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ESG transformation through private equity and digital twin in energy supply chain: An evolutionary game analysis

Abstract

Purpose – This study aims to explore the long-term decision-making behavior of energy enterprises, private equity organizations (PEs), and governments in the context of Environmental, Social and Governance (ESG)-driven transformation. Given the cost barriers associated with ESG adoption and the new opportunities presented by PEs investments, understanding how these stakeholders interact and make strategic choices is crucial for facilitating a sustainable energy sector.

Design/methodology/approach – This paper proposes a tripartite evolutionary game model to investigate the interactions among the three stakeholders. The model illustrates the feasibility of deploying digital twin (DT) technology in energy enterprises. We then analyze the impact of key factors on three stakeholders' decision-making and derive strategies and conditions for their evolutionary stabilization.

Findings – The findings show that governments should provide policy incentives to attract enterprises to adopt innovative technologies to improve ESG levels. ESG as an important non-financial indicator, provides a basis for PEs to invest in it. When PEs invests in it, enterprises will have more funds to deploy DT, which may form a technological barrier.

Research limitations/implications – This study provides valuable insights into sustainable supply chains by examining the decision-making processes of diverse stakeholders in relation to sustainability.

Originality/value – This paper employs an evolutionary game theory approach to elucidate the impact of using and not using DT technology on the decision-making process of three stakeholders. Insights are provided for the decision-making process of three stakeholders. It also reveals how governments and PEs can promote ESG development in energy enterprises.

Keywords: Environmental, Social, and Governance (ESG), energy supply chain, private equity, digital twin, evolutionary game.

Article Type: Research paper

1. INTRODUCTION

Currently, an increasing number of energy enterprises are actively engaging in ESG practices to facilitate high-quality development through their own initiatives. (Lu and Li, 2024). For instance, State Grid ICT released its 2023 Environmental, Social and Governance (ESG) report, aiming to promote energy digitization and intelligence, such as the "blockchain + 5G" demand response system selected by the National Energy Administration in 2023 (State Grid ICT, 2024). The disclosure rate of ESG-related reports across China's A-share industry will increase annually from 2021-2023, growing from 30.18% in 2021 to 41.36% in 2023 (National Business Daily, 2024). At the same time, the stock exchange released the "Guidelines for Sustainability Reporting by Listed Companies" requiring mandatory ESG disclosure involving 459 listed companies, marking a new stage in the standardization of ESG disclosure for Chinese companies (Shanghai, Shenzhen and Beijing Stock Exchange, 2024).

The rise of ESG provides investors with a multidimensional framework to assess enterprises' operations beyond economic interests, facilitating more informed investment decisions. Private equity organizations (PEs) are expanding their role across investment markets, supporting investee enterprises' profitability through flexible strategies and diversified portfolios. ESG has also become a key factor in supply chain sustainability decisions (Dai and Tang, 2022). Additionally, research has found that the purchasing department can play a special role when appropriately involved. Internally, it serves as a link by sharing knowledge and expertise with other company departments, and at the same time, it acts as a bridge by stimulating the company through innovation and R&D activities (Fiorini *et al.*, 2023). A growing number of studies have demonstrated the effectiveness of innovative technologies in improving firm performance. (Büyüközkan and Göçer, 2018) examine how digital supply chains can leverage diverse innovative technologies, indicating that digital supply chains can attain superior performance and ultimately generate more significant value. Digital energy business models are essential for achieving energy transition policy goals. By adopting reasonable resource requirements, economic benefits and energy efficiency can be maximized and minimizing environmental impact (Yang, 2025). For energy enterprises, digital twin (DT) technology plays a pivotal role in optimizing data flow, improving resource allocation and enhancing control across production processes, thereby supporting sustainable development (Zhao *et al.*, 2022). However, the high cost of technology remains a significant obstacle to the green transition. manufacturers are more likely to invest in DT technology and provide ESG services when the investment level and order loss ratio are low, and the tax rate is high (Zhang *et al.*, 2024). Energy sources such as wind and nuclear power are characterized by intermittency, volatility and stochasticity, and it is a complex challenge to effectively combine these new energy sources with traditional fossil energy sources (Xinhua Finance, 2024). The growing emphasis on Environmental, Social, and Governance (ESG) practices has driven energy enterprises to actively engage in sustainable development, supported by government mandates and increasing investor interest. While ESG initiatives and emerging technologies, such as digital twin (DT) systems, can enhance operational efficiency and sustainability, high implementation costs remain a significant barrier to widespread adoption. Research shows that green investment can play a leading role, numerous firms have made the twin transition by investing in both digitalization and environmental sustainability and plan to further increase their investments (Veugelers *et al.*, 2023). At the same time, private equity investments (PEs) provide financial backing for ESG-driven innovation, creating opportunities for long-term profitability, and collaboration between governments, investors, and enterprises to facilitate a greener energy sector. At the same time, PEs are facing the investment demand to meet ESG goals. An increasing number of PEs are integrating ESG factors and sustainable development concepts into their investment strategies and valuation processes (Bian *et al.*, 2023). This makes it possible for cost barriers and the new opportunities brought by PEs to drive transformation in the industry. Therefore, the long-term decision-making behavior of energy enterprises, PEs, and governments has become an interesting topic.

Amid the increasing significance of ESG development, governments have persistently mandated the disclosure of corporate ESG reports. For energy enterprises, enhancing ESG practices can reduce costs, particularly through the adoption of new technologies. However, these advancements come at high cost. Strong ESG performance can attract long-term investors, providing financial support for sustainable growth, while PEs investment in technology-driven energy enterprises allow for potential high returns and cooperation with governments and enterprises can also reduce investment risks. Fu *et al.* (2024) exploring the interrelations among energy commodities, clean energy equities, and ESG investments in China. Over a long horizon, ESG investments emerge as the foremost contributors. Governments support not only raises societal ESG standards, but also supports economic growth.

Current research focuses on single dimension of ESG and supply chain, such as combining ESG and supply chain metrics to create rating models that assess upstream and downstream performance with financial and non-financial variables (Sardanelli *et al.*, 2022). The application of DT can facilitate the simplification of data collection, enhance data accuracy, and enable cleaner production, thereby reducing pollution and energy consumption (Tao *et al.*, 2019). Using an environmentally responsible approach to supply chain management can effectively improve enterprises' reputation and ESG levels (Quintana-García *et al.*, 2021). PE investment reduces environmental degradation by providing investments in cleaner technologies, energy-efficient sources and renewable investments (Malik and Sharma, 2024). The dynamic process of trade-offs between PEs and other stakeholders as drivers of sustainability reforms in energy enterprises is also underexplored. To fill this gap, this study aims to elucidate the dynamic decision-making process among governments policies, energy enterprises, and PEs, and then derive the results of the tripartite stabilization solution under the long-term behavior, which will provide a theoretical basis for the revision of governments policies as well as PEs investment in energy enterprises.

Energy enterprises are often hesitant to adopt DT technology due to high cost. PEs investment can effectively promote enterprise innovation and has a more significant impact on substantive innovation (Liang *et al.*, 2023). This means that PEs can facilitate the deployment of DT by energy enterprises. As long-term investors, PEs can provide significant financial support, though with heightened risks due to complex exit mechanisms and uncertain market conditions (Calafiore *et al.*, 2020). Therefore, this research seeks optimal strategies to help PEs mitigate risks through a focus on long-term changes.

The existing literature has not thoroughly examined how PEs influence the performance of energy enterprises through ESG investment. Simultaneously, existing studies frequently neglect to consider the financial implications of adopting new technologies and the interactions among stakeholders. Governments, as important supporters, use policy guidance to help enterprises determine the direction of development; however, such policies remain underdeveloped and require funding. To help PEs and energy enterprises make better decisions and improve government policy making, this paper provides theoretical support for the decision making of the three stakeholders by analyzing long-term dynamic changes.

This paper proposes a tripartite evolutionary game model that analyzes the decision-making behavior of energy enterprises, PEs, and governments. Energy enterprises need to contemplate how new technologies can elevate ESG levels while also assessing the cost associated with DT. PEs, being investment institutions with a focus on long-term gains, are well-positioned to aid firms in their ESG transformation. Governments, as supporting institutions, need to promote technological innovation and sustainable development of energy enterprises while controlling expenditures. The objective is to find out the impacts among the three stakeholders and the optimal decision-making in the context of sustainable development and ESG transformation of energy enterprises. Then show how key factors influence their optimal decisions, providing ESG transformation recommendations and managerial insights. Thus, we explore the following questions. (1) How to analyze the relationship among energy enterprises, PEs and governments from the model? (2) In the tripartite evolutionary game model, what is the equilibrium point of governments, PEs, and energy enterprises? (3) How do the key factors affect the optimal strategies of the three stakeholders?

To address these issues, first we develop a tripartite evolutionary game model with PEs, energy enterprises and governments, and find the equilibrium point. Subsequently, the conditions for stabilizing strategies are derived in accordance with Lyapunov's first law. Ultimately, a sensitivity analysis is conducted to elucidate the impact of the primary factors on the tripartite decisions (Cai and Kock, 2009). The main findings of this study are as follows. First, when environmental fines are low, PEs tend to invest, but they more conservative due to future uncertainties and challenging exit mechanisms. Governments penalties encourage energy enterprises to proactively innovate their supply chains for ESG improvement. Second, given the high cost of DT deployment, governments support ESG improvements, while PEs focus on long-term returns, showing greater interest when enterprises face technological barriers. PEs' decisions also accelerate government actions. Third, social returns from government decisions reflect market dynamics, providing a basis for energy enterprises and PEs' decision-making.

This paper delivers contributions in the following ways. First, this paper employs an evolutionary game theory approach to provide insights for PEs and energy enterprises in decision-making processes. PEs can provide enterprises with a substantial amount of capital, thereby facilitating greater investment in technological innovation. Currently, there is a paucity of research examining the role of PEs in facilitating ESG improvements in energy enterprises. Second, the deployment of DT by energy enterprises requires huge financial support, improving ESG performance remains a formidable challenge, and few studies have explored ESG enhancement from the operational perspective of enterprises. This paper proposes to expand the research idea by studying the mutual influence with other stakeholders to seek the optimal decision for sustainable development. Environmental penalties can drive technological change in businesses and force them to adopt more sustainable practices. Government ESG supportive policies can further promote PEs' participation in environmental, social, and governance-driven investments. Third, due to the high cost of the technology and its impact on stakeholders, few studies have discussed the risk of investment. This paper examines the long-term evolution to elucidate how the use and non-use of DT technology impact the decision-making processes of three stakeholders, this study offers valuable insights into sustainable supply chain management.

Under the trend of sustainable development, energy enterprises are paying more attention to ESG reporting. This is not only a response to the social development trend, but it also draws in more investors. Currently, the governments steadily promote ESG development, while energy enterprises are working to improve ESG and require new technologies to optimize their supply chains. This paper constructs a three-party evolutionary game model to study the interactions among the three stakeholders in the sustainable development of energy enterprises. By identifying equilibrium points and analyzing key factors, the study explores the feasibility of implementing DT technologies. It aims to provide managerial insights for energy enterprises, private equity firms, and the government, thereby advancing the ESG transformation and supply chain innovation of energy enterprises.

The remainder of the paper is structured as follows. We first review the relevant literature in Section 2, and the assumptions and model description are given in Section 3. Section 4 provides a stability analysis of the tripartite evolutionary game model. In Section 5, the numerical study is conducted. Finally, conclusions are summarized in Section 6.

2. LITERATURE REVIEW

2.1. Sustainable supply chain and digital twin

DT can replicate physical information in the digital space, and this technology can comprehensively optimize and innovate the supply chain. Liu *et al.* (2021) provides a comprehensive overview of the potential applications of DT in supply chain management, which can effectively enhance processing quality and reduce production costs. A comprehensive DT model can provide a detailed representation of the production process (Qi *et al.*, 2021). A comparison of CPS and DT highlights the potential research value of DT in the future and its role in advancing manufacturing development (Tao *et al.*, 2019). The integration of DT can enhance enterprise sustainability, enabling competitiveness and improved performance in the manufacturing industry (Li *et al.*, 2020). As awareness of the economic benefits of digital technology grows, it will be at the heart of Industry 4.0, driving industrial restructuring and upgrading, while DT can facilitate cost control across the factory. (Jiang *et al.*, 2021). Furthermore, DT provides a new perspective on sustainable production. Miehe *et al.* (2021) deploy DT technology for sustainability-orientated, data-driven production monitoring and management. Theoretically, DT enables effective measurement of carbon emissions and reduction of the carbon footprint (Yu *et al.*, 2022). Governments and industries are increasingly focused on DT's role in current technological transformations and its future applications. (Rasheed *et al.*, 2020). However, Singh *et al.* (2021) indicate that one of the biggest challenges to overcome in implementing DT is the high cost. The development of a complete DT system usually requires the acquisition of high-performance computers and sensors to collect data, making DT an expensive investment. DT applied to the supply chain of energy enterprises can better enable carbon tracking and control of carbon emissions, but few studies consider the high cost of building DT, which is a deterrent to energies companies (Zhang *et al.*, 2023). Current research has demonstrated that DT contributes to industry sustainability. The transformation of industries can help enterprises control costs. Meanwhile, a substantial amount of research has indicated that the implementation of DT entails high costs. There is a paucity of research examining the impact of DT deployment cost on decision-making processes within energy enterprises, and this paper addresses this aspect.

2.2. Relationship between PEs and ESG

PEs have a significant role to play in resolving companies' financial distress, with equity-backed companies restructuring faster to help enterprises resolve their financial difficulties (Hotchkiss *et al.*, 2021). Performance enhancements and sustained growth in target companies are facilitated by PEs through financial assistance and the introduction of management models (Cohn *et al.*, 2022). One study uses panel logit regression to estimate the probability of PEs acquiring companies. Wilson *et al.* (2022) explain PEs are more inclined to invest in enterprises with advanced manufacturing technologies and future growth potential, while also acquiring mature companies to balance the risk level of their portfolios. For private enterprises in which PEs invest, there will be an increase in employment and greater productivity gains for the invested target company. PEs investment funds can effectively help enterprises improve performance, which is a positive contribution for the investee enterprise (Davis *et al.*, 2021). However, this preference of PEs is not conducive to enterprises that hope to make technological innovations. Since PEs are unable to determine whether enterprises can improve their performance after paying high costs, they can only make choices between future potential and risk control. More and more PEs are incorporating ESG factors into their investment strategies, and the value of ESG to PEs is that it can effectively manage investment risk and create more value (Zaccone and Pedrini, 2020). As awareness of sustainability and responsible practices grows, the influence of ESG on investment decisions is becoming increasingly significant (Lange and Banadaki, 2024). ESG is also a goal for enterprises to realize their social responsibility, and enterprises are also the main body to realize the goal of sustainable development. Gillan *et al.* (2021) examine enterprises can enhance their overall image and value by strengthening their investment in the ESG field, which will ultimately bring long-term growth for the enterprises. PEs provide enterprises with capital supply, strategic guidance, and other support to enhance their governance level and R&D and innovation capabilities, while PEs also have high risks and do not invest easily. On the basis of previous studies, this paper explores the impact of PEs on energy enterprises, filling the gap of previous studies.

2.3. Evolutionary game

Evolutionary game is a way to study multi-agent evolutionary relationship and the dynamic change of agent decision. Common Evolutionary game include two-party evolutionary game and three-party evolutionary game (Johari *et al.*, 2019). A tripartite evolutionary game model is used to analyze the roles of governments, polluting enterprises, and the public in environmental pollution control. The study identifies the importance of government incentives and penalties, public participation, and the impact of lowering sewage disposal costs on encouraging enterprises to comply with emission standards. (Zhou *et al.*, 2022). There are also research studies using this model to explore how government policies can encourage manufacturers to adopt more environmentally friendly designs and electronic equipment recyclers to dispose of electronic equipment in a safe and proper manner to promote the healthy development of the end-of-life electrical and electronic equipment recycling industry (Li *et al.*, 2022). Wang *et al.* (2023)According to the information disclosure quality and investment return efficiency of ESG enterprises, establishes a dynamic incentive mechanism. Through game analysis, the dynamic game mechanism between investors and enterprises under consideration of reciprocal preferences is revealed from the perspective of group behavior. An analytical model based on evolutionary game theory is used to examine the dynamic strategic interactions between manufacturers, consumers and governments. It is shown that high investment levels may discourage manufacturers from providing ESG services, while low tax rates may lead to manufacturer complacency. Moreover, when consumers value fairness and equity, they provide positive feedback on the underlying services. Zhang *et al.* (2024) emphasize that market incentives are not sufficient to promote ESG services and require third-party interventions such as government rules, policy incentives, and data security measures. There are also paper that establish a DTS-supported ESG assessment architecture, derive the positive impact of DT technology on the ESG assessment of vaccine logistics supply chains (VLSCs), and validate that DTS can provide a better solution for the ESG assessment of VLSCs (Zhang *et al.*, 2023). The existing literature has validated that evolutionary game models can effectively analyze long-term dynamic changes and can also well analyze the impact of ESG.

High-carbon industries like petrochemicals and smelting face critical challenges in achieving low-cost green transitions, making effective carbon tracking essential. The existing literature has demonstrated that evolutionary game theory can effectively analyze the long-term behavior of stakeholders and capture changes. Numerous studies have applied evolutionary game models to analyze dynamic changes in supply chain management and have used these models to provide theoretical support for decision-making by governments and businesses. However, research on ESG and PEs investment is limited. With the increasing application of DT, its impact within energy companies has not been fully explored. Previous supply chain studies rarely address the influence of government policies and energy enterprises decisions on green innovation and emerging technologies within the context of PEs investment. Therefore, this paper constructs a tripartite evolutionary game model of PEs, energy enterprises and governments to analyze how the three parties involved interact with each other to make the supply chain of energy enterprises achieve better ESG outcomes.

3. THE MODEL

3.1. Assumptions

To facilitate modeling, this study proposes the following assumptions. The notation used throughout this paper is summarized in Table 1 for easy reference.

Assumption 1. We consider the energy enterprises, the PEs, and the governments as a complete system in the natural environment without considering other constraints. And all of them are boundedly rational have individual learning ability and can make own behavioral decisions independent with each other because of information asymmetry (Gu *et al.*, 2021). Each of stakeholders have two different strategic options to achieve maximize their own profits. The energy enterprises can choose whether to use DT technology or not. PEs can choose whether to make investment for energy enterprises. Governments can choose whether to support energy enterprises use DT technology improve their ESG performance. Let x, y, z denote the probabilities of corresponding strategy strategic options for the energy enterprises (whether to use DT), PEs (whether to make investment) and the governments (whether to support energy enterprises use DT), respectively, which are functions of time $t \in [0, 1]$. The strategy of different stakeholders can evolve gradually and finally stabilizes at the optimal point with the pass of time, that is, the game subjects will adjust their own options with much more trial until they reach their ESS.

Assumption 2. Energy enterprises always face additional cost when improving ESG performance, especially when introducing new technologies. Specifically, once energy enterprises use DT technology to improve ESG performance, the technology cost is issued. These costs include technology introduction fees, additional worker learning cost, technology installation fees, and other operating and corporate governance cost.

Assumption 3. The main profit model of PEs is to obtain the future profit growth of the enterprise through equity investment (Gupta and Van Nieuwerburgh, 2021). Moreover, the investment strategy of PEs is generally affected by the policy (Shahbaz *et al.*, 2020). An ongoing governments policy have a positive impact on PEs investment strategies. This means more profit opportunities and more growth potential. Using this approach can reduce the overall risk of the PEs portfolio. At the same time, compared with other investors, PEs generally show a higher return performance (Harris *et al.*, 2023), which means that they are more inclined to invest in high-risk projects with high returns.

Assumption 4. This paper assumes that governments support ESG improvements by energy enterprises, regardless of their level of technology adoption, with the aim of maximizing social benefits. Thus, governments employ effective support policies and targeted incentives. A general budget is allocated for ESG improvements, while additional incentives encourage DT adoption, thereby promoting industry-wide progress. As regulators, governments also impose penalties on energy enterprises that pollute the environment to prevent serious pollution in the future.

<<<Insert Table 1>>>

3.2. Model description

Emission reduction retrofits and technology upgrades in energy enterprises are vital for ESG performance and industry-wide sustainability, with PEs and governments as key drivers. This study examines sustainable development regulations, focusing on energy enterprises deciding whether to adopt DT for ESG improvement, PEs choosing to invest, and governments deciding on support. Evolutionary game theory has been effectively utilized to analyze long-term changes and identify optimal decisions, and it has been widely applied to analyze the decisions of multiple stakeholders. For example, it has been used to analyze how regulators can assist investors in monitoring corporate greenwashing behavior (Liu *et al.*, 2024). Additionally, it has been employed to examine the impact of green bond issuance by banks on corporate technological innovation (Gao *et al.*, 2024). Given its broad applications in areas such as ESG and investment, evolutionary game theory is suitable for this study. We apply the evolutionary game theory, analyze time-dependent outcomes and explore the stable solution of stakeholders' long-term behavior. First, based on the different strategies of each stakeholder, a tripartite evolutionary game model among energy enterprises, PEs, and governments is established to assess DT's impact on ESG performance. Then we analyze the strategy stability of the game and the influence of each factor on the strategy decision of each party. Based on Lyapunov's first law, the combination of evolutionary stability strategies is obtained under different conditions, and the conditions for the existence of stable points in the tripartite evolution are discussed (Zhang *et al.*, 2024). Finally, in the sensitivity analysis, the impact of different factors on decision-making is analyzed. The alternative strategies for each stakeholder are shown in Fig. 1.

<<<Insert Fig. 1>>>

Each party gets two pure strategies in the decision-making process. The strategy decision always accompanied by the revenue and cost. Specifically, energy enterprises (player 1) can choose whether to use the DT technology to improve ESG performance, that is, the strategic choice space of energy enterprises is α=(use DT, do not use DT), The probability of use DT technology to improve ESG performance is defined as x $(0 \leq x \leq 1)$, and the probability of do not use DT technology is defined as $(1-x)$. Once energy enterprises decide to use the DT technology to improve their ESG performance, they have to make the DT investment cost C_{DT}. Because compare with the traditional manufacturing, the introduction of DT technology often requires much more operating costs to achieve the function of DT technology to improve their ESG performance. In addition, energy enterprises can earn the revenue from their primary business R_c and have the daily operating cost C_c. Because of the adoption of DT technology to improve the ESG performance, it can reduce certain management cost C_M, and also $C_{DT} > C_M$ (Javaid *et al.*, 2023). When enterprises do not use DT technology, they also face punishment by the governments and have to pay fines f, because of environmental pollution caused by behindhand emission control technology. The fine be collected by the governments and use for environmental remediation. And also, If PEs do not invest in energy enterprises, this sends a negative signal to other investors, the market may perceive the company has a higher investment risk. At this time, energy enterprises have losses from the social level T_c. Strictly speaking, it would be a punishment.

PEs (player 2) can decide whether to make investment for energy enterprises, that is, the strategic choice space is β =(investment for energy enterprises, not investment for energy enterprises). The probability of investment for energy enterprises is defined as y $(0 \leq y \leq 1)$, and the probability of do not investment for energy enterprises is defined as $(1-y)$. Investment institutions are willing to invest in new technologies to gain more returns (Jiang *et al.*, 2023). The PEs make equity investment is I_p to energy enterprises, and the income brought to the investment is R_p. Moreover, PEs investment tend to have a strong policy orientation. When the governments support energy enterprises to use DT technology, PEs make additional investments I_{pg} in energy companies in order to achieve a higher level of return on equity and get additional investment income R_{pg}. And also, when energy enterprises use more advanced technologies, such as DT technology. For PEs means that energy enterprises can have more returns from technological innovation in the future compared to competitors who do not use similar technologies. It is expected to bring additional benefits R_{pc} to PEs, $I_p > I_{pg} > R_p > R_{pg} \geq R_{pc}$. However, when the invested energy enterprises do not choose to use the investment funds for the development of DT technology, the development of energy enterprises do not meet the expectation of PEs, so the equity return of PEs will be reduced h, $h > R_p > R_{pc}$. Meanwhile, $\theta(\theta > 1)$ can be seen as yield rate when PEs choose to make investment. Because when θ is greater than 1, PEs' income will be greater than the input cost, and then PEs will have the incentive to make investment. And also, based on PEs' profit-seeking investment goal, as a limited-rational decision maker, PEs will only invest when the return is greater than the input cost, that is, $\theta R_p > I_p, \theta R_{pg} > I_{pg}$.

Governments (player 3) can choose whether to support energy enterprises use DT technology improve their ESG performance, that is, the strategic choice space is γ =(support energy enterprises use DT technology, do not support energy enterprises use DT technology). The probability of support energy enterprises use DT technology is defined as z $(0 \leq z \leq 1)$, and the probability of do not support energy enterprises use DT technology is defined as $(1-z)$. The governments generally support energy enterprises to innovate to reduce emissions, especially by adopting cleaner energy sources to improve ESG (Wang *et al.*, 2023). The governments use dedicated funds D_s to provide energy enterprises to improve their ESG performance, and no matter what technology companies use to improve ESG performance. This is because the governments are concerned about the total contribution of energy enterprises to society by improving their ESG performance. When the governments support the use of DT technology by energy enterprises, the governments provide separate funds M_{DT} for energy enterprises to support them and get social benefits T_g. When the governments do not support energy enterprises to introduce DT technology, the governments will increase spending on environmental governance D_g (Wang and Ye, 2024). And at the same time, in order to encourage the enthusiasm of market capital, when PEs invests in energy enterprises, the governments will increase their investment I_g in energy enterprises at the same time.

In accordance with the above assumptions and descriptions, we propose the mixed strategy game matrix according to the relationships of energy enterprises, PEs, and governments. The payoff matrix including eight strategy profiles is shown in Table 2.

<<<Insert Table 2>>>

4. MODEL ANALYSIS

4.1. Equilibrium analysis of evolutionary game model

The expected payoff functions of energy enterprises choosing the using DT strategy and not using DT strategy are denoted as E_{11} and E_{12}, the average expected payoff function is defined $\bar{E}_1$, respectively.

$$\begin{aligned} E_{11} &= yz\left(R_c - C_c - C_{DT} + C_M + I_p + I_{pg} + D_s + M_{DT} + I_g\right) \\ &\quad + y(1-z)\left(R_c - C_c - C_{DT} + C_M + I_p + D_s + I_g\right) \end{aligned} \tag{1}$$

$$+(1-y)(1-z)(R_c - C_c - C_{DT} + C_M - T_c + D_s).$$

$$\begin{aligned} E_{12} = {} & yz\big(R_c - C_c + I_p + I_{pg} - f + D_s + M_{DT} + I_g\big) \\ & + y(1-z)\big(R_c - C_c + I_p - f + I_g\big) \\ & + z(1-y)(R_c - C_c - C_{DT} + C_M - T_c + D_s + M_{DT}) \\ & + (1-y)(1-z)(R_c - C_c - f + D_s). \end{aligned} \tag{2}$$

$$\bar{E}_1 = xE_{11} + (1-x)E_{12}. \tag{3}$$

Specifically, E_{11} represents the expected payoff for energy enterprises choosing the using DT strategy. It includes four scenarios: the expected payoff when PEs invest and the government supports or does not support, and the expected payoff when PEs do not invest and the government supports or does not support. Similarly, E_{12} represents the expected payoff for energy enterprises not using the DT strategy. It also includes the expected payoffs for the four scenarios mentioned in E_{11}. The subsequent expected payoff functions in this paper are similar to those here and thus are not described in detail. The replicator dynamics equation of energy enterprises can be expressed as follows:

$$\begin{aligned} F(x) = \frac{dx}{dt} & = x(x-1)(E_{12} - E_{11}) \\ & = x(x-1)[C_{DT} - C_M + D_s - f + (C_M - C_{DT} - D_s + f)z] - 2D_s y \\ & + (C_{DT} - C_M + 2D_s - f)yz. \end{aligned} \tag{4}$$

The first derivative of x and $G(y)$ are calculated respectively as follows:

$$\begin{aligned} \frac{d\big(F(x)\big)}{dx} = {} & (2x-1)[C_{DT} - C_M + D_s - f + (C_M - C_{DT} - D_s + f)z - 2D_s y \\ & + (C_{DT} - C_M + 2D_s - f)yz]. \end{aligned} \tag{5}$$

$$\begin{aligned} G(y) = {} & C_{DT} - C_M + D_s - f + (C_M - C_{DT} - D_s + f)z - 2D_s y \\ & + (C_{DT} - C_M + 2D_s - f)yz. \end{aligned} \tag{6}$$

According to the stability theorem of differential equation, the probability of energy enterprises choosing using DT strategy in a stable state must satisfy the condition: $F(x) = 0$ and $\frac{d(F(x))}{dx} < 0$. Because $\frac{\partial(G(y))}{\partial y} > 0$, $G(y)$ is an increasing function of y. If $G(y) = 0$, we can get $y = y^* = \frac{(z-1)(C_M - C_{DT} - D_s + f)}{2D_s + z(C_M - C_{DT} - 2D_s + f)}$, that means energy enterprises are unable to determine stabilization strategies.

When $G(y) < 0$, $y < y^*$, then $\frac{d(F(x))}{dx}|_{x=0} < 0$, which means that $x = 0$ (not using DT) is ESS of energy enterprises. In addition, when $G(y) > 0$, $y > y^*$, then $\frac{d(F(x))}{dx}|_{x=1} < 0$, which means that $x = 1$ (using DT) is ESS of energy enterprises.

Proposition 1. In the process of evolution, the probability of energy enterprises uses DT increases accordingly as the increase probability of PEs investment. As governments grant to support energy enterprises to reduce emissions increase, the cost of using DT increases, and the probability that energy enterprises choose not to use DT increases. The probability of energy enterprises chooses to use DT increases as the cost of reduction increases or the fines for causing environmental pollution increase. At the same time the ESG levels of energy enterprises increases as well.

$$V_{C_1} = \int_0^1 \int_0^1 \frac{(z-1)(C_M - C_{DT} - D_s + f)}{2D_s + z(C_M - C_{DT} - 2D_s + f)} dydz = \frac{z(1-z)(C_{DT} - C_M + D_s - f)}{2D_s - z(C_{DT} - C_M + 2D_s - f)}; \quad (7)$$

$$V_{C_2} = 1 - V_{C_1}. \quad (8)$$

The replicated dynamic phase diagram is shown in Fig. 2. We can acquire the first order partial derivative of correlated factors from the above probability expressions. The positive and negative values of the first-order partial derivative are indicators for judging the changing trend of factors and probabilities. Specifically, $\frac{\partial V_{C_1}}{\partial D_s} > 0$, $\frac{\partial V_{C_1}}{\partial C_{DT}} > 0$, $\frac{\partial V_{C_1}}{\partial C_M} < 0$, $\frac{\partial V_{C_1}}{\partial f} < 0$. Therefore, the increasing of D_s, C_{DT} can increase the probability of energy enterprises do not use DT. The decreasing of C_M, f can increase the probability of energy enterprises use DT.

<<<Insert Fig. 2>>>

Proposition 1 manifests that with moderate reductions in government grants, enterprises will consider adopting the DT system to enhance ESG performance. However, the high cost of DT can hinder ESG improvements. Energy enterprises weigh these costs carefully, maximize the use of DT to reduce unnecessary cost. Government fines also incentivize enterprises to improve ESG performance and reduce emissions.

The expected payoff functions of PEs choosing invest energy enterprises strategy and not invest energy enterprises strategy are defined as E_{21} and E_{22},the average expected payoff function is set as $\bar{E}_2$, respectively.

$$E_{21} = xz(\theta R_p - I_p + \theta R_{pc} - I_{pg} + \theta R_{pg}) + x(1-z)(\theta R_p - I_p + \theta R_{pc}) + z(1-x)(\theta R_p - I_p - I_{pg} - h + \theta R_{pg}) + (1-x)(1-z)(\theta R_p - I_p - h). \tag{9}$$

$$E_{22} = 0. \tag{10}$$

$$\bar{E}_2 = yE_{21}. \tag{11}$$

The replicator dynamics equation of PEs is given as follows:

$$F(y) = \frac{dy}{dt} = y(y-1)(E_{22} - E_{21}) = y(1-y)(\theta R_p - I_p - h - zI_{pg} + x\theta R_{pc} + z\theta R_{pg} + xh). \tag{12}$$

The first derivative of y and $H(x)$ are calculated respectively as follows:

$$\frac{d(F(y))}{dy} = (1-2y)(\theta R_p - I_p - h - zI_{pg} + x\theta R_{pc} + z\theta R_{pg} + xh). \tag{13}$$

$$H(x) = \theta R_p - I_p - h - zI_{pg} + x\theta R_{pc} + z\theta R_{pg} + xh. \tag{14}$$

According to the stability theorem of differential equation, the probability of PEs choosing invest energy enterprises strategy in a stable state must satisfy the condition: $F(y) = 0$ and $\frac{d(F(y))}{dy} < 0$. If $H(x) = 0$, we can get $x = x^* = \frac{zI_{pg} - z\theta R_{pg} - \theta R_p + I_p + h}{\theta R_{pc} + h}$. If $I_{pg} > \theta R_{pg}$, $H(x)$ is an increase function of x, because $\frac{\partial(H(x))}{\partial x} > 0$. Thus, when $x < x^*$, $H(x) < 0$, then $\frac{d(F(y))}{dy}|_{y=1} < 0$, which means that $y = 1$ (invest energy enterprises) is ESS of PEs. In addition, when $x > x^*$, $H(x) > 0$, then $\frac{d(F(y))}{dy}|_{y=0} < 0$, which means that $y = 0$ (not invest energy enterprises) is ESS of PEs. In a practical sense, the income of PEs is always less than the cost of investment, so this case is not considered. If $I_{pg} < \theta R_{pg}$, $H(x)$ is a decrease function of x, because $\frac{\partial(H(x))}{\partial x} < 0$. Thus, when $x < x^*$, $H(x) > 0$, $\frac{d(F(y))}{dy}|_{y=0} < 0$, which means that $y = 0$ (not invest energy enterprises) is ESS of PEs. In addition, when $x > x^*$, $H(x) < 0$, $\frac{d(F(y))}{dy}|_{y=1} < 0$, which means that $y = 1$ (invest energy enterprises) is ESS of PEs.

Proposition 2. In the process of evolution, the probability of PEs invests energy enterprises strategy increases correspondingly with the rising probability of use DT by energy enterprises. The probability of PEs invests energy enterprises strategy is positively correlated with the amount of money invested to the energy enterprises, PEs judgment errors reduced income by energy enterprises don't use DT, additional money invested by the PEs in accordance with the policy direction. The probability of PEs invests energy enterprises strategy is negative correlated with the investment income of PEs, additional income from additional investments.

$$V_{P_1} = \int_0^1 \int_0^1 \frac{zI_{pg} - z\theta R_{pg} - \theta R_p + I_p + h}{\theta R_{pc} + h} dydz = \frac{I_p - \theta R_p + h + zI_{pg} - z\theta R_{pg}}{\theta R_{pc} + h}; \quad (15)$$

$$V_{P_2} = 1 - V_{P_1}. \quad (16)$$

The replicated dynamic phase diagram is shown in Fig. 3. We acquire the first order partial derivative of correlated factors from the above probability expressions. The positive and negative values of the first-order partial derivative are indicators for judging the changing trend of factors and probabilities. Specifically, $\frac{\partial V_{C_1}}{\partial D_s} > 0$, $\frac{\partial V_{C_1}}{\partial C_{DT}} > 0$, $\frac{\partial V_{C_1}}{\partial C_M} < 0$, $\frac{\partial V_{C_1}}{\partial f} < 0$. Therefore, the increasing of D_s, C_{DT} can increase the probability of energy enterprises do not use DT. The decreasing of C_M, f can increase the probability of energy enterprises use DT.

<<<Insert Fig. 3>>>

Proposition 2 manifests that with appropriate reductions in governments grants, enterprises will consider adopting the innovative system DT to optimize their ESG performance. At the same time, the high cost of introduce DT can be a hindrance for energy enterprises to improve their ESG performance. Energy enterprises will also weigh the cost when using DT and maximize the use of DT to reduce unnecessary cost. Governments fines have also spurred enterprises to improve their ESG performance and reduce pollution emission.

The expected payoff functions of governments choosing "support enterprises use DT" strategy and "not support enterprises use DT" strategy are denoted as E_{31} and E_{32}, the average expected payoff function is defined $\bar{E}_3$, respectively.

$$\begin{aligned} E_{31} &= xy(T_g - D_s - M_{DT} - I_g) + y(1-x)(T_g - D_s - I_g + f) \\ &+(1-y)(T_g - D_s - M_{DT}) + (1-x)(1-y)(T_g - D_s + f). \end{aligned} \quad (17)$$

$$E_{32} = xy\left(T_g - D_s - M_{DT} - I_g\right) + y(1-x)\left(T_g - D_s - I_g + f\right) + x(1-y)\left(-D_s - D_g\right) + (1-x)(1-y)\left(-D_s - D_g + f\right). \quad (18)$$

$$\bar{E}_3 = xE_{31} + (1-x)E_{32}. \quad (19)$$

The replicator dynamics equation of governments can be expressed as follows:

$$F(z) = \frac{dz}{dt} = z(z-1)(E_{32} - E_{31}) = z(z-1)\left(xM_{DT} - T_g - D_g\right). \quad (20)$$

The first derivative of z and $K(x)$ are calculated respectively as follows:

$$\frac{d\left(F(z)\right)}{dz} = (2z-1)\left(xM_{DT} - T_g - D_g\right). \quad (21)$$

$$K(x) = xM_{DT} - T_g - D_g. \quad (22)$$

According to the stability theorem of differential equation, the probability of governments choosing support energy enterprises use DT strategy in a stable state must satisfy the condition: $F(z) = 0$ and $\frac{d(F(z))}{dz} < 0$. Because $\frac{\partial(K(x))}{\partial x} > 0$, $K(x)$ is an increasing function of x. If $K(x) = 0$, we can get $x = x^* = \frac{D_g + T_g}{M_{DT}}$, that means governments are unable to determine stabilization strategies. When $x < x^*$, $K(x) < 0$, then $\frac{d(F(z))}{dz}|_{z=1} < 0$, which means that $z = 1$ (support energy enterprises use DT) is an ESS of governments. In addition, when $x > x^*$, $K(x) > 0$, then $\frac{d(F(z))}{dz}|_{z=0} < 0$, which means that $z = 0$ (not support energy enterprises use DT) is an ESS of governments.

Proposition 3. In the process of evolution, the probability of governments does not support energy enterprises use DT strategy increases correspondingly with the rising probability of use DT by energy enterprises. The probability of governments support energy enterprises uses DT strategy is positively correlated with social income from governments support enterprises using DT and governments payments for environmental by energy enterprises do not use DT. The probability of governments does not support energy enterprises use DT strategy is positively correlated with grants to energy enterprises by support for enterprise to use DT.

$$V_{G_1} = \int_0^1 \int_0^1 \frac{T_g + D_g}{M_{DT}} dxdy = \frac{T_g + D_g}{M_{DT}}; \tag{23}$$

$$V_{G_2} = 1 - V_{G_1}. \tag{24}$$

The replicated dynamic phase diagram is shown in Fig. 4. We acquire the first order partial derivative of correlated factors from the above probability expressions. The positive and negative values of the first-order partial derivative are indicators for judging the changing trend of factors and probabilities. Specifically, $\frac{\partial V_{G_1}}{\partial T_g} > 0$, $\frac{\partial V_{G_1}}{\partial D_g} > 0$, $\frac{\partial V_{G_1}}{\partial M_{DT}} < 0$. Therefore, the increasing of T_g, D_g can increase the probability of governments support energy enterprises use DT. The decrease of M_{DT} can increase the probability of governments do not support energy enterprises use DT.

<<<Insert Fig. 4>>>

Proposition 3 manifests that governments hope energy enterprises' revenues can reduce governments expenditure. Governments hope that energy enterprises will adopt new technologies to improve the environment and increase ESG performance, thereby reducing governments additional cost. However, there is a trade-off in granting support, making governments grants closely tied to energy enterprises' decisions, and also providing incentives for innovation.

4.2. Analysis of evolutionary stable strategies

Based on the above analysis, a tripartite replicator dynamics system can be constituted as equation

$$\begin{cases} F(x) = x(x-1)[C_{DT} - C_M + D_s - f + (C_M - C_{DT} - D_s + f)z - 2D_s y + (C_{DT} - C_M + 2D_s - f)yz] \\ F(y) = y(1-y)(\theta R_p - I_p - h - zI_{pg} + x\theta R_{pc} + z\theta R_{pg} + xh) \\ F(z) = z(z-1)(xM_{DT} - T_g - D_g). \end{cases} \tag{25}$$

Let the equation set including three formulas equal to zero, which stands for this system will no longer evolve and achieve equilibrium. Following the theory proposed by (Friedman, 1991), ESS only exists in pure strategies, therefore, we exclude the mixed strategies in the equilibrium part. Eight pure strategies are E_1 (0,0,0), E_2 (1,0,0), E_3 (0,1,0), E_4 (0,0,1), E_5 (1,1,0), E_6 (1,0,1), E_7 (0,1,1), E_8(1,1,1). In this tripartite replicator dynamics system, we conclude the stability of these equilibrium points according to the differential equations from the local stability analysis of the Jacobian matrix. The Jacobian matrix can be depicted as.

$$J = \begin{bmatrix} J_1 & J_2 & J_3 \\ J_4 & J_5 & J_6 \\ J_7 & J_8 & J_9 \end{bmatrix} = \begin{bmatrix} \frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} & \frac{\partial F(x)}{\partial z} \\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} & \frac{\partial F(y)}{\partial z} \\ \frac{\partial F(z)}{\partial x} & \frac{\partial F(z)}{\partial y} & \frac{\partial F(z)}{\partial z} \end{bmatrix},$$

where $J_1 = -(2x-1)[C_M - C_{DT} - D_s + f + z(C_{DT} - C_M + D_s - f) + 2D_s y + yz(C_M - C_{DT} - 2D_s + f)]$, $J_2 = -x(x-1)[2D_s + z(C_M - C_{DT} - 2D_s + f)]$, $J_3 = -x(x-1)[C_{DT} - C_M + D_s - f + y(C_M - C_{DT} - 2D_s + f)]$, $J_4 = y(y-1)(\theta R_{pc} + h)$, $J_5 = (2y-1)(\theta R_p - I_p - h - zI_{pg} + x\theta R_{pc} + z\theta R_{pg} + xh)$, $J_6 = -y(y-1)(I_{pg} - \theta R_{pg})$, $J_7 = z(z-1)M_{DT}$, $J_8 = 0$, $J_9 = -(2z-1)(D_g + T_g - xM_{DT})$.

According to the first method of Lyapunov's stability test, the equilibrium point is an ESS if all eigenvalues of the Jacobi matrix have negative real parts. If at least one of the eigenvalues of the Jacobi matrix is positive, the equilibrium point is unstable. If the Jacobi matrix has an eigenvalue of 0 and the rest of the eigenvalues are negative, the equilibrium point is in a critical state and the stability cannot be determined by the sign of the eigenvalues. By substituting the eight pure strategy equilibrium points into the Jacobian matrix, the corresponding eigenvalues can be derived in Table 3.

<<<Insert Table 3>>>

Proposition 4. When $D_g + T_g < M_{DT}$ and $C_{DT} + D_s < C_M + f$, the only ESS point is $E_2(1,0,0)$ where energy enterprises use DT, PEs do not invest energy enterprises and governments do not support energy enterprises use DT.

Proposition 4 signifies that governments grants to support energy enterprises use DT are greater than the sum of the payments for environmental remediation and the social benefits of supporting energy enterprises use of DT. At the same time, the sum of cost reduction of energy enterprises using DT and the fines for environmental pollution are also greater than the cost of using DT and the governments grants to energy enterprises to reduce emissions. This represents energy enterprises use DT to improve their ESG performance when $x = 1$, PEs not invest energy enterprises when $y = 0$, the governments do not support energy enterprises use DT when $z = 0$. Energy enterprises using DT can receive additional governments grants, enhance ESG performance, and be exempt from fines. However, governments may limit support for DT due to its high expense. Since DT adoption can reduce expenses, reduce pollution, and improve ESG, energy enterprises are inclined to adopt it. PEs often reluctant to invest in new technologies due to the high costs and risks associated with them. Meanwhile, governments, while continuing to support market development, are also looking to reduce spending.

Proposition 5. When $C_{DT} > C_M + f$ and $\theta R_p - I_p + \theta R_{pc} - I_{pc} < h$, the only ESS point is $E_7(0,1,1)$ where energy enterprises do not use DT, PEs invest energy enterprises and governments support energy enterprises use DT.

Proposition 5 signifies that cost for energy enterprises using DT exceeds the sum DT reductions and penalties for environmental pollution. The sum of net profit $(\theta R_p - I_p)$ on PEs investments and net profit $(\theta R_{pg} - I_{pg})$ on investments based on policy direction is less than the reduction in return from PEs errors of judgment. This represents energy enterprises do not use DT to improve their ESG performance when $x = 0$, PEs invest energy enterprises when $y = 1$, the governments support energy enterprises use DT when $z = 1$. Due to high DT cost that outweigh potential returns, energy enterprises choose not to use DT. To promote sustainability and enhance ESG awareness, governments actively support the adoption of DT, which yields broader societal benefits. However, if enterprises avoid DT, PEs' judgments have erred. Because PEs is equity investments, it be difficult for PEs to make a quick exit decision. when performance lags. Nonetheless, adhering to the high-risk, high-return principle, PEs often hold shares long-term, anticipating future profit gains even if energy enterprises do not avoid DT.

5. NUMERICAL STUDY

5.1. Evolutionary convergence trajectory to ESS

In order to verify the effectiveness of the evolutionary stability analysis, we referred to the existing literature for the parameters of government subsidies and investment (Jiang *et al.*, 2023; Zhao *et al.*, 2023). At the same time, we refer to the explanation of DT, for the parameter setting of the costs and benefits of DT (Xiao and Zhang, 2025). Many places have relevant government subsidy policies. Science and Technology Bureau of Guangzhou Nansha Economic and Technological Development Zone provides high subsidies for science and technology, offering up to 10 million yuan in funding support for breakthrough project. We combine the actual situation to give the values of the variables for simulation analysis, so as to illustrate the process and results of the evolutionary game. The numerical settings are based on the model assumptions in Section 3, and numerical group 1 and numerical group 2 also follow the conditions in Proposition 4 and Proposition 5, respectively. Therefore, the numerical settings can be changed within the scope of the conditions without changing the final results. The numerical settings in this study are based on references to relevant literature and practical situations. For numerical group 1, let $I_g = 10, D_s = 5, R_c = 150, C_{DT} = 90, C_M = 75, f =$

$30, C_c = 70, T_c = 15, I_p = 60, R_p = 30, R_{pc} = 20, I_{pg} = 40, h = 35, R_{pg} = 20, M_{DT} = 30, D_g = 5, T_g = 10, \theta = 2.2$, which meets the conditions in Proposition 4. For numerical group 2, let $I_g = 10, D_s = 5, R_c = 150, C_{DT} = 110, C_M = 75, f = 20, C_c = 70, T_c = 15, I_p = 60, R_p = 30, R_{pc} = 20, I_{pg} = 40, h = 35, R_{pg} = 20, M_{DT} = 30, D_g = 5, T_g = 10, \theta = 2.2$ which meets the conditions in Proposition 5. The evolutionary trajectories of the proposed model for numerical group 1 are shown in Fig. 5, where all the $x - y - z$ curves converge at the same point $E_2(1,0,0)$. The results in Fig. 5 indicate that when the corresponding conditions are met, the equilibrium point is $E_2(1,0,0)$ regardless of the initial strategy probability combinations of the three stakeholders. Besides, Fig. 6 illustrates the evolutionary trajectories with the numerical group 2, all the $x - y - z$ curves converge at the same point $E_7(0,1,1)$. From the above results, we find that no matter what initial strategy probability the three stakeholders adopt, all curves will converge at ESS. Meanwhile, we also note that evolutionary results may be affected by cost and policies. Thus, the following sensitivity analysis is conducted to analyze the impact of different factors on the ESS.

<<<Insert Fig. 5>>>

<<<Insert Fig. 6>>>

5.2. Main factor sensitivity analysis

5.2.1. The impact of penalty of environmental pollution on tripartite game strategies

To describe the impact of penalty of environmental pollution (f factor) of three stakeholders under $E_2(1,0,0)$, let f =(21,27,33). Fig. 7 (a) shows that cover still converges to $E_2(1,0,0)$ under the influence of f. Fig. 7 (b) indicates that as f decrease, x converges to 0 more quickly, suggesting that enterprises tend to use DT. Fig. 7 (c) shows that the increase in f accelerates the trend of y approaching 0, indicating that PEs investment institutions are reluctant to invest in enterprises. Fig. 7 (d) reveals that as f increases, z converges to 0 faster. Meanwhile, combined with Fig. 7 (a), it can be seen that when y becomes 0, it can significantly speed up the rate at which z approaches 0.

<<<Insert Fig. 7>>>

The results indicate that high environmental penalties motivate enterprises to adopt DT to enhance ESG levels, demonstrating that penalties effectively drive ESG reform. Penalties impact enterprise performance and reputation, factors crucial to PEs investment decisions. When penalties are low, PEs may be more inclined to invest, yet often remain cautious due to future uncertainties and challenging exit mechanisms. Governments aim to raise ESG awareness and encourage energy enterprises to adopt new technologies but prefer minimal initial investment. Since penalties contribute to governments revenue, increased penalties can reduce governments support for ESG reform. On the other hand, due to the conservative strategy of PEs, the governments also choice to observe the practice of enterprises DT.

Fig. 8 (a) shows the influence of f on the evolution results under $E_7(0,1,1)$. Fig. 8 (b) reveals that as f decreases, x approaches 0 more rapidly, indicating that energy enterprises tend to choose not to implement DT. As can be seen from Fig. 8 (c), the smaller f is, the faster y approaches 1, which means PEs are more willing to choose investment. In Fig. 8 (d), it can be understood that as f decreases, z approaches 1 more quickly, suggesting that the governments are inclined to choose to support energy enterprises in using DT to improve their ESG levels.

<<<Insert Fig. 8>>>

The simulation results demonstrate that due to the high cost of enterprise deployment of DT, when environmental pollution penalties are reduced, enterprises would rather pay penalties than use DT to improve their ESG levels, as this would seriously affect enterprise earnings. Moreover, when penalties are small, the impact on enterprises performance is also minor. Therefore, PEs tend to seize the opportunity to invest in energy enterprises. The governments hope that enterprises can take the initiative to improve their ESG levels and reduce environmental pollution, rather than being forced to reform under high penalties. Thus, governments choose to support enterprises in adopting DT. However, due to immature technology and high deployment cost, enterprises remain hesitant to change.

5.2.2. The impact of cost of DT by energy enterprises on tripartite game strategies

Next, we discuss the impact of the cost of using DT technology C_{DT} =(85,90,95) by energy enterprises on three stakeholders. Fig. 9 (a) shows the evolution process of different C_{DT} values, which eventually converges to $E_2(1,0,0)$. In Fig. 9 (b), the smaller the C_{DT}, the faster the value of x approaches 1, indicating that energy enterprises will tend to use DT technology. In Fig. 9 (c), the smaller the C_{DT}, the faster the value of y approaches 0, meaning that investment institutions are reluctant to invest. Fig. 9 (d) shows that the smaller the C_{DT}, the faster the value of z converges to 0, indicating that the governments tend not to support enterprises in adopting DT technology.

<<<Insert Fig. 9>>>

This situation may occur in the early stages of DT adoption when market understanding is limited. With low DT deployment cost, energy enterprises are inclined to adopt it to improve ESG and reduce other expenses. However, PEs, focused on long-term stability, view low entry costs as a risk for increased competition, potentially affecting returns. PEs prefer investments that create industry barriers for sustained returns. Governments, seeking to improve ESG levels, are cautious about initial spending in this nascent market, often following PEs decisions. However, if enterprises are willing to change and the cost of adopting DT is high, the governments are also willing to support enterprises reform.

Fig. 10 (a) shows the evolution result of C_{DT} =(100,110,120) in different values still converge to point $E_7(0,1,1)$. Fig. 10 (b) shows that as C_{DT} increases, x approaches 0 faster, indicating that energy enterprises tend not to adopt DT technology. Fig. 10 (c) shows that as C_{DT} increases, the rate at which y approaches 1 also increases, meaning that PEs are more willing to invest in enterprises. Fig. 10 (d) describes that as C_{DT} increases, z also approaches 1 faster, indicating that the governments are willing to support enterprises in adopting DT technology.

<<<Insert Fig. 10>>>

From the numerical results, when the cost of deploying DT is high, energy enterprises also need to consider their operating and therefore choose not to adopt DT technology. PEs realize the development prospects of DT technology. Although the cost of use is high, they value long-term returns more and are therefore willing to invest in exchange for higher returns. The governments have a strong willingness to promote ESG and hopes to raise society's awareness of ESG. Generally, energy enterprises have a greater impact on the environment, and the governments are willing to help enterprises adopt new technologies to optimize the supply chain.

5.2.3. The impact of governments social gains on tripartite game strategies

The impact of T_g =(6,10,14) on evolution under $E_2(1,0,0)$ is also we need to consider. Fig. 11 (a) shows the evolution process of different T_g, which eventually all converge to $E_2(1,0,0)$. Fig. 11 (b) indicates that the smaller T_g is, the faster x approaches 1, indicating that enterprises are more willing to adopt DT technology. Fig. 11 (c) shows that when T_g becomes smaller, y approaches 0 slightly faster, but the change is not obvious. Fig. 11 (d) shows that when T_g becomes smaller, z approaches 0 faster, indicating that the governments are reluctant to support energy enterprises in using DT technology.

<<<Insert Fig. 11>>>

The above evolutionary results illustrate that T_g can reflects the market competition environment. A smaller governments social gains means that the technology is still in the early stage and has not attracted much attention. And this is a good opportunity for enterprises to establish technological barriers. Therefore, adopting DT to improve the supply chain at this time may have more advantages in future competitions. PEs pay more attention to the performance of enterprises. However, under uncertain future, PEs are more inclined to wait. The governments can obtain fewer social benefits, and the social awareness of ESG is still shallow. Naturally, it is unwilling to support energy enterprises in adopting DT technology.

Fig. 12 (a) shows the process in which T_g =(6,10,14) values converge to $E_7(0,1,1)$. Fig. 12 (b) shows that as T_g decreases, the speed at which x converges to 0 accelerates, but this process is not obvious, indicating that enterprises tend not to adopt DT technology. Fig. 12 (c) shows that as T_g decreases, y approaches 1 faster, but this change is also not significant, indicating that PEs is more willing to invest in enterprises. Fig. 12 (d) shows that as T_g increases, the speed at which z approaches 1 is faster, indicating that the governments are willing to support enterprises in adopting DT.

<<<Insert Fig. 12>>>

The above simulation results indicate that the governments' social gains have little impact on the decisions of energy enterprises and PEs. Energy enterprises pay more attention to enterprise performance. In this case, the cost of deploying DT technology is high and it will not expand revenue. Therefore, enterprises not choose to adopt DT. PEs investment is equity investment and cannot be easily withdrawn due to the special exit mechanism. Therefore, PEs can only continue to invest until there is an opportunity to exit. Due to the increase in society's ESG awareness and the increase in governments revenue, the governments are naturally willing to support the supply chain reform of energy enterprises.

6. CONCLUSION

6.1. Major finding

Energy enterprises primarily focus on profitability while facing significant challenges in enhancing their ESG performance. Their ability to transform core products, i.e., coal, oil, and electricity, is inherently constrained, and substantial capital investments are required for technological advancements. As a result, improving ESG performance remains a formidable challenge. However, environmental penalties and regulatory pressures can act as catalysts for change, compelling enterprises to adopt more sustainable practices. Therefore, in this paper, we investigate the optimal decision-making strategies of energy enterprises, governments, and PEs in the context of sustainable development. We then employ a tripartite evolutionary game model to analyze how the long-term behavior of each stakeholder in the energy enterprise supply chain impacts the system and to identify the equilibrium point. Additionally, numerical simulation analysis is utilized to demonstrate the effects of evolutionary stabilization strategies at different stabilization points for each participant. Additionally, we explore the impact of the main factors through sensitivity analysis, which ultimately leads to several key findings.

Our findings demonstrate that high DT implementation cost make energy enterprises more likely to pay pollution penalties than invest in technology, indicating that penalties effectively encourage ESG reforms. When environmental fines are low, PEs tend to invest, but they more conservative due to future uncertainties and challenging exit mechanisms. PEs' decisions often influence governments policy, which often aligns with PEs decisions. Lower DT cost makes enterprises more willing to adopt the technology, though this can attract competitors and prompt PEs, focused on long-term returns, to remain cautious or reluctant to invest. And when technology costs are high, governments make policy incentives to encourage enterprises to try new technologies in order to promote technological change and improve ESG. Given government backing for ESG improvements and the focus of PEs on long-term returns, enterprises facing technological barriers are more prone to encountering technological monopolies, thereby showing greater interest. In addition, governments' social returns reflect the market's reflection, which informs PEs' decisions. Lower social returns will consequently reduce the probability that PEs will choose to invest.

The key contributions of this study are as follows. While focusing on profitability, energy enterprises also need to undergo ESG transformation. Adjustments through DT can effectively enhance ESG performance but require substantial funding. PEs and governments can provide capital and policy support to boost long-term enterprise development and sustainable innovation. The social recognition of ESG, alongside supportive policies, can further facilitate PEs participation in ESG-driven investments. This, in turn, helps enterprises overcome technological bottlenecks and enhances the overall ESG performance of the energy sector. By examining the decision-making processes of multiple stakeholders including energy enterprises, PE investors, and policymakers, this study offers valuable insights into sustainable supply chain management. It contributes to a deeper understanding of how financial mechanisms, technological advancements, and regulatory frameworks interact to shape ESG-driven transformations in the energy industry.

In the context of sustainable development, ESG transformation necessitates collaborative efforts from all stakeholders. DT application can effectively enhance the performance of energy enterprises and achieve ESG transformation, but it also brings significant costs. This study offers theoretical support for decision-making by energy enterprises, PEs, and governments through an analysis of long-term dynamics. By examining the role of PEs investments in corporations, the study confirms the significant impact of ESG initiatives and provides a framework for future research on green investments. Additionally, it enriches research on ESG transformation and provides direction for future studies. While our research centers on the ESG transformation of energy enterprises, the scope of ESG transformation is by no means limited to this sector. Achieving sustainable development requires the collective efforts of all industries. Existing research has illustrated the significance of ESG investments within the manufacturing sector (Gu, 2024). Consequently, our study offers valuable insights for enterprises pursuing ESG transformation across various industries.

6.2. Managerial insights

Based on the key findings, this leads to several important management implications. First, due to the high cost of deploying DT, energy enterprises themselves are not willing to pay such a large cost to improve ESG. Instead, energy enterprises' products (e.g., oil, coal, etc.) are closely related to the environment, and improving ESG has become a top priority. For energy companies with insufficient funds, other solutions can be adopted to improve ESG levels to gain support from PEs or the government. When funds are sufficient, energy companies should use emerging technologies such as DT to improve the supply chain, establish industry barriers. Therefore, in order for energy enterprises to have incentives to develop new technologies, governments should appropriately increase penalties for environmental pollution, and at the same time give energy enterprises financial incentives in terms of ESG to promote ESG development. In addition, as an important non-financial metric, ESG provides PEs with a basis for investment. PEs can consider injecting capital into potential energy enterprises to increase their incentives to deploy DT. It helps energy enterprises to build technological barriers and dominate in a competitive market. This not only increases PEs returns, but also improves the ESG levels of enterprises and attracts more investors.

Society's ESG awareness also influences government policymaking. When societal ESG awareness is low, the government's social benefits are also reduced, making it less conducive for the government to support enterprises' sustainable development. Governments should therefore raise social awareness of ESG issues and encourage spontaneous change among the public and businesses through appropriate policies, such as green economy subsidies. The high cost of DT technologies should also be taken into account, and governments should encourage the development of new technologies to help enterprises tide over the difficulties in terms of policy and finance. Since PEs often remain cautious about emerging technologies, the government should take the lead, guide investment through policies to encourage investment and corporate technological development, and at the same time raise social ESG awareness.

6.3. Limitations and future studies

Although some conclusions have been drawn from the study of the energy supply chain, there are limitations have not been taken into account. In this paper, the impact of the distribution channel model of energy enterprises on the supply chain are not considered, and perhaps more discussion will be done in future work. Quantum computing can process data more efficiently and quickly, which also provides ideas for optimizing supply chain (Awan *et al.*, 2022). At the same time, PEs investments are also risky, and different investment institutions have different risk preferences, which can also be added to the model for further analysis in the future. In addition, ESG rating reports also have an impact on whether energy enterprises can get investment from PEs and also affect the investment decisions of PEs. However, there is insufficient quantitative research in this area, our analysis focuses solely on DT application, future work could leverage large language models to analyze how rating reports influence investment decisions within the energy sector. Based on this study, future research directions can be expanded. This study highlights the importance of green investments by PEs. Subsequent research might examine how green financing affects corporate behavior and performance.

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Table 1

Summary of the notation.

Symbol	Definition
Decision variables	
x	Probability of using DT by energy enterprises
y	Probability of PEs investment
z	Probability of governments support for energy enterprises to use DT
Parameters	
M_{DT}	The governments provide funds to be grants when energy enterprises use DT
I_g	To encourage PEs investment, the governments provided funds to energy enterprises
D_s	The governments provide funds for energy enterprises to improve ESG performance
D_g	Governments expenditure on environmental protection funds, when the governments do not support DT
T_g	The governments social gains for the result from supporting DT
R_c	The basic operation revenue of energy enterprises
C_{DT}	The cost of DT by energy enterprises
C_M	The save environmental protection cost of energy enterprises when use DT
I_p	The investment funds form PEs
f	The penalty of environmental pollution
C_c	The operating cost of energy enterprises
T_c	The energy enterprises lose the social reputation when PEs do not invest energy enterprises
R_p	The revenue of PEs from equity investments
R_{pc}	The additional revenue of PEs when energy enterprises use DT
I_{pg}	The additional investment funds from PEs
h	The PEs investment loss due to energy enterprises are not using DT
R_{pg}	The extra revenue of PEs due to additional investment
θ	Return rate on investment

Table 2

The payoff matrix of the tripartite decision.

Energy enterprises	**PEs**	**Governments**	
		Support enterprises use DT (z)	Not support enterprises use DT $(1-z)$
Using DT (x)	Invest energy enterprises (y)	$R_c - C_c - C_{DT} + C_M + I_p + I_{pg} + D_s + M_{DT} + I_g, \theta R_p - I_p + \theta R_{pc} - I_{pg} + \theta R_{pg}, T_g - D_s - M_{DT} - I_g$	$R_c - C_c - C_{DT} + C_M + I_p + D_s + I_g, \theta R_p - I_p + \theta R_{pc}, -D_s - D_g - I_g$
	Not invest energy enterprises $(1-y)$	$R_c - C_c - C_{DT} + C_M - T_c + D_s + M_{DT}, 0, T_g - D_s - M_{DT}$	$R_c - C_c - C_{DT} + C_M - T_c + D_s, 0, -D_s - D_g$
Not using DT $(1-x)$	Invest energy enterprises (y)	$R_c - C_c + I_p + I_{pg} - f + D_s + M_{DT} + I_g, \theta R_p - I_p - I_{pg} - h + \theta R_{pg}, T_g - D_s - I_g + f$	$R_c - C_c + I_p - f + I_g, \theta R_p - I_p - h, f - D_s - D_g - I_g$
	Not invest energy enterprises $(1-y)$	$R_c - C_c - f + D_s + M_{DT}, 0, T_g - D_s + f$	$R_c - C_c - f + D_s, 0, f - D_s - D_g$

Table 3

Local stability analysis of equilibrium points.

Equilibrium points	The eigenvalues of the Jacobi matrix				Local stability
E_i	λ_1	λ_2	λ_3	symbol	results
$E_1(0,0,0)$	$D_g + T_g$	$I_p - \theta R_p + h$	$C_M - C_{DT} - D_s + f$	$(+, \times, \times)$	Unstable point
$E_2(1,0,0)$	$D_g - M_{DT} + T_g$	$I_p - \theta R_p - \theta R_{pc}$	$C_{DT} - C_M + D_s - f$	$(\times, -, \times)$	Conditional ESS
$E_3(0,1,0)$	$D_g + T_g$	$\theta R_p - I_p - h$	$C_M - C_{DT} + D_s + f$	$(+, \times, +)$	Unstable point
$E_4(0,0,1)$	0	$-D_g - T_g$	$I_p + I_{pg} - \theta R_p - \theta R_{pg} + h$	$(0, -, +)$	Unstable point
$E_5(1,1,0)$	$\theta R_p - I_p + \theta R_{pc}$	$D_g - M_{DT} + T_g$	$C_{DT} - C_M - D_s - f$	$(+, \times, -)$	Unstable point
$E_6(1,0,1)$	0	$M_{DT} - D_g - T_g$	$I_p + I_{pg} - \theta R_p - \theta R_{pc} - \theta R_{pg}$	$(0, \times, \times)$	Unstable point
$E_7(0,1,1)$	$-D_g - T_g$	$C_M - C_{DT} + f$	$\theta R_p - I_{pg} - I_p + \theta R_{pg} - h$	$(-, \times, \times)$	Conditional ESS
$E_8(1,1,1)$	$M_{DT} - D_g - T_g$	$C_{DT} - C_M - f$	$\theta R_p - I_{pg} - I_p + \theta R_{pc} + \theta R_{pg}$	$(\times, -, +)$	Unstable point

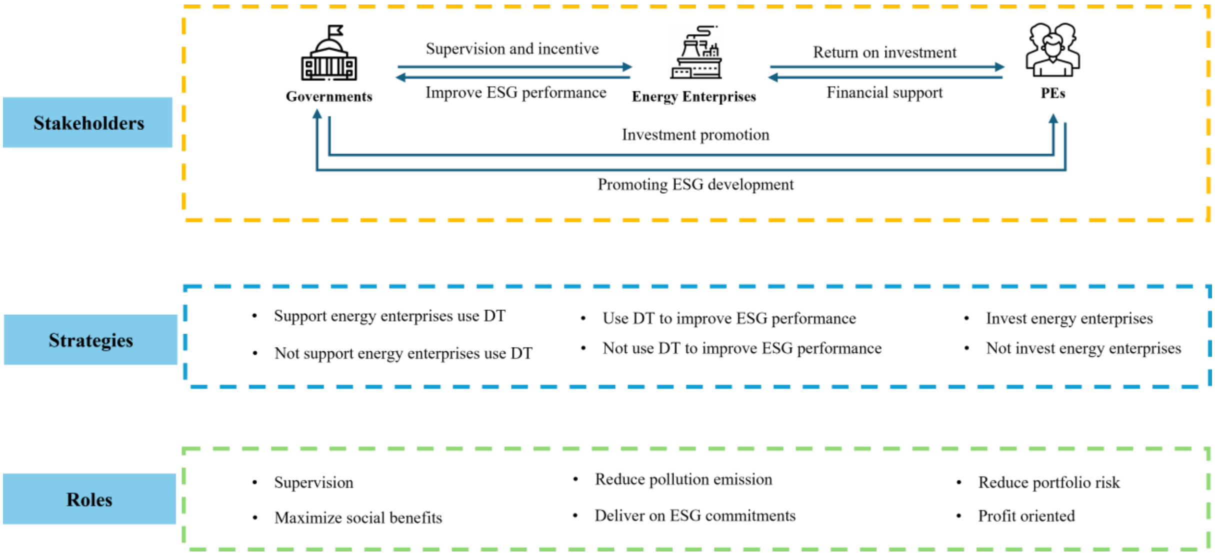


Fig. 1. Game relationships among three stakeholders

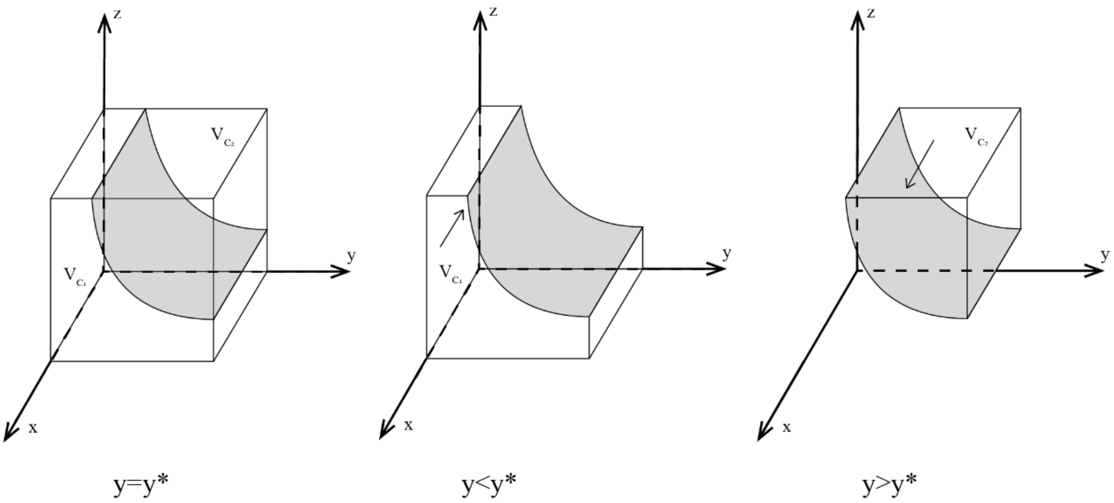
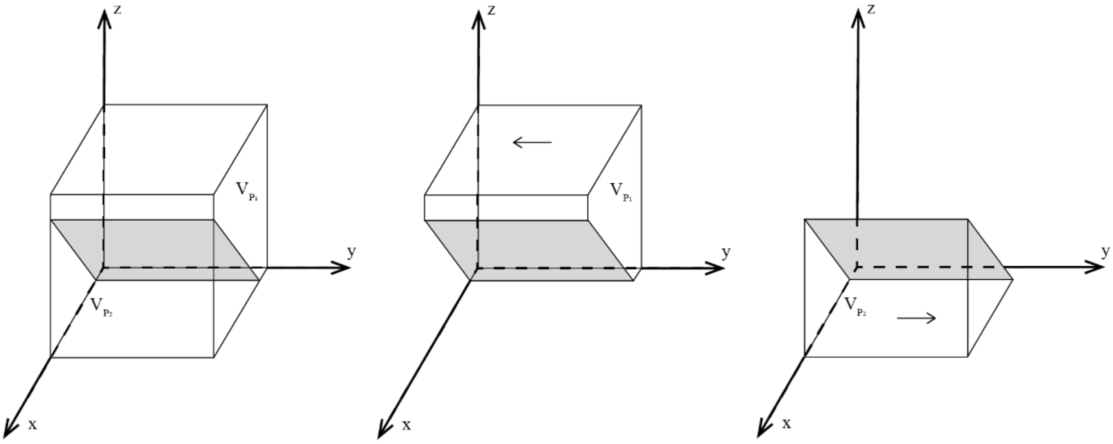
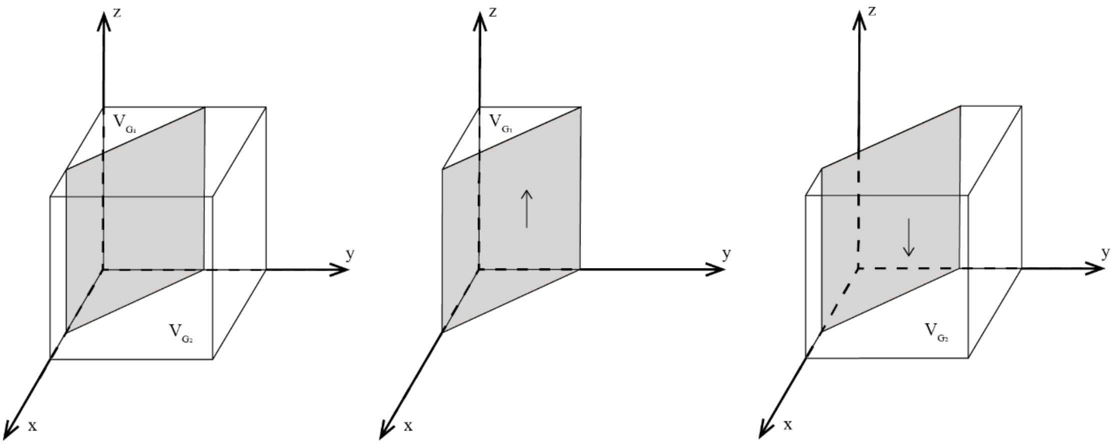


Fig. 2. Replicated dynamic phase diagram of energy enterprises



x=x* x<x* x>x*

Fig. 3. Replicated dynamic phase diagram of PEs



x=x* x<x* x>x*

Fig. 4. Replicated dynamic phase diagram of governments

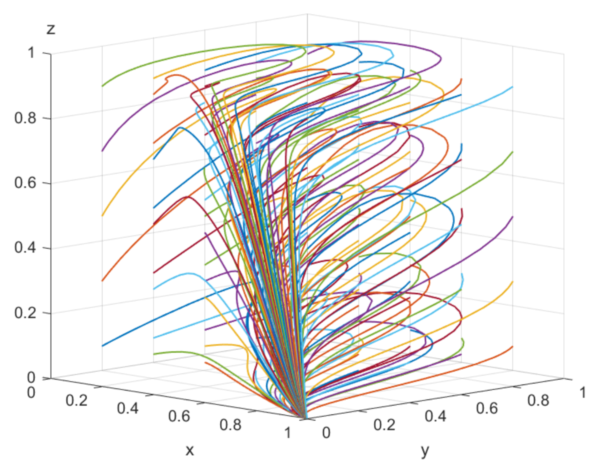


Fig. 5. Tripartite Strategy Evolutionary Trajectories at $E_2(1,0,0)$ (100 times)

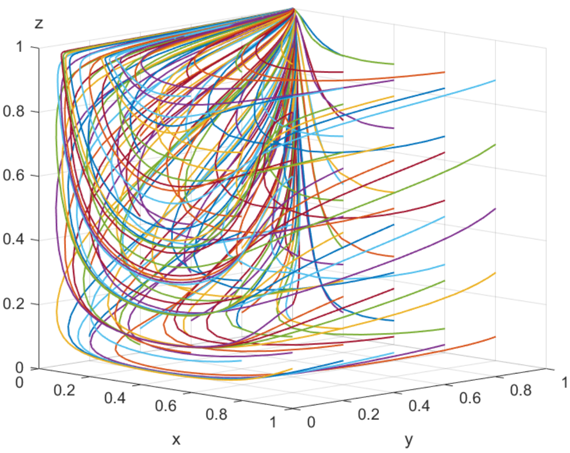
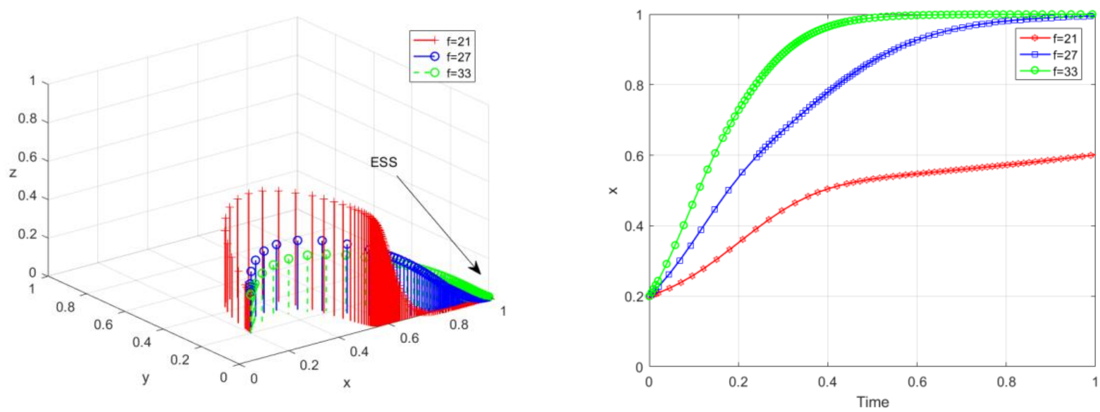
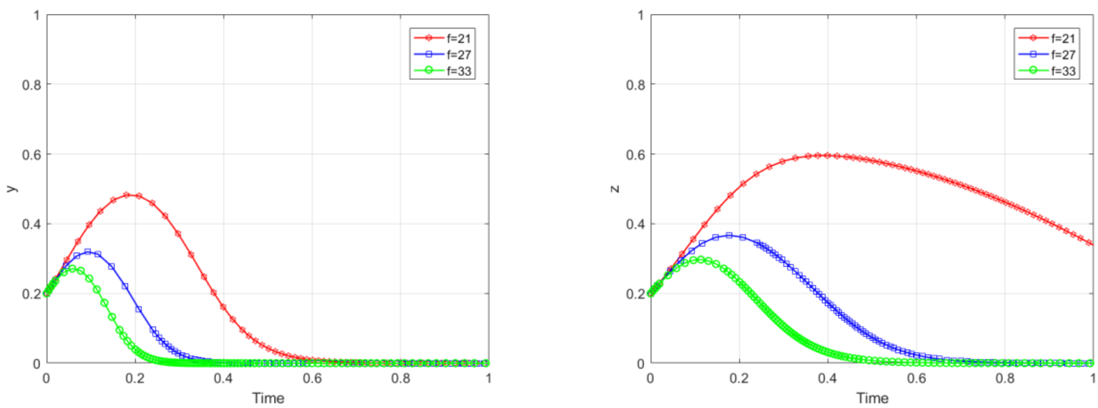


Fig. 6. Tripartite Strategy Evolutionary Trajectories at $E_7(0,1,1)$ (100 times)

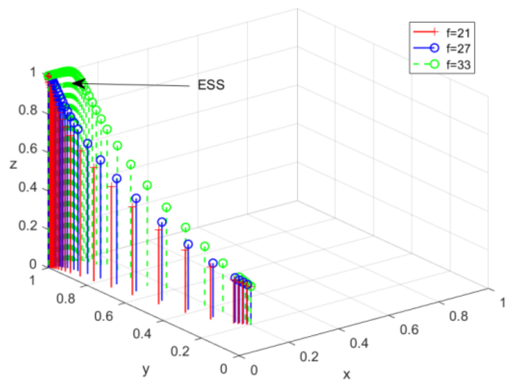


(a) (b)

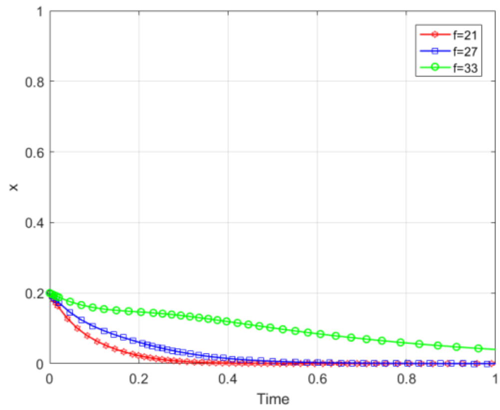


(c) (d)

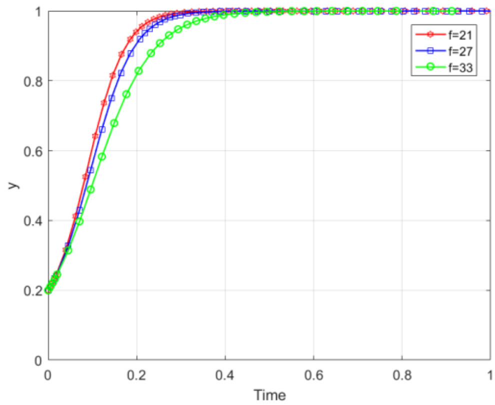
Fig. 7. The impact of f on $E_2(1,0,0)$



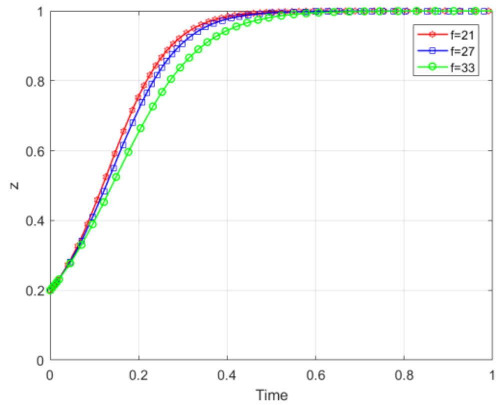
(a)



(b)



(c)



(d)

Fig. 8. The impact of f on $E_7(0,1,1)$

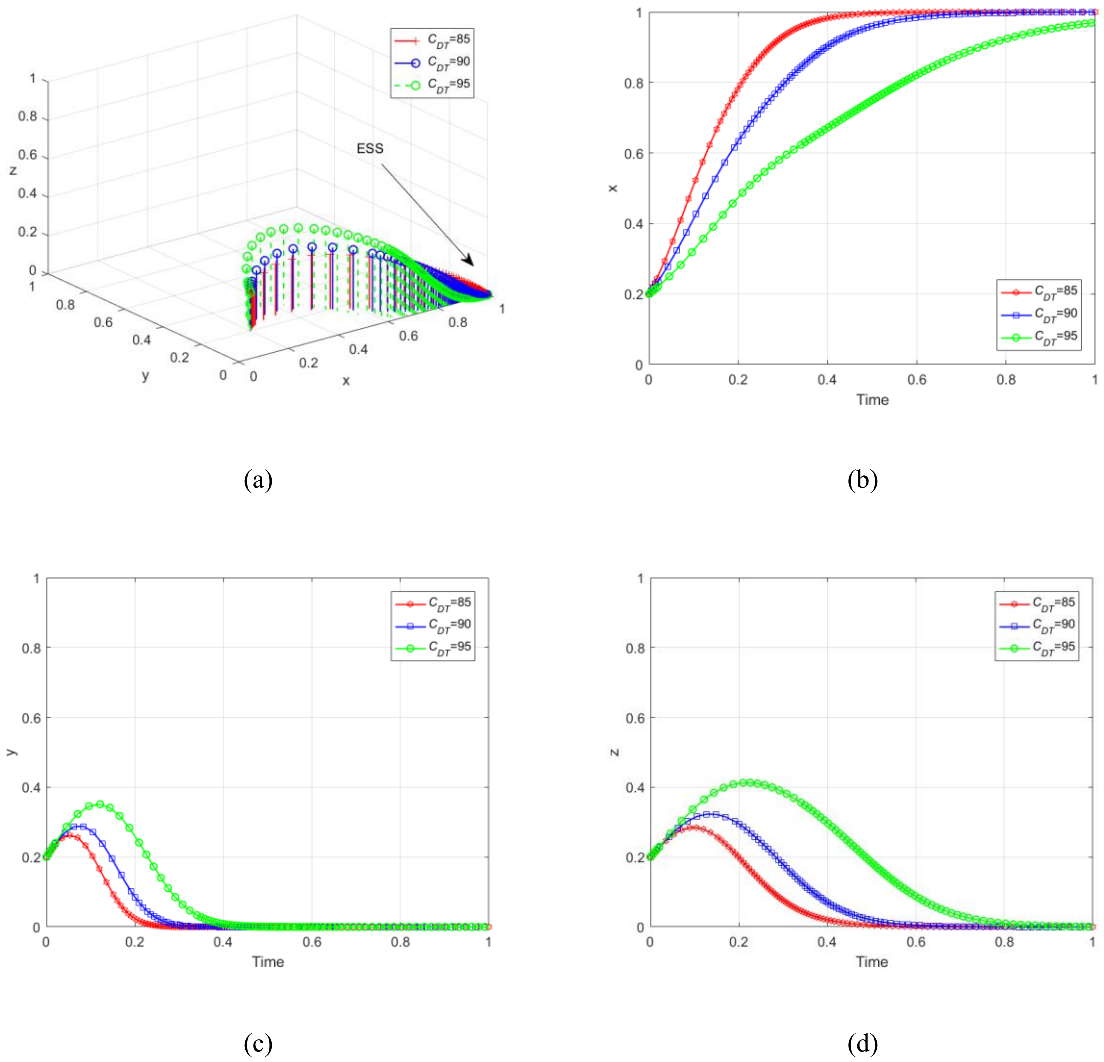
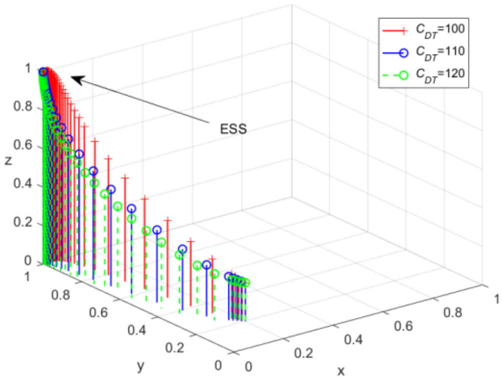
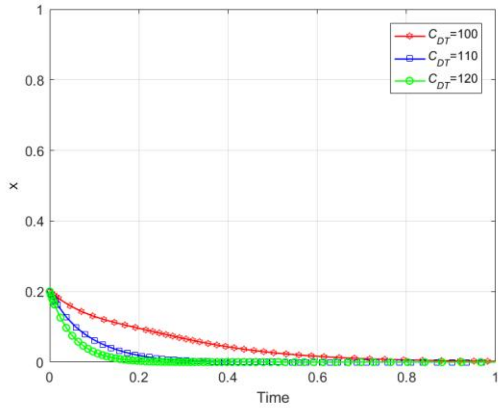


Fig. 9. The impact of C_{DT} on $E_2(1,0,0)$



(a)



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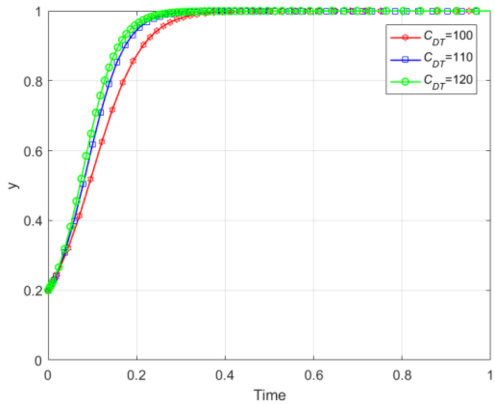
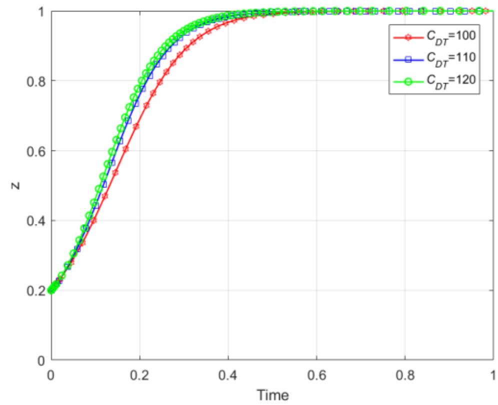


(c)



(d)

Fig. 10. The impact of C_{DT} on $E_7(0,1,1)$

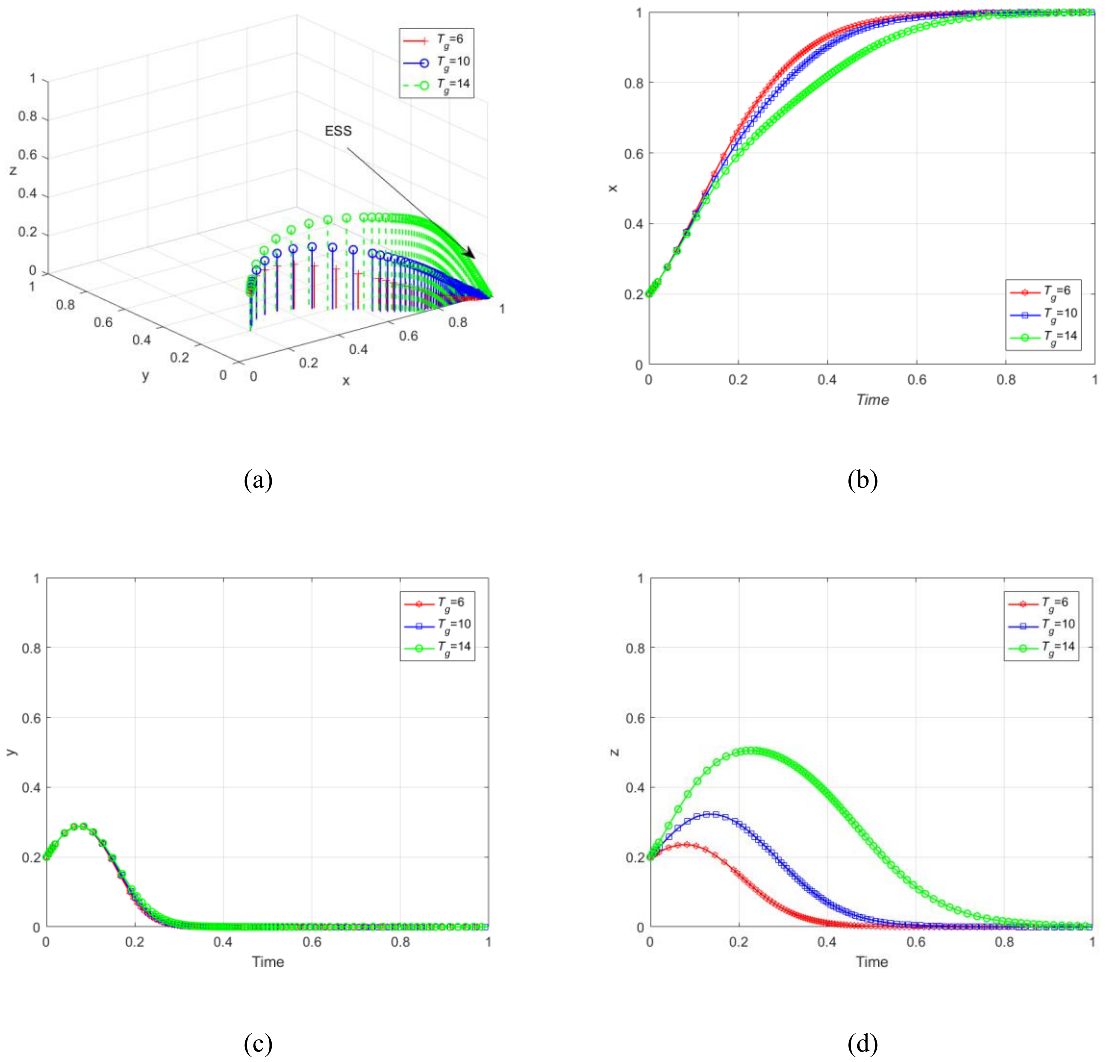


Fig. 11. The impact of T_g on $E_2(1,0,0)$

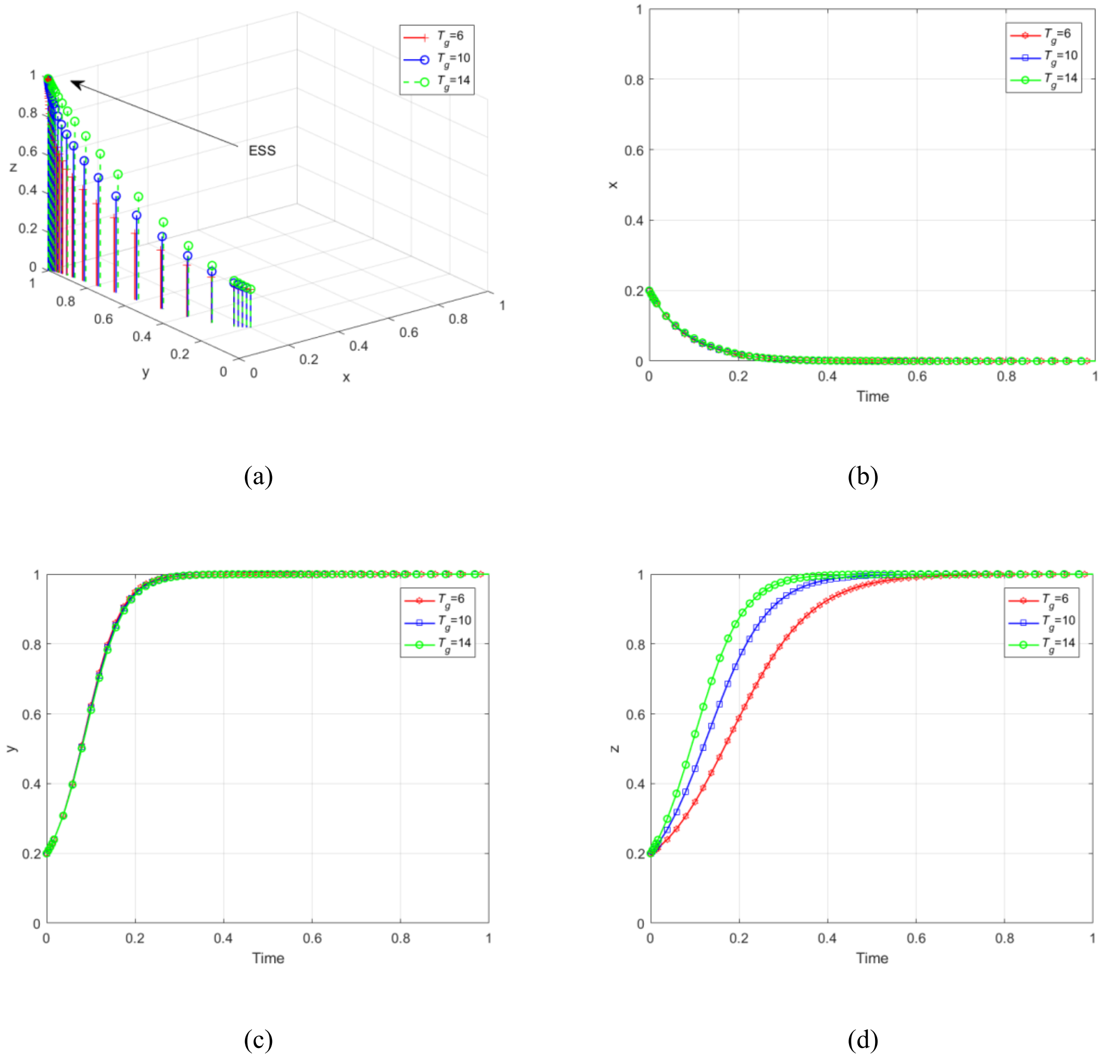


Fig. 12. The impact of T_g on $E_7(0,1,1)$

Appendix: Proof of propositions

Proof. of Proposition 1. According to the stability analysis of energy enterprises' strategies, when $G(y) < 0$, $y < y^*$, then $\frac{d(F(x))}{dx}|_{x=0} < 0$, which means that $x = 0$ (not using DT) is ESS of energy enterprises. Otherwise, $x = 1$ (using DT) is ESS of energy enterprises. Therefore, with the gradual increase of y or z, the stable strategy of energy enterprises moves from $x = 0$ to $x = 1$. The probability of not use DT by energy enterprises is denoted by C_1, volume is V_{C_1}. The probability of use DT by energy enterprises is denoted by C_2, volume is V_{C_2}.

Proof. of Proposition 2. According to the stability analysis of energy enterprises' strategies, when $x < x^*$, $H(x) > 0$, $\frac{d(F(y))}{dy}|_{y=0} < 0$, which means that $y = 0$ (not invest energy enterprises) is ESS of PEs. Otherwise, $y = 1$ (invest energy enterprises) is ESS of PEs. Therefore, with the gradual decrease of x or z the stable strategy of PEs moves from $y = 0$ to $y = 1$. The probability of not invest energy enterprises is denoted by P_1, volume is V_{P_1}. The probability of invest energy enterprises is denoted by P_2, volume is V_{P_2}.

Proof. of Proposition 3. According to the stability analysis of governments' strategies, when $x < x^*$, $K(x) < 0$, then $\frac{d(F(z))}{dz}|_{z=1} < 0$, which means that $z = 1$ (support energy enterprises use DT) is an ESS of governments. Otherwise, $z = 0$ (not support energy enterprises use DT) is an ESS of governments. Therefore, with the gradual decrease of x or z the stable strategy of governments moves from $z = 0$ to $z = 1$. The probability of not support energy enterprises use DT is denoted by G_1, volume is V_{G_1}. The probability of support energy enterprises use DT is denoted by G_2, volume is V_{G_2}.

Proof. of Proposition 4. As mentioned in the modelling part, $\theta R_p > I_p$, so that $I_p - \theta R_p - \theta R_{pc} < 0$. When $D_g + T_g < M_{DT}$ and $C_{DT} + D_s < C_M + f$, for $E_2(1,0,0)$, all the eigenvalues are negative, which is the only ESS point under this condition.

Proof. of Proposition 5. When $C_{DT} > C_M + f$ and $\theta R_p - I_p + \theta R_{pg} - I_{pg} < h$, for $E_7(0,1,1)$, all the eigenvalues are negative, which is the only ESS point under this condition.