate in the innovation strategy when they play the game with the researchers who choose not to cooperate in the innovation strategy. The researchers who choose the discrimination cooperation strategy will no longer play a game with the researchers who choose the non-cooperation strategy, and the non-cooperation strategy is the optimal strategy for the two types of digital green innovation main researchers. In this case, the cooperative digital green innovation atmosphere of photovoltaic building materials manufacturing enterprises cannot be formed. Its evolution process is shown in Figure 2.

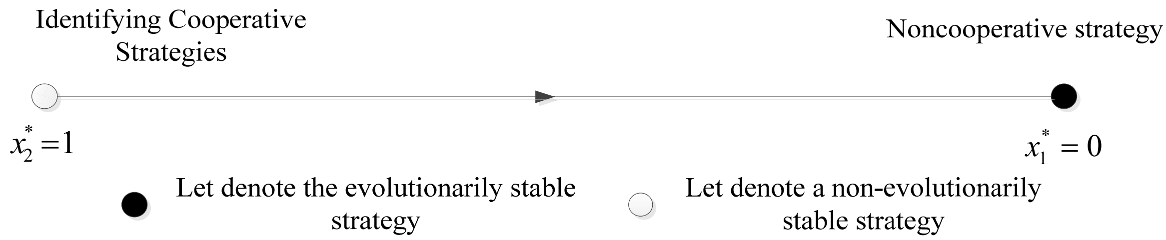


**Figure 2.** Evolutionary dynamics of cooperative innovation behavior when $\frac{c'}{1-\tau}>\frac{d}{1-\tau}+(1-\omega)(b_1+b_2-c)$.

Proposition 2: If $0\le\frac{c'}{1-\tau}<\frac{(b_1+b_2-c)\omega^2}{1-\tau}-(1-\omega)b_3$ and $b_1+b_2-c>\frac{(1-\tau)(1-\omega)b_3}{\omega^2}$, $x_2^*=1$ is an evolutionarily stable strategy.

Proof: When $0\le\frac{c'}{1-\tau}<\frac{(b_1+b_2-c)\omega^2}{1-\tau}-(1-\omega)b_3$ and $b_1+b_2-c>\frac{(1-\tau)(1-\omega)b_3}{\omega^2}$, $x_3^*=1$ can be obtained, because it is in contradiction with $x_3^*=1$, so it is discarded. In this case, $\dot{x}'\big|_{x=x_1^*}>0, \dot{x}'\big|_{x=x_2^*}<0$, according to the qualitative theory of differential equations, $x_2^*=1$ is an evolutionary stable strategy. Certificate completed.

Proposition 2 shows that after $\frac{1}{(1-\tau)}$ round of the game, when the cost $\frac{c'}{1-\tau}$ of collecting and analyzing information of the researchers of the two types of digital green innovation subjects is less than the difference between the expected payment $\frac{(b_1+b_2-c)\omega^2}{1-\tau}$ and the expected payment $(1-\omega)b_3$ of the non-cooperation strategy when they play the game with the researchers who choose the discriminative cooperation strategy and the difference is positive, Researchers who choose non-cooperative strategies will disappear in two types of digital green innovation agents. At this time, identifying the cooperation strategy is the optimal strategy for the two types of digital green innovation subject researchers. In this case, the cooperative digital green innovation atmosphere of photovoltaic building materials manufacturing enterprises can be formed. Its evolution process is shown in Figure 3.

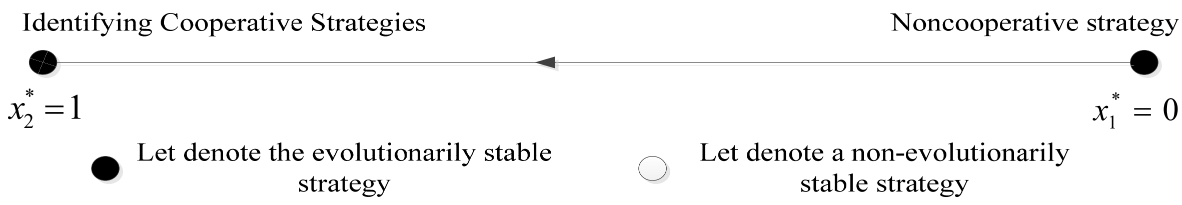


**Figure 3.** Evolution dynamics of cooperative innovation behavior when $0 \le \frac{c'}{1-\tau} < \frac{(b_1+b_2-c)\omega^2}{1-\tau} - (1-\omega)b_3$ and $b_1+b_2-c > \frac{(1-\tau)(1-\omega)b_3}{\omega^2}$.

Proposition 3: When $\max\left\{0, \frac{(b_1+b_2-c)\omega^2}{1-\tau} - (1-\omega)b_3\right\} < \frac{c'}{1-\tau} < \frac{d}{1-\tau} + (1-\omega)(b_1+b_2-c)$, $x_3^* = 1 - \frac{c' + (1-\tau)(1-\omega)b_3 - (b_1+b_2-c)\omega^2}{(1-\tau)(1-\omega)(b_3+b_1+b_2-c)+d-(b_1+b_2-c)\omega^2}$ is an evolutionarily stable strategy.

Proof: When $\max\left\{0, \frac{(b_1+b_2-c)\omega^2}{1-\tau} - (1-\omega)b_3\right\} < \frac{c'}{1-\tau} < \frac{d}{1-\tau} + (1-\omega)(b_1+b_2-c)$, $x_1^*$, $x_2^*$ and $x_3^*$ are all within the interval [0,1], then $\dot{x}'\big|_{x=x_1^*} > 0, \dot{x}'\big|_{x=x_2^*} > 0, \dot{x}'\big|_{x=x_3^*} < 0$, from the qualitative theory of differential equations, only $x_3^* = 1 - \frac{c' + (1-\tau)(1-\omega)b_3 - (b_1+b_2-c)\omega^2}{(1-\tau)(1-\omega)(b_3+b_1+b_2-c)+d-(b_1+b_2-c)\omega^2}$ is an evolutionarily stable strategy. Certificate completed.

Proposition 3 shows that after $\frac{1}{(1-\tau)}$ round of the game, when the researchers of the two types of digital green innovation subjects pay the cost of collecting and analyzing each other's information $\frac{c'}{1-\tau}$ is less than the sum of the expected profit $(1-\omega)(b_1+b_2-c)$ and the loss $\frac{d}{1-\tau}$ when they play the game with the researchers who choose not to cooperate in innovation strategy. Moreover, when $\frac{c'}{1-\tau}$ is greater than the difference between the expected payoff $\frac{(b_1+b_2-c)\omega^2}{1-\tau}$ of the researchers who choose the discrimination cooperation strategy and the expected payoff of the non-cooperation strategy and zero, there are researchers who choose the discrimination cooperation strategy and researchers who choose the non-cooperation strategy in the two types of digital green innovation subjects. At this time, the proportion of researchers who choose to identify the cooperative strategy is $1 - \frac{c' + (1-\tau)(1-\omega)b_3 - (b_1+b_2-c)\omega^2}{(1-\tau)(1-\omega)(b_3+b_1+b_2-c)+d-(b_1+b_2-c)\omega^2}$, and the proportion of researchers who choose the non-cooperative strategy is $\frac{c' + (1-\tau)(1-\omega)b_3 - (b_1+b_2-c)\omega^2}{(1-\tau)(1-\omega)(b_3+b_1+b_2-c)+d-(b_1+b_2-c)\omega^2}$. The flowchart of its evolution is shown in Figure 4.

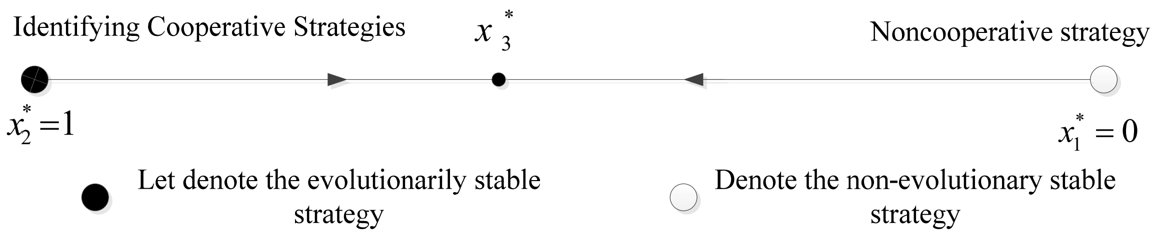


**Figure 4.** The evolutionary dynamics of cooperative innovation behavior when $\max\left\{0,\frac{(b_1+b_2-c)\omega^2}{1-\tau}-(1-\omega)b_3\right\}<\frac{c'}{1-\tau}<\frac{d}{1-\tau}+(1-\omega)(b_1+b_2-c)$.

According to Propositions 1, 2 and 3, in the two cases of propositions 2 and 3, there will eventually be two evolutionary equilibria in the two types of subjects of cooperative digital green innovation of photovoltaic building materials manufacturing enterprises. One is dominated by researchers who choose to identify cooperation strategies, and the other is the coexistence of researchers who choose to identify cooperation strategies and researchers who choose not to cooperate strategies. At this time, the cooperative digital green innovation atmosphere of photovoltaic building materials manufacturing enterprises can be formed.

## 4. Evolutionary game analysis of digital green innovation atmosphere formation under indirect reciprocity behavior

### *4.1. Model assumption and construction*

Indirect reciprocity does not require repeated encounters between cooperators but can obtain rewards from third parties, which is more applicable to explaining large-scale group cooperative behavior. Reputation is the key to the function of indirect reciprocity, and individual reputation information must be diffused in the group [46].

On the basis of the above assumptions, the third strategy of scientific researcher–unconditional cooperation strategy is introduced. Here, the strategies of the two types of digital green innovation subjects are of three types: unconditional cooperation, non-cooperation, and discriminating cooperation. Suppose that the proportions of researchers with unconditional cooperation strategies, non-cooperation strategies, and discriminative cooperation strategies in the two types of digital green innovation subjects are denoted by $x_1$, $x_2$ and $x_3$, respectively. Researchers who cooperate unconditionally tend to choose cooperative innovation strategies under any circumstances. Uncooperative researchers tend to pursue strategies of innovation for nothing while hiding their knowledge from each other. Researchers who cooperate tend to evaluate the reputation of the other party by collecting and analyzing the information of the other party before the game before deciding whether to cooperate with the other party to innovate. If the reputation of the other party is “good”, then the cooperative innovation strategy is selected, and if the reputation of the other party is “bad”, then the non-cooperative innovation strategy is selected [47]. The cooperative digital green innovation atmosphere of photovoltaic building materials manufacturing enterprises is formed through a reciprocal game between the two types of digital green innovation subjects and researchers.

Suppose that each researcher sticks to his or her original strategy until he or she reconsiders his or her strategy—that is, whether to change his or her strategy type. In each reflective stage, the probability of the next round of cooperative innovation occurring is $\tau$, $0 \le \tau < 1$; thus, the expected number of rounds of cooperative innovation occurring in each reflective stage is $\frac{1}{(1-\tau)}$. In each round of the game, if the researcher chooses the cooperative innovation strategy, the cost paid is $c$, the reward of cooperative innovation given by the two types of digital green innovation subjects is $b_1$, the intrinsic incentive is $b_2$, and the other party of a cooperative innovation will get the benefit of the cooperative innovation is $b_3$.

Nowak and Sigmund constructed an indirect reciprocity model based on image scoring, and proposed that individuals rely on the first-level information to evaluate the reputation of others [48]. Many studies have shown that, in reality, people rarely actively process deeper information. Therefore, Nowak and Sigmund's impression scoring strategy was adopted as the reputation evaluation standard in this study. That is, it is assumed that researchers who identify cooperation will evaluate each other's reputation based on first-level information, and the reputation of researchers depends on their strategy in the last round of the game. If a researcher chooses the cooperative innovation strategy in the last round, his or her reputation is "good". If he or she chooses the non-cooperative innovation strategy in the last round, his or her reputation is "bad". For convenience, assuming that the initial reputation of researchers of the two types of digital green innovation subjects is "good" and that the reputation information of researchers is complete, $g_t$ is used to represent the proportion $(g_1 = 1)$ of researchers with a "good" reputation after the $t$ round of the game, which can be obtained as follows:

$$g_t = x_1 + g_{t-1}x_3,\ \ t = 2,3,4... \tag{4}$$

For scientific researchers who cooperate unconditionally, the expected payment for each round is $b_1 + b_2 - c + b_3(x_1 + x_3)$, and the total payment ultimately obtained for each reflective phase is as follows:

$$\pi_1 = \frac{b_1 + b_2 - c + b_3(x_1 + x_3)}{1-\tau} \tag{5}$$

For non-cooperative scientific researchers, the expected payoff is $b_3(x_1 + x_3)$ for the first round, $b_3x_1$ for each subsequent round, and the total payoff ultimately obtained for each reflective phase is expressed as:

$$\pi_2 = \left(\frac{1}{1-\tau} - 1\right)b_3x_1 + b_3(x_1 + x_3) = \frac{1}{1-\tau}b_3x_1 + b_3x_3 \tag{6}$$

For researchers who identify cooperation, the expected payoff is $b_1 + b_2 - c + b_3(x_1 + x_3)$ in the first round, and ($t > 1$) at the beginning of the game in round $t$, where the proportion of researchers with a "good" reputation is $g_{t-1}$, and the corresponding expected payoff is $(b_1 + b_2 - c)g_t + b_3(x_1 + x_3)$, and the proportion of researchers with a "bad" reputation is $1 - g_{t-1}$, and the corresponding expected payoff is $(b_1 + b_2 - c)g_t + b_3 x_3$. The expected payoff for round $t$ is obtained as $(b_1 + b_2 + b_3 - c)g_t$, and the total payoff ultimately obtained for each reflection stage is

$$\begin{aligned}\pi_3 &= (b_1 + b_2 + b_3 - c)(\tau g_2 + \tau^2 g_3 + \cdots + \tau^{t-1} g_t) + b_1 + b_2 - c + b_3(x_1 + x_3) \\ &= (b_1 + b_2 + b_3 - c)g - b_3 x_2\end{aligned} \tag{7}$$

where

$$g = g_1 + \tau g_2 + \tau^2 g_3 + \cdots + \tau^{t-1} g_t \tag{8}$$

Substituting Eq 4 into Eq 8 yields the following:

$$g = \frac{1 - \tau + \tau x_1}{(1 - \tau)(1 - \tau x_3)} \tag{9}$$

Since the structure of the game does not change by subtracting the same numerical value from all payoff functions, Eqs 5–7 are subtracted simultaneously by $\pi_2$ to simplify all payoff functions as

$$\pi_1' = \pi_1 - \pi_2 = \frac{\tau b_3 x_3 + b_1 + b_2 - c}{1 - \tau} \tag{10}$$

$$\pi_2' = \pi_2 - \pi_2 = 0 \tag{11}$$

$$\pi_3' = \pi_3 - \pi_2 = \frac{1 - \tau + \tau x_1}{1 - \tau}\left(\frac{b_1 + b_2 + b_3 - c}{1 - \tau x_3} - b_3\right) \tag{12}$$

To reflect the changing dynamics of the three strategy types chosen by the two types of digital green innovation subjects, this study adopts Taylor's classic replication dynamic model of Eq 13:

$$\dot{x}_i = x_i(\pi_i - \bar{\pi}) \tag{13}$$

where $\bar{\pi} = \sum x_i \pi_i (x_i > 0, \sum X_i = 1)$ represents the average payment.

### *4.2. Stability analysis of cooperative digital green innovation atmosphere of photovoltaic building materials manufacturing enterprises*

Substituting Eqs 10–12 into Eq 13, a three-dimensional dynamic system for the evolution of cooperative digital green innovation atmosphere of photovoltaic building materials manufacturing enterprises can be obtained:

$$\begin{cases}\dot{x}_1 = x_1\left(\dfrac{\tau b_3 x_3 + b_1 + b_2 - c}{1 - \tau} - \bar{\pi}\right)\dfrac{c - b_1 - b_2}{1 - \tau} > 0 \\ \dot{x}_2 = -\bar{\pi} x_2 \\ \dot{x}_3 = x_3\left[\dfrac{1 - \tau + \tau x_1}{(1 - \tau)}\left(\dfrac{b_1 + b_2 + b_3 - c}{1 - \tau x_3} - b_3\right) - \bar{\pi}\right]\end{cases} \tag{14}$$

where $\overline{\pi} = x_1\pi_1' + x_2\pi_2' + x_3\pi_3'$.

(1) When the cost of cooperative innovation is greater than its benefits $(c > b_1 + b_2 > 0)$,

(2) Let $\dot{x}_i = 0$, three stationary points— $e_1(1,0,0)$, $e_2(0,1,0)$, and $e_3(0,0,1)$ —and two stationary lines $e_1e_3(x_2 = 0)$, $x_3 = \frac{c - b_1 - b_2}{\tau b_3}$ of the evolutionary game (let $\tau b_3 > c - b_1 - b_2$) can be obtained. The evolutionary stable strategy proposed by Maynard Smith is defined as follows: $\Delta^{ESS} = \left\{ x \in \Delta^{NE} : u(y,y) < u(x,y), \forall y \in \beta^*(x), y \neq x \right\}$, where $\Delta$ is the set of mixed strategies, $\beta^*(x)$ is the optimal reaction function, and $x$ is the evolutionary stable strategy. This study refers to this definition to analyze the evolutionary stability of each stagnation point. The Nash equilibrium point is equivalent to the saturated stagnation point in population evolution. Therefore, the stability of the equilibrium point can be verified by saturation analysis of the equilibrium point. When the transverse eigenvalue of the stagnation point is less than or equal to 0, that is, $\dot{x}_i / x_i \leq 0$, the stagnation point is the saturation point, that is, the Nash equilibrium point. The results of the saturation analysis at each stagnation point are shown in Table 3.

**Table 3.** Results of saturation analysis of the stationary points.

| Stationary point | $\frac{\dot{x}_1}{x_1}$ | $\frac{\dot{x}_2}{x_2}$ | $\frac{\dot{x}_3}{x_3}$ | Saturability |
|---|---|---|---|---|
| $e_1(1,0,0)$ | 0 | $\frac{c-b_1-b_2}{1-\tau}>0$ | 0 | Unsaturation |
| $e_2(0,1,0)$ | $\frac{c-b_1-b_2}{1-\tau}<0$ | 0 | $b_1+b_2-c<0$ | Saturation |
| $e_3(0,0,1)$ | 0 | $\frac{c-b_1-b_2-\tau b_3}{1-\tau}<0$ | 0 | Saturation |
| $e_1e_3(x_2 = 0)$ | 0 | $\frac{c-b_1-b_2-\tau b_3 x_3}{1-\tau}$ | 0 | When $x_3 \geq \frac{c-b_1-b_2}{\tau b_3}$ is saturated |
| $x_3 = \frac{c-b_1-b_2}{\tau b_3}$ | 0 | 0 | 0 | Saturation |

The evolutionary stabilization strategy in the saturation point is then determined. For $e_2(0,1,0)$ there is,

$$u(x,y) - u(y,y) = -\frac{(y_1 + y_3 - \tau y_3)(\tau b_3 y_3 + b_1 + b_2 - c)}{(1-\tau)(1-\tau y_3)} \tag{15}$$

When $c > b_1 + b_2$, if $y_3 < \frac{c - b_1 - b_2}{\tau b_3}$, Eq 15 is always greater than 0. Therefore, $e_2(0,1,0)$ is an evolutionary stable strategy. In other words, when the cost of cooperative innovation paid by researchers is greater than its benefits, the non-cooperative strategy is evolutionarily stable.

For $e_1e_3(x_2 = 0)$ there is

$$u(x,y) - u(y,y) = \frac{(1 - y_1 - y_3)(\tau b_3 y_3 + b_1 + b_2 - c)(1 - \tau x_3)}{(1-\tau)(1-\tau y_3)} \tag{16}$$

When $y_2 = 0$ is equal to 0, Eq 16 is not guaranteed to be greater than 0. Thus, the points on the stationary point line $e_1e_3(x_2 = 0)$ are non-evolutionarily stable strategies (including point $e_1e_3(x_2 = 0)$). For the stationary line $x_3 = \frac{c - b_1 - b_2}{\tau b_3}$, since both $e_2(0,1,0)$ and $e_3(0,0,1)$ are saturation points. Therefore, the point $F(0, \frac{\tau b_3 + b_1 + b_2 - c}{\tau b_3}, \frac{c - b_1 - b_2}{\tau b_3})$ where it intersects $e_2e_3$ is a saddle point.

To summarize, the phase diagram of the evolution process is shown in Figure 5, when the cost of cooperative innovation of researchers is greater than their benefits. When $x_3 = 0$, that is, there is no discrimination cooperation strategy among researchers of the two types of digital green innovation subjects, only unconditional cooperation strategy and non-cooperation strategy, the system will evolve along $e_1e_2$, from $e_1$ to $e_2$, at this time, the cooperative digital green innovation atmosphere of photovoltaic building materials manufacturing enterprises cannot be formed. On $e_2e_3$, that is, when there is no unconditional cooperation strategy among the researchers of the two types of digital green innovation subjects, there is a fixed point $F(0, \frac{\tau b_3 + b_1 + b_2 - c}{\tau b_3}, \frac{c - b_1 - b_2}{\tau b_3})$ that makes the edge bi-directional stable; that is to say, there is a competition between the researchers of the two types of digital green innovation subjects to identify the cooperation strategy and the non-cooperation strategy. When $x_3 < \frac{c - b_1 - b_2}{\tau b_3}$, the system will converge to $e_2(0,1,0)$ and the noncooperative strategy is evolutionarily stable. Here, the cooperative digital green innovation atmosphere of photovoltaic building materials manufacturing enterprises cannot be formed. When $x_3 > \frac{c - b_1 - b_2}{\tau b_3}$, the system will converge to $e_1e_3(x_2 = 0)$, and there are unconditional cooperation strategies and discriminative cooperation strategies among researchers of the two types of digital green innovation subjects. In this case, the cooperative digital green innovation atmosphere of photovoltaic building materials manufacturing enterprises can be formed, but it is not an evolutionary stable equilibrium because random drift will make researchers who choose not to cooperate invade and eventually occupy the whole system.

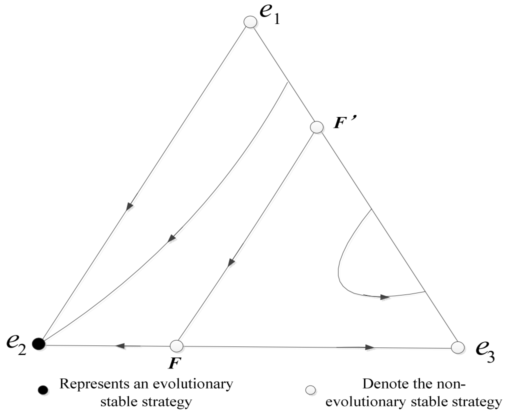


**Figure 5.** At $c > b_1 + b_2 > 0$: the evolution dynamics of researchers' cooperative innovation behavior under the time-matched reciprocity behavior.

(3) when the cost of a cooperative innovation is less than its benefits $(b_1 + b_2 > c > 0)$.

Similarly, three stationary points $e_1(1,0,0)$, $e_2(0,1,0)$, $e_3(0,0,1)$ and a stationary line $e_1e_3(x_2 = 0)$ of the evolutionary game can be obtained. The results of the saturation analysis at each stagnation point are shown in Table 4.

**Table 4.** Results of saturation analysis of the stationary point.

| Stationary point | $\frac{\dot{x}_1}{x_1}$ | $\frac{\dot{x}_2}{x_2}$ | $\frac{\dot{x}_3}{x_3}$ | Saturability |
|---|---|---|---|---|
| $e_1(1,0,0)$ | 0 | $\frac{c-b_1-b_2}{1-\tau}<0$ | 0 | Saturation |
| $e_2(0,1,0)$ | $\frac{c-b_1-b_2}{1-\tau}>0$ | 0 | $b_1+b_2-c>0$ | Unsaturation |
| $e_3(0,0,1)$ | 0 | $\frac{c-b_1-b_2-\tau b_3}{1-\tau}<0$ | 0 | Saturation |
| $e_1e_3(x_2=0)$ | 0 | $\frac{c-b_1-b_2-\tau b_3 x_3}{1-\tau}<0$ | 0 | Saturation |

The evolutionary stabilization strategy in the saturation point is then determined. For $e_1e_3(x_2 = 0)$ there is

$$u(x,y)-u(y,y)=\frac{(1-y_1+y_3)(\tau b_3 y_3+b_1+b_2-c)(1-\tau x_3)}{(1-\tau)(1-\tau y_3)} \tag{17}$$

When $y_2 = 0$, Eq 17 is equal to 0, which cannot be guaranteed to be constant greater than 0. Therefore, the points on the stationary point line $e_1e_3(x_2 = 0)$ are non-evolutionary stable strategies (including points $e_1(1,0,0)$ and $e_3(0,0,1)$). The phase diagram of the evolution process is shown in Figure 6, where the researchers' cost of cooperative innovation is less than its benefits. The system will converge to $e_1e_3(x_2 = 0)$, and there are both unconditional cooperation strategies and discriminative cooperation strategies among researchers of the two types of digital green innovation subjects. Although the point on the stationary point $e_1e_3(x_2 = 0)$ is a non-evolutionarily stable strategy, the random drift will only move the stationary point along $e_1e_3(x_2 = 0)$ but will not leave this edge. Thus, it is impossible for researchers who choose an uncooperative strategy to invade. In this case, a cooperative digital green innovation atmosphere of photovoltaic building materials manufacturing enterprises can be formed.

These observations show that the relationship between the cost paid by researchers to choose cooperative innovation strategies and the cooperative innovation rewards and internal incentives given by the two types of digital green innovation subjects are the key factors affecting the formation of cooperative digital green innovation atmosphere in photovoltaic building materials manufacturing enterprises. Only when the rewards and intrinsic incentives of cooperative innovation are greater than the costs of cooperative innovation can a stable cooperative digital green innovation atmosphere of photovoltaic building materials manufacturing enterprises be formed. However, when the rewards and intrinsic incentives for cooperative innovation are less than the cost of cooperative innovation, a stable cooperative digital green innovation atmosphere cannot be formed. In the second case, if the initial proportion of discriminating cooperation strategy in the researchers of the two types of digital green innovation subjects exceeds a threshold, the result of system evolution will converge to the existence of unconditional cooperation strategy and discriminating cooperation strategy in the researchers of the two types of digital green innovation subjects. Random drift will make researchers who choose not to cooperate invade and eventually occupy the whole system. If the initial proportion of researchers employing cooperative strategies in the two types of digital green innovation subjects is less than this threshold. The results of system evolution will converge directly to the uncooperative strategy of researchers occupying the entire system.

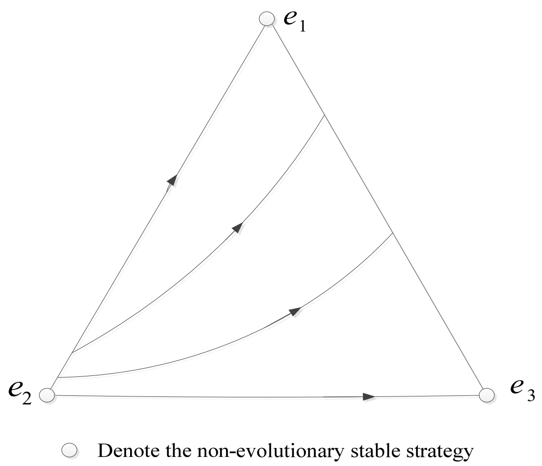


**Figure 6.** When $b_1 + b_2 > c > 0$, the evolutionary dynamics of a cooperative innovation behavior under an indirect reciprocity.

## 5. Case study

### *5.1. Case overview*

Longi Green Energy Enterprise was founded in 2000 under the full name Longi Green Energy Technology Co., Ltd. (referred to as "Longi Shares"). The enterprise is the world's most valuable solar energy technology company. Longi Shares is walking on the product innovation road of changing the photovoltaic building materials industry through digital green technology innovation to change the world energy pattern. From photovoltaic materials and photovoltaic power generation equipment to solar power plant systems, Longi Shares provides a full range of services for photovoltaic building materials.

Relying on strong scientific and technological innovation capabilities, Longi focuses on two photovoltaic building material modules—material manufacturing and digital green technology innovation solutions—and its business covers monocrystalline silicon wafers, single crystal cell modules, distributed power stations, and ground power station system solutions, which have effectively promoted the progress of global photovoltaic building materials and driven the rapid transformation of human energy use. With the vision of "the world's most valuable solar technology company", Longi Shares adheres to the principle of digital green technology innovation to drive productivity, and Longi Shares has insisted on high research and development (R&D) investment for several consecutive years. In 2018, the enterprise invested 1.231 billion yuan in R&D. From the listing in 2012 to the end of 2018, the cumulative R&D investment was 3.695 billion yuan, ranking first in the industry.

Longi Shares has long adhered to continuous investment in the R&D of photovoltaic building materials to achieve continuous technological progress and product acceleration. In terms of technology patents, by the end of 2020, the company has obtained a total of 1001 authorized patents. In terms of product efficiency, Longi components pass the efficiency test of authoritative institutions and have created world records many times. In terms of R&D personnel allocation, Longi has incorporated a number of industry-leading technical experts and scientific research and technology leaders into the company's R&D team, with a scale of more than 800 people. It has also built a first-class photovoltaic building materials technology center, deepened communication and exchanges with well-known universities at home and abroad, and reached long-term strategic partnerships with several top research institutions.

Further, Longi Shares adheres to the concept of a digital green sharing, opening the breakthrough process of key technologies such as LIR technology and sharing with enterprises in the photovoltaic building materials industry. The company cultivates the growth of the key support chain, fostering the entrance of the entire industrial chain of photovoltaic building materials into the "diamond wire cutting" era in advance, and jointly promoting the rapid decline of photovoltaic power generation and electricity costs with industry partners. Longi has always been at the forefront of solar photovoltaic technology, focusing on bringing better and more sustainable value innovation to customers. Adhering to the corporate culture concept of "reliable, value-added, pleasant", Longi Shares continues to provide excellent energy and services for society, relying on the long-term accumulation of multiple advantages, including large-scale production, whole industry chain, innovation, brand, and talent advantages, with a commitment to developing into the world's most valuable solar technology company.

**Table 5.** The main development history of Longi Shares.

| Year | Incident |
|---|---|
| 2000 | The company was built |
| 2004 | Transformed from the semiconductor industry into the solar photovoltaic industry |
| 2006 | Established the strategic positioning of professional manufacturer of monocrystalline silicon wafer |
| 2012 | Listed on the main board of Shanghai Stock Exchange |
| 2013 | Became the largest producer of monocrystalline silicon wafers |
| 2014 | Implemented vertical integration layout, cut into the photovoltaic industry downstream |
| 2018 | Longi Shares and Lanzhou University cooperated to build a customized class |
| 2021 | Longi set up Future Technology Research Institute with Lanzhou University |
| 2022 | Longi Shares and Xi 'an Jiaotong University engaged in scientific and technological innovation cooperation |

To promote the wide application of worldwide "photovoltaic + energy storage" energy solutions, Longi is expected to launch a global digital green technology innovation challenge in the future, aiming to discover outstanding innovative talents in cutting-edge technologies and related fields worldwide. This will complete the digital construction of the platform to foster global green energy innovation resource docking and interaction, provide precise technical services for partners, continue to empower new industry incubation and technological innovation, allow more people to enjoy digital green energy, and accelerate the process of green and low-carbon energy reform. The main development history of Longi Shares is shown in Table 5.

### *5.2. Case study on the formation of digital green innovation atmosphere based on direct reciprocity mechanism*

In July 2018, the College of Physical Science and Technology of Lanzhou University launched a comprehensive reform based on "teaching reform", establishing a teaching and research department around the "curriculum group" to explore the "top-notch talents 2.0", "new engineering talents", and multi-level professional personnel training models based on the principles of "graded teaching, classified training, solid foundation and broad export". To this end, the college issued the "institution–institute, institution–enterprise, and institution-institute" cooperation plan to build a platform for multi-level talent training. In this context, the college cooperated with Longi, Guangdong Odi Sensor Technology Co., Ltd., and other units to build customized classes, aiming to rely on physics, microelectronics, and materials majors to create a new model of interdisciplinary and highly integrated with enterprises to cultivate cutting-edge talents to meet the needs of the future photovoltaic building materials industry. Push the industry forward. The customized class is formed by the voluntary registration of school students, the implementation of open, dynamic, virtual management, focusing on cultivating college students' hobbies and interests, and shaping a new era of enterprise scientists. Subsequently, the college and the enterprise will expand the scope of undergraduate and graduate students to set up customized classes according to their actual needs.

In 2021, Lanzhou University Longi Institute of Future Technology was established. Longi Institute of Future Technology of Lanzhou University was inaugurated, marking another new beginning for deepening cooperation between the two sides. Longi Future Technology Research Institute of Lanzhou University is a scientific research and technology research platform for photovoltaic building materials technology, devices and materials jointly built by Lanzhou University and Longi Shares to serve the national strategy of "carbon peak" and "carbon neutrality" and support the national energy low-carbon transformation. The Institute focuses on key materials and technologies for the efficient utilization of solar energy, the development and design of efficient solar cell modules, efficient energy storage materials and technologies, and the utilization of low-cost and high-value-added silicon industry waste. It gives full play to the respective advantages of both parties, forms a deep strategic integration of universities and enterprises, and provides strong support for the future development of clean energy science and technology and talent training. This will stimulate the digital green innovation power of enterprises and universities and form a strong digital green innovation atmosphere. To further expand the coverage of innovation projects, Longi Shares has held several industrial summit forums and expert seminars, gathering more digital green innovation resources into the photovoltaic building materials industry innovation database and driving the development of digital green innovation in production, the university, and research. The innovation mode of cooperation between Longi Shares and the scientific research institutions is shown in Figure 7.

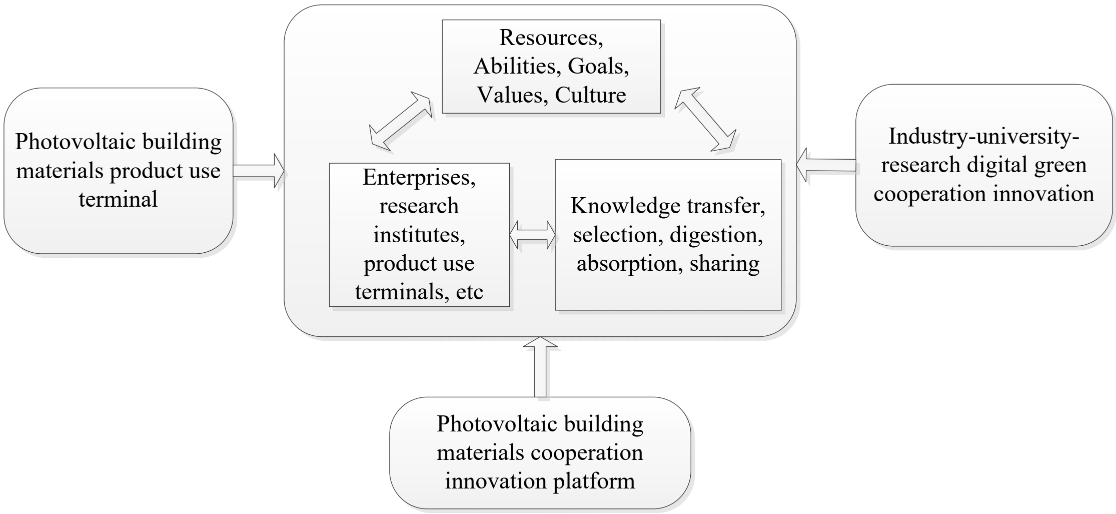


**Figure 7.** The cooperation innovation model of Longi Shares and the scientific research institutions.

This model shows that the identification of cooperation strategy is the best strategy for Longi Shares and scientific researchers, Longi Shares and scientific research institutions to establish a sharing mechanism. The basic conditions of science and technology have been greatly improved, and scientific research institutions use their own advanced technology to transform product concepts into products in a timely fashion and digital green technology into productivity. The company mainly provides capital and equipment support in the R&D process. The product eventually enters the commercial stage. The product user terminal participates in the small trial and final test of the research results to ensure that the product development closely conforms to market demand. Based on their own production conditions and the market demand for product commissioning until the final mass production, the scientific research institutes and universities help the enterprises solve the technical problems in mass production, promoting the production of enterprise products. To foster the innovation and development of the enterprises, as well as the enthusiasm of scientific research institutions, universities, and other researchers to cooperate and innovate, Longi is committed to the digital green innovation and development of products. This forms a digital green innovation atmosphere between Longi Shares and scientific research institutions.

### *5.3. Case analysis of the formation of digital green innovation atmosphere under indirect reciprocity mechanism*

Longi Shares uses the product use terminal to connect market demand with industrial innovation to innovate and upgrade photovoltaic building materials products, put forward innovative concepts, or directly carry out product and development. Based on the digital green innovation platform, the scientific research institutions cooperate with the product use terminals and enterprises to carry out product innovation and new technology integration and provide technical support for new product innovation. Through the public innovation platform, the enterprises have access to product innovation solutions and make use of their own R&D and market advantages for product production and marketing. The scientific research institutes are connected with the market demand for photovoltaic building materials, avoiding the phenomenon of the research direction derailment that scientific research institutes and universities face on their way to the market.

In the process of cooperation and innovation between Longi Shares and scientific research institutions, knowledge is exchanged and shared through the digital green cooperation and innovation platform, the knowledge base is continuously integrated and expanded, and explicit knowledge and implicit knowledge are frequently interactive. From the product conception stage to the product commercialization stage, the invisible knowledge of the industrial terminal is transferred to enterprises and scientific research institutes, and the scientific research institutes continue to make the invisible knowledge explicit. They then transfer explicit knowledge to the enterprises. The enterprises share the explicit knowledge, form products and introduce them into the market, realize the socialization of knowledge, promote a new round of knowledge creation process, and gradually regenerate knowledge. Finally, the knowledge spiral development of the industry-university-research knowledge base is realized.

To absorb better projects to a greater extent, some projects that the market is eager to develop and fail to participate in the innovation competition can be submitted by the staff of scientific research institutions, and the strategic committee of Longi Shares regularly holds review activities. For projects that involve development cooperation, a final research report is formed through market research for approval and development. In the process of product development and production, Longi Shares collects projects through cooperative innovation competitions and selects projects suitable for enterprise development. Researchers can carry out innovative projects independently, and enterprises can dock with scientific research according to their own strategies, which can prevent them from being out of touch with the photovoltaic building materials market, promote the development of cooperative innovation platforms for scientific research institutions, and win considerable profits for the enterprises.

**Table 6.** R&D expenses of Longi Shares from 2016 to 2020 (100 million RMB).

| Project | 2016 | 2017 | 2018 | 2019 | 2020 |
|---|---|---|---|---|---|
| Research and development expenditure | 0.00 | 0.00 | 2.02 | 3.04 | 4.99 |
| Proceeds of business | 115.31 | 163.62 | 219.88 | 328.97 | 545.83 |
| Proportion (%） | 0.00 | 0.00 | 0.92 | 0.92 | 0.91 |

To summarize, under the indirect reciprocity mechanism, the market-driven orientation effectively integrates the cooperative innovation of Longi Shares and scientific research institutions. Longi Shares and scientific research institutes are effectively combined to form an innovation-driven model in which market information is constantly screened and tested, and feedback is provided. Longi Shares and the scientific research institute enter an open interactive platform for knowledge exchange, transformation, and sharing, organically combining market demand and production R&D to implement cooperative innovation. This effectively promotes the development of industrial cooperation and innovation and promotes the formation of an innovative atmosphere.

### *5.4. Comparative analysis*

The photovoltaic building materials industry chain cooperation innovation led by Longi has a long history. Previously, Longi has repeatedly cooperated with upstream and downstream partners of the industrial chain in digital green innovation, forming a strong atmosphere of digital green innovation, and successfully incubated a number of innovative technologies that lead the industry. Among them, the breakthroughs with Laplace in the mass production of PERC battery technology and the next generation of high-efficiency battery reserves, the cooperation with Dyer Laser to use laser micro-etching technology for HPBC industrialization, and the cooperation and innovation with Shenzhen Shigold in graphite ship and thermal field insulation products have made positive contributions to the cost reduction and efficiency of the entire industry and even the reduction of photovoltaic power cost. Recently, the digital green innovation atmosphere formed by cooperation and innovation between Longi Shares and universities has brought two major innovation achievements to Longi, which are based on the concept of product 2681, a world record for silicon heterojunction conversion efficiency of 26.81%, developed in November 2022. Longi achieved a 31.8% conversion efficiency of crystalline silicon-perovskite stacked cells on commercial grade suede-CZ silicon wafers. The continuous progress of technology is the biggest push for the cost reduction of photovoltaic power generation. At present, Longi has focused on green energy, such as photovoltaic and hydrogen energy, combined with a number of universities and external R&D teams to build a solid digital green cooperative innovation R&D system, forming a strong digital green innovation atmosphere, and gradually launching R&D of key core technologies. It is expected to work closely with industry, colleges and universities, and peers upstream and downstream to improve the conversion efficiency of photovoltaic building materials in the next step and further reduce the cost of KWH. In the future, the platform will take open sharing, innovation, and win-win as its purpose, and take the mission of transmitting innovation dynamics, collecting global ideas, integrating solutions, docking high-quality resources, and promoting technological innovation in the global photovoltaic industry toward its mission of building the world's leading green energy ecosystem. The number of scientific researchers in Longi is shown in Figure 8.

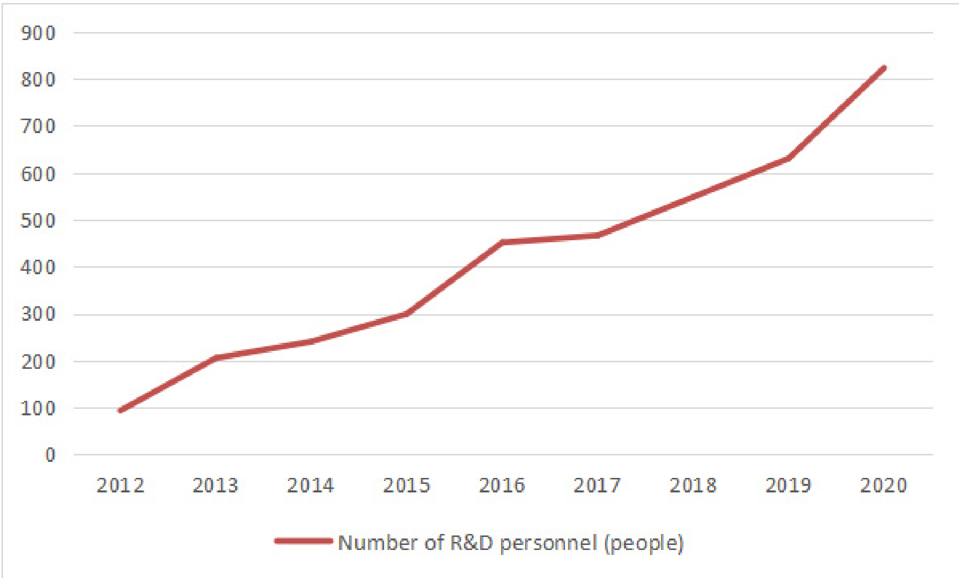


**Figure 8.** Number of scientific researchers at Longi Shares.

Longi Shares and the universities are not only the beneficiaries of the formation of digital green innovation atmosphere; the firm supporters of digital green innovation atmosphere also benefit from this collaboration. In a strong innovation atmosphere, enterprises and universities continue to exchange and cooperate, build a good innovation platform for universities, and improve the scientific research environment. The universities and research institutes jointly develop new technologies for photovoltaic building materials with enterprises based on the cooperative innovation platform to overcome the difficulties of technological innovation.

## 6. Conclusions and implications

### *6.1. Research conclusions*

This study constructs an evolutionary game model for the formation of cooperative digital green innovation atmosphere of photovoltaic building materials manufacturing enterprises under two mechanisms of direct reciprocity and indirect reciprocity, and conducts stability analysis. Several conclusions can be drawn from this study.

Under direct reciprocity behavior, when the cost of collecting and analyzing each other's information is less than the difference between the expected payment of choosing the identification cooperation strategy and that of choosing the non-cooperation strategy, and the difference is positive, the identification cooperation strategy is the optimal strategy for researchers in the two types of digital green innovation entities. In this case, the cooperative digital green innovation atmosphere of photovoltaic building materials manufacturing enterprises can be formed. However, there are two other cases—one is the coexistence of researchers who choose to identify cooperative strategies and those who choose not to cooperate; the other is that the cooperative digital green innovation atmosphere cannot be formed.

Under the indirect reciprocity behavior, when the reward and intrinsic incentive of cooperative innovation are greater than the cost of the cooperative innovation, the cooperative digital green innovation atmosphere of photovoltaic building materials manufacturing enterprises can be formed. When the reward and intrinsic incentive of the cooperative innovation are less than its cost, the cooperative digital green innovation atmosphere of photovoltaic building materials manufacturing enterprises cannot be formed.

### *6.2. Theoretical contribution*

The existing research on innovation climate mainly focuses on the individual and team levels within organizations, while there are few studies on the innovation climate among organizations. With the increasingly fierce competitiveness of the external environment and the increasing complexity of technology, interdependence among various digital green innovation subjects with different knowledge resources continues to increase, and cooperation between different subjects becomes more and more frequent. In particular, the major innovation projects in the fields of basic research and high technology require the cooperation of digital green innovation subjects with distributed knowledge. In the process of cooperation, photovoltaic building materials manufacturing enterprises, universities, and scientific research institutions need to achieve a consistent understanding of each other's innovation atmosphere to facilitate the formation of an innovation atmosphere between different subjects.

However, there are few studies on the formation of digital green innovation atmosphere between enterprises, universities, and scientific research institutions. Most existing studies have used questionnaires and structural equation models to study the antecedent variables, outcome variables, and measurement scales of innovation atmosphere, with a few studies on the formation of the cooperative digital green innovation atmosphere of photovoltaic building materials manufacturing enterprises using evolutionary game methods based on the perspective of reciprocity behavior. Based on the definition of the connotation of a cooperative digital green innovation atmosphere of enterprises, this study analyzes the formation mechanism of cooperative digital green innovation atmosphere of photovoltaic building materials manufacturing enterprises based on reciprocity theory. This study constructs an evolutionary game model for the formation of cooperative digital green innovation atmosphere of photovoltaic building materials manufacturing enterprises under two mechanisms—direct reciprocity and indirect reciprocity—and conducts stability analysis. It provides important theoretical guidance for photovoltaic building materials manufacturing enterprises to cultivate a cooperative digital green innovation atmosphere.

### *6.3. Enlightenment from practice*

It is important to foster a mutually beneficial cooperative atmosphere for collaborative digital green innovation. Innovation climate is the common perception of enterprises, universities, and scientific research institutions on the situation of collaborative digital green innovation. The innovation atmosphere reflects the overall attitude of enterprises, universities, and scientific research institutions toward cooperative digital green innovation, and also affects the behavioral choices of the two types of digital green innovation subjects in the process of a cooperative digital green innovation. The innovation atmosphere should be one that has a free and loose innovation environment with a strong academic atmosphere and tolerance for failure for the two types of digital green innovation subjects. The innovation atmosphere will subtly affect the researchers of the two types of digital green innovation subjects. It is a soft intellectual constraint to arouse their enthusiasm for innovation and encourage them to dare to take risks, study hard and be innovative [49]. Therefore, enterprises should take corresponding measures to form a cooperative digital green innovation atmosphere.

First, enterprises should create an environment of open exchange and cooperation. Since major breakthroughs in the frontier of science and technology in digital green innovation mostly come from interdisciplinary disciplines, conditions should be created for researchers in different fields of the two types of digital green innovation subjects to frequently discuss and inspire each other, and promote the exchange and collision of ideas, so as to stimulate each other's inspiration and develop innovative ideas. China should strongly support trans-regional and trans-national collaborative research on digital green innovation projects, especially high-level international research cooperation projects. The nation should make full use of global frontier scientific and technological resources to improve the digital green innovation ability of Chinese enterprises.

Second, innovation entities should cultivate a culture of mutual cooperation and establish a clear incentive and punishment management mechanism in terms of reputation. Reciprocity emphasizes cooperation, coordination, and selflessness. The cultivation of a reciprocal cooperation culture should be combined with specific cultural platforms, give full play to the initiative of the two types of digital green innovation subjects, guide the reciprocal behavior of members normatively, and gradually endow psychological identity into the subject culture by influencing the value orientation of the digital green innovation subject members. The overall goal of pursuing cooperative digital green innovation of enterprises is transformed into the conscious behavior of each subject member, and the cooperation efficiency of both parties is effectively improved to produce synergistic effects.

Notably, reputation is the comprehensive embodiment of all previous behaviors and results of the subjects of digital green innovation, and it allows the subject's behavior to be recognized by society and to obtain resources and opportunities to complete value creation. Reputation needs to be accumulated and maintained for a long time, and it is an important measure of whether the members of the subject cooperate with each other. A good reputation is a prerequisite for efficient and continuous cooperation between the two types of digital green innovation principals. The reputation effect is also an important incentive mechanism for the cooperation of the main members of the two types of digital green innovation. Principal members with a good reputation will consider their long-term interests;

thus, they have a high enthusiasm to maintain their own reputation and will therefore exert a high level of effort to promote cooperation. However, subject members with a bad reputation will only consider short-term interests; thus, their enthusiasm for maintaining their own reputation is low, and they are more likely to engage in opportunistic behaviors. Therefore, the two types of digital green innovation entities should encourage members to make high efforts to maintain their reputations through the reputation effect. Further, clear incentive and punishment management mechanisms should be implemented to reward members who pay high effort and punish members who engage in opportunistic behaviors.

Finally, enterprises should establish a fair and equitable profit distribution mechanism for cooperative digital green innovation. The fundamental purpose and source of cooperation between enterprises and scientific research institutions in digital green innovation is to maximize profits. Therefore, both parties can have a third party as an impartial party. The agreement plan on the profit distribution mechanism should be continuously improved according to the cooperative R&D costs, resources, talents, and other factors invested by both parties, which will allow for meeting the interests of both parties as much as possible and promote the formation of a cooperative digital green innovation atmosphere.

### *6.4. Deficiencies and future research directions*

In this study, numerical simulation and simulation analysis methods are used to study the formation mechanism of a collaborative digital green innovation atmosphere in photovoltaic building materials manufacturing enterprises. This study lacks suitable case studies; thus, future research should offer a more relevant case analysis to reveal the reciprocal mechanism of a cooperative digital green innovation. Further, this study mainly analyzes the internal factors in the process of collaborative digital green innovation of enterprises and does not consider the influence of government policy orientation and other factors in the external environment on the collaborative digital green innovation of enterprises, which can be further discussed in future research.

Finally, this investigation of the formation mechanism of cooperative digital green innovation atmosphere of photovoltaic building materials manufacturing enterprises does not consider the influence of other market participants. In the future, the influence mechanism of other participants on this relationship can be studied to offer more constructive and targeted conclusions and insights. Future research should also consider working with civil society—that is, energy communities—to advance energy efficiency in residential buildings at the local community level while driving social innovation.

## Use of AI tools declaration

The author declare that the research was conducted and presented in this article have not used AI tools at all stages of the research process.

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## Conflict of interest

All authors declare no conflicts of interest in this paper.

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