

Article

Game Analysis on Energy Enterprises' Digital Transformation—Strategic Simulation for Guiding Role, Leading Role and Following Role

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Abstract: The aim of this study is to explore the dynamics and impediments in exploring the digital transformation process of energy enterprises, considering industry competition and government involvement. Compared with other industries, energy enterprises have both economic tasks and social responsibilities at the same time, while their business modes have certain “inertia”. Therefore, the process of their digital transformation cannot avoid the balance of interests between the different agents. From the perspective of competition and cooperation in the sector, this study constructs a tripartite evolutionary game model among the government and energy enterprises, analyzes the evolutionary stable strategies of the game system, and simulates different initial intentions and key parameters for all roles. The results show that in the process of digital transformation, the symbiotic relationship between energy enterprises and the cooperative relationship between enterprises and government can be embodied, and the effective game process has sufficient economic guidance. The government plays the guiding role in the digital transformation of energy enterprises, and its initial intention has a significantly stronger impact than the energy enterprise’s intentions. The effective strategy reflects the principle of “waiting for an opportunity to act, giving priority to efficiency, and giving consideration to justice”. Under the given policy environment, energy enterprises with comparative advantages in terms of transformation costs, direct benefits and synergy will become the leading role that is more sensitive to the opportunities of digital transformation, and the following energy enterprise will adjust its own strategies in time according to the effect of the leading role’s digital transformation so as to achieve the stability of the system. Accordingly, this study can provide reference support for energy enterprises to develop digital transformation strategies and for governments to formulate reasonable and effective policies.

Keywords: digital transformation; energy enterprises; government incentives; evolutionary game; numerical simulation

JEL Classification: C73; O31



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1. Introduction

The efficient integration of digital technology with the real economy has become a constant hot topic for governments, businesses and academia. Digital transformation has also become the core growth pole and a new engine to promote China’s economy to high-quality development [1]. According to the ‘White Paper on China’s Digital Economy Development (2021)’, during the 13th Five-Year Plan period, China’s digital industry developed rapidly and the total digital economy ranked second in the world, with the digital economy accounting for 38.6% of the national GDP. In 2022, the State Council issued the ‘14th Five-Year Plan for the Development of Digital Economy’ to accelerate the digital transformation of the energy sector and put the ‘digital construction and transformation of

equipment, facilities and industrial processes’ in all aspects and fields of the energy sector as one of the important tasks during the 14th Five-Year Plan.

The country has clearly defined the goal of developing ‘digital industry’ and ‘digital industrialisation’, and some local governments have intensively introduced a series of support policies. However, at present, the digitalization of energy enterprises in China is relatively low and the transformation process is slow, for the following reasons: On the one hand, the exploration of the value of energy data resources by enterprises is at the initial stage [2]. Some energy enterprises are slow in thinking about digital transformation and have a weak foundation for transformation, resulting in low willingness and low ability to transform [3]. On the other hand, the digital transformation of energy enterprises has significant externalities, and energy enterprises are ‘afraid’ of the uncertainty in the transformation process, especially in the absence of policy guidance. Energy enterprises do not have enough motivation to transform on their own [4]. Therefore, as the maker of industrial development policies and the guide of actions, the government should take the necessary guiding measures to promote the digital transformation of energy enterprises [5].

At present, relevant scholars have focused on the following three aspects of the research between government and enterprise digital transformation: first, through empirical, theoretical and review methods to explore the positive impact of digital transformation achieved at the medium and macro levels [6–8], most of the research on energy digital transformation focuses on the impact of digital transformation on energy security [9], energy efficiency [10] and carbon emissions [11]; second, through constructing cooperative game models to explore the possibility of how digital transformation can be carried out collaboratively among enterprises and the impact of key parameters on the digital transformation of enterprises [12]; thirdly, through methods such as evolutionary games to investigate the effect of government implementation of a specific policy on promoting enterprise transformation. In summary, although there is a wealth of research on government incentives for digital transformation, few scholars have considered the balance of interests between government and energy enterprises in digital transformation and the ‘effective range’ of incentives from an intra-industry competition perspective.

Based on this, this study explores the factors influencing the digital transformation of energy enterprises and the mechanisms and effects of policy incentives (subsidies and penalties) on the digital transformation of energy enterprises while balancing intra-organizational competition and government involvement. This study breaks through the limitations of previous research on the impact of policies on enterprise transformation itself and explores the effective scope and optimal intensity of incentive policies on the digital transformation of different energy enterprises, providing reference support for the government to formulate reasonable and effective policies to promote the digital transformation of energy enterprises.

2. Literature Review

With the construction of a new generation of digital infrastructure and the development of digital technology, data has become a key factor of production in the digital economy, being collected, stored and used for production on a large scale, contributing increasingly to economic growth and the improvement of people’s quality of life [6]. ‘Digitalization’ is the action, process and development of digital technology applications [13]. Digital transformation is the use of big data, blockchain, cloud technology, 5G, artificial intelligence and other new-generation digital technologies to reshape the main body’s strategy, vision, organizational structure, capabilities, processes and culture in order to adapt to the ever-changing digital economy [14,15]. The digital transformation of traditional industries is an important way to deepen structural reform on the supply side and achieve high-quality industrial development [16]. Energy enterprises are the direct executors of the digitalization of the energy industry, and their transformation ability and willingness to transform will directly affect the effectiveness of the digital transformation of the energy industry. Therefore, it is urgent to explore scientific, reasonable and cost-effective incentive

principles to promote the digital transformation of energy enterprises so as to effectively support the realization of the ‘energy saving and emission reduction’ strategy, the ‘energy security’ strategy, the ‘industrial digitalization’ goal and the ‘dual carbon’ goal from the bottom up.

At the enterprise level, under the trend of digital transformation, user value-led and alternative competition have become the fundamental forces driving the transformation of corporate goals and the innovation of governance structures [17,18]. The integration of resources becomes the bridge between digital capabilities and open innovation—enterprises promote the identification, acquisition, matching and utilization of digital resources through digital capabilities, which further empowers open innovation and drives the internal management mode of enterprises to become networked, modular and flexible [19]. At the industrial level, digital transformation promotes the networked, intelligent and collaborative development of the industrial value chain [20,21], and its value is reflected in industrial efficiency [22], industrial integration [23], organizational competition and upgrading [24]. In addition, digital transformation contributes to the improvement of total factor productivity [25] and can exert the empowering effect of digital resources and digital technology by improving the level of innovation capability [26–28], promoting technological progress [29], optimizing the human capital structure [30], and promoting the integration of advanced manufacturing and information technology [31,32]. In the general economic context, digital transformation can further increase the demand for human capital, which is a key factor for modern economic growth [33–36].

At present, domestic and foreign scholars have also conducted some studies on government involvement in the digital transformation of enterprises. Reducing costs, increasing revenues and encouraging innovation are the main ways in which digital transformation empowers enterprise development; among them, the policy effect of enterprise innovation is the most significant [37]. Jiang et al. (2022) argue that financial support from local governments is key to maintaining the vitality of the digital transformation of small and medium-sized enterprises [38]; Gong et al. (2022) found that the legal construction environment and financial science and technology expenditure have a facilitating effect on the digital transformation of enterprises, and the most significant effect is government financial expenditure [39]; Lin and Li (2023) construct an oligopoly game model in which R&D subsidies for firms whose product markets are set in the domestic market will promote transformation and upgrading [40]. Therefore, it can be seen that increasing government transfer payments and technological innovation R&D subsidies have a significant driving effect on the digital transformation of enterprises [41,42]. However, Zhou et al. (2022) also point out that while government subsidies can weaken information asymmetry and reduce the cost of innovation [43], inappropriate subsidy policies can create an inefficient pattern of social resource allocation, i.e., excessive subsidies and tax breaks not only do not promote the digital transformation of firms but may instead breed corporate laziness [44]. Therefore, the positive impact of policy subsidies on the digital transformation of enterprises exists within a ‘limited range’.

Analyzing the existing related studies, one is to explore the positive impacts of digital transformation achieved at micro and meso levels through empirical, theoretical and review methods, and the studies on energy digital transformation mostly focus on the impacts of digital transformation on economic and social issues such as energy security [45], energy efficiency [46], energy consumption [47] and carbon emissions [12]; the other is to explore the effects of government financial subsidies, reward and punishment policies and other means to promote enterprise transformation through the game and other methods, but few scholars consider the balance of benefits of different subjects in digital transformation from the perspective of intra-industry competition. To this end, this study explores the influencing factors of the digital transformation of energy enterprises and the mechanism and effect of policy incentives on the digital transformation of energy enterprises based on inter-firm competition and government participation. The marginal contributions of this study are in three aspects: first, using evolutionary game theory to explore the influencing

factors of the digital transformation process of energy enterprises from a microscopic perspective, combining it with simulations for verification, and enriching the relevant theories in the field of energy digitalization; Secondly, we comprehensively consider the internal and external environmental changes of energy enterprises' digital transformation, position government functions, consider the decision-making process of energy enterprises' digital transformation, and explore the evolutionary game model between government and multiple energy enterprises; thirdly, we break through the limitations of previous research on the impact of policies on enterprises' transformation itself, explore the effective interval and optimal intensity of incentive policies on the digital transformation of different energy enterprises, and provide reference support for the government to formulate reasonable and effective policies.

3. Game Model Building

The digital transformation of energy enterprises is a complex system-wide project. In the initial stage, the individual marginal benefits of digital transformation for energy enterprises will be smaller than the social marginal benefits, and without government incentives, energy enterprises will be reluctant to carry out digital transformation. At this point, if the government implements incentive policies to promote the digital transformation of energy enterprises, some enterprises will be the first to start their digital transformation strategies, and other enterprises will choose to compete or cooperate by referring to the digital transformation effects of other enterprises. As all participants are 'finite rational', they will be able to learn and adjust their strategies during the digital transformation process. For the purpose of analysis and without loss of generality, all actors are considered a group system. In the 'state of nature', there are two subgroups of enterprises (large-scale enterprises and small-scale enterprises), and one enterprise is randomly selected from each of the two subgroups, denoted as 'enterprise 1' and 'enterprise 2'. In this study, we construct a model of digital transformation for each enterprise. In this study, we construct an evolutionary game model for two energy firms and the government, as shown in Figure 1.

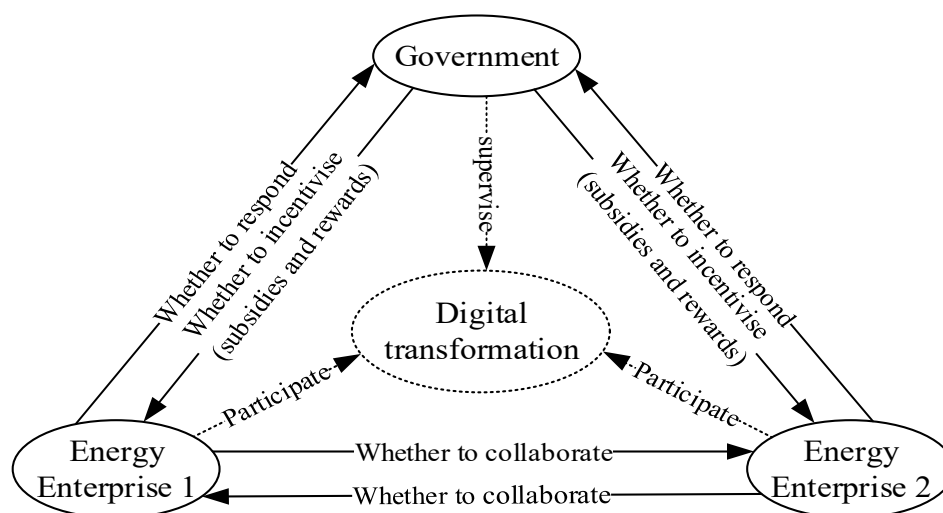


Figure 1. Tripartite evolutionary game logic of the government's participation in the digital transformation of energy enterprises.

3.1. Basic Assumptions

In order to construct a game model and analyze the strategic equilibrium point of each participant's stability and the relationship between the influence of the relevant elements, the following research hypotheses are made. The relevant parameters are set out in Table 1.

Table 1. Model parameters and meanings.

Gaming Subjects	Parameters	Meaning of Expression
Energy Enterprise 1	x	Probability that energy enterprise 1 is actively engaged in digital transformation
	π_1	Both energy enterprises 1 and 2 maintain the original technology and form of production and the benefits that energy enterprise 1 can obtain
	L_1	Energy enterprise 2 undergoes a digital transformation, resulting in losses suffered by energy enterprise 1 in maintaining its original technology and form of production
	R_1	Direct benefit gained by energy enterprise 1 after digital transformation
	β_1	Coefficient of synergistic benefit to energy enterprise 1 from collaborative digital transformation of energy enterprises
	C_1	The cost of digital transformation for energy enterprise 1
Energy Enterprise 2	y	Probability that energy enterprise 2 is actively engaged in digital transformation
	π_2	Both energy enterprise 1 and 2 maintain the original technology and form of production and the benefits that energy enterprise 2 can obtain
	L_2	Energy enterprise 1 undergoes a digital transformation, resulting in losses suffered by energy enterprise 2 in maintaining its original technology and form of production
	R_2	Direct benefit gained by energy enterprise 2 after digital transformation
	β_2	Coefficient of synergistic benefit to energy enterprise 2 from collaborative digital transformation of energy enterprises
	C_2	The cost of digital transformation for energy enterprise 2
Government	z	Probability of government incentives for the digital transformation of energy enterprises
	α	Coefficient of public benefit from government incentives for the digital transformation of energy companies
	C_g	The cost of implementing government incentives
	π_g	Additional social benefits to the government from the collaborative digital transformation of energy enterprises 1 and 2
	S	Government incentives to subsidize digitally transformed energy enterprises
	P	Government penalties for energy companies that fail to act on incentives

Hypothesis 1: In the process of digital transformation of energy enterprises, the strategy choice of both energy enterprises 1 and 2 is {transformation, no transformation}, and the strategy choice of the government is {incentive, no incentive}.

Hypothesis 2: The probability that energy enterprise 1 will undergo digital transformation is $x(0 \leq x \leq 1)$, and the probability that it will not undergo transformation is $1 - x$; the probability that energy enterprise 2 will undergo digital transformation is $y(0 \leq y \leq 1)$, and the probability that it will not undergo transformation is $(1 - y)$; the probability that the government will provide incentives to energy enterprises for digital transformation is $z(0 \leq z \leq 1)$, and the probability that it will not provide incentives is $(1 - z)$.

Hypothesis 3: If the production technology of energy enterprise 1 and energy enterprise 2 is given, the revenue of both can be defined as π_1 and π_2 , respectively ($\pi_i > 0$).

Hypothesis 4: Since digital technology can promote technological innovation, accelerate capital accumulation, and achieve higher factor productivity under the same conditions, energy enterprises that do not undergo digital transformation will face certain potential losses, such as reduced product competitiveness and market share; their potential losses are recorded as L_i ($i = 1, 2$; $L_i > 0$).

Hypothesis 5: The cost of digital transformation for energy enterprises is recorded as C_i ($i = 1, 2$; $C_i > 0$), including the investment in equipment replacement, digital talent training and digital capability enhancement; meanwhile, the direct benefit of digital transformation for energy enterprises is recorded as R_i ($i = 1, 2$; $R_i > 0$).

Hypothesis 6: The government introduced incentives to subsidize energy enterprises for digital transformation S_i ($i = 1, 2$; $S_i > 0$), and penalize energy enterprises that fail to act P_i ($i = 1, 2$; $P_i > 0$).

Hypothesis 7: If energy enterprises are incentivized by the government to increase the probability of digital transformation, this will inevitably lead to technological innovation, which in turn will contribute to more revenue by increasing product competitiveness or process efficiency; therefore, if the energy enterprises make digital transformation and earn higher revenue, they will have to pay the government a portion of the money in the form of taxes, and let the government revenue factor be $\alpha (0 < \alpha < 1)$. The cost of the government's incentive strategy is $C_g (C_g > 0)$, including the time, effort, and expense of building digital technology infrastructure, promoting digital transformation support for energy enterprises, and identifying and penalizing negative digital transformation energy enterprises.

Hypothesis 8: If both energy enterprises 1 and 2 choose the digital transformation strategy, a collaboration effect will be formed between them, e.g., the cost of transformation can be reduced by building a digital platform together. The benefit coefficient due to the collaboration is $\beta_i (i = 1, 2; \beta_i > 1)$; the additional social benefit brought by the collaboration of digital transformation among energy enterprises belongs to the government, which is recorded as $\pi_g (\pi_g > 0)$, e.g., ensuring stable energy supply, increasing local employment, etc.

3.2. Model Logic

Accordingly, according to the benefit maximization principle, the benefits of the government, energy enterprise 1, and energy enterprise 2 are analyzed, and a tripartite game payment matrix and benefit tree are given for the government's "incentive" and "no incentive", and the digital "transformation" and "no transformation" of energy enterprise 1 and energy enterprise 2 (Table 2 and Figure 2).

Table 2. Digital Transformation Decision Benefit Matrix of the Tripartite Game.

Government	Energy Enterprise 1	Energy Enterprise 2	
		Transformation y	No Transformation $1-y$
Incentive z	Transformation x	$\alpha(R_1 + R_2) + \pi_g - S_1 - S_2 - C_g$	$\alpha R_1 - S_2 + P_2 - C_g$
		$\beta_1 R_1 + S_1 - C_1$ $\beta_2 R_2 + S_2 - C_2$	$R_1 + S_1 - C_1$ $\pi_2 - L_2 - P_2$
	No transformation $1-x$	$\alpha R_2 - S_1 + P_1 - C_g$	$P_1 + P_2 - C_g$
		$\pi_1 - L_1 - P_1$ $R_2 + S_2 - C_2$	$\pi_1 - P_1$ $\pi_2 - P_2$
No incentive $1-z$	Transformation x	π_g $\beta_1 R_1 - C_1$ $\beta_2 R_2 - C_2$	$R_1 - C_1$ $\pi_2 - L_2$
		0	0
	No transformation $1-x$	$\pi_1 - L_1$ $R_2 - C_2$	π_1 π_2

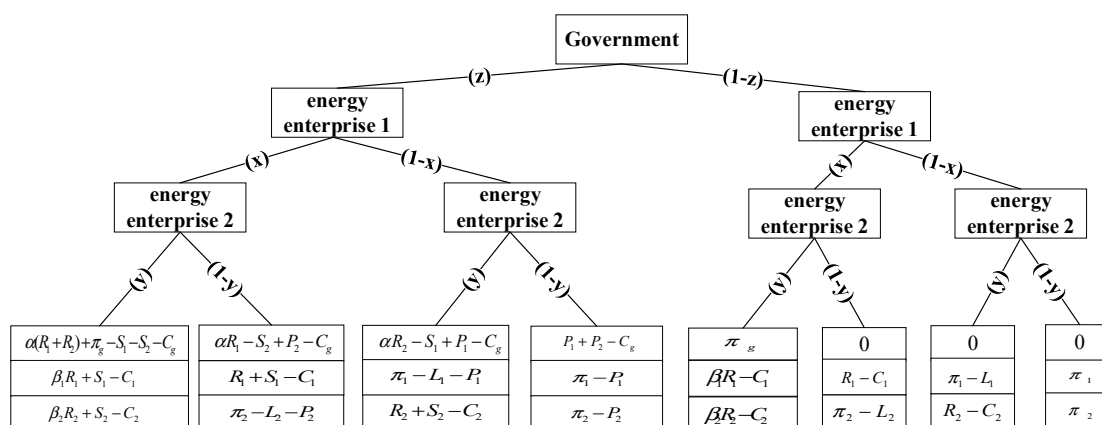


Figure 2. Revenue tree of a tripartite evolutionary game for digital transformation.

4. Evolutionary Game Analysis

4.1. Strategic Stability Analysis of Energy Enterprise 1

Let the expected benefits of “transformation” and “no transformation” of energy enterprise 1 be E_{1a} and E_{1b} , respectively, and their average expected benefits be $\bar{E}_1$. Let the expected benefits of “transformation” and “no transformation” of energy enterprise 1 be and, respectively, and their average expected benefits be, then:

$$E_{1a} = y\beta_1 R_1 + zS_1 - C_1 \quad (1)$$

$$E_{1b} = \pi_1 - zP_1 - yL_1 \quad (2)$$

$$\bar{E}_1 = xE_{1a} + (1-x)E_{1b} \quad (3)$$

Then the dynamic replication equation for energy enterprise 1 is:

$$\begin{aligned} F(x) &= \frac{dx}{dt} = x(E_{1a} - \bar{E}_1) \\ &= x(1-x)(y\beta_1 R_1 + zS_1 + zP_1 + yL_1 - \pi_1 - C_1) \end{aligned} \quad (4)$$

The first-order derivative of $F(x)$ is:

$$\frac{dF(x)}{dx} = (1-2x)(y\beta_1 R_1 + zS_1 + zP_1 + yL_1 - \pi_1 - C_1) \quad (5)$$

To facilitate the calculation, it is stipulated that:

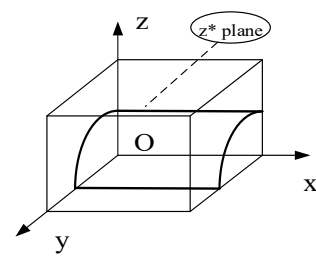
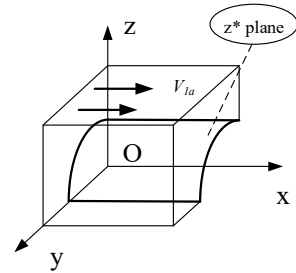
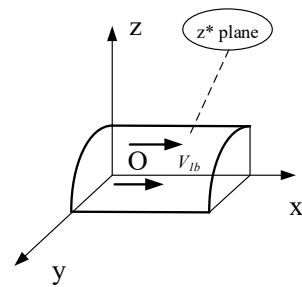
$$M(z) = y\beta_1 R_1 + zS_1 + zP_1 + yL_1 - \pi_1 - C_1 \quad (6)$$

Let $M(z) = 0$, and the solution obtained is the equilibrium point of the evolutionary game: $z^* = \frac{\pi_1 + C_1 - y(\beta_1 R_1 + L_1)}{S_1 + P_1}$. Due to $\frac{dM(z)}{dz} > 0$, $M(z)$ is an increasing function of z . When $z = z^* = \frac{\pi_1 + C_1 - y(\beta_1 R_1 + L_1)}{S_1 + P_1}$, $M(z) = 0$, namely $\frac{dF(x)}{dx} \equiv 0$. $F(x) \equiv 0$, at this point, the game is in steady-state regardless of the value of x . When $z \neq z^* = \frac{\pi_1 + C_1 - y(\beta_1 R_1 + L_1)}{S_1 + P_1}$, there are two equilibrium steady states of $x = 0$ and $x = 1$. When $z > z^* = \frac{\pi_1 + C_1 - y(\beta_1 R_1 + L_1)}{S_1 + P_1}$, $\frac{dF(x)}{dx}|_{x=0} > 0$, $\frac{dF(x)}{dx}|_{x=1} < 0$; at this point, $x = 1$ is the evolutionary stabilization strategy for energy enterprise 1. When $z < z^* = \frac{\pi_1 + C_1 - y(\beta_1 R_1 + L_1)}{S_1 + P_1}$, $\frac{dF(x)}{dx}|_{x=0} < 0$, $\frac{dF(x)}{dx}|_{x=1} > 0$; at this point, $x = 0$ is the evolutionary stabilization strategy for energy enterprise 1. The dynamic evolutionary path of energy enterprise 1 transformation is represented in a three-dimensional probabilistic coordinate system, as shown in Figure 3.

The probability x of digital transformation of energy enterprise 1 in Figure 3 is taken as the volume value V_{1a} , and the probability $(1-x)$ of no transformation is taken as the volume value V_{1b} . The calculation of the dual integral yields:

$$V_{1b} = \iint_{\substack{0 \leq x \leq 1 \\ 0 \leq y \leq 1}} \frac{\pi_1 + C_1 - y(\beta_1 R_1 + L_1)}{S_1 + P_1} dx dy = \frac{\pi_1 + C_1 - \frac{1}{2}(\beta_1 R_1 + L_1)}{S_1 + P_1} \quad (7)$$

$$V_{1a} = 1 - V_{1b} = 1 - \frac{\pi_1 + C_1 - \frac{1}{2}(\beta_1 R_1 + L_1)}{S_1 + P_1} \quad (8)$$

(a) $z = z^*$ Situation(b) $z > z^*$ Situation(c) $z < z^*$ Situation**Figure 3.** Phase diagram of dynamic evolution for the digital transformation of energy enterprise 1.

4.2. Strategic Stability Analysis of the Energy Enterprise 2

Let the expected benefits of “transformation” and “no transformation” of energy enterprise 2 be E_{2a} and E_{2b} , respectively, and their average expected benefits be $\bar{E}_2$.

$$E_{2a} = x\beta_2 R_2 + zS_2 - C_2 \quad (9)$$

$$E_{2b} = \pi_2 + zP_2 - xL_2 \quad (10)$$

$$\bar{E}_2 = yE_{2a} + (1 - y)E_{2b} \quad (11)$$

Then the dynamic replication equation for energy enterprise 2 is:

$$\begin{aligned} F(y) &= \frac{dy}{dt} = y(E_{2a} - \bar{E}_2) \\ &= y(1 - y)(x\beta_2 R_2 + zS_2 + zP_2 + xL_2 - \pi_2 - C_2) \end{aligned} \quad (12)$$

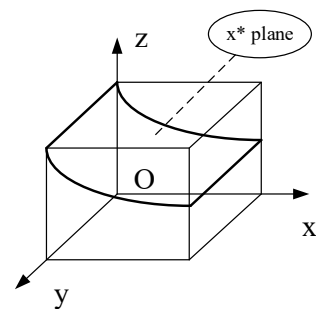
The first-order derivative of $F(y)$ is:

$$\frac{dF(y)}{dy} = (1 - 2y)(x\beta_2 R_2 + zS_2 + zP_2 + xL_2 - \pi_2 - C_2) \quad (13)$$

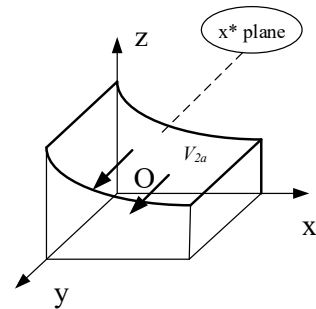
To facilitate the calculation, it is stipulated that:

$$H(x) = x\beta_2 R_2 + zS_2 + zP_2 + xL_2 - \pi_2 - C_2 \quad (14)$$

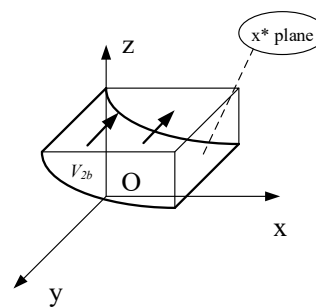
Let $H(x) = 0$, and the solution is the equilibrium point of the evolutionary game: $x^* = \frac{(\pi_2 + C_2) - (S_2 + P_2)z}{\beta_2 R_2 + L_2}$. Due to $\frac{d[H(x)]}{dx} > 0$, $H(x)$ is an increasing function of x . When $x = x^* = \frac{(\pi_2 + C_2) - (S_2 + P_2)z}{\beta_2 R_2 + L_2}$, $H(x) = 0$, namely $\frac{dF(y)}{dy} \equiv 0$. $F(y) \equiv 0$, at this point, the game is stable regardless of the value of y . When $x \neq x^* = \frac{(\pi_2 + C_2) - (S_2 + P_2)z}{\beta_2 R_2 + L_2}$, there are two equilibrium steady states of $y = 0$ and $y = 1$, as follows: When $x > x^* = \frac{(\pi_2 + C_2) - (S_2 + P_2)z}{\beta_2 R_2 + L_2}$, $\frac{dF(y)}{dy}|_{y=0} > 0$, $\frac{dF(y)}{dy}|_{y=1} < 0$. At this point, $y = 1$ is the evolutionary stabilization strategy for energy enterprise 2. Similarly, When $x < x^* = \frac{(\pi_2 + C_2) - (S_2 + P_2)z}{\beta_2 R_2 + L_2}$, $\frac{dF(y)}{dy}|_{y=0} < 0$, $\frac{dF(y)}{dy}|_{y=1} > 0$. At this point, $y = 0$ is the evolutionary stabilization strategy for energy enterprise 2. The dynamic evolutionary path of digital transformation of energy enterprise 2 is represented in a three-dimensional probabilistic coordinate system, as shown in Figure 4.



(a) $x = x^*$ Situation



(b) $x > x^*$ Situation



(c) $x < x^*$ Situation

Figure 4. Phase diagram of dynamic evolution for the digital transformation of energy enterprise 2.

The probability y of digital transformation of energy enterprise 2 in Figure 4 is taken as the volume value V_{2a} , and the probability $(1 - y)$ of no transformation is taken as the volume value V_{2b} . The calculation of the dual integral yields:

$$V_{2b} = \int_0^1 \int_0^1 \frac{(\pi_2 + C_2) - (S_2 + P_2)z}{\beta_2 R_2 + L_2} dz dy = \frac{(\pi_2 + C_2) - \frac{1}{2}(S_2 + P_2)}{\beta_2 R_2 + L_2} \quad (15)$$

$$V_{B1} = 1 - V_{B2} = 1 - \frac{(\pi_2 + C_2) - \frac{1}{2}(S_2 + P_2)}{\beta_2 R_2 + L_2} \quad (16)$$

Inference 1. The willingness of energy enterprise 1 to embrace digital transformation and the strength of government incentives have a positive effect on the choice of the digital transformation strategy for energy enterprise 2.

Proof. When the initial strategy of energy enterprise 1 is in V_{1a} space, $z > z^* = \frac{\pi_1 + C_1 - y(\beta_1 R_1 + L_1)}{S_1 + P_1}$; the equilibrium strategy is $x = 1$, that is, when the willingness of energy enterprise 2 to digital transformation or the degree of government incentives both increase, energy enterprise 1 cannot sustain itself profitably by maintaining its original technology for production due to external policy support and internal market competition; in order to seek to maximize economic benefit, it will eventually prefer digital transformation. Therefore, the stabilization strategy of energy enterprise 1 gradually evolves from $x = 0$ to $x = 1$ as y and z gradually increase. Energy enterprise 2 is evidenced by the same reason. $\square$

Inference 2. Increasing the benefits and reducing the costs of digital transformation can increase the probability of digital transformation for energy enterprises.

Proof. Obtain the first-order partial derivative of the parameter R_1 in the digital transformation probability V_{1a} for energy enterprise 1: $\frac{d(V_{1a})}{d(R_1)} = \frac{\beta_1}{2(S_1 + P_1)}$, there exists $\frac{d(V_{1a})}{d(R_1)} > 0$; therefore, V_{1a} is a monotonically increasing function of R_1 . Obtain the first order partial derivative of the parameter C_1 for the probability V_{1a} of digital transformation of energy enterprise 1: $\frac{\delta(V_{1a})}{\delta(C_1)} = -\frac{1}{2(S_1 + P_1)}$, there exists $\frac{\delta(V_{1a})}{\delta(C_1)} < 0$; therefore, V_{1a} is a monotone decreasing function of C_1 . As R_1 increases, the V_{1b} volume gradually decreases and the V_{1a} volume gradually increases. When C_1 increases, the V_{1b} volume gradually increases and the V_{1a} volume gradually decreases, i.e., the probability of digital transformation of energy enterprise 1 is negatively related to the cost of digital transformation and positively related to the benefit of digital transformation. The same can be proved for energy enterprise 2. $\square$

Inference 3. Improving the digital transformation cooperative coefficient can boost the probability of digital transformation of energy enterprises.

Proof. Obtain the first-order partial derivative of parameter β_1 in the digital transformation probability V_{1a} for energy enterprise 1: $\frac{\delta(V_{1a})}{\delta(\beta_1)} = \frac{R_1}{2(S_1 + P_1)}$, there exists $\frac{\delta(V_{1a})}{\delta(\beta_1)} > 0$; therefore, V_{1a} is a monotonically increasing function of β_1 . When β_1 increases, the volume of V_{1b} gradually decreases and the volume of V_{1a} gradually increases, i.e., increasing β_1 can promote the probability of the digital transformation of energy enterprise 1. The same can be proved for energy enterprise 2. $\square$

Inference 4. When $(\pi_1 + C_1) > \frac{\beta_1 R_1 + L_1}{2}$ increasing the government penalty will have a positive impact on the digital transformation of energy enterprises.

Proof. Obtain the first-order partial derivative of parameter S_1 in the digital transformation probability V_{1a} for energy enterprise 1: $\frac{\delta V_{1a}}{\delta(S_1)} = \frac{(\pi_1 + C_1) - (\beta_1 R_1 + L_1)/2}{(S_1 + P_1)^2}$. When $(\pi_1 + C_1) > \frac{\beta_1 R_1 + L_1}{2}$, there exists $\frac{\delta V_{1a}}{\delta(S_1)} > 0$. At this point, V_{1a} is a monotonically increasing function of S_1 . The same can be demonstrated for energy enterprise 2. Faced with increasing penalties, each energy enterprise cannot gain benefits by maintaining the original technology production and starting to experiment with digital transformation strategies, i.e., increasing penalties can increase the energy enterprises' willingness to embrace digital transformation. $\square$

4.3. Strategic Stability Analysis of the Government

Let the expected benefits of government incentives for the digital transformation of energy firms be E_{ga} , the expected benefits of no incentives E_{gb} , and their average expected benefits $\bar{E}_g$, then:

$$E_{ga} = \alpha(R_1x + R_2y) + (1 - y)P_2 + (1 - x)P_1 + xy\pi_g - C_g \quad (17)$$

$$E_{gb} = xy\pi_g \quad (18)$$

$$\bar{E}_g = zE_{ga} + (1 - z)E_{gb} \quad (19)$$

Then the dynamic replication equation for the government is:

$$\begin{aligned} F(z) &= \frac{dz}{dt} = z(E_{ga} - \bar{E}_g) \\ &= z(1 - z)[\alpha(xR_1 + yR_2) + (1 - y)P_2 + (1 - x)P_1 - xS_1 - yS_2] - C_g \end{aligned} \quad (20)$$

The first-order derivative of $F(z)$ is:

$$\frac{dF(z)}{dz} = (1 - 2z)[(\alpha R_1 - P_1 - S_1)x + (\alpha R_2 - P_2 - S_2)y + P_1 + P_2 - C_g] \quad (21)$$

To facilitate the calculation, it is stipulated that:

$$G(y) = (\alpha R_1 - P_1 - S_1)x + (\alpha R_2 - P_2 - S_2)y + P_1 + P_2 - C_g \quad (22)$$

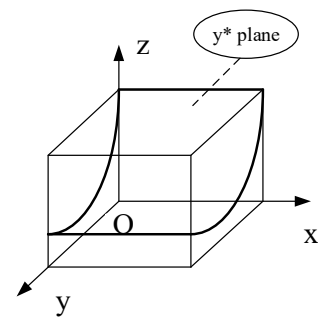
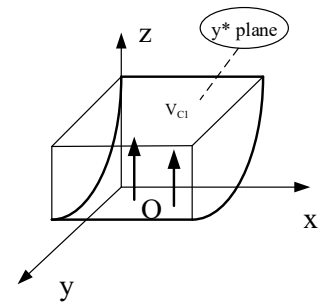
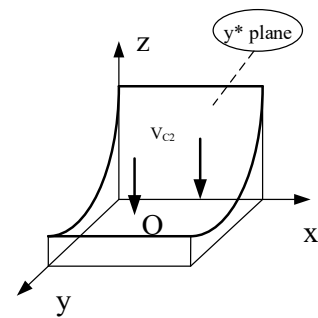
Let $G(y) = 0$, the solution is the equilibrium point of the evolutionary game: $y^* = \frac{C_g - x(\alpha R_1 - P_1 - S_1) - (P_1 + P_2)}{\alpha R_2 - P_2 - S_2}$.

When $y = y^* = \frac{C_g - x(\alpha R_1 - P_1 - S_1) - (P_1 + P_2)}{\alpha R_2 - P_2 - S_2}$, there exists $G(y) = 0$, namely $\frac{dF(z)}{dz} \equiv 0$. $F(z) \equiv 0$, at this point, the game is in steady-state regardless of the value of z . When $y \neq y^* = \frac{C_g - x(\alpha R_1 - P_1 - S_1) - (P_1 + P_2)}{\alpha R_2 - P_2 - S_2}$, it is divided into the following two cases:

Case 1: When $\alpha R_2 - P_2 - S_2 > 0$, there exists $\frac{dG(y)}{dy} > 0$; therefore, $G(y)$ is an increasing function of y . When $y > y^* = \frac{C_g - x(\alpha R_1 - P_1 - S_1) - (P_1 + P_2)}{\alpha R_2 - P_2 - S_2}$, there exists $\frac{dF(z)}{dz}|_{z=0} > 0$ and $\frac{dF(z)}{dz}|_{z=1} < 0$. At this point, $z = 1$ is the probability of the government's strategy. When $y < y^* = \frac{C_g - x(\alpha R_1 - P_1 - S_1) - (P_1 + P_2)}{\alpha R_2 - P_2 - S_2}$, exists $\frac{dF(z)}{dz}|_{z=0} < 0$ and $\frac{dF(z)}{dz}|_{z=1} > 0$, at this point $z = 0$ is the probability of the government's strategy.

Case 2: When $\alpha R_2 - P_2 - S_2 < 0$, there exists $\frac{dG(y)}{dy} < 0$. Therefore, $G(y)$ is a decreasing function of y . When $y > y^* = \frac{C_g - x(\alpha R_1 - P_1 - S_1) - (P_1 + P_2)}{\alpha R_2 - P_2 - S_2}$, there exists $\frac{dF(z)}{dz}|_{z=0} < 0$ and $\frac{dF(z)}{dz}|_{z=1} > 0$. At this point, $z = 0$ is the probability of the government's strategy. When $y < y^* = \frac{C_g - x(\alpha R_1 - P_1 - S_1) - (P_1 + P_2)}{\alpha R_2 - P_2 - S_2}$, there exists $\frac{dF(z)}{dz}|_{z=0} > 0$ and $\frac{dF(z)}{dz}|_{z=1} < 0$. At this point, $z = 1$ is the probability of the government's strategy.

The dynamic evolutionary path of government incentives in a three-dimensional probabilistic coordinate system is shown in Figure 5.

(a) $y = y^*$ situation(b) $y > y^*$ situation(c) $y < y^*$ situation**Figure 5.** Phase diagram of the dynamic evolution of government incentives.

The probability z of government incentives in Figure 5 is taken as the volume value V_{ga} , and the probability $(1 - z)$ of no incentives is taken as the volume V_{gb} . The calculation of the dual integral yields:

$$V_{gb} = \int_0^1 \int_0^1 \frac{C_g - x(\alpha_1 R_1 - P_1 - S_1) - (P_1 + P_2)}{\alpha_2 R_2 - P_2 - S_2} dz dx = \frac{C_g - \frac{\alpha_1 R_1 - S_1}{2} - \left(\frac{1}{2}P_1 + P_2\right)}{\alpha_2 R_2 - P_2 - S_2} \quad (23)$$

$$V_{ga} = 1 - V_{gb} = 1 - \frac{C_g - \frac{\alpha_1 R_1 - S_1}{2} - \left(\frac{1}{2}P_1 + P_2\right)}{\alpha_2 R_2 - P_2 - S_2} \quad (24)$$

Inference 5. When $\alpha_1 R_1 - P_1 - S_1 > 0$ and $\alpha_2 R_2 - P_2 - S_2 > 0$, the government incentive strategy is related to the willingness of energy enterprise 1 and energy enterprise 2 to transform.

Inference 6. When $\alpha_1 R_1 - P_1 - S_1 > 0$ and $\alpha_2 R_2 - P_2 - S_2 > 0$, the larger P or smaller S , the greater the willingness of the government to provide incentives and vice versa.

Proof. When $\alpha R_1 - P_1 - S_1 > 0$ and $\alpha_2 R_2 - P_2 - S_2 > 0$, there exists $\frac{dG(y)}{dx} > 0$ and $\frac{dG(y)}{dy} > 0$; therefore, $G(y)$ is an increasing function to x and y . Thus, the government's incentive strategy is positively related to the willingness of energy enterprise 1 and 2 to transform. Obtain the first-order partial derivatives of the parameters S_1 and P_1 in the probability V_{ga} of government incentives: $\frac{\delta(V_{ga})}{\delta(S_1)} = -\frac{1}{2(\alpha_2 R_2 - P_2 - S_2)}$, $\frac{\delta(V_{ga})}{\delta(P_1)} = \frac{1}{2(\alpha_2 R_2 - P_2 - S_2)}$. When $\alpha_2 R_2 - P_2 - S_2 > 0$, there exists $\frac{\delta(V_{ga})}{\delta(S_1)} < 0$ and $\frac{\delta(V_{ga})}{\delta(P_1)} > 0$, that is, V_{ga} is the increasing function of P_1 and is the decreasing function of S_1 . Similarly, V_{ga} is an increasing function of P_2 and a decreasing function of S_2 . Inference 5 and Inference 6 show that there is a difference between the synergistic benefit of digital transformation of energy enterprises and the penalties for enterprises that do not transform. When the government gives small subsidies to energy enterprises that are smaller than the difference, the government will choose the incentive strategy. Conversely, a larger subsidy must be provided before the government will choose the incentive, which is not consistent with the principle of a rational policy decision at this point. $\square$

4.4. Stability Analysis of System Equilibrium Points

It follows that, in terms of digital transformation, the tripartite evolutionary game model between the government and energy enterprises can be represented by the three-dimensional dynamical system D .

$$D = \left\{ \begin{array}{l} F(x) = \frac{dx}{dt} = x(1-x)(y\beta_1 R_1 + zP_1 + zS_1 + yL_1 - \pi_1 - C_1) \\ F(y) = \frac{dy}{dt} = y(1-y)(x\beta_2 R_2 + zP_2 + zS_2 + xL_2 - \pi_2 - C_2) \\ F(z) = \frac{dz}{dt} = z(1-z)[\alpha(x\beta_1 R_1 + y\beta_2 R_2) + (1-y)P_2 + (1-x)P_1 - (xS_1 + yS_2) - C_g] \end{array} \right\} \quad (25)$$

Based on replication dynamical system D , let $F(x) = F(y) = F(z) = 0$. Then, we obtain eight pure strategy equilibrium points: $E1(0,0,0)$, $E2(0,0,1)$, $E3(0,1,0)$, $E4(0,1,1)$, $E5(1,0,0)$, $E6(1,0,1)$, $E7(1,1,0)$ and $E8(1,1,1)$. Drawing on the differential stability discriminant utilized by Federson et al. (2019) and Reinhard (1980) in their studies, when all eigenvalues of the Jacobian matrix are negative, the corresponding equilibrium point is the evolutionarily stable strategy (ESS) point of the system D [48,49], otherwise it is an unstable point, where it is a saddle point when there are zero eigenvalues. Solving the eigenvalues of the Jacobian matrix corresponding to each equilibrium point in order to analyze its stability, the calculation procedure and results of the eigenvalues of the Jacobian matrix are shown in Equation (26).

$$J = \begin{pmatrix} \frac{\delta F(x)}{\delta x} & \frac{\delta F(x)}{\delta y} & \frac{\delta F(x)}{\delta z} \\ \frac{\delta F(y)}{\delta x} & \frac{\delta F(y)}{\delta y} & \frac{\delta F(y)}{\delta z} \\ \frac{\delta F(z)}{\delta x} & \frac{\delta F(z)}{\delta y} & \frac{\delta F(z)}{\delta z} \end{pmatrix} = \begin{pmatrix} (1-2x)(y\beta_1 R_1 + zP_1 + zS_1 + yL_1 - \pi_1 - C_1) & x(1-x)(\beta_1 R_1 + L_1) & x(1-x)(P_1 + L_1) \\ y(1-y)(\beta_2 R_2 + L_2) & (1-2y)(x\beta_2 R_2 + zP_2 + zS_2 + xL_2 - \pi_2 - C_2) & y(1-y)(P_2 + L_2) \\ z(1-z)(\alpha\beta_1 R_1 - P_1 - S_1) & z(1-z)(\alpha\beta_2 R_2 - P_2 - S_2) & (1-2z)[\alpha(x\beta_1 R_1 + y\beta_2 R_2) + (1-y)P_2 + (1-x)P_1 - (xS_1 + yS_2) - C_g] \end{pmatrix} \quad (26)$$

The Jacobian matrix eigenvalues and stability conditions of the three-dimensional dynamic system D are shown in Tables 3 and 4, and the stability of each equilibrium point is thus determined.

Table 3. Stability analysis on the equilibrium points of the three-dimensional dynamic system D.

Equilibrium Point	λ_1	λ_2	λ_3	Stability
E1	$-(\pi_1 + C_1)$	$-(\pi_2 + C_2)$	$P_1 + P_2 - C_g$	Case 1
E2	$S_1 + P_1 - (\pi_1 + C_1)$	$S_2 + P_2 - (\pi_2 + C_2)$	$-(P_1 + P_2 - C_g)$	Case 2
E3	$\beta_1 R_1 + L_1 - \pi_1 - C_1$	$\pi_2 + C_2$	$\alpha R_2 + P_1 - S_1 - C_g$	Instability point
E4	$\beta_1 R_1 + L_1 + P_1 + S_1$	$\pi_2 + C_2 - P_2 - S_2$	$C_g + S_1 - \alpha R_2 - P_1$	Case 3
E5	$-\pi_1 - C_1$	$\beta_2 R_2 + L_2 - \pi_2 - C_2$	$\alpha R_1 + P_2 - S_2 - C_g$	Instability point
E5	$\pi_1 + C_1$	$\beta_2 R_2 + L_2 + P_2 + S_2$	$C_g + S_1 - \alpha R_2 - P_1$	Case 4
E7	$P_1 + S_1 - \pi_1 - C_1$	$-\pi_2 - C_2$		
E7	$\pi_1 + C_1 - \beta_1 R_1 - L_1$	$\pi_2 + C_2 - \beta_2 R_2 - L_2$	$\alpha(R_1 + R_2) - S_1 - S_2 - C_g$	Case 5
E8	$\pi_1 + C_1 - \beta_1 R_1 - L_1$	$\pi_2 + C_2 - \beta_2 R_2 - L_2$	$C_g - \alpha(R_1 + R_2) + S_1 + S_2$	Case 6

Table 4. Evolutionary stability conditions of the three-dimensional dynamic system D.

Name	Stability Characterization
Case 1	$P_1 + P_2 < C_g$
Case 2	$\pi_1 + C_1 > S_1 + P_1, \pi_2 + C_2 > S_2 + P_2, C_g < P_1 + P_2$
Case 3	$\beta_1 R_1 + L_1 + P_1 + S_1 < \pi_1 + C_1, \pi_2 + C_2 < P_2 + S_2, \alpha R_2 + P_1 > C_g + S_2$
Case 4	$\pi_1 + C_1 > P_1 + S_1, \beta_2 R_2 + L_2 + P_2 + S_2 < C_2 + \pi_2, \alpha R_1 + P_2 > C_g + S_1$
Case 5	$\beta_1 R_1 + L_1 - \pi_1 > C_1, \beta_2 R_2 + L_2 - \pi_2 > C_2, \alpha(R_1 + R_2) < C_g + S_1 + S_2$
Case 6	$\beta_1 R_1 + L_1 + P_1 + S_1 - \pi_1 > C_1, \beta_2 R_2 + L_2 + P_2 + S_2 - \pi_2 > C_2, \alpha(R_1 + R_2) - S_1 - S_2 > C_g$

Case 1: When $\pi_1 + C_1 > S_1 + P_1, \pi_2 + C_2 > S_2 + P_2$ and $C_g < P_1 + P_2, E1(0,0,0)$ satisfy all eigenvalues are negative, at this point, the asymptotic stabilization strategy is {no transformation, no transformation, no incentive}, i.e., the benefit of maintaining the original technology production for energy enterprises 1 and 2 is greater than the difference between government subsidies and enterprise penalties and the cost of digital transformation, and the government penalty for the inaction of energy enterprises 1 and 2 is less than the cost of government incentives. At this point, the government does not implement the incentive strategy and energy enterprises 1 and 2 do not undergo digital transformation.

Case 2: When $\pi_1 + C_1 > 0, \pi_2 + C_2 > 0, P_1 + P_2 > C_g, E2(0,0,1)$ satisfies all eigenvalues are negative, the asymptotic stabilization strategy is {no transformation, no transformation, no incentive}, that is, the government's penalty for the inaction of energy enterprises 1 and 2 is smaller than the cost for the government to carry out the incentive, and the government tends to incentivize the digital transformation of energy enterprises when the profit and transformation cost of energy enterprises 1 and 2 to maintain the original technology for production is greater than zero. However, in the initial stage of digitalization, the policy support is not strong enough to attract energy enterprises to carry out the digital transformation, and both energy enterprises 1 and 2 maintain the original technology to continue production.

Case 3: When $\beta_1 R_1 + L_1 + P_1 + S_1 < \pi_1 + C_1, \pi_2 + C_2 < P_2 + S_2$ and $\alpha R_2 + P_1 > C_g + S_2, E4(0,1,1)$ satisfies all eigenvalues are negative, the asymptotic stabilization strategy is {transformation, no transformation, incentive}, that is, the sum of the government's gain from incentivizing the digital transformation of energy enterprise 1 and the penalty for the inaction of energy enterprise 2 is greater than the sum of the cost of implementing the incentive strategy and the subsidy to energy enterprises, and the sum of the synergistic gain from digital transformation of energy enterprise 1, the loss it will face if it does not go digital, the government's subsidy, and the government's penalty is less than the sum of the gain from maintaining the production of the original technology and the cost of going digital. If the sum of the penalties for not going digital and the subsidies for going digital is greater than the sum of the benefits of maintaining the original technology and the costs

of going digital, the government chooses to incentivize the energy enterprise to go digital. Energy enterprise 1 chooses not to go digital, and energy enterprise 2 chooses to go digital.

Case 4: When $\pi_1 + C_1 > P_1 + S_1$, $\beta_2 R_2 + L_2 + P_2 + S_2 < C_2 + \pi_2$ and $\alpha R_1 + P_2 > C_g + S_1$, $E7(1,0,1)$ satisfy all eigenvalues are negative, the asymptotic stabilization strategy is {transformation, no transformation, incentive}, That is, the sum of the benefit gained by the government from incentivizing energy enterprise 2 to undergo digital transformation and the penalty for the inaction of energy enterprise 1 is greater than the sum of the cost of implementing the incentive strategy and the subsidy to the energy enterprise. The sum of the synergistic benefit of digital transformation for energy enterprise 2, the loss that it will face if it does not go digital, the government subsidy, and the government penalty is less than the sum of the benefit of maintaining the production of the original technology and the cost of digital transformation. When the sum of the penalty for not going digital and the subsidy received by energy enterprise 1 for going digital is greater than the sum of the benefit of maintaining the production of the original technology and the cost of going digital, the government chooses to incentivize energy enterprises to go digital, energy enterprise 2 chooses not to go digital, and energy enterprise 1 chooses to go digital.

Case 5: When $\beta_1 R_1 + L_1 - \pi_1 > C_1$, $\beta_2 R_2 + L_2 - \pi_2 > C_2$ and $\alpha(R_1 + R_2) < C_g + S_1 + S_2$, $E6(1,1,0)$ satisfies all eigenvalues are negative, the asymptotic stabilization strategy is {transformation, transformation, no incentive}, that is, the benefit gained from the government's incentive for each energy enterprise to undergo digital transformation is less than the sum of the subsidies to each energy enterprise and the cost of implementing the incentive policy, and the sum of the synergistic benefit of digital transformation for energy enterprises 1 and 2, the loss they will face if they do not go digital, the government's subsidy, and the government's fine is greater than the sum of the benefit of maintaining the production of the original technology and the cost of going digital, and energy enterprise 1 and energy enterprise 2 will still go digital despite the government chooses not to implement the incentive strategy.

Case 6: When $\beta_1 R_1 + L_1 + P_1 + S_1 > C_1 + \pi_1$, $\beta_2 R_2 + L_2 + P_2 + S_2 > C_2 + \pi_2$ and $\alpha(R_1 + R_2) > C_g + S_1 + S_2$, $E8(1,1,1)$ satisfies all eigenvalues are negative, the asymptotic stabilization strategy is {transformation, transformation, incentive}, that is, when the benefit gained from the government's incentive to each energy enterprise for digital transformation is greater than the sum of the subsidies to each energy enterprise and the costs of implementing the incentive policy, and the sum of the synergistic benefit of digital transformation for energy enterprises 1 and 2, the losses they will face if they do not go digital, the government's subsidies, and the government's fines are less than the sum of the benefits of maintaining the production of the original technology and the costs of going digital, the government chooses the incentive strategy and energy enterprise 1 and energy enterprise 2 go digital.

From the above analysis, it is clear that there are six asymptotic stabilization strategies for system D : $E1(0,0,0)$, $E2(0,0,1)$, $E4(0,1,1)$, $E6(1,0,1)$, $E7(1,1,0)$ and $E8(1,1,1)$. Analysis shows that: $E2(0,0,1)$, $E4(0,1,1)$, $E6(1,0,1)$ and $E7(1,1,0)$ refer to the fact that there is no agreement between the government and energy enterprises on digital transformation; $E1(0,0,0)$ means that the government does not stimulate the digital transformation of energy enterprises, and energy enterprises do not carry out digital transformation, which is contrary to the policy of promoting energy digital transformation in the 14th Five-Year Plan and is out of touch with the actual situation; $E8(1,1,1)$ indicates that the government stimulates the digital transformation of energy enterprises, and each energy enterprise also actively carries out digital transformation, in line with the current policy requirements and realistic situation; Therefore, $E8(1,1,1)$ of scenario 6 is the ideal state for digital transformation of energy enterprises.

5. Numerical Simulation Analysis

5.1. Setting of Basic Parameters

Matlab2018b is used to numerically simulate the evolutionary game behaviors of energy enterprise 1, energy enterprise 2, and the government under scenario 6, where energy enterprise 1 represents the subject with higher transformation costs, lower direct benefits, and weaker synergy capabilities; energy enterprise 2 represents the subject with comparative advantages in terms of transformation costs, direct benefits, and synergy capabilities; and the government represents the policy maker and behavioral regulator. In order for the system to reach the ideal state, the three conditions $\beta_1 R_1 + L_1 + P_1 + S_1 > C_1 + \pi_1$, $\beta_2 R_2 + L_2 + P_2 + S_2 > C_2 + \pi_2$ and $\alpha(R_1 + R_2) > C_g + S_1 + S_2$ need to be satisfied. Drawing on the results of Qi and Zhou (2019), the initial values of the parameters are set according to the actual situation [50], as shown in Table 5.

Table 5. Initial value setting of parameters for the digital transformation system of energy enterprises.

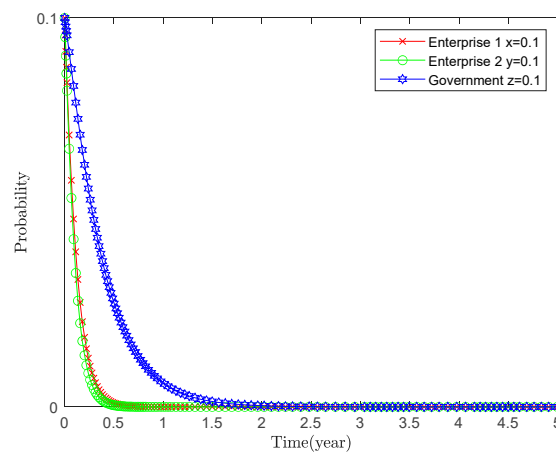
R_1	R_2	λ_1	λ_2	L_1	L_2	C_1	π_1	π_2	C_2	P_1	P_2	S_1	S_2	α	C_g
7	8	1.2	1.3	2	2	8	2	3	9	4	4	3	3	0.4	3

5.2. The Effect of Different Initial Intentions on the Subject's Game

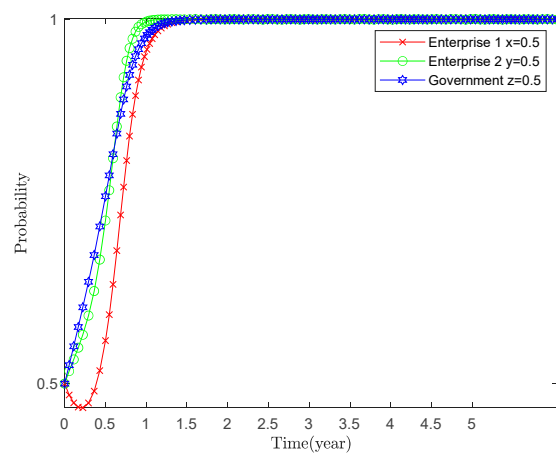
In the strategic scenario, the outcome of the game does not depend on the decision of one party but is jointly influenced by the participating subjects. The simulation of the change in the initial willingness of the game subject can visualize the process of the influence of the subject's decision on the outcome of the game and other subjects. Figures 6 and 7 show the results of the evolutionary game with different combinations of willingness among the simulated subjects.

As can be seen from Figure 6, when the initial willingness of the subjects is low ($x = y = z = 0.1$). Digital transformation systems for energy enterprises evolve in the direction of $E1(0,0,0)$. When the subjects' initial willingness is all at a neutral angle or higher ($x = y = z = 0.5$ or $x = y = z = 0.9$), The system evolves in the direction of $E8(1,1,1)$. Comparing Figure 6a–c, it can be seen that the subject with the fastest convergence is energy enterprise 2 and the slowest convergence is the government, indicating that energy enterprise 2 in the system is the most sensitive to the opportunities of digital transformation; energy enterprise 1 will adjust its own strategy in time according to the transformation effect of energy enterprise 2's digital transformation; while the government will observe the willingness and social benefit of energy enterprises 1 and 2's digital transformation before deciding its own strategy to ensure that the incentive strategy can bring the expected benefit.

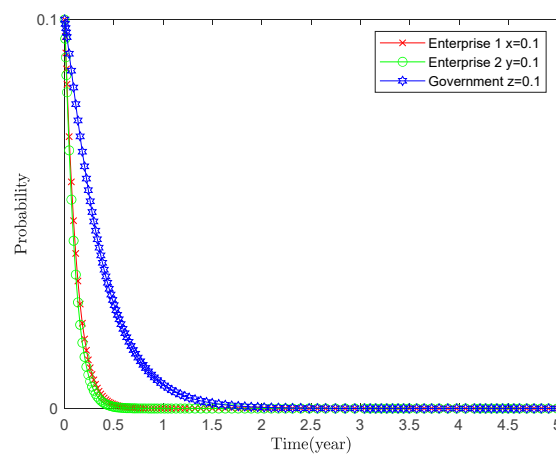
Combining Figures 6 and 7, it can be seen that the initial willingness of the subject's strategy has a significant impact on whether the three parties can evolve to the {transformation, transformation, incentive} state, and a change in the initial willingness of any of the subjects in energy enterprise 1, energy enterprise 2, or the government will have an impact on the direction of convergence of the system. From Figure 7c, it can be seen that when the initial willingness of the government increases, energy enterprises have the shortest time to converge on the digital transformation strategy, and when the probability of choosing the incentive strategy is closer to one, the system evolves to the ideal state $E8(1,1,1)$ at a much faster rate. Therefore, the government should actively participate in the digital transformation of energy enterprises, guide energy enterprises to promote the digital transformation process and encourage collaborative transformation among enterprises to reduce the cost of digitalization, so as to further improve the effectiveness of the digital transformation of energy enterprises.



(a) The initial willingness of each subject is at the 0.1 level.

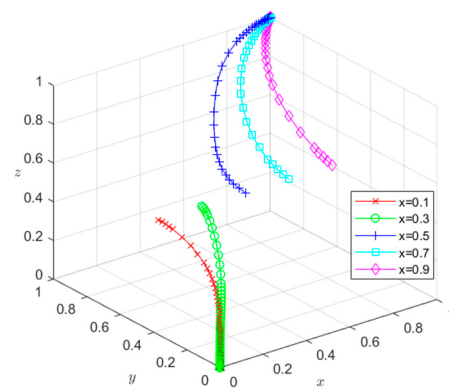


(b) The initial willingness of each subject is at the 0.5 level.

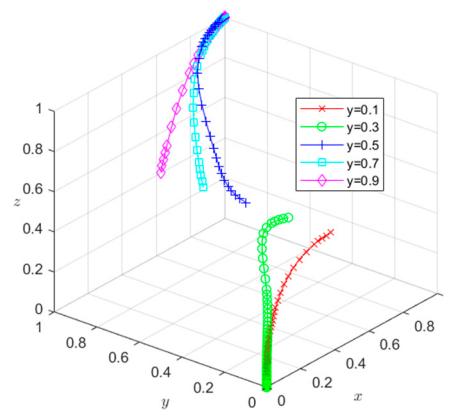


(c) The initial willingness of each subject is at the 0.9 level.

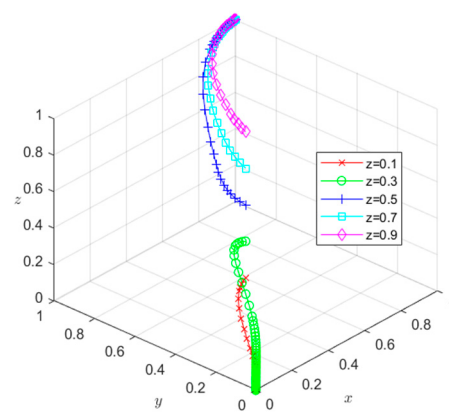
Figure 6. Influence of simultaneous changes in the initial intention of agents on the evolution path of the digital transformation system of energy enterprises.



(a) z changes, but x and y remain the same.



(b) x changes, but y and z remain the same.



(c) y changes, but x and z remain the same.

Figure 7. Influence of the change in the initial intention of an individual agent on the evolution path of the digital transformation system of energy enterprises.

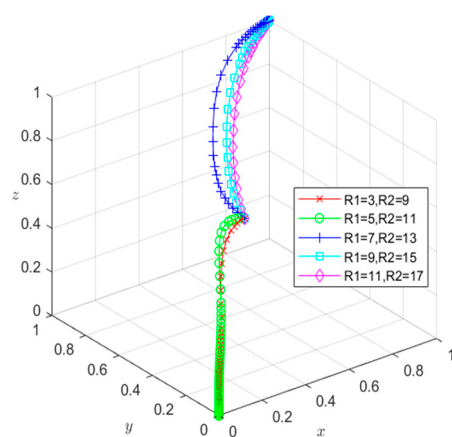
5.3. Effect of Changes in Key Parameters on System Evolution

From the stability conditions of the ideal state, it is known that the system will gradually evolve to the {transformation, transformation, incentive} ideal state when and only when the combined benefit of active participation of energy enterprise 1, energy enterprise 2 and the government in digital transformation is greater than the benefit of negative participation in digitalization; therefore, the influence factors need to be combined

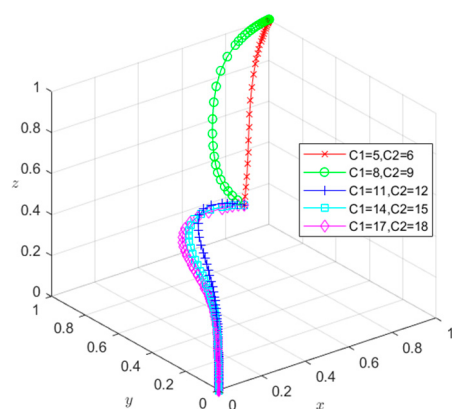
with the scenario model to further explore the impact of changes in key parameters on the evolutionary direction of the digital transformation system of energy enterprises.

5.3.1. The Impact of Digital Transformation Costs and Benefits for Energy Companies on System Evolution Trends

Figure 8a,c–e show simulations of the impact of changes in the digital transformation benefits of energy companies on the evolutionary trend of the system when R_1 takes values of 3, 5, 7, 9, 11 and R_2 takes values of 9, 11, 13, 15, 17, respectively, with the other parameters given. From Figure 8c,d, it can be seen that when $R_1 < 7$, $R_2 < 13$, the benefit of digital transformation does not reach the expected benefit of energy enterprises 1 and 2, and fails to stimulate the willingness of energy enterprises 1 and 2 to digital transformation. Additionally, the government also chooses not to stimulate, and the system is stable in the state $E1(0,0,0)$. When $R_1 = 7$, $R_2 = 13$, the system starts to converge in the direction of $E8(1,1,1)$. Additionally, the rate of convergence of the system is gradually accelerated as the values of R_1 and R_2 keep increasing. After analyzing the reasons for this, since energy enterprises are rational subjects pursuing profit maximization when the combined benefit of digital transformation is greater than the benefit of maintaining the original technology, energy enterprises 1 and 2 will actively carry out the transformation, and the probability of government incentives subsequently increases.

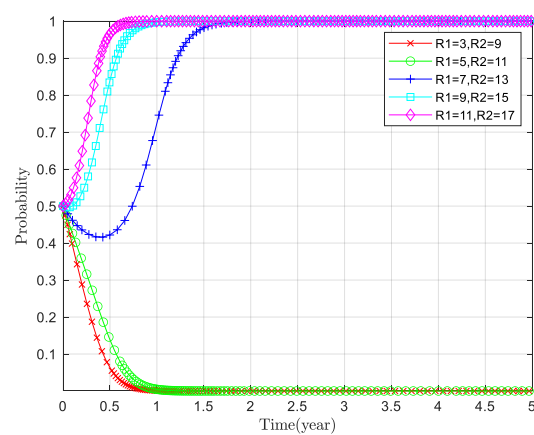


(a) The effect of R_1 and R_2 on the system.

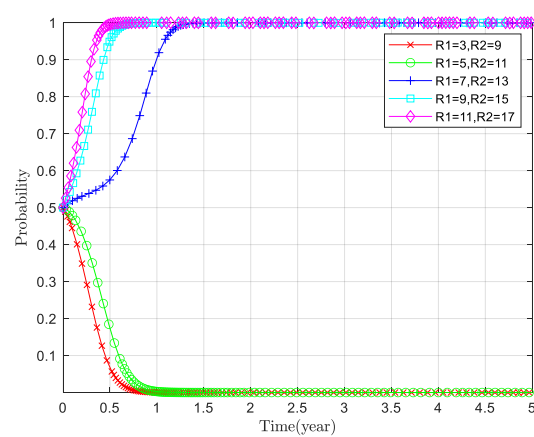


(b) The effect of C_1 and C_2 on the system.

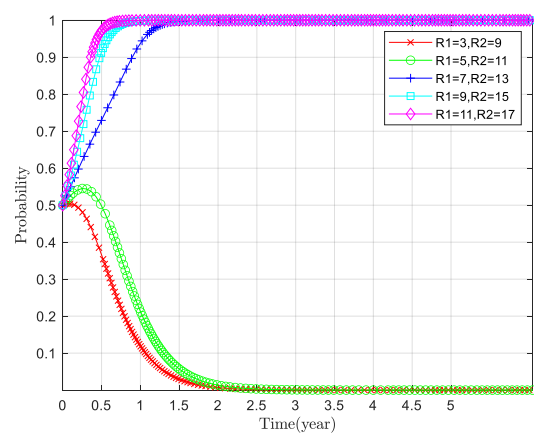
Figure 8. Cont.



(c) The effect of R_1 and R_2 on energy enterprise 1.

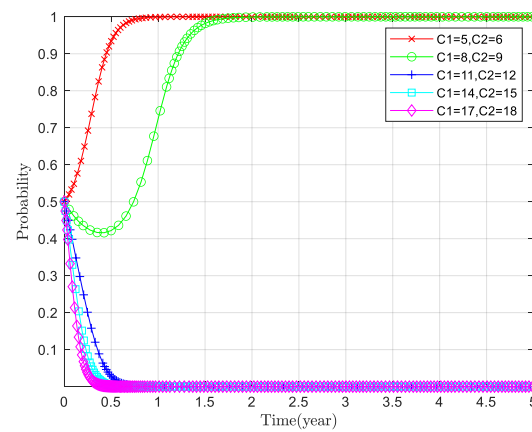


(d) The effect of R_1 and R_2 on energy enterprise 2.

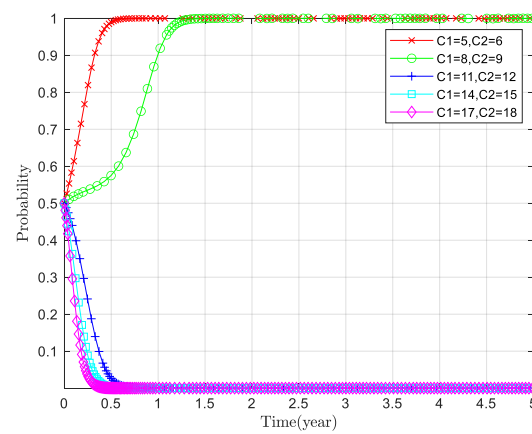


(e) The effect of R_1 and R_2 on government.

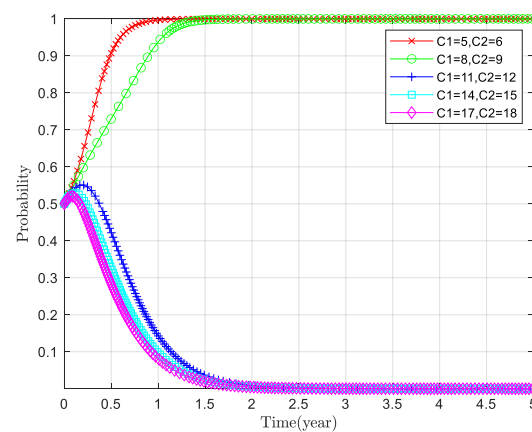
Figure 8. Cont.



(f) The effect of C_1 and C_2 on energy enterprise 1.



(g) The effect of C_1 and C_2 on energy enterprise 2.



(h) The effect of C_1 and C_2 on the government.

Figure 8. Influence of benefits and costs on the evolution trend of the digital transformation system of energy enterprises.

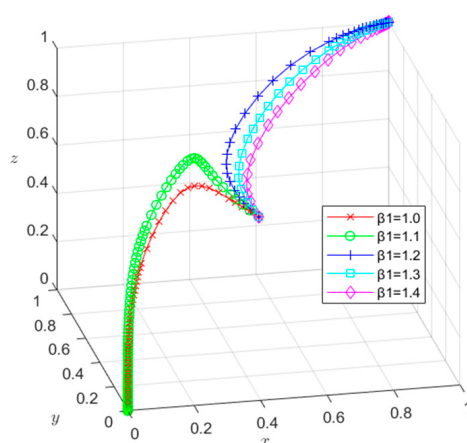
Figure 8b,f–h show simulations of the impact of changes in the digital transformation costs of energy companies on the evolutionary trend of the system when C_1 takes values of 5, 8, 11, 14, 17 and C_2 takes values of 6, 9, 12, 15, 18, respectively, with the other parameters set. Figure 8f–h show that the system evolves towards $E8(1,1,1)$ when $C_1 \leq 8$, $C_2 \leq 9$.

However, when $C_1 > 8$, $C_2 > 9$, C_1 and C_2 are increasing, the system gradually evolves to $E_1(0,0,0)$ with an increasingly faster rate.

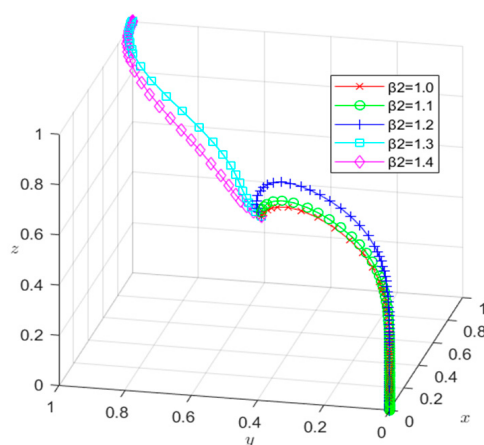
This shows that energy enterprises prefer to maintain the status quo despite the high cost of transformation. Energy enterprises will choose to transform when and only when the benefits of digital transformation exceed the comprehensive costs of digital transformation, and the government, in order to avoid the blind implementation of policies, will choose whether to stimulate the digital transformation of energy enterprises after observing the status of digital transformation, which is consistent with the previous analysis. Therefore, the government needs to reasonably increase the investment in digital transformation infrastructure and reduce the equipment cost of digital transformation to improve the possibility of digital transformation survival, so as to stimulate the willingness of energy enterprises towards digital transformation.

5.3.2. Influence of the Cooperative Coefficient on System Evolutionary Trends

Figure 9a–h shows the simulation of the impact of the change in the coefficient of synergy benefit of digital transformation of energy enterprises on the evolutionary trend of the system when β_1 takes values of 1.0, 1.1, 1.2, 1.3, 1.4 and β_2 takes values of 1.1, 1.2, 1.3, 1.4, 1.5, respectively, with the other parameters given. When the cooperative coefficients $\beta_1 < 1.2$ or $\beta_2 < 1.3$, the system evolves towards $E_1(0,0,0)$ as shown in Figure 9a,b.

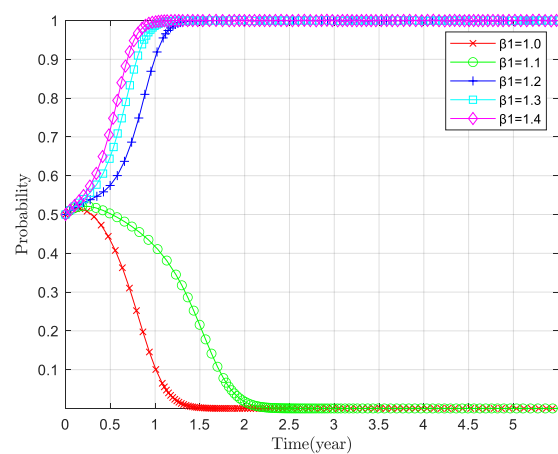


(a) Effect of β_1 on the evolutionary trend of the system.

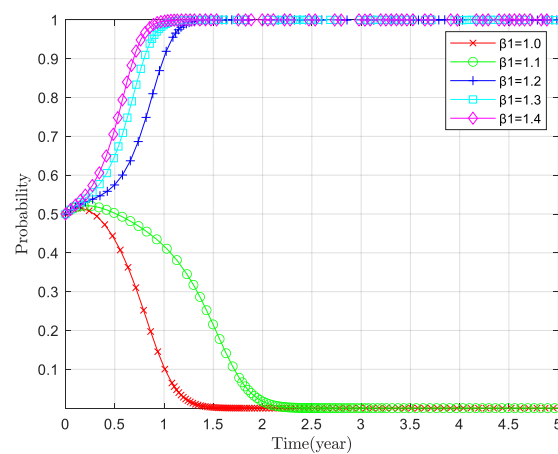


(b) Effect of β_2 on the evolutionary trend of the system.

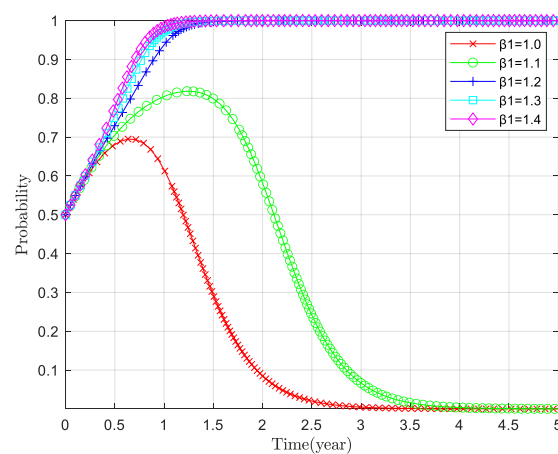
Figure 9. Cont.



(c) Effect of β_1 on energy enterprise 1.

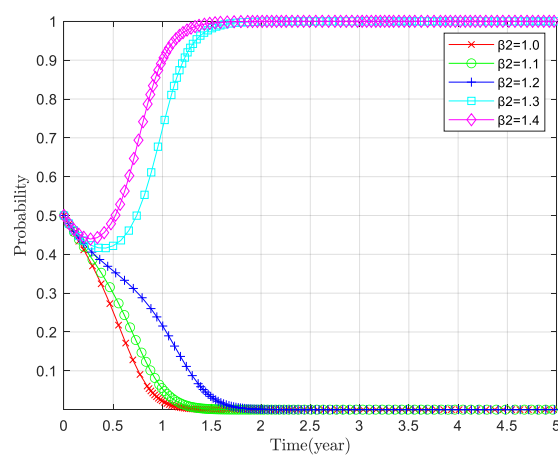


(d) Effect of β_1 on energy enterprise 2.

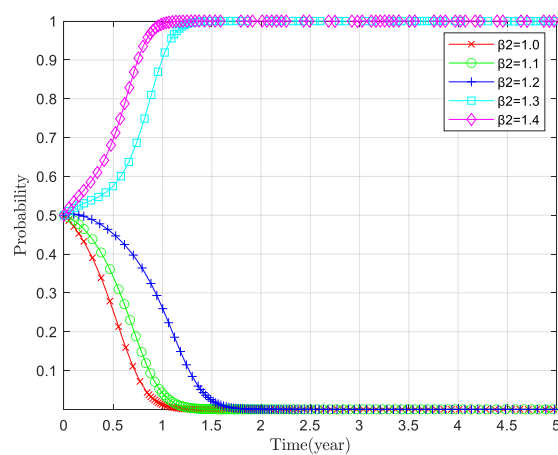


(e) Effect of β_1 on government.

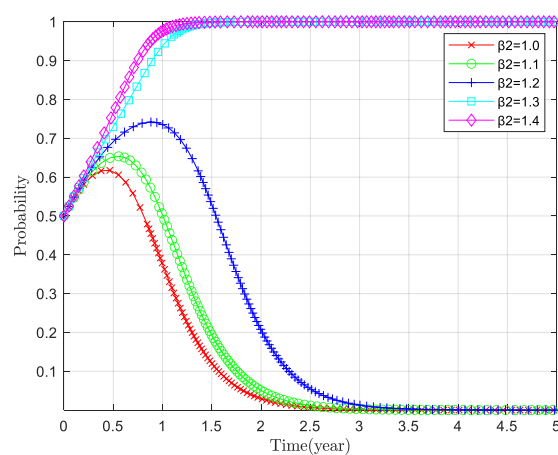
Figure 9. Cont.



(f) Effect of β_2 on energy enterprise 1.



(g) Effect of β_2 on energy enterprise 2.



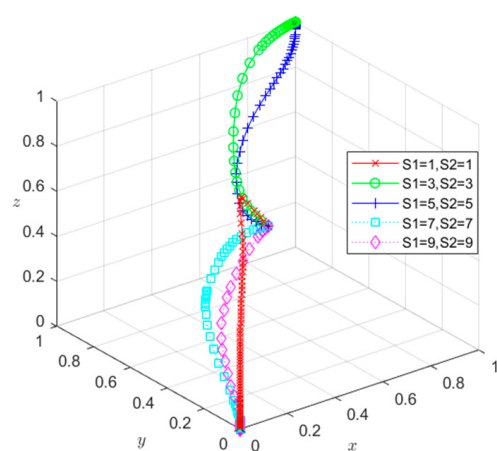
(h) Effect of β_2 on government.

Figure 9. Influence of the cooperative coefficient on the evolution trend of the digital transformation system of energy enterprises.

In the initial stage of transformation, because no stable cooperation relationship has been formed between energy enterprises that choose to carry out digital transformation, the cooperative coefficient between enterprises is low, making the comprehensive benefits of energy enterprises smaller than the comprehensive costs of digital transformation. At this time, both energy enterprises will maintain the original technology for production. From Figure 9e,h, we can see that the evolution of government incentive paths shows an inverted U-shape, indicating that the synergistic cooperation of digital transformation effectively stimulates the willingness for government incentives, but after a period of time, the willingness of the government will gradually decline until it subsides to zero. When the cooperative coefficient $\beta_1 \geq 1.2$ or $\beta_2 \geq 1.3$, it can be seen from Figure 9c–h that the system starts to evolve to $E8(1,1,1)$, and as the cooperative coefficient keeps increasing, the system converges faster and faster and finally stabilizes in the ideal state of {transformation, transformation, incentive}. After analyzing the reasons: With the deepening and improvement of digital transformation cooperation among energy enterprises, the degree of digital transformation has gradually increased, and the willingness of energy enterprises to transform and the willingness of the government to provide incentives have also strengthened.

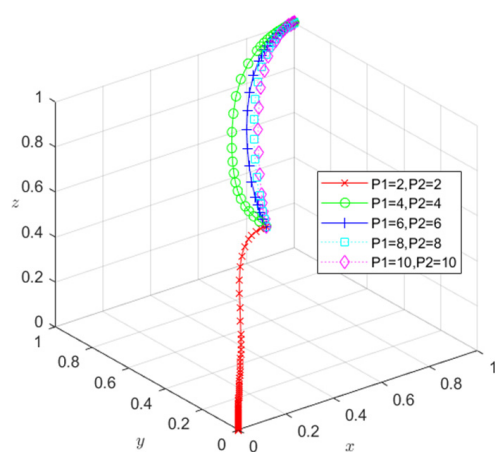
5.3.3. Impact of Government Subsidy and Penalty on System Evolutionary Trend

Figure 10a,c–e show simulations of the effect of changes in government subsidies on the evolutionary trend of the system when S takes values of 1, 3, 5, 7, 9, respectively, with the other parameters given. When the government subsidy is 1, although the government attaches great importance to the new policy and provides guidance, the amount of subsidy is much smaller than the cost of digital transformation, and the energy enterprises do not achieve the expected benefits after trying and choose to maintain the production of the original technology one after another, and the system finally stabilizes in equilibrium $E1(0,0,0)$. When the government subsidies increase to 3 and 5 (increasing subsidies), on the one hand, the cost of digital transformation for energy enterprises is relatively reduced and the willingness to transform gradually increases; on the other hand, if energy enterprises do not choose digital transformation, they will lose a certain market share, thus forcing them to carry out digital transformation, so the system evolves to the equilibrium state $E8(1,1,1)$ and the convergence rate is accelerated. When the government subsidy intensity is between 7 and 9, excessive subsidy puts great pressure on the government's fiscal transfers, the probability of government incentives begins to decline, and the system evolves toward the equilibrium state $E1(0,0,0)$.

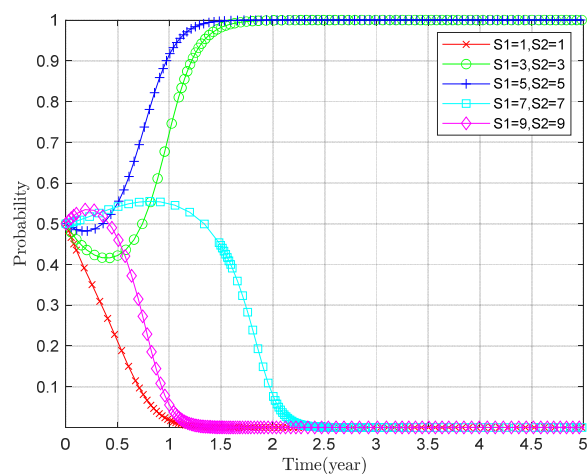


(a) The effect of S changes on the system.

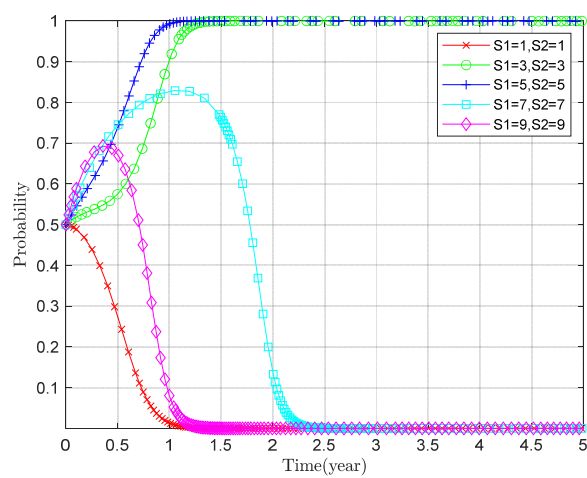
Figure 10. Cont.



(b) The effect of P changes on the system.



(c) The effect of S on enterprise 1.



(d) The effect of S on enterprise 2.

Figure 10. Cont.

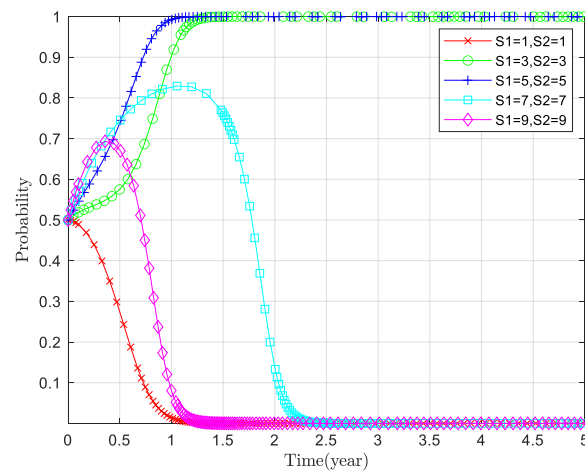
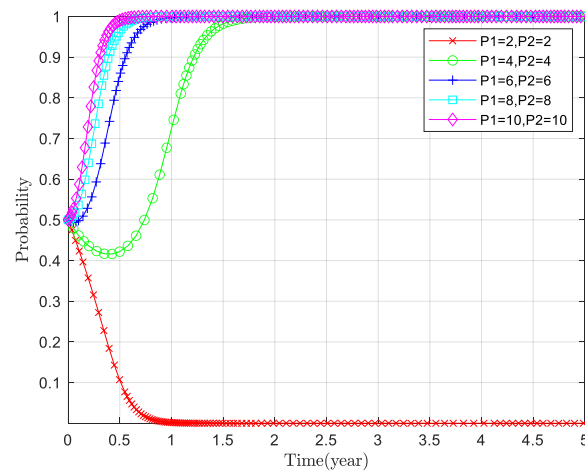
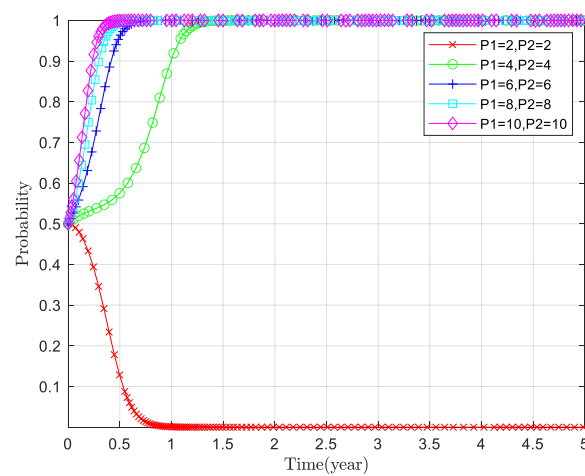
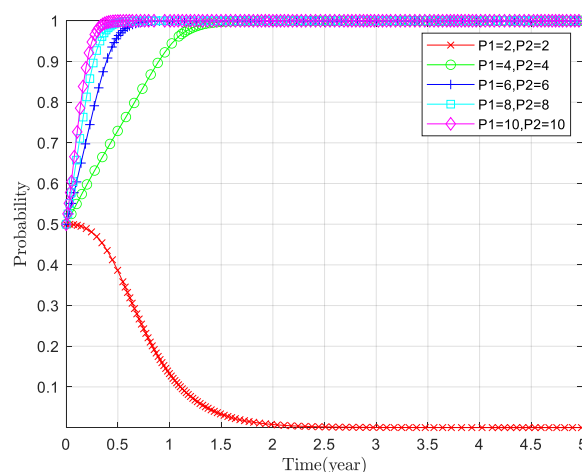
(e) The effect of S on government.(f) The effect of P on enterprise 1.(g) The effect of P on enterprise 2.

Figure 10. Cont.



(h) The effect of P on government.

Figure 10. Influence of subsidies and penalties on the evolution trend of the digital transformation system of energy enterprises.

This shows that there is a threshold range of maximum and minimum values for the positive influence of government subsidies on system evolution, and the value of government subsidies to energy enterprises should be controlled in the “central region” between the small and large threshold values; too high or too low values will prevent all three from evolving to the ideal state. For energy enterprise 1, the system eventually stabilizes at $E1(0,0,0)$ when $S_1/C_1 > 3/8$ or $S_1/C_1 < 5/8$. For energy enterprise 2, the system eventually stabilizes at $E1(0,0,0)$ when $S_2/C_2 > 3/9$ or $S_2/C_2 < 5/9$.

Therefore, government subsidy to energy enterprise 2, which has a larger economy and higher profitability, should be maintained at about 33%, and subsidy to energy enterprise 1, which has a smaller economy and lower profitability, should be maintained at about 38%, which will facilitate the participation of all system entities in digital transformation. It can be seen that energy enterprise 2 is positioned as the “leader” of digital transformation, and energy enterprise 1 is the “follower”.

Figure 10b,f–h show simulations of the impact on the evolutionary trend of the system when the government penalty for inactive energy firms changes when P takes values of 2, 4, 6, 8, 10, respectively, with the other parameters given.

When the government penalty is 2, the benefit of maintaining the original production technology is higher than the difference between the government subsidy and the penalty, and energy enterprises will choose to “rest on their laurels” in order to minimize the uncertainty loss in the digital transformation, and the system gradually stabilizes at $E1(0,0,0)$. When the penalty for inaction increases to 4, energy enterprise 2 is no longer profitable to maintain its original production technology and starts to transform. Due to the benefits of digital technology in the competitive market, energy enterprise 1 also starts to promote the digital transformation process, and the system gradually converges to the ideal state. With the increase in the penalty, the convergence rate accelerates and finally stabilizes at $E8(1,1,1)$. This shows that when the government punishes energy enterprises less, they are more inclined to maintain the original technology production out of their own interests; when the punishment is increased, their behavior gradually tends to digital transformation in order to pursue the maximum benefit in the face of the income and fine of inactive enterprises; and the stronger the punishment, the more obvious the effect. Therefore, the government should weigh the public interest of society, use both rewards and punishments, and master its strengths to facilitate the digital transformation system of energy enterprises to evolve to the ideal state. Thus, the government is positioned as a “guide” for the digital transformation of energy enterprises.

6. Findings and Discussion

6.1. Findings

This study also considers the impact of industry competition and government participation on the digital transformation of energy enterprises, establishes a three-party evolutionary game model of “energy enterprise 1—energy enterprise 2—government”, analyzes the evolutionary strategies of each party and the stability of the combined evolutionary strategies, and combines numerical simulations to analyze the impact of the initial willingness of the participants and key variables on the strategy evolution and stability results. The impact of changes in the initial willingness of the participants and key variables on the evolution and stability of the strategy is also analyzed with numerical simulations. The specific findings are summarized as follows:

(1) In the process of digital transformation, a symbiotic relationship between energy companies and a cooperative relationship between companies and the government are reflected, and the effective game process is sufficiently economically oriented. First, the choice of the digital transformation strategy for energy enterprises is influenced by the willingness of other enterprises to transform and government incentives, and the influence vector is positive. Second, increasing the benefit of digital transformation and reducing the cost of digital transformation can increase the probability of digital transformation of energy enterprises, and increasing the collaborative coefficient of digital transformation can promote the possibility of digital transformation of energy enterprises. Again, when the basic benefits of energy enterprises and their transformation costs reach a certain level, increasing the government’s penalty will have a positive externality on the digital transformation of energy enterprises [51]. Finally, when the public benefit gained by the government through incentivizing the digital transformation of energy enterprises is greater than the cost incurred by the government for making corresponding incentive policies, the government incentive strategy will be significantly related to the willingness of energy enterprises to transform; and the greater the penalty or the smaller the subsidy, the greater the willingness of the government incentive.

(2) The government is the “guide” of the digital transformation of energy enterprises, and its initial willingness to influence the effect is significantly stronger than that of energy enterprises, and the effective strategy reflects the principle of “the discretionary approaches, prioritizing efficiency and taking equity into account”. In terms of “the discretionary approaches”, in order to avoid blind implementation of policies and ensure that the incentive strategy can bring the expected benefits, the government usually observes the willingness and social benefits of digital transformation among leaders and followers first and then decides whether to provide incentives and the intensity of policies. In terms of “prioritizing efficiency”, the government will show a wait-and-see attitude because the energy enterprises that choose to carry out digital transformation at the initial stage of transformation have not formed a stable partnership with each other, and the lower collaborative capacity will make the comprehensive benefits of energy enterprises less than the comprehensive costs of digital transformation. However, as the collaborative cooperation of digital transformation among energy enterprises deepens, it will effectively stimulate the willingness for government incentives and gradually increase the support; when the collaborative cooperation becomes mature, the government will also rationally reduce the incentives. In terms of “taking equity into account”, an appropriate increase in penalty will facilitate the evolution of the system to the ideal state, and a reasonable subsidy should not only be maintained within a certain threshold [52] but also reflect the incentive difference between the leaders and the followers.

(3) Given the established policy environment, energy enterprises with comparative advantages in terms of transformation costs, direct benefits and collaborative capabilities will become the “leader”, and the leaders are more sensitive to digital transformation opportunities. The “follower” energy enterprises will adjust their strategies to the effects of the digital transformation of the leaders in order to achieve a steady-state system. When government incentives are low, both leaders and followers will choose to maintain

their production models without digital transformation in order to minimize the loss of uncertainty in digital transformation. As government incentives grow, leading energy companies will begin digital transformation because their old production models are not profitable. As the benefits brought by digital technology generate positive externalities in market competition, followers also start to enter the ranks of digital transformation; when government incentives further increase, the system gradually converges to the ideal state, especially with the increase of penalties. The convergence rate of transformation among leaders and followers continues to accelerate and eventually reaches the level of full digital transformation [53]. Whether a leader or a follower, a reasonable reduction in transformation costs, an effective increase in direct benefits, and a scientific increase in collaborative capabilities will help the system evolve in the direction of the ideal state.

6.2. Discussion

6.2.1. Theoretical Implications

Our study contributes to the literature by exploring the dynamics and impediments to the digital transformation of energy firms through the construction of a three-party game model with the theme “Energy enterprise 1—Energy enterprise 2—Government”. Firstly, the initial strategy simulations of the game subjects show that the choice of the digital transformation strategy by energy companies is positively influenced by the willingness of other companies to transform and the incentives of the government. Secondly, reducing digital transformation costs and increasing synergistic benefits are key to facilitating the digital transformation of energy firms. Finally, government participation can effectively promote the transformation of enterprises, and the greater the penalty, the higher the willingness of energy enterprises to digital transformation, but government subsidies are only in the “effective range” to promote the evolution of the whole game system to the ideal state.

6.2.2. Practical Implications

Our study also offers some meaningful practical implications.

Firstly, as the executive body of energy digitization, energy enterprises should take the responsibility to actively cooperate with other energy enterprises in the fields of digital technology and digital economy with the support of government policies, build a common platform to reduce the cost of digital transformation, and thus create more opportunities for collaborative benefits.

Secondly, the government, as the policymaker, should fire the first shot of digital transformation and create a favorable external environment for the digital transformation of energy enterprises. The government should also have discretionary approaches, take advantage of the situation, actively develop digital transformation incentive policies, increase the digital technology facilities built, build industrial Internet platforms, accelerate the flow of information and technology for digital transformation, alleviate the difficulties in the initial stage of digital transformation of energy enterprises in terms of capital and technology, and improve the transformation ability and willingness of energy enterprises to transform.

Lastly, in order to reduce the “heavy burden” of subsidies to the financial sector, the government can support the digital transformation of energy enterprises by prioritizing, gradually investing and subsidizing in batches, playing a guiding role and gradually reducing the proportion of subsidies, so as to finally realize the collaborative benefits and generate a virtuous cycle in the digital transformation of energy enterprises. At the same time, the government should, to a certain extent, increase the penalty for inaction for energy enterprises, incorporate digital economy benefits into regional performance assessment objectives, and actively guide the digital transformation of energy enterprises.

6.2.3. Limitations and Directions for Future Research

Although some important insights were found in our study, we acknowledge the limitations of our research. Firstly, the process of digital transformation for energy companies involves many stakeholders, including energy enterprises, governments, R&D institutions, financial institutions, public organizations, etc. In this study, only energy enterprises and the government were considered, and other stakeholders were neglected. Secondly, in order to construct a sensitivity analysis of the parameters, this work uses only case simulations. It requires further analysis with actual data. Thirdly, the parameters used in our game model are assumed to be static, and dynamic parameters could enrich this paper. These issues need to be explored in future research.

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