

Received June 2, 2022, accepted June 15, 2022, date of publication June 20, 2022, date of current version June 24, 2022.

Digital Object Identifier 10.1109/ACCESS.2022.3184422

Knowledge-Sharing Strategies of University-Industry Alliances Promoting Green Technology Innovation in Ecosystems: Based on the Utility of Multichannel Funding

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This work was supported in part by the National Social Science Foundation of China under Grant 20XGL030.

ABSTRACT Green technology innovation (GTI) requires a large capital investment, while the role of these capital investments in promoting GTI needs to be further confirmed. To improve GTI, university-industry alliances (U-Is) in green innovation ecosystems engage in knowledge-sharing behaviors and form different knowledge-sharing strategies based on changes in cooperation modes. Employing a differential game, this study explores the utility of multichannel funding for innovation revenues in different cooperative modes of U-Is and the impact on revenue distributions. This article considers three game models in five cases: Nash noncooperative game with no multichannel funding, Nash noncooperative game with external funding but no government subsidies, Nash noncooperative game with multichannel funding, Stackelberg game, and cooperative game. Solving the game model and applying the numerical analysis results in certain interesting conclusions. Our research finds that, first, in the cooperative game, the strongest willingness to share knowledge occurs in the university-industry alliance, in which the total revenues of both parties reach the Pareto optimum. Second, multichannel funding can serve as an incentive mechanism for enterprises and universities to improve the knowledge-sharing willingness, the GTI level, and the revenues of the two players, while the utility of the multichannel funding is strongest in the cooperative game. In addition, in the Stackelberg game, enterprises share subsidies with universities, which stimulates their willingness to share knowledge, and both parties' revenues are better than they are in the three cases of noncooperation. Eventually, the revenue-sharing ratio of the enterprise has a smaller threshold, and the university can share more benefits relative to the absence of the multichannel funding, which helps balance the U-I in the green innovation ecosystem. These conclusions make a substantial contribution to the selection of cooperation modes and the formulation of revenues distribution contracts in university-industry alliances.

INDEX TERMS University-industry, multichannel funding, green technology innovation, knowledge sharing, green innovation ecosystem.

I. INTRODUCTION

As the economy develops rapidly in developing countries, green technology innovation (GTI) is gaining increasing attention [1] and has become key to promoting an environmentally friendly economy and enhancing sustainable competitiveness [2]. The irreversibility of global weather and environmental pollution requires China's manufacturing industry to transform and upgrade to green technology [3].

The associate editor coordinating the review of this manuscript and approving it for publication was Francisco J. Garcia-Penalvo¹.

A single organization may not be able to engage in GTI, and most scholars now believe that university-industry alliances (U-Is) can help improve green technology [1], [3]. Due to the massive human and financial investment in R & D, green innovation ecosystems composed of U-Is can improve the GTI level and increase the success rate of cooperation [4]–[6]. U-Is, as practical organizations of the green innovation ecosystem, have heterogeneous resources [7]. In them, through university-industry collaboration (UIC), universities can gain access to market resources and research funding, while companies can compensate for the lack

of R & D capabilities, thus realizing a win-win model [7]–[9]. In a complex environment, GTI is nonlinear, dynamic, and complex, which makes it important to explore the cooperation mechanism and effect of university-industry alliances in green innovation ecosystems [1], [7], [10], [11].

Many scholars believe that knowledge is key to U-Is innovation, and GTI is no exception [12]. The GTI processes of U-Is make it clear that knowledge sharing is more apparent in green innovation ecosystems [13]. GTI is formed through knowledge transfer, sharing, and absorption, thereby forming the core competitiveness of U-Is in green innovation ecosystems [7]. Because of the dilemma of climate change and environmental pollution, we urgently need to realize how U-Is can change their knowledge-sharing strategies to promote GTI [14]. However, adequate funding sources are a prerequisite for knowledge-sharing behaviors in U-Is.

GTI is so difficult to develop and breakthroughs are so difficult to attain that a large amount of capital investment is required [15]. Innovation investments are not limited to a single channel but consist of multichannel funding. In recent years, government subsidies have worked to promote GTI [16], while with policy support and guidance, external institutions, such as financial institutions and other social organizations, provide long-term financial guarantees for GTI, which together maintain the steadiness of U-Is [17]. However, green innovative activities are accompanied by uncertainty and high risk, resulting in the expected effects of innovation funding deviating significantly from expectations [18]. Until now, little literature has focused on the utility of the multichannel funding inputs in U-Is for GTI, whereas such research is key to enhancing the effectiveness and efficiency of GTI and UIC. Fig. 1 provides the research framework of this study.

Differential game theory, a combination of modern control and game theories, is an important approach for addressing the dynamic decision-making process in which two or more participants continually adjust their behavioral strategies. Differential game theory has achieved good results in investment optimization and revenue improvement. Since GTI breakthroughs are a long-term and arduous process in which the university and the enterprise are devoted to green technology knowledge, GTI naturally becomes obsolete over time [19]. Differential games are used to propose knowledge-sharing decisions between universities and firms in the GTI process; moreover, differential equations can be used to describe the GTI process. In today's world, green innovation ecosystems based on U-Is have increasingly been established, but research remains rare on their funding utilization effects in different cooperation modes. A differential game model consists of a university and an enterprise as the main participants. To achieve GTI, the university and the enterprise choose different knowledge-sharing strategies based on different collaboration modes. To consider multichannel funding, our article focuses on three questions:

- 1) How will the knowledge-sharing strategies of the enterprise and the university change the GTI level?
- 2) In which game model does the university-industry alliance's revenue reach a Pareto optimum? What does this model choice mean in practice?
- 3) In which game model does multichannel funding have the strongest effect on the revenue improvement of university-industry alliances, and what is the impact on the revenue distribution in this alliance?

Based on this analysis, and combining game theory and the cooperative model of U-Is in green innovation ecosystems, we consider five situations in which different funding sources join. We do so by developing three game models, all of which correspond to real situations: in the Nash noncooperative game, the U-I involves no direct cooperation and usually is used for consulting or to use the university results directly; in the Stackelberg game, the enterprise has an urgent demand for GTI and seeks to cooperate with the university in joint R & D efforts, but their cooperation is not very close; in the cooperative game, universities and enterprises enter into an intimate relationship, which means both sides have a common GTI goal.

The novelty of our paper is as follows: (1) A differential game model is developed to explore the GTI process, which we divide into three processes: “innovation input-innovation output-economic output”. (2) Innovation investment, an extremely important innovation resource, is divided into government subsidies and other external investments, and a theoretical framework is developed to focus on the impact of multichannel funding on economic output. Discussed in detail are the impact of the Pareto improvement in the different cooperative modes and the distribution of revenues by adding multichannel funding. (3) A simulation method is used to explain and verify these conclusions. Moreover, the conclusions of our paper can provide, to a certain extent, support for scientific decisions on incentive mechanisms, revenue distribution, and contract design between enterprises and universities.

This article is divided into seven sections. Section 2 presents the related literature review. The model description and assumptions are proposed in Section 3. Section 4 demonstrates the optimal strategies for five scenarios. The comparative and numerical analyses are shown in Sections 5 and 6, respectively. Finally, Section 7 includes the conclusions and limitations.

II. LITERATURE REVIEW

Green technology innovation (GTI) is key to achieving an environmentally friendly society and promoting the transformation and upgrade of the manufacturing industry, whose complexity implies that a single organization cannot accomplish this innovation activity; thus, university-industry alliances (U-Is) are built based on green innovation ecosystems. Knowledge sharing is key to U-Is interactions, where energy flows, is absorbed, and is utilized for GTI. Consequently, the literature review of our article is divided

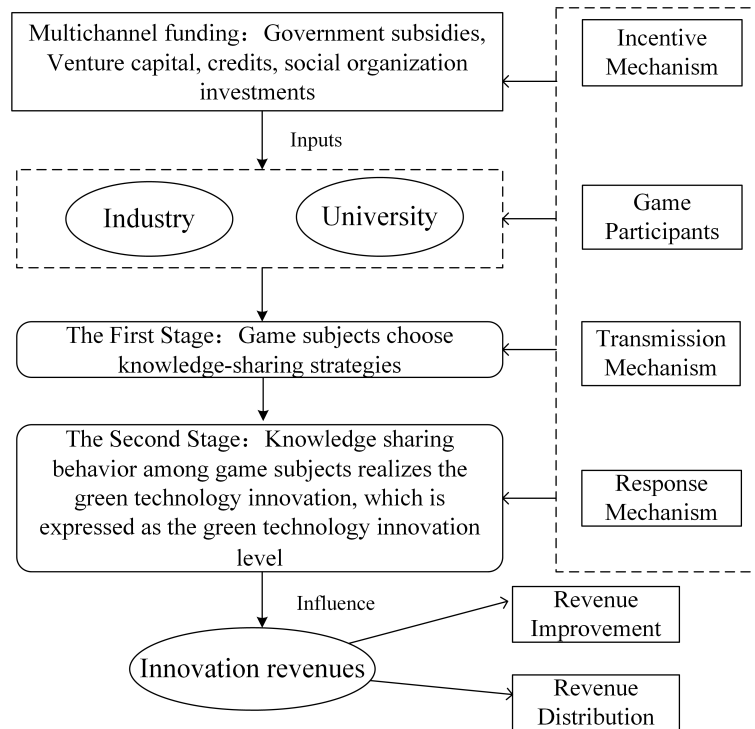


FIGURE 1. Research framework.

into four parts: green technology innovation, university-industry alliances for green innovation ecosystems, knowledge sharing in university-industry alliances, and research gaps.

A. GREEN TECHNOLOGY INNOVATION

Green technology innovation (GTI), as a critical part of green innovation ecosystems, gives a sustainable competitive advantage for environmental protection and resource conservation [20]. Shi and Lai [21] defined green technology as being environmentally sound in its production and use. Fernando and Wah [22] developed a theoretical structure to investigate the factors that contribute to the environmental performance of green technologies and found that the value of eco-innovation allows firms to respond to challenges from market competitors. Additionally, Fernando *et al.* [23] argued that innovation capacity promotes GTI; therefore, they examined the variables that may affect innovation capacity. In contrast, GTI faces many barriers and challenges, and must overcome problems such as insufficient numbers of researchers, deficient policy measures for technology innovation, and a shortage of financial chains to enhance green innovation performance [24].

GTI is effective at achieving environmental protection and improving economic performance, but the process is arduous and uncertain [25]. Hence, multiorganizational collaboration is the solution to accomplish GTI. The importance of multiorganizational cooperation for GTI has been verified by scholars [26].

B. UNIVERSITY-INDUSTRY ALLIANCES FOR GREEN INNOVATION ECOSYSTEMS

Green innovation ecosystems are increasingly based on university-industry alliance-based interactions to achieve GTI more rapidly and efficiently. Bonaccorsi and Piccaluga [27] first built the theoretical framework of organizational relationships between universities and firms and found that the collaborative essence of the two players is to carry out cross-organizational knowledge transfer activities; thus, UICs have attracted much attention. Trust, communication, and the use of intermediary institutions are conducive to knowledge transfer in U-Is [28]. In contrast, Wu *et al.* [29] sought solutions to the institutional and structural barriers that exist when firms and universities collaborate as a way of facilitating the formation of an innovation ecosystem. Hence, Leiponen and Helfat [30] believed that establishing scientific links between universities and enterprises could overcome obstacles and become an important guarantee for obtaining external knowledge and sustainable innovation, which could enhance their innovation performance [31]. The government is inseparably linked to the establishment of U-Is. Both Yang *et al.* [1] and Etzkowitz and Zhou [17] focused on the interactive innovation behaviors among universities, industries, and governments in innovation ecosystems and explored their policy measures for the establishment and development of university-industry alliance-based innovation ecosystems. Further, Carayannis *et al.* [32] believed that in the regional innovation ecosystem, not only are universities, enterprises and governments needed, but

citizens and the environment also act as promoters and participants.

In cases in which firms and universities are underdriven, government innovation subsidies may be used; both the two-difference model used by Czarnitzki and Lopes-Bento [33] and the three-stage Stackelberg game model developed by Song *et al.* [16] have verified the positive impact of R & D subsidies on innovative performance. Additionally, the innovation funding source is not limited to government subsidies but also comes from credit funds from financial institutions or investments from other social organizations.

C. KNOWLEDGE SHARING IN UNIVERSITY-INDUSTRY ALLIANCES

U-Is enable enterprises to expand and update their knowledge bases, explore scientific knowledge and develop new ideas that lead to knowledge sharing, resulting in GTI. Knowledge-sharing participants are committed to maximizing their interests, so the knowledge-sharing process is also a game between participants in terms of content and approach. However, differences in the choice of knowledge-sharing strategies can also result in changes in the GTI level. To solve direct and public problems, Koessler [34] first developed the Bayesian model to study knowledge-sharing strategies and introduced the concept of equilibrium, describing sufficient conditions for the existence of fully revealed or unrevealed equilibria. On this basis, Bandyopadhyay and Pathak [35] studied the knowledge spillover and cooperation in outsourcing projects using the Cournot competition in the condition of complete information and identified the factors that enhance team productivity.

All of these studies have proposed knowledge-sharing strategies in a static framework. Currently, diverse communication media allow us to share knowledge anytime and anywhere, which proves that knowledge sharing is a dynamic process; thus, it is essential to investigate knowledge-sharing strategies in a dynamic framework. Lin and Wang [36] established dynamic games in construction project teams to discover incentive factors for knowledge-sharing behaviors. Guofeng *et al.* [37] designed incentive dynamic models to explore knowledge-sharing behaviors in three scenarios considering risk factors. They found that the optimal knowledge-sharing amount and the optimal benefits in the centralized decision-making contract were both the highest. To explore optimal R & D strategies on digital twin technology, Guo *et al.* [38] built a differential game in the school-enterprise system.

D. RESEARCH GAPS

Currently, few scholars have explored the GTI process in innovation ecosystems, and little is known about the utility of multichannel funding in the different U-I cooperation modes, which is determined by their knowledge-sharing strategies in cooperation. In addition, for the alliance-based university-industry, although the roles of venture capital and government subsidies in innovation have been widely studied, no

theoretical framework has yet been established for the utility of multichannel funding—such as government subsidies, credit, and venture capital—for GTI in U-Is. Consequently, we develop a dynamic theoretical framework to investigate the knowledge-sharing strategies of U-Is for GTI considering multichannel funding.

III. MODEL DESCRIPTIONS AND ASSUMPTIONS

A. MODEL DESCRIPTIONS

This paper explores the game behaviors of green technology innovation (GTI) between enterprises and universities in green innovation ecosystems. In the GTI process, enterprises and universities form alliances because they have heterogeneous resources. Enterprises hope to cooperate with universities to take risks and improve their own green R & D capability deficiencies, while universities are eager to expand research funding and transform knowledge results. The GTI process is long and requires a large amount of capital, so enterprises seek funding from external institutions such as financial institutions and social organizations to engage in GTI. In addition, the government is an advocate for green innovation ecosystems and is willing to subsidize both enterprises and universities to stimulate GTI. Funding provided by these external institutions and government funding constitute the multichannel funding that is invested in the GTI process. The GTI level of U-Is in green innovation ecosystems varies over time. Fig. 2 depicts the operational principle of the GTI of U-Is.

B. MODEL VARIABLE SELECTION

To make our differential game model more reasonable, we must understand the GTI process in U-Is. In combination with Yin *et al.* [3] and game theory, we divided the GTI process of university-industry alliance cooperation into three stages: “innovation input-innovation output-economic output”. Furthermore, we added multichannel funding consisting of government subsidies and innovation investments from external institutions as incentive mechanisms to participate in the innovation process.

First, enterprises cooperate with universities to promote GTI. However, the core of U-Is is knowledge sharing, which is transformed into innovation through the process of “sharing-absorbing-transforming” [13]. The research of Guofeng *et al.* [37] and Lin and Wang [36] used a knowledge-sharing strategy as a transmission mechanism of cooperation and found that cooperative subjects enhanced GTI by dynamically choosing knowledge-sharing strategies in different cooperation modes.

Second, this knowledge is transformed into a GTI product or service, which reflects the innovative capacity of companies and universities. The GTI level for such innovative products or services is judged against a standard, but when more knowledge is shared, the GTI level is higher [39]. Therefore, we used the GTI level as a state variable in the model, which varies with the change in knowledge-sharing

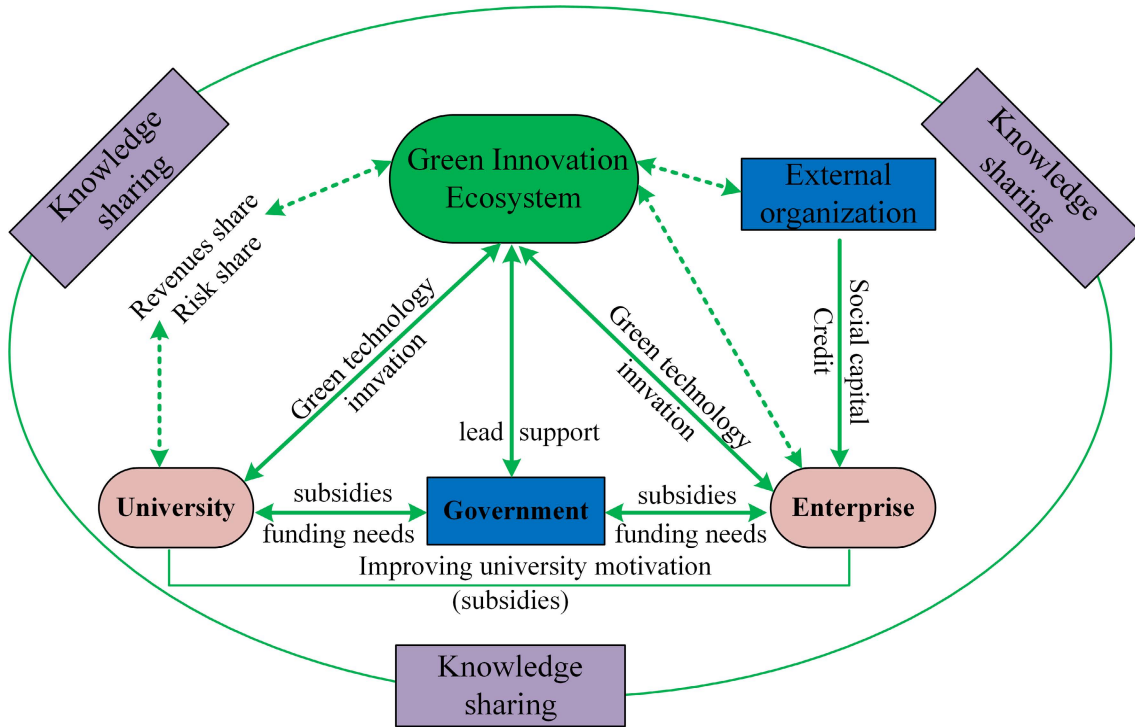


FIGURE 2. U-I operational principle.

strategies among cooperative subjects. According to Wei and Wang [40], we use a differential equation to represent the process of transforming this knowledge into GTI. As a result, the differential equation of GTI level contains three variable types: the innovation capabilities of enterprises and universities [3], the amount of knowledge sharing [37], and the innovation decay factor [40].

Third, based on Yin *et al.* [3], GTI follows a process of “innovation input-innovation output-economic output”. In game theory, we often use revenue to refer to cooperative benefits and economic outputs [41]. Combined with differential game theory, these revenues are related not only to knowledge-sharing strategies but also to GTI level. Our paper uses the impact of knowledge-sharing strategies on returns as the rates of marginal benefits according to Guofeng *et al.* [37] and Lin and Wang [36].

Additionally, the incentive mechanism of multichannel funding designed in this paper consists of two parts: government subsidies and innovation investments from external institutions, which consist of venture capital, credit from financial institutions, investment from other social organizations, etc. This paper discusses the corresponding impact on economic outputs by observing the response in innovation inputs and outputs after the addition of this incentive mechanism. To determine the way funding is added, we refer to Yin’s differential model [42].

Table 1 shows the notations of the main parameters of the model.

TABLE 1. Main parameter notations.

Parameter	Descriptions
k_e	The knowledge-sharing cost coefficient of the enterprise
k_s	The knowledge-sharing cost coefficient of the university
ω_e	The green technology innovation ability of the enterprise
ω_s	The green technology innovation ability of the university
$C_e(t)$	The knowledge-sharing costs of the enterprise
$C_s(t)$	The knowledge-sharing costs of the university
δ	The decay rate of the green technology innovation
ϕ	The investment coefficient of external institutions
φ	The input coefficient of government subsidies
α	The revenue-sharing ratio of the enterprise
ξ	The cost-sharing coefficient of the enterprise for the university
\mathcal{E}_e	The marginal benefit coefficients of the enterprise
\mathcal{E}_s	The marginal benefit coefficients of the university
μ	The degree of impact of the technology innovation on the revenues
Decision	Descriptions
$A_e(t)$	The amount of enterprise knowledge sharing
$A_s(t)$	The amount of university knowledge sharing
State	Descriptions
$G(t)$	The green technology innovation level

C. MODEL ASSUMPTIONS

Assumption 1. The amount of enterprise knowledge sharing (i.e., the willingness of the enterprise to share knowledge) is $A_e(t)$ (t denotes the time), and the amount of university knowledge sharing (i.e., the willingness of the university to share knowledge) is $A_s(t)$ with $A_e(t) \geq 0$ and $A_s(t) \geq 0$. For convenience, it is assumed that knowledge is discernible and measurable. Based on Guofeng *et al.* [37] and Lin and Wang [36], the knowledge-sharing cost is assumed to be:

$$C_e = \frac{k_e}{2} A_e^2(t), \quad C_s = \frac{k_s}{2} A_s^2(t) \tag{1}$$

where $k_e > 0$ denotes the cost coefficient of the enterprise and $k_s > 0$ denotes the cost coefficient of the university. $C_e(t)$ and $C_s(t)$ represent the knowledge-sharing costs of the enterprise and the university, respectively.

Assumption 2. During university-industry collaboration, GTI is achieved by sharing and absorbing knowledge. Suppose that $G(t)$ denotes the GTI level, which is determined by the knowledge-sharing amounts of the enterprise and the university. In recent years, researchers have gradually realized that GTI requires multiagent cooperation, and according to Wei and Wang [40] and Yin and Li [42], the differential equation is used to describe the evolution of the GTI level as follows:

$$\begin{cases} G'(t) = \frac{dG(t)}{dt} = \omega_e A_e(t) + \omega_s A_s(t) - \delta G(t) \\ G(0) = g \geq 0 \end{cases} \quad (2)$$

where ω_e and ω_s refer to the coefficient of the knowledge-sharing amount of the enterprise and the university affecting the GTI level (i.e., GTI ability). The rapid rate of technology updates leads to technology obsolescence, so $\delta > 0$ represents the decay ratio of GTI in the innovation process and $G(0)$ denotes the initial GTI level.

Assumption 3. According to Liu *et al.* [43] and Yin and Li [42], the enterprise knowledge-sharing costs are assumed to be $f(A_e(t))$, and the enterprise costs are a function related to the enterprise knowledge-sharing amount. We set ϕ as the coefficient of the external organization support such as financial credit and other social capital support, and the coefficient of investment support is determined by the potential value of the GTI of corporates. To simplify the extrapolation, let $f(A_e(t)) = A_e(t)$.

Government subsidies are provided in a variety of ways and are involved in the whole GTI process [44]. Accordingly, the government is assumed to offer a subsidy to both firms and universities, and the degree of the government subsidies is connected with the GTI level, $f(G(t))$, and set φ as the government subsidy coefficient, which is determined by the potential GTI level. To simplify the extrapolation, let $f(G(t)) = G(t)$. Based on these conditions, the input function of multichannel funding is

$$I(t) = \phi A_e + \varphi G \quad (3)$$

Assumption 4. Based on the research of Guofeng *et al.* [37] and Lin and Wang [36], the amount of knowledge sharing by multiagent cooperative subjects affects the revenue equation. In addition, Yin *et al.* [39] emphasized that the GTI level also affects revenue. Thus, considering the financial inputs from external institutions and government and drawing on the literature [38], we calculate the total revenue of the U-I as

$$\pi(t) = (\varepsilon_e + \phi) A_e + \varepsilon_s A_s + (\mu + \varphi) G \quad (4)$$

where ε_e and ε_s denote the marginal benefit coefficients of knowledge sharing of the enterprise and the university, respectively. μ denotes the degree of the effect of the GTI level on the total benefits.

Assumption 5: The enterprise shares ξ ($\xi \in [0, 1]$) times the cost to incentivize the universities to share knowledge. The total benefits of the GTI are allocated between the two players, with the firm's allocation ratio being α ($\alpha \in (0, 1)$) and the university's allocation ratio being $1 - \alpha$. In an infinite period, the same discount ratio ρ is owned by the two players, and $\rho > 0$.

$$J_e = \int_0^\infty e^{-\rho t} \left[\alpha \pi(t) - \frac{k_e}{2} A_e^2 - \xi \frac{k_s}{2} A_s^2 \right] dt \quad (5)$$

$$J_s = \int_0^\infty e^{-\rho t} \left[(1 - \alpha) \pi(t) - (1 - \xi) \frac{k_s}{2} A_s^2 \right] dt \quad (6)$$

The differential game model established in this paper has three control variables A_e, A_s, ξ , and one state variable $G(t)$.

IV. MODEL SOLUTION

In this section, we solve five scenarios: Nash noncooperative game without multichannel funding, Nash noncooperative game with external funding and without government subsidies, Nash noncooperative game with multichannel funding, Stackelberg game, and cooperative game. This article analyzes the optimal knowledge-sharing strategies and the revenues of the two players.

A. NASH NONCOOPERATIVE GAME

In the Nash noncooperative game, companies and universities are independent of each other when they maximize their interests. The model is a decentralized decision-making one with no cost sharing, and the companies do not want to share costs with the universities; thus, $\xi = 0$.

1) NASH NONCOOPERATIVE GAME WITHOUT MULTICHANNEL FUNDING

In the Nash noncooperative game, if neither the external agency nor the government provides funding, then $\phi = 0, \varphi = 0$. Therefore, the objective equations of the enterprise and the university are represented as, respectively (denoted by superscript N1)

$$J_e = \int_0^\infty e^{-\rho t} \left[\alpha \pi(t) - \frac{k_e}{2} A_e^2 \right] dt \quad (7)$$

$$J_s = \int_0^\infty e^{-\rho t} \left[(1 - \alpha) \pi(t) - \frac{k_s}{2} A_s^2 \right] dt \quad (8)$$

2) NASH NONCOOPERATIVE GAME WITH EXTERNAL FUNDING BUT NO GOVERNMENT SUBSIDIES

In the Nash noncooperative game, if external institutions such as financial institutions provide support but the government does not provide subsidies, then $\phi \neq 0, \varphi = 0$. The decision-making functions of the enterprise and the university are shown as, respectively (denoted by superscript N2)

$$J_e = \int_0^\infty e^{-\rho t} \left[\alpha \pi(t) - \frac{k_e}{2} A_e^2 \right] dt \quad (9)$$

$$J_s = \int_0^\infty e^{-\rho t} \left[(1 - \alpha) \pi(t) - \frac{k_s}{2} A_s^2 \right] dt \quad (10)$$

3) NASH NONCOOPERATIVE GAME WITH MULTICHANNEL FUNDING

In the Nash noncooperative game, if external institutions and the government both provide financial support, then $\phi \neq 0, \varphi \neq 0$. The decision-making functions of the enterprise and the university are shown as, respectively (denoted by superscript N3)

$$J_e = \int_0^\infty e^{-\rho t} \left[\alpha \pi(t) - \frac{k_e}{2} A_e^2 \right] dt \quad (11)$$

$$J_s = \int_0^\infty e^{-\rho t} \left[(1 - \alpha) \pi(t) - \frac{k_s}{2} A_s^2 \right] dt \quad (12)$$

B. STACKELBERG GAME

In the Stackelberg game, the enterprise adopts a certain percentage of the knowledge-sharing costs for the university to encourage green technology innovation, and in green innovation ecosystems, the enterprise is the leader and the university is the follower. The game mechanisms between the two players can be described as follows: the enterprise acts first and determines the optimal knowledge-sharing strategy and the optimal subsidy proportion for the university; then, the university chooses the optimal knowledge-sharing strategy after observing the enterprise's actions. In doing so, both external institutions and the government provide financial support to the firm, and the firm shares the knowledge-sharing costs with the university:

$$\xi \frac{k_s}{2} A_s^2, \xi \in [0, 1]$$

Meanwhile, the revenue objective functions for the enterprise and the university are, respectively (denoted by superscript S):

$$J_e = \int_0^\infty e^{-\rho t} \left[\alpha \pi(t) - \frac{k_e}{2} A_e^2 - \xi \frac{k_s}{2} A_s^2 \right] dt \quad (13)$$

$$J_s = \int_0^\infty e^{-\rho t} \left[(1 - \alpha) \pi(t) - (1 - \xi) \frac{k_s}{2} A_s^2 \right] dt \quad (14)$$

C. COOPERATIVE GAME

In the cooperative game, the goal is to maximize the overall interests of the U-I and together determine the best decision for all participants. At this point, the target total benefit function of the U-I is (denoted by superscript C):

$$J = J_e + J_s = \int_0^\infty e^{-\rho t} \left[\pi(t) - \frac{k_e}{2} A_e^2 - \frac{k_s}{2} A_s^2 \right] dt \quad (15)$$

The optimal knowledge-sharing strategies, the equilibrium trajectory of the GTI level, and the optimal benefits function are shown in Table 2. The proofs of these strategies and benefits functions are presented in the Appendix.

V. COMPARATIVE ANALYSIS

Corollary 1. In the Nash noncooperative game, the comparison results for the optimal knowledge-sharing strategies for both sides in the three cases of the Nash noncooperative game are $A_e^{N3} > A_e^{N2} > A_e^{N1}, A_s^{N3} > A_s^{N2} = A_s^{N1}$

This corollary indicates that, in the Nash noncooperative game, if financial support is received from both external agencies and the government, the knowledge-sharing willingness of the two players is significantly enhanced, indicating that financial inputs can stimulate the initiatives of enterprises and universities. In addition, if external institutions invest funding in enterprises but the government does not subsidize enterprises and universities, the enterprises' willingness to share knowledge is enhanced, while the universities' willingness to share knowledge remains unchanged.

Corollary 2. Compared with the three scenarios of the Nash noncooperative game with multichannel funding, the Stackelberg game, and the cooperative game, the optimal knowledge-sharing strategies of the two players are $A_e^C > A_e^S > A_e^{N3}, A_s^C > A_s^S = A_s^{N3}$

The above corollary demonstrates that, in the Stackelberg game, the knowledge-sharing willingness of the firm is equal to the Nash noncooperative game with multichannel funding, whereas the knowledge-sharing willingness of the university is significantly enhanced. This phenomenon occurs because firms' providing funding incentivizes universities to engage in knowledge sharing for green technology innovation (GTI), which can incentivize universities to engage in the green innovation ecosystem. In addition, the knowledge-sharing willingness of both firms and universities is improved in the cooperative game, which is better than any other game situation, indicating that power-equivalent technical cooperation stimulates the initiatives of companies and universities.

Corollary 3. In the five game scenarios, the comparison of the GTI level of the U-I is $G^C > G^S > G^{N3} > G^{N2} > G^{N1}$

Corollary 3 indicates that multichannel funding such as credits and subsidies as an incentive mechanism can encourage the enhancement of the GTI level of the U-I. Additionally, the enterprise burden on the knowledge-sharing costs of universities can stimulate the enhancement of the GTI level of the U-I. In the cooperative game, the GTI reaches its highest level as enterprises and universities become more willing to share knowledge.

Corollary 4. In the three scenarios of the Nash noncooperative game, the comparison of the profits of the enterprise and the university is $V_e^{N3} > V_e^{N2} > V_e^{N1}, V_s^{N3} > V_s^{N2} > V_s^{N1}, V^{N3} > V^{N2} > V^{N1}$

This corollary indicates that, in the case of nondirect cooperation between firms and universities, firm and university benefits are higher when either party invests funding than when they do not, and the total benefits of the U-I are maximized when both parties invest. In the case of external institutions and the government investing innovation funding in the U-I, the willingness of enterprises and universities to share knowledge increases, as does the GTI capacity, thus enhancing the benefits of the U-I.

Corollary 5. In the Stackelberg game scenario, the comparison of firms' and universities' profits is $V_e^S > V_e^{N3}, V_s^S > V_s^{N3}, V^S > V^{N3}$

Corollary 5 indicates that both firms' and universities' respective profits from GTI are higher than they are in the

TABLE 2. Equilibrium results.

Model	N1	N2	N3	S	C
Optimal knowledge-sharing strategies					
A_e	$\frac{\alpha[\varepsilon_e(\rho+\delta)+\omega_e\mu]}{k_e(\rho+\delta)}$	$\frac{\alpha[(\varepsilon_e+\phi)(\rho+\delta)+\omega_e\mu]}{k_e(\rho+\delta)}$	$\frac{\alpha(\varepsilon_e+\phi)(\rho+\delta)+\omega_e(\mu+\varphi)}{k_e(\rho+\delta)}$	$\frac{\alpha(\varepsilon_e+\phi)(\rho+\delta)+\omega_e(\mu+\varphi)}{k_e(\rho+\delta)}$	$\frac{\alpha(\varepsilon_e+\phi)+\omega_eV_e'(G)}{k_e}$
A_s	$\frac{(1-\alpha)[\varepsilon_s(\rho+\delta)+\omega_s\mu]}{k_s(\rho+\delta)}$	$\frac{(1-\alpha)[(\varepsilon_s+\phi)(\rho+\delta)+\omega_s\mu]}{k_s(\rho+\delta)}$	$\frac{(1-\alpha)[(\varepsilon_s+\phi)(\rho+\delta)+\omega_s(\mu+\varphi)]}{k_s(\rho+\delta)}$	$\frac{(1-\alpha)[(\varepsilon_s+\phi)(\rho+\delta)+\omega_s(\mu+\varphi)]}{k_s(\rho+\delta)}$	$\frac{\varepsilon_s(\rho+\delta)+\omega_s(\mu+\varphi)}{(\rho+\delta)k_s}$
Equilibrium trajectory of green technology innovation level					
$G(t)$	$\frac{Q_\delta^{N1}}{\delta} + (g - \frac{Q_\delta^{N1}}{\delta})e^{-\delta t}$	$\frac{Q_\delta^{N2}}{\delta} + (g - \frac{Q_\delta^{N2}}{\delta})e^{-\delta t}$	$\frac{Q_\delta^{N3}}{\delta} + (g - \frac{Q_\delta^{N3}}{\delta})e^{-\delta t}$	$\frac{Q_\delta^S}{\delta} + (g - \frac{Q_\delta^S}{\delta})e^{-\delta t}$	$\frac{Q_\delta^C}{\delta} + (g - \frac{Q_\delta^C}{\delta})e^{-\delta t}$
$Q(t)$	$\omega_e A_e^{N1} + \omega_s A_s^{N1}$	$\omega_e A_e^{N2} + \omega_s A_s^{N2}$	$\omega_e A_e^{N3} + \omega_s A_s^{N3}$	$\omega_e A_e^S + \omega_s A_s^S$	$\omega_e A_e^C + \omega_s A_s^C$
Optimal benefits					
V_e	$\alpha bG^{N1} + \frac{\alpha^2}{2}m + \alpha(1-\alpha)n$	$\alpha bG^{N2} + \frac{\alpha^2}{2}l + \alpha(1-\alpha)n$	$\alpha bG^{N3} + \frac{\alpha^2}{2}h + \alpha(1-\alpha)j$	$\alpha dG^S + \frac{\alpha^2}{2}h + \frac{(1+\alpha)^2}{8}j$	$\alpha dG^C + \frac{\alpha}{2}h + \frac{\alpha}{2}j$
V_s	$(1-\alpha)bG^{N1} + \alpha(1-\alpha)m + \frac{(1-\alpha)^2}{2}n$	$(1-\alpha)bG^{N2} + \alpha(1-\alpha)l + \frac{(1-\alpha)^2}{2}n$	$(1-\alpha)bG^{N3} + \alpha(1-\alpha)h + \frac{(1-\alpha)^2}{2}j$	$(1-\alpha)dG^S + \alpha(1-\alpha)h + \frac{(1-\alpha)^2}{4}j$	$\alpha dG^C + \frac{(1-\alpha)}{2}h + \frac{(1-\alpha)}{2}j$
V	$bG^{N1} + \frac{\alpha(2-\alpha)}{2}m + \frac{(1-\alpha^2)}{2}n$	$bG^{N2} + \frac{\alpha(2-\alpha)}{2}l + \frac{(1-\alpha^2)}{2}n$	$bG^{N3} + \frac{\alpha(2-\alpha)}{2}h + \frac{(1-\alpha^2)}{2}j$	$dG^S + \frac{\alpha(2-\alpha)}{2}h + \frac{(1+\alpha)(3-\alpha)}{8}j$	$dG^C + \frac{h}{2} + \frac{j}{2}$
Appendix					
$b = \frac{\mu}{\rho+\delta}, d = \frac{\mu+\varphi}{\rho+\delta}, m = \frac{[\varepsilon_e(\rho+\delta)+\omega_e\mu]^2}{\rho(\rho+\delta)^2k_e}, n = \frac{[\varepsilon_s(\rho+\delta)+\omega_s\mu]^2}{\rho(\rho+\delta)^2k_s}, l = \frac{[(\varepsilon_e+\phi)(\rho+\delta)+\omega_e\mu]^2}{\rho(\rho+\delta)^2k_e}, h = \frac{[(\varepsilon_e+\phi)(\rho+\delta)+\omega_e(\mu+\varphi)]^2}{\rho(\rho+\delta)^2k_e}, j = \frac{[\varepsilon_s(\rho+\delta)+\omega_s(\mu+\varphi)]^2}{\rho(\rho+\delta)^2k_s}$					

TABLE 3. Comparative static analysis of the key parameters.

Parameters	A_e	A_s	G	V_e	V_s	V
k_e	↘	—	↘	↘	↘	↘
k_s	—	↘	↘	↘	↘	↘
ω_e	↗	—	↗	↗	↗	↗
ω_s	—	↗	↗	↗	↗	↗
\mathcal{E}_e	↗	—	↗	↗	↗	↗
\mathcal{E}_s	—	↗	↗	↗	↗	↗
μ	↗	↗	↗	↗	↗	↗

Legend: increase (↗), decrease (↘), ambiguous (—)

Nash noncooperative game, as are total profits. Firms’ investing in innovation subsidies to universities increases universities’ willingness to share knowledge, which increases the GTI level and ultimately enhances the benefits of green innovation ecosystems.

Corollary 6. In the cooperative game, the comparison of the total GTI benefit is $V^C > V^S > V^{N3} > V^{N2} > V^{N1}$

This corollary shows that, in the cooperative game, the total U-I benefit is best among the five game scenarios and reaches the Pareto optimum. In this case, the enterprise and the university act as one entity, and both parties constitute a community of interests. As a result, both work together in the alliance, and their willingness to share knowledge is maximized. Consequently, the total benefit of the green innovation ecosystem also reaches its maximum value.

Corollary 7. A comparative static analysis of the effects of the key parameters of this paper on the willingness of firms and universities to share knowledge, the GTI level, and the benefits can be obtained from the equilibrium results, as presented in Table 3.

Table 3 shows the following results: (1) The knowledge-sharing willingness of enterprises and universities is inversely connected with their respective knowledge-sharing costs k_e, k_s and is positively correlated with their respective GTI abilities ω_e, ω_s and marginal revenue coefficients $\mathcal{E}_e, \mathcal{E}_s$, which indicates that GTI ability and marginal revenue are the driving force of GTI and that the knowledge-sharing costs of enterprises and universities depend on their resistance to knowledge sharing. (2) The GTI level of the U-I and enterprise and university revenues are negatively correlated

with the knowledge-sharing costs of the enterprise and the university k_e, k_s , and positively correlated with the GTI ability ω_e, ω_s and marginal revenue of the two players $\mathcal{E}_e, \mathcal{E}_s$, which means that the GTI ability and marginal revenue are the dynamic factors for improving GTI, while the knowledge-sharing cost of enterprises and universities is the resistance to the GTI of both parties. Firms and universities seeking higher GTI levels and innovation benefits must improve their own innovation capabilities and marginal benefits and reduce knowledge-sharing costs.

Corollary 8. In the three cases of the Nash noncooperative, Stackelberg, and cooperative games, the first-order partial derivatives of the benefits with respect to ϕ and φ are compared as $\partial V^C/\partial\phi > \partial V^S/\partial\phi = \partial V^N/\partial\phi, \partial V^C/\partial\varphi > \partial V^S/\partial\varphi > \partial V^N/\partial\varphi$.

The above corollary shows that, regardless of the type of capital invested in the GTI process, its utility is maximized in the cooperative game.

Corollary 9. The revenue-sharing ratio of the alliance has a threshold value that causes the benefits of the U-I to reach the Pareto optimum in the cooperative game. Since the GTI level varies in the cooperation modes, the threshold value of the benefit distribution is difficult to solve. Thus, we solved for the threshold value of the benefit distribution at the steady state of the GTI level. Along with the range of the revenue distribution rate in the Stackelberg game, the range of the revenue-sharing ratio of the enterprise can be shown as follows:

$$\frac{1}{3} < \alpha < z \tag{16}$$

$$\begin{cases} z = \frac{4\rho d\omega_e x + 2\rho d\omega_s y + 2k_e x^2 + k_s y^2}{4\rho d\omega_e x + 2\rho d\omega_s y + 4k_e x^2 + k_s y^2} \\ x = \frac{(\varepsilon_e + \phi)(\rho + \delta) + \omega_e(\mu + \varphi)}{(\rho + \delta)k_e} \\ y = \frac{\varepsilon_s(\rho + \delta) + \omega_s(\mu + \varphi)}{(\rho + \delta)k_s} \end{cases} \tag{17}$$

According to Corollary 9, we obtain the first-order partial derivative of z with respect to ϕ, φ , yielding $\partial z/\partial\phi < 0, \partial z/\partial\varphi < 0$. This corollary implies that the threshold of

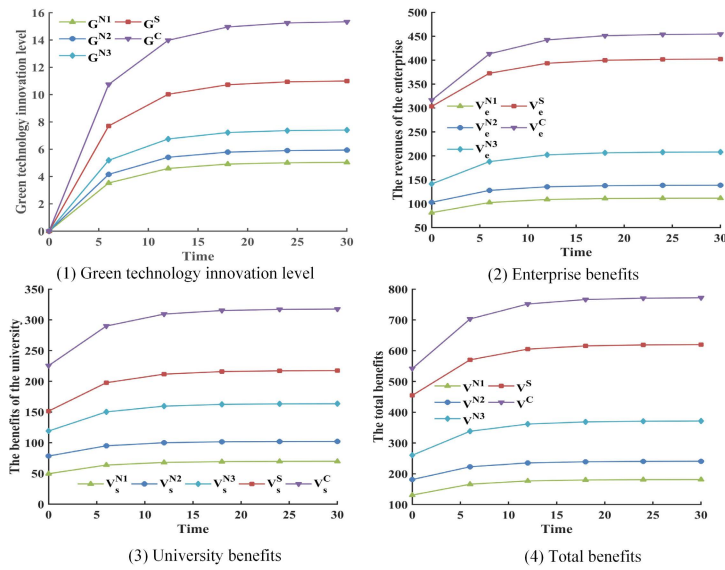


FIGURE 3. Trajectories of the green technological innovation level and the benefits.

the firm’s revenue-sharing ratio shrinks when multichannel funding increases. Thus, universities can gain more benefits from the alliance.

VI. NUMERICAL ANALYSIS

In this section, we apply numerical simulations to observe the varying trajectories of the green technology innovation (GTI) level as well as the revenues of the two players and the U-I. Based on the previous literature [38], similar parameter values were select, and the rest refer to expert opinions. Therefore, we set the following parameter values: $k_e = 2$, $k_s = 2$, $\omega_e = 0.3$, $\omega_s = 0.4$, $\mathcal{E}_e = 2$, $\mathcal{E}_s = 3$, $\phi = 2$, $\varphi = 1.5$, $\mu = 3$, $\delta = 0.2$, $\rho = 0.1$, $G(0) = g = 0$, $\alpha = 0.6$

A. TRAJECTORIES OF THE GREEN TECHNOLOGY INNOVATION LEVEL AND THE REVENUES

Fig. 3 (1) shows that the GTI level increased incrementally with time, and its growth then stabilized. In the Nash noncooperative game, considering only the influence of multiparty funding inputs on the GTI of the U-I, the GTI level gradually increased, which indicates that the multiparty financial inputs drove the GTI level to the optimal level in the nondirect cooperative situation. In the Stackelberg game, the GTI level increased more relative to the Nash noncooperative case, which indicates that the funding support provided by enterprises to universities is an incentive that can significantly improve the GTI level. The highest GTI level was reached in the cooperative game, which indicates that the collaborative model was the most dynamic model for stimulating GTI.

As shown in Fig. 3 (2)-(4), the optimal benefits of the enterprise, the university, and the U-I increased over time in the five situations and then reached a period of stable growth. In the three scenarios of the Nash noncooperative game, firm, university, and total revenues increased significantly with the

inputs of external institutional funding and government subsidies, and the Pareto optimum was reached when multiple parties invested. Firm revenue increased most significantly in the Stackelberg game, while university revenue increased most significantly in the cooperative game, indicating that the university can play the most active role in the absence of leaders, and the Pareto optimum of the whole system can be achieved in the cooperative game.

B. MULTICHANNEL FUNDING ROLE

In this section, we investigate the effectiveness of the coefficient of the innovation investment of external institutions, ϕ , and the coefficient of government subsidies, φ , in enhancing enterprise, university, and U-I revenues in different collaborative modes. Therefore, we set $t = 10$ and $\phi, \varphi \in [0, 5]$ to observe the revenue trajectories based on the above parameter settings.

Fig. 4 shows that firm, university, and total revenue all increased with the investment coefficient of external institutions. The slope in this figure shows that investments from external innovation capital were most effective in the cooperative game. Corollaries 1-3 indicate that the knowledge-sharing willingness of firms and universities is clearly seen to be the direct cause of the GTI level, the improvement in which allows firms and universities to increase their benefits. Therefore, innovation revenues can be improved in two major ways: enhance the enthusiasm of both enterprises and universities to participate in GTI and increase the efficiency of knowledge absorption and technology transformation.

Fig. 5 shows that, regardless of the game scenario, larger government subsidy coefficients resulted in higher benefits for the enterprise, university, and U-I. Based on the slope of the payoff curve, the utility of the government subsidy coefficient on the payoff in the cooperative game was clearly

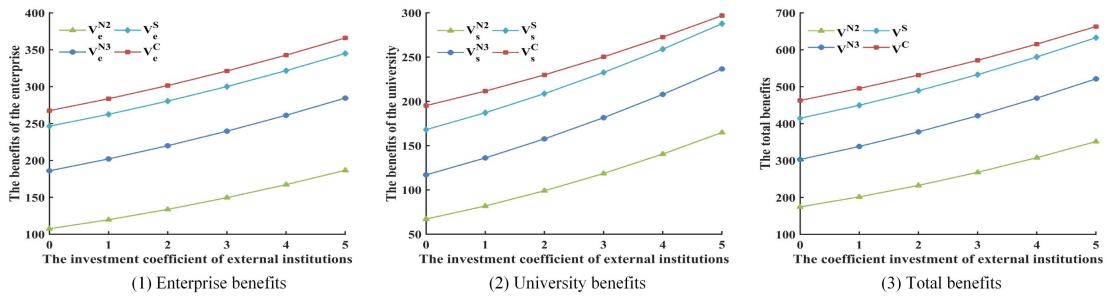


FIGURE 4. ϕ sensitivity to benefits.

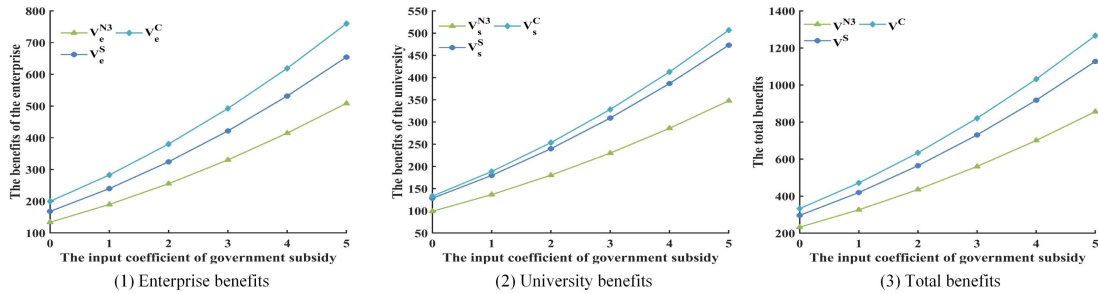


FIGURE 5. ϕ sensitivity to benefits.

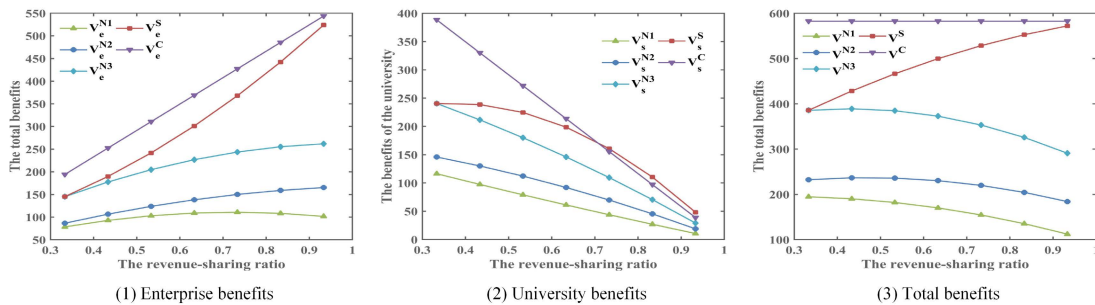


FIGURE 6. α sensitivity to benefits.

greater than it was in the Nash noncooperative and Stackelberg games, which is consistent with the utility of external institutional funding input. Similarly, government subsidies promoted firm and university willingness to share knowledge and thus enhanced GTI, which ultimately led to increased revenues. In Figs 4 and 5, the slopes indicate that increased government subsidies had a stronger effect on the revenue enhancement of the firm, university, and university-industry alliance than did increasing external institutional funding.

C. INNOVATION REVENUE DISTRIBUTION

The value of the revenue-sharing ratio, α , affected U-I stability. Enterprise-led university innovation is not conducive to sustainability. Next, we looked for the range of the revenue-sharing ratio that allowed the revenues of the enterprise and the university in the cooperative game to be consistently higher than they were in the Stackelberg game.

Fig. 6 shows that, regardless of the revenue distribution proportion, both the enterprise and U-I total benefits were maximized in the cooperative game. For corporate earnings,

the utility of the corporate revenue-sharing ratio in the Nash noncooperative game was much smaller than were those in the Stackelberg and cooperative game. However, an increase in the firm revenue-sharing ratio led to a decrease in total revenue in the Nash noncooperative game, which suggests that excessive profits for firms when cooperation is not close are not conducive to university participation in GTI activities. Consequently, regarding the university’s returns, a threshold value of the corporate revenue-sharing ratio makes the university’s returns Pareto optimal in the cooperative game. Once the corporate revenue-sharing ratio exceeds a fixed value, the university revenue in the Stackelberg game is larger than its benefit in the cooperative game, which destabilizes the U-I. Therefore, we further discuss the effect of adding the intensity of multichannel funding on the threshold of the revenue-sharing ratio.

Fig. 7 shows that the university revenue decreased with the revenue-sharing ratio of enterprise α , which is a subtractive function of α . Furthermore, the university benefit in the Stackelberg and cooperative games intersected and was

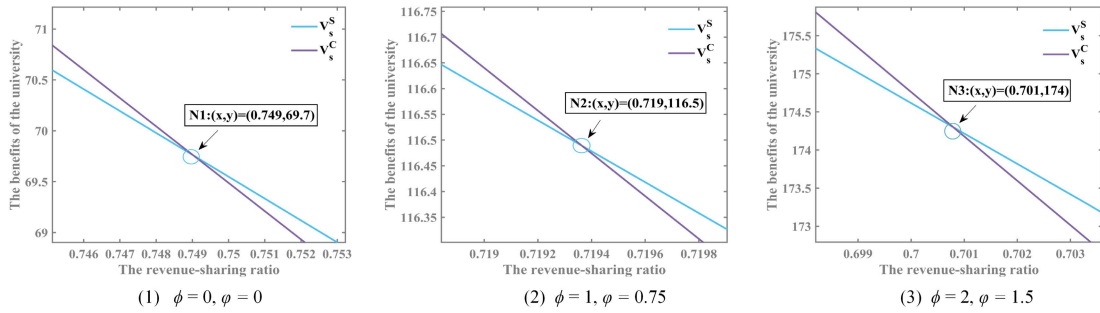


FIGURE 7. α sensitivity to university benefits.

assumed to be N . When $1/3 < \alpha < N$, the value of the university benefit in the cooperative game was greater than it was in the Stackelberg game. In contrast, when $N < \alpha < 1$, the value of the university benefit in the Stackelberg game was greater. When fsolve solver was used in MATLAB to calculate the critical points of the benefits in the Stackelberg and cooperative games in Fig. 6, when $\phi = 0, \varphi = 0$, the firm's revenue-sharing ratio ranged from $1/3 < \alpha < 0.749$, when $\phi = 1, \varphi = 0.75$, the firm's revenue-sharing ratio ranged from $1/3 < \alpha < 0.719$; and when $\phi = 2, \varphi = 1.5$, the firm's revenue-sharing ratio ranged from $1/3 < \alpha < 0.701$. As the multichannel funding investment increased, the threshold of the enterprise revenue-sharing ranges narrowed. This result means that the GTI level of the U-I can be increased significantly with a multichannel funding investment, while universities can allocate more benefits.

VII. CONCLUSION
A. RESEARCH RESULTS

In this paper, we establish a differential game model to consider how multichannel funding affects the green technology innovation (GTI) of university-industry alliances (U-Is) in different cooperative modes and portray the dynamic GTI process over time. The investment of multichannel funding causes three chain reactions in the GTI process, which is first reflected in the knowledge-sharing strategies between the two game subjects, then expressed at the GTI level, and ultimately leads to the change in innovation benefits. Our research found that multichannel funding not only has different enhancing effects on revenue due to different cooperative modes but also has an important impact on revenue sharing in the cooperative game. Our study finds that, first, in the cooperative game, the strongest willingness to share knowledge leads to the highest GTI level; thus, the benefits reach the Pareto optimum. This situation can provide an important reference for selecting the cooperation mode of U-Is. Second, multichannel funding is a strong incentive mechanism in GTI, and it has a large stimulus effect in all three of the game models. Allocating knowledge-sharing costs among firms can also be used by universities as an incentive mechanism in the Stackelberg game; for example, this cost-mitigation measure is beneficial to promoting GTI. Finally, multichannel funding consisting of external institutional investment and government subsidies

has the best utility in the cooperative game. Consequently, the threshold of the firm's revenue distribution rate will be narrowed through multichannel funding investment. The above conclusions enable the better use of funding and the development of revenue-sharing contracts. The theoretical contributions of our paper are as follows:

- 1) The existing literature focuses on different GTI strategies, such as green technology transfer [43] and information-sharing strategies [40]. To achieve GTI, multiagent cooperation approaches are emerging, in which U-Is play an important role. Accordingly, the U-I combination has its own unique interaction mechanism, that is, knowledge sharing. Our paper thus centers on the impact of the knowledge-sharing strategies on the GTI level, which is ultimately reflected in the innovation performance.
- 2) Already the existing literature focuses on funding in the innovation process. For example, Yin *et al.* [45] and Elahi *et al.* [46] emphasized the importance of government subsidies and credit support in emergency and disaster management, respectively. However, they did not delve into which cooperative model has the strongest utility nor do they examine the impact of capital investment on the revenue distribution. We discuss the impact of the inclusion of GTI funding from a more microscopic perspective with a clearer guide.
- 3) Compared to the prior literature, the most valuable findings of our paper are that multichannel funding improves Pareto returns and the returns distribution in GTI. We find that multichannel funding has the strongest Pareto improvement effect in the cooperative game and causes the threshold value of the enterprise revenue-sharing ratio to narrow. These findings provide significant references for the selection of a university-industry alliance cooperation mode and the design of revenue distribution contracts.

B. MANAGERIAL IMPLICATIONS

These research findings provide the following practical guidance for GTI in U-Is. Based on the methodological level, a differential game can provide a long-term perspective for exploring how multichannel funding can play a role in GTI.

We find that the Pareto optimality of returns is realized in the cooperative game. According to our game model, both the Stackelberg and the cooperative games represent direct cooperation in U-Is, but leadership power differs between the two games. In the Stackelberg game, the company leads the alliance, while in the cooperative game, the company and the university have equal amounts of power. In the collaborative green innovation situation, universities have greater levels of autonomy and decision-making power, which is needed for U-I stabilization. This situation means that the cooperative model with equal power can stimulate GTI vitality and further improve its level. Most scholars ignore the autonomy of universities in the UIC, and a number of scholars have suggested that universities establish independent organizations—such as technology transfer offices, university incubators, and cooperative research centers as intermediary departments—to solve such problems. Therefore, collaborative innovation is a win-win choice for enterprises and universities for achieving GTI.

Next, our scenario includes two incentives: multichannel funding and the allocation of knowledge-sharing costs. Enterprises choose different incentive mechanisms based on cooperative modes, which provides absolute theoretical support for enhancing GTI. Multichannel funding is a strong incentive mechanism that stimulates an increase in the willingness to share knowledge, enhances GTI, and ultimately improves the innovative benefits in all three cooperative modes. In addition, when enterprises lead universities to cooperate in U-Is, enterprise cost sharing is an effective incentive mechanism that can encourage universities to actively participate in GTI R & D. However, universities are too dependent on enterprises' subsidies, which is not conducive to long-term development.

Moreover, multiple rounds of funding are more motivational for both sides in the cooperative game; therefore, UIC for green innovation is the best choice, wherein both parties should strive for social funding to complete long-term and arduous green innovative activities. Additionally, multichannel funding can change the threshold of the corporate's revenue distribution rate, which is significant for the dynamic improvement of revenue distribution contracts. The threshold value of the revenue-sharing ratio decreases as innovation investments increase. In this relationship, striving for more innovation investments is conducive to improving university revenue in the alliance. As a result, the government should actively guide, enterprises should create the conditions, universities should take the initiative to cooperate, and society should actively finance to promote the formation of the alliance-based university-industry green innovation ecosystem to promote the progress of science and technology and improve the conversion rate of scientific research results, eventually resulting in enhanced economic development.

C. LIMITATIONS

Despite the above conclusions, our article has some limitations. Expectations and variances in the level of knowledge

sharing that occurs between firms and universities and the multiple funding inputs were not discussed. In addition, many key variables in addition to funding have important effects on university-industry co-innovation; thus, future scholars may consider adding relevant variables based on this paper.

APPENDIX

A. PROOF OF EQUILIBRIUM RESULTS

1) NASH NONCOOPERATIVE GAME WITHOUT MULTICHANNEL FUNDING

We define $V_e(G)$, $V_s(G)$ as revenues equations. Accordingly, the following Hamilton-Jacobi-Bellman (HJB) equations satisfied by $V_i(G)$ are shown below

$$\rho V_e(G) = \max_{A_e \geq 0} \left\{ \alpha (\varepsilon_e A_e + \varepsilon_s A_s + \mu G) - \frac{k_e}{2} A_e^2 + V'_e(G) (\omega_e A_e + \omega_s A_s - \delta G) \right\} \quad (A.1)$$

$$\rho V_s(G) = \max_{A_s \geq 0} \left\{ (1 - \alpha) (\varepsilon_e A_e + \varepsilon_s A_s + \mu G) - \frac{k_s}{2} A_s^2 + V'_s(G) (\omega_e A_e + \omega_s A_s - \delta G) \right\} \quad (A.2)$$

Take the partial derivatives of equations (1) and (2) with respect to A_e and A_s , and set them equal to zero

$$A_e = \frac{\alpha \varepsilon_e + \omega_e V'_e(G)}{k_e} \quad (A.3)$$

$$A_s = \frac{(1 - \alpha) \varepsilon_s + \omega_s V'_s(G)}{k_s} \quad (A.4)$$

According to the formation of equations (1) and (2), we can know that the revenues functions are the linear expression of G . Totally, we suppose

$$V_e(G) = a_1 G + a_2 \quad (A.5)$$

$$V_s(G) = b_1 G + b_2 \quad (A.6)$$

where a_1, a_2, b_1, b_2 are unknown constants, we can infer that

$$V'_e(G) = \frac{dV_e(G)}{dG} = a_1 \quad (A.7)$$

$$V'_s(G) = \frac{dV_s(G)}{dG} = b_1 \quad (A.8)$$

Substituting equations (5)-(8) into equations (1) and (2), respectively, results in

$$a_1 = \frac{\alpha \mu}{\rho + \delta}, \quad b_1 = \frac{(1 - \alpha) \mu}{\rho + \delta} \quad (A.9)$$

$$a_2 = \frac{\alpha^2 [\varepsilon_e \rho + \delta + \omega_e \mu]^2}{2\rho(\rho + \delta)^2 k_e} + \frac{\alpha(1 - \alpha) [\varepsilon_s(\rho + \delta) + \omega_s \mu]^2}{\rho(\rho + \delta)^2 k_s} \quad (A.10)$$

$$b_2 = \frac{\alpha(1 - \alpha) [\varepsilon_e \rho + \delta + \omega_e \mu]^2}{\rho(\rho + \delta)^2 k_e} + \frac{(1 - \alpha)^2 [\varepsilon_s(\rho + \delta) + \omega_s \mu]^2}{2\rho(\rho + \delta)^2 k_s} \quad (A.11)$$

Substituting a_1, b_1 into A_e, A_s , the optimal knowledge-sharing strategies of the enterprise and the university A_e^{N1}, A_s^{N1} can be solved.

$$A_e^{N1} = \frac{\alpha [\varepsilon_e(\rho + \delta) + \omega_e \mu]}{k_e(\rho + \delta)} \quad (A.12)$$

$$A_s^{N1} = \frac{(1 - \alpha) [\varepsilon_s(\rho + \delta) + \omega_s \mu]}{k_s(\rho + \delta)} \quad (A.13)$$

And then the results are substituted in the state equation, we can obtain the equilibrium trajectory of green technology innovation level:

$$\begin{cases} G^{N1} = \frac{Q^{N1}}{\delta} + \left(g - \frac{Q^{N1}}{\delta}\right) e^{-\delta t} \\ Q^{N1} = \omega_e A_e^{N1} + \omega_s A_s^{N1} \end{cases} \quad (A.14)$$

By substituting a_1, a_2, b_1, b_2 into equations (5) and (6), the optimal revenue functions of the enterprise and the university and the total revenues of the U-I $V_e^{N1}, V_s^{N1}, V^{N1}$ can be obtained respectively,

$$V_e^{N1} = \frac{\alpha\mu}{\rho + \delta} G^{N1} + \frac{\alpha^2 [\varepsilon_e(\rho + \delta) + \omega_e\mu]^2}{2\rho(\rho + \delta)^2 k_e} + \frac{\alpha(1 - \alpha) [\varepsilon_s(\rho + \delta) + \omega_s\mu]^2}{\rho(\rho + \delta)^2 k_s} \quad (A.15)$$

$$V_s^{N1} = \frac{(1 - \alpha)\mu}{\rho + \delta} G^{N1} + \frac{\alpha(1 - \alpha) [\varepsilon_e(\rho + \delta) + \omega_e\mu]^2}{\rho(\rho + \delta)^2 k_e} + \frac{(1 - \alpha)^2 [\varepsilon_s(\rho + \delta) + \omega_s\mu]^2}{2\rho(\rho + \delta)^2 k_s} \quad (A.16)$$

$$V^{N1} = \frac{\mu}{\rho + \delta} G^{N1} + \frac{\alpha(2 - \alpha) [\varepsilon_e(\rho + \delta) + \omega_e\mu]^2}{2\rho k_e(\rho + \delta)^2} + \frac{(1 - \alpha^2) [\varepsilon_s(\rho + \delta) + \omega_s\mu]^2}{2\rho k_s(\rho + \delta)^2} \quad (A.17)$$

2) NASH NONCOOPERATIVE GAME WITH EXTERNAL FUNDING BUT NO GOVERNMENT SUBSIDIES

Assuming that there are continuously differentiable and bounded return functions $V_e(G), V_s(G)$, for all HJB equations, the following revenues functions satisfying the HJB equation are shown below:

$$\rho V_e(G) = \max_{A_e \geq 0} \left\{ \alpha (\varepsilon_e A_e + \varepsilon_s A_s + \mu G + \phi A_e) - \frac{k_e}{2} A_e^2 + V'_e(G) (\omega_e A_e + \omega_s A_s - \delta G) \right\} \quad (A.18)$$

$$\rho V_s(G) = \max_{A_s \geq 0} \left\{ (1 - \alpha) (\varepsilon_e A_e + \varepsilon_s A_s + \mu G + \phi A_e) - \frac{k_s}{2} A_s^2 + V'_s(G) (\omega_e A_e + \omega_s A_s - \delta G) \right\} \quad (A.19)$$

The calculation process is the similar to the previous one, so it is omitted here.

The optimal knowledge-sharing amount of the two players is

$$A_e^{N2} = \frac{\alpha [(\varepsilon_e + \phi)(\rho + \delta) + \omega_e\mu]}{k_e(\rho + \delta)} \quad (A.20)$$

$$A_s^{N2} = \frac{(1 - \alpha) [(\varepsilon_s + \phi)(\rho + \delta) + \omega_s\mu]}{k_s(\rho + \delta)} \quad (A.21)$$

The equilibrium trajectory of green technology innovation level is:

$$\begin{cases} G^{N2} = \frac{Q^{N2}}{\delta} + \left(g - \frac{Q^{N2}}{\delta}\right) e^{-\delta t} \\ Q^{N2} = \omega_e A_e^{N2} + \omega_s A_s^{N2} \end{cases} \quad (A.22)$$

The revenues of the enterprise, the university, and the U-I are:

$$V_e^{N2} = \frac{\alpha\mu}{\rho + \delta} G^{N2} + \frac{\alpha^2 [(\varepsilon_e + \phi)(\rho + \delta) + \omega_e\mu]^2}{2\rho(\rho + \delta)^2 k_e} + \frac{\alpha(1 - \alpha) [\varepsilon_s(\rho + \delta) + \omega_s\mu]^2}{\rho(\rho + \delta)^2 k_s} \quad (A.23)$$

$$V_s^{N2} = \frac{(1 - \alpha)\mu}{\rho + \delta} G^{N2} + \frac{\alpha(1 - \alpha) [(\varepsilon_e + \phi)(\rho + \delta) + \omega_e\mu]^2}{\rho(\rho + \delta)^2 k_e} + \frac{(1 - \alpha)^2 [\varepsilon_s(\rho + \delta) + \omega_s\mu]^2}{2\rho(\rho + \delta)^2 k_s} \quad (A.24)$$

$$V^{N2} = \frac{\mu}{\rho + \delta} G^{N2} + \frac{\alpha(2 - \alpha) [(\varepsilon_e + \phi)(\rho + \delta) + \omega_e\mu]^2}{2\rho k_e(\rho + \delta)^2} + \frac{(1 - \alpha^2) [\varepsilon_s(\rho + \delta) + \omega_s\mu]^2}{2\rho k_s(\rho + \delta)^2} \quad (A.25)$$

3) NASH NONCOOPERATIVE GAME WITH MULTICHANNEL FUNDING

$V_e(G), V_s(G)$ defined as benefits functions satisfying Hamilton-Jacobi-Bellman (HJB) equation, resulting in?

$$\rho V_e(G) = \max_{A_e \geq 0} \left\{ \alpha (\varepsilon_e A_e + \varepsilon_s A_s + \mu G + \phi A_e + \varphi G) - \frac{k_e}{2} A_e^2 + V'_e(G) (\omega_e A_e + \omega_s A_s - \delta G) \right\} \quad (A.26)$$

$$\rho V_s(G) = \max_{A_s \geq 0} \left\{ (1 - \alpha) (\varepsilon_e A_e + \varepsilon_s A_s + \mu G + \phi A_e + \varphi G) - \frac{k_s}{2} A_s^2 + V'_s(G) (\omega_e A_e + \omega_s A_s - \delta G) \right\} \quad (A.27)$$

Referring to the inference process above, we can obtain, when the two players have financial support from external organizations and the government:

The optimal knowledge-sharing amount of the two players is

$$A_e^{N3} = \frac{\alpha [(\varepsilon_e + \phi)(\rho + \delta) + \omega_e(\mu + \varphi)]}{k_e(\rho + \delta)} \quad (A.28)$$

$$A_s^{N3} = \frac{(1 - \alpha) [(\varepsilon_s + \phi)(\rho + \delta) + \omega_s(\mu + \varphi)]}{k_s(\rho + \delta)} \quad (A.29)$$

The equilibrium trajectory of green technology innovation level is:

$$\begin{cases} G^{N3} = \frac{Q^{N3}}{\delta} + \left(g - \frac{Q^{N3}}{\delta}\right) e^{-\delta t} \\ Q^{N3} = \omega_e A_e^{N3} + \omega_s A_s^{N3} \end{cases} \quad (A.30)$$

The revenues of the enterprise, the university, and the U-I are:

$$V_e^{N3} = \frac{\alpha(\mu + \varphi)}{\rho + \delta} G^{N3} + \frac{\alpha^2 [(\varepsilon_e + \phi)(\rho + \delta) + \omega_e(\mu + \varphi)]^2}{2\rho(\rho + \delta)^2 k_e} + \frac{\alpha(1 - \alpha) [\varepsilon_s(\rho + \delta) + \omega_s(\mu + \varphi)]^2}{\rho(\rho + \delta)^2 k_s} \quad (A.31)$$

$$V_s^{N3} = \frac{(1 - \alpha)(\mu + \varphi)}{\rho + \delta} G^{N3} + \frac{\alpha(1 - \alpha) [(\varepsilon_e + \phi)(\rho + \delta) + \omega_e(\mu + \varphi)]^2}{\rho(\rho + \delta)^2 k_e} + \frac{(1 - \alpha)^2 [\varepsilon_s(\rho + \delta) + \omega_s(\mu + \varphi)]^2}{2\rho(\rho + \delta)^2 k_s} \quad (A.32)$$

$$V^{N3} = \frac{\mu + \varphi}{\rho + \delta} G^{N3} + \frac{\alpha(2 - \alpha) [(\varepsilon_e + \phi)(\rho + \delta) + \omega_e(\mu + \varphi)]^2}{2\rho k_e(\rho + \delta)^2}$$

$$+ \frac{(1 - \alpha^2) [\varepsilon_s(\rho + \delta) + \omega_s(\mu + \varphi)]^2}{2\rho k_s(\rho + \delta)^2} \quad (A.33)$$

4) STACKELBERG GAME

Based on the solution method of the Stackelberg game, we first settle on the optimal knowledge-sharing strategy of the university. The optimal revenues function of the university satisfying the HJB equation is

$$\rho V_s(G) = \max_{A_s \geq 0} \left\{ (1 - \alpha)(\varepsilon_e A_e + \varepsilon_s A_s + \mu G + \phi A_e + \varphi G) - (1 - \xi) \frac{k_s}{2} A_s^2 + V_s'(G)(\omega_e A_e + \omega_s A_s - \delta G) \right\} \quad (A.34)$$

Based on the first-order condition of A_s in the equation (34), we have

$$A_s = \frac{(1 - \alpha)\varepsilon_s + \omega_s V_s'(G)}{(1 - \xi)k_s} \quad (A.35)$$

The enterprise, as a rational decision-maker, can precisely predict the optimal strategy of the university, and thus the enterprise will decide its optimal strategy based on the university's response function equation (35). Therefore, continuing with the optimal decision problem for the enterprise, we get

$$\rho V_e(G) = \max_{A_e \geq 0} \left\{ \alpha(\varepsilon_e A_e + \varepsilon_s A_s + \mu G + \phi A_e + \varphi G) - \frac{k_e}{2} A_e^2 - \xi \frac{k_s}{2} A_s^2 + V_e'(G)(\omega_e A_e + \omega_s A_s - \delta G) \right\} \quad (A.36)$$

Substituting equation (35) into equation (36), equation (36) is obtained by taking the first-order partial derivatives of A_e and ξ , making them equal to zero respectively, we have

$$A_e = \frac{\alpha(\varepsilon_e + \phi) + \omega_e V_e'(G)}{k_e} \quad (A.37)$$

$$\xi = \frac{(3\alpha - 1)\varepsilon_s + \omega_s [2V_e'(G) - V_s'(G)]}{(1 + \alpha)\varepsilon_s + \omega_s [2V_e'(G) + V_s'(G)]} \quad (A.38)$$

Referring to the inference process above, we can obtain the equilibrium results.

The optimal amount of knowledge sharing of two players is

$$A_e^S = \frac{\alpha[(\varepsilon_e + \phi)(\rho + \delta) + \omega_e(\mu + \varphi)]}{k_e(\rho + \delta)} \quad (A.39)$$

$$A_s^S = \frac{(1 - \alpha)[(\varepsilon_s + \phi)(\rho + \delta) + \omega_s(\mu + \varphi)]}{k_s(\rho + \delta)} \quad (A.40)$$

The optimal subsidy strategy for the enterprise to the university is

$$\xi^S = \begin{cases} \frac{3\alpha - 1}{1 + \alpha}, & \frac{1}{3} < \alpha \leq 1 \\ 0, & \text{others} \end{cases} \quad (A.41)$$

The equilibrium trajectory of green technology innovation level is:

$$\begin{cases} G^S = \frac{Q^S}{\delta} + \left(g - \frac{Q^S}{\delta}\right) e^{-\delta t} \\ Q^S = \omega_e A_e^S + \omega_s A_s^S \end{cases} \quad (A.42)$$

The revenues of the enterprise, the university, and the U-I are:

$$V_e^S = \frac{\alpha(\mu + \varphi)}{\rho + \delta} G^S + \frac{\alpha^2 [(\varepsilon_e + \phi)(\rho + \delta) + \omega_e(\mu + \varphi)]^2}{2\rho(\rho + \delta)^2 k_e} + \frac{(1 + \alpha)^2 [\varepsilon_s(\rho + \delta) + \omega_s(\mu + \varphi)]^2}{8\rho(\rho + \delta)^2 k_s} \quad (A.43)$$

$$V_s^S = \frac{(1 - \alpha)(\mu + \varphi)}{\rho + \delta} G^S + \frac{\alpha(1 - \alpha)[(\varepsilon_e + \phi)(\rho + \delta) + \omega_e(\mu + \varphi)]^2}{\rho(\rho + \delta)^2 k_e} + \frac{(1 - \alpha^2) [\varepsilon_s(\rho + \delta) + \omega_s(\mu + \varphi)]^2}{4\rho(\rho + \delta)^2 k_s} \quad (A.44)$$

$$V^S = \frac{\mu + \varphi}{\rho + \delta} G^S + \frac{\alpha(2 - \alpha) [(\varepsilon_e + \phi)(\rho + \delta) + \omega_e(\mu + \varphi)]^2}{2\rho(\rho + \delta)^2 k_e} + \frac{(1 + \alpha)(3 - \alpha) [\varepsilon_s(\rho + \delta) + \omega_s(\mu + \varphi)]^2}{8\rho(\rho + \delta)^2 k_s} \quad (A.45)$$

5) COOPERATIVE GAME

Satisfying the HJB function, the optimal benefits function $V(G)$ is

$$\rho V(G) = \max_{A_e, A_s \geq 0} \left\{ \alpha(\varepsilon_e A_e + \varepsilon_s A_s + \mu G + \phi A_e + \varphi G) - \frac{k_e}{2} A_e^2 - \frac{k_s}{2} A_s^2 + V'(G)(\omega_e A_e + \omega_s A_s - \delta G) \right\} \quad (A.46)$$

The optimal knowledge-sharing amount of the two players is

$$A_e^C = \frac{(\varepsilon_e + \phi)(\rho + \delta) + \omega_e(\mu + \varphi)}{(\rho + \delta)k_e} \quad (A.47)$$

$$A_s^C = \frac{\varepsilon_s(\rho + \delta) + \omega_s(\mu + \varphi)}{(\rho + \delta)k_s} \quad (A.48)$$

The equilibrium trajectory of green technology innovation level is:

$$\begin{cases} G^C = \frac{Q^C}{\delta} + \left(g - \frac{Q^C}{\delta}\right) e^{-\delta t} \\ Q^C = \omega_e A_e^C + \omega_s A_s^C \end{cases} \quad (A.49)$$

The revenues of the enterprise, the university, and the U-I are:

$$V_e^C = \frac{\alpha(\mu + \varphi)}{\rho + \delta} G^C + \frac{\alpha [(\varepsilon_e + \phi)(\rho + \delta) + \omega_e(\mu + \varphi)]^2}{2\rho(\rho + \delta)^2 k_e} + \frac{\alpha [\varepsilon_s(\rho + \delta) + \omega_s(\mu + \varphi)]^2}{2\rho(\rho + \delta)^2 k_s} \quad (A.50)$$

$$V_s^C = \frac{(1 - \alpha)(\mu + \varphi)}{\rho + \delta} G^C + \frac{(1 - \alpha)[(\varepsilon_e + \phi)(\rho + \delta) + \omega_e(\mu + \varphi)]^2}{2\rho(\rho + \delta)^2 k_e} + \frac{(1 - \alpha) [\varepsilon_s(\rho + \delta) + \omega_s(\mu + \varphi)]^2}{2\rho(\rho + \delta)^2 k_s} \quad (A.51)$$

$$V^C = \frac{\mu + \varphi}{\rho + \delta} G^C + \frac{[(\varepsilon_e + \phi)(\rho + \delta) + \omega_e(\mu + \varphi)]^2}{2\rho(\rho + \delta)^2 k_e} + \frac{[\varepsilon_s(\rho + \delta) + \omega_s(\mu + \varphi)]^2}{2\rho(\rho + \delta)^2 k_s} \quad (A.52)$$

B. PROOF OF COROLLARY

Proof of Corollary 8: The first-order partial derivatives of ϕ in V^N , V^S , and V^C , respectively, are obtained

$$\frac{\partial V^N}{\partial \phi} = \frac{\omega_e \alpha}{k_e} + \frac{\alpha(2 - \alpha)(\varepsilon_e + \phi)[(\rho + \delta) + \omega_e(\mu + \varphi)]}{\rho(\rho + \delta)k_e} \tag{A.53}$$

$$\frac{\partial V^S}{\partial \phi} = \frac{\omega_e \alpha}{k_e} + \frac{\alpha(2 - \alpha)[(\rho + \delta) + \omega_e(\mu + \varphi)]}{\rho(\rho + \delta)k_e} \tag{A.54}$$

$$\frac{\partial V^C}{\partial \phi} = \frac{\omega_e}{k_e} + \frac{[(\rho + \delta) + \omega_e(\mu + \varphi)]}{\rho(\rho + \delta)k_e} \tag{A.55}$$

Combining the equations (53)-(55), we can obtain $\partial V^C/\partial \phi > \partial V^S/\partial \phi = \partial V^N/\partial \phi$. Next, we solve the first-order partial derivatives of V^N , V^S , and V^C with respect to φ are as follows, respectively

$$\begin{aligned} \frac{\partial V^N}{\partial \varphi} &= \frac{\alpha \omega_e^2 \mu}{(\rho + \delta)^2 k_e} + \frac{(1 - \alpha) \omega_s^2 \mu}{(\rho + \delta)^2 k_s} \\ &+ \frac{\alpha(2 - \alpha) \omega_e [(\varepsilon_e + \phi)(\rho + \delta) + \omega_e(\mu + \varphi)]}{\rho(\rho + \delta)^2 k_e} \\ &+ \frac{(1 - \alpha)^2 \omega_s [\varepsilon_s(\rho + \delta) + \omega_s(\mu + \varphi)]}{\rho(\rho + \delta)^2 k_s} \end{aligned} \tag{A.56}$$

$$\begin{aligned} \frac{\partial V^S}{\partial \varphi} &= \frac{\alpha \omega_e [(\varepsilon_e + \phi)(\rho + \delta) + \omega_e(\mu + \varphi)]}{k_e(\rho + \delta)^2} \\ &+ \frac{\alpha \omega_e^2(\mu + \varphi)}{(\rho + \delta)^2 k_e} \\ &+ \frac{(1 + \alpha) \omega_s [\varepsilon_s(\rho + \delta) + \omega_s(\mu + \varphi)]}{2k_s(\rho + \delta)^2} \\ &+ \frac{(1 + \alpha) \omega_s^2(\mu + \varphi)}{2(\rho + \delta)^2 k_s} \\ &+ \frac{\alpha(2 - \alpha) \omega_e [(\varepsilon_e + \phi)(\rho + \delta) + \omega_e(\mu + \varphi)]}{\rho(\rho + \delta)^2 k_e} \\ &+ \frac{(1 + \alpha)(3 - \alpha) \omega_s [\varepsilon_s(\rho + \delta) + \omega_s(\mu + \varphi)]}{4\rho(\rho + \delta)^2 k_s} \end{aligned} \tag{A.57}$$

$$\begin{aligned} \frac{\partial V^C}{\partial \varphi} &= \frac{\omega_e [(\varepsilon_e + \phi)(\rho + \delta) + \omega_e(\mu + \varphi)]}{k_e(\rho + \delta)^2} + \frac{\omega_e^2(\mu + \varphi)}{(\rho + \delta)^2 k_e} \\ &+ \frac{\omega_s [\varepsilon_s(\rho + \delta) + \omega_s(\mu + \varphi)]}{k_s(\rho + \delta)^2} + \frac{\omega_s^2(\mu + \varphi)}{(\rho + \delta)^2 k_s} \\ &+ \frac{\omega_e [(\varepsilon_e + \phi)(\rho + \delta) + \omega_e(\mu + \varphi)]}{\rho(\rho + \delta)^2 k_e} \\ &+ \frac{\omega_s [\varepsilon_s(\rho + \delta) + \omega_s(\mu + \varphi)]}{\rho(\rho + \delta)^2 k_s} \end{aligned} \tag{A.58}$$

Combining the equations (56)-(58), we can obtain $\partial V^C/\partial \varphi > \partial V^S/\partial \varphi > \partial V^N/\partial \varphi$.

Proof of Corollary 9: According to the above analysis, the Pareto optimal revenue of green technology innovation is implemented in the Cooperative game, which is: $V_s^C > V_s^S$. From the equilibrium results of the returns in Table 2, we have

$$\begin{aligned} V_s^C - V_s^S &= (1 - \alpha)d(G^C - G^S) + \left(\frac{1}{2} - \alpha\right)(1 - \alpha)h \\ &+ \frac{1 - \alpha^2}{4}j > 0 \end{aligned} \tag{A.59}$$

Solving for equation (56) and combining the constraints on α under the Stackelberg game, we have

$$\frac{1}{3} < \alpha < \frac{4\rho d \omega_e x + 2\rho d \omega_s y + 2k_e x^2 + k_s y^2}{4\rho d \omega_e x + 2\rho d \omega_s y + 4k_e x^2 + k_s y^2} \tag{A.60}$$

$$\text{where } \begin{cases} x = \frac{(\varepsilon_e + \phi)(\rho + \delta) + \omega_e(\mu + \varphi)}{(\rho + \delta)k_e} \\ y = \frac{\varepsilon_s(\rho + \delta) + \omega_s(\mu + \varphi)}{(\rho + \delta)k_s} \end{cases} \tag{A.61}$$

Corollary 9 is proved.

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