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A Game Strategy for Getting Electricity Investment Interface Extension in Adaptation to the Construction of Hainan's High-Level Free Trade Port

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Abstract:
This study focuses on the extension of the ' Getting Electricity ' investment interface as its main theme, taking the construction of key parks in the Hainan Free Trade Port ((Hainan Province, China)) as the real-world background. this study constructs an evolutionary model for the cooperative operation mechanism among the power grid company, customers, and government in the extension of the electricity investment interface. It analyzes the strategic interactions among the three parties during the implementation of the interface extension. Furthermore, the study conducts a stability analysis of the equilibrium among the government, power grid enterprises, and park customers under scenarios where value-added services are provided by the power grid enterprises. Different pathways for coordinating the interests of the three parties under various standards of investment interface extension are presented. This provides critical support for formulating targeted policies on 'Getting Electricity' investment extensions and maximizing the comprehensive efficiency of electric power resources at a broader level.

Keywords: power grid access project, Hainan free trade port, getting electricity; evolutionary game.

FOREWORD

The extension of "Getting electricity" investment represents a cost distribution issue involving multiple stakeholders in the grid investment. In recent years, to continuously optimize the business environment for electricity consumption, various regions in China have successively introduced preferential policies related to the extension of the power grid investment interface. These policies clarify the investment entities for grid connection projects, stipulating that the external line connection costs, previously borne by users, will now be shared by the government and power grid enterprises, thereby reducing the electricity burden on users. However, the current shared investment mechanism is still in its initial exploration phase, lacking a unified standard for cost distribution ratios, and its rationality is subject to further discussion [1, 2]. Therefore, it is imperative to conduct an in-depth study on fair and reasonable investment strategies shared between the government and enterprises for Power grid access projects under the new investment interface division.

The issue of multi-agent investment allocation is essentially about achieving a Pareto improvement of the system under conditions of information asymmetry [3-7]. Regarding the cost allocation problem of multi-agent investment in the power grid, the academic community has mainly conducted studies on the investment ratio of certain types of power grid projects based on current development trends of the power grid. Sun et al. (2020) [8] and Wang et al. (2021) [9] propose investment strategies for cooperative investment by grid companies, power generation companies, the government, and social capital in incremental distribution investment businesses; Li et al.(2021) [10], Simon et al.(2022) [11]calculate the shared storage costs and grid congestion costs that should be allocated to microgrids based on the Shapley value method; Huang et al.(2020) [12] and Zhao et al.(2015) [13] uses dynamic game theory to analyze the conflict of interests in joint investments by distribution networks and microgrid operators in a single microgrid; Wang et al.(2020) [14], Cheng et al.(2014) [15] employs elastic network algorithms to construct a model for the allocation of transmission and distribution costs in individual grid projects. There have also been studies on the allocation of investment among entities through cooperative game theory. From a fairness perspective, Samuel et al. (2020) [16] and Shuai et al. (2021) [17] use cooperative game theory to achieve cost allocation among members of a multi-microgrid alliance. An et al. (2020) [18] and Li & Zhang (2022) [19] combine cooperative game theory with the DEA method to analyze multi-stage cost and resource allocation issues. Based on the cost characteristic function of cooperative alliances, Zheng et al. (2021) [20] analyzes the allocation of total operating costs among member enterprises. Cao et al. (2023) [21] constructs a Nash-Harsanyi bargaining game model to explore investment strategies for grid connection projects under the extension of the investment interface.

The aforementioned studies analyze the distribution ratios among multiple investors for incremental networks, microgrids, and individual grid costs but have not addressed the common issue of non-identity between project costs and benefits in grid companies' extension of power investment redlines [22]. This issue involves investments made by grid companies, but the primary beneficiaries are other entities. additionally, there has been a lack of analysis from the perspective of project implementation on the pathways to quickly achieve coordination of interests among the three parties.

In summary, this paper applies evolutionary game theory to construct an evolutionary game model involving the government, power grid enterprises, and park customers. It characterizes the strategic interactions among the three parties during the implementation of the "Getting Electricity" investment interface extension. The study analyzes the dynamic evolutionary paths and optimization spaces of their game strategies, clarifies the pathways for coordinating the interests of the three parties under different investment interface extension standards, and provides implementation recommendations.

ANALYZE THE FRAMEWORK

The basic framework of the cooperative operation mechanism for typical park electricity customers obtaining power services is illustrated in Figure 1. Within this mechanism, the government, grid companies, and key park customers form a tripartite entity. The government serves as the provider of incentive policies, such as the extension of the electricity investment interface, and promotes key park electricity access projects by designing, formulating, and implementing relevant policies, playing a leading role in the planning and execution of electricity access projects [23].

Grid companies are the recipients of the electricity investment interface extension policy, collaborating with the government to develop policies related to electricity access projects in key parks. They refine the regulations for electricity access and supply services in these parks and are responsible for their implementation, promoting the expansion of high-quality electricity services within the parks [24].

Park customers are beneficiaries of end-use energy and energy-saving supply service policies, representing the interests of the demand side. Electricity access and related supply service projects reduce the energy costs for park customers and provide efficient and convenient services for handling electricity, connection, and usage. As the implementers and beneficiaries of electricity access projects in key parks, achieving a Pareto improvement in the interests of both grid companies and customers is the foundation and guarantee for the successful implementation of electricity supply services in key parks [25].

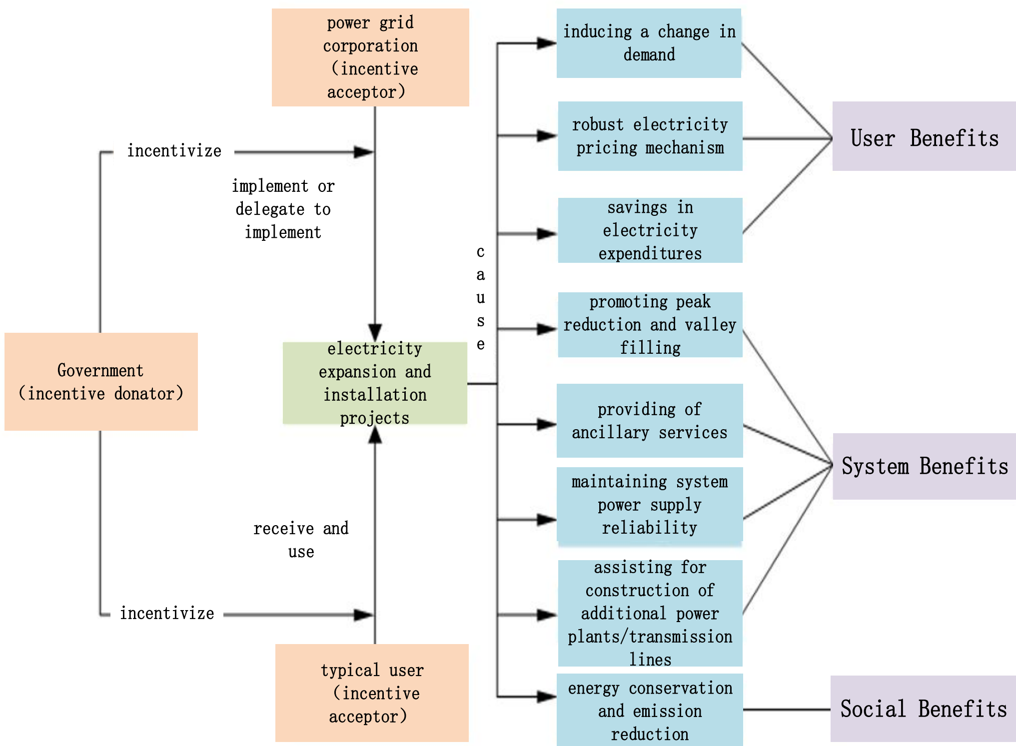


Figure 1. Basic framework of the power supply service cooperation operation mechanism in the park

MODEL BUILDING

Game Behavior List and Variable Symbol List

Game behavior list

Based on the requirements of relevant Chinese policies, we assume the following scenarios:

1. The three main entities involved are government-related departments (such as park management committees), grid companies, and park electricity customers.

2. Without loss of generality, the electricity customers are assumed to be high-voltage, new permanent electricity users.

Based on the three main entities involved in the high-voltage, new permanent electricity investment interface extension service, the game participants and the pure strategy choices under study are listed [26]. The criterion for the behavior choice of the three participating entities is whether they can obtain the expected benefits from the park's electricity investment interface extension service. The specific content is as shown in Table 1.

Table 1. Game participants and corresponding pure strategy choices

No.	Game Participants	Game behavior (strategy choice)	Probability of strategy selection
1	The Government	Incentives to Getting Electricity Investment Interface Extension Services (" Incentives ")	x
		Do not incentivize the extension service for Getting electricity investment interface ("Do not incentivize")	$1-x$
2	Power grid Company	Implement the extension service for Getting electricity investment interface ("Implement")	y
		Do not implement the extension service for Getting electricity investment interface ("Do not implement")	$1-y$
3	Park power customer	Accept the extension service for Getting electricity investment interface ("Accept")	z
		Do not accept the extension service for Getting electricity investment interface ("Do not accept")	$1-z$

List of variable symbols

Table 2 lists the variable symbols that will be used later in this chapter and their meanings.

Table 2. List of variable symbols

Objects	Variables	Meaning
Government and power grid Company	R_0	Government's original comprehensive income
	C_1	Policy cost of government incentivizing grid companies
	C_2	Loss due to decreased social and environmental benefits when grid companies do not implement the service
	R_1	Social and environmental gains when grid companies implement the service without government incentives
	R_2	Social and environmental gains when grid companies implement the service with government incentives
Government and park customers	C'_1	Policy cost of government incentivizing park customers
	C'_2	Loss due to decreased social and environmental benefits when park customers do not accept the service
	R'_1	Social and environmental gains when park customers accept the service without government incentives
	R'_2	Social and environmental gains when park customers accept the service with government incentives
Power grid Company	I_0	Grid company's original revenue
	I_{11}	Equivalent policy benefits (tax relief) when grid company implements the service with government incentives

	I_{12}	Equivalent policy benefits (government-subsidized service extension) for implementing the service with government incentives, formula:
	I_1	Equivalent policy benefits (tax relief, government-subsidized service extension) for implementing the service with government incentives, formula:
	I_2	Social and managerial benefits equivalent to system gains from implementing the service project
	N_1	Number of overhead connection projects
	S_{11}	Cost per overhead connection project
	N_2	Number of underground cable connection projects
	S_{12}	Cost per underground cable connection project
	α	Participation degree of grid company in service extension (default is 1)
	S_1	Total cost of grid company participating in service extension, formula:
Park power customer	D_0	Original expenses of park customers
	D_1	Equivalent policy benefits (loan discounts) for park customers accepting the service with incentives
	D_2	Cost reduction benefits for park customers accepting the service project
	D_3	Equivalent benefits of time reduction and fewer procedures for park customers accepting the service project
	F_1	Expenses incurred by park customers when accepting the service project

Three-party Game Model of Government, Power Grid Company and Park Customers

Expected revenue of the government under different circumstances

First, analyze the government's benefits when grid companies and park customers implement different schemes, as shown in Table 3.

Table 3. Expected benefits of the government in different situations

The Government	Grid Company	Park customers	Earnings
No incentives, With a probability of 1-x	Not implemented, *1-y*	Do not accept, *1-z*	$R_0 - C_2 - C_2'$
	Implement *y*	Not accepted, *1-z*	$R_0 + R_1 - C_2'$
	Not implemented, *1-y*	Accept, *z*	$R_0 - C_2 + R_1'$
	Implement *y*	Acceptance, *z*	$R_0 + R_1 + R_1'$
Excitation, with probability *x*	Not implemented, *1-y*	Do not accept, *1-z*	$R_0 - C_1 - C_1' - C2 - C_2'$
	Implement *y*	Not accepted, *1-z*	$R_0 - C_1 + R_2 - C_1' - C_2'$
	Do not implement, *1-y*	Accept, *z*	$R_0 - C_1 - C_2 - C_1' + R_2'$
	Implement *y*	Acceptance, *z*	$R_0 - C_1 + R_2 - C_1' + R_2'$

(a) The expected benefits of the government not incentivizing getting Electricity value-added services are:

$$U_{gov}^{(0)} = (1-y)(1-z)(R_0 - C_2 - C_2') + y(1-z)(R_0 + R_1 - C_2')$$
$$+(1-y)z(R_0 - C_2 + R_1') + yz(R_0 + R_1 + R_1')$$
$$= R_0 + yR_1 - (1-y)C_2 - (1-z)C_2' + zR_1'.$$

(b) The expected benefits of the government incentivizing getting Electricity value-added services are:

$$U_{gov}^{(1)} = (1-y)(1-z)(R_0 - C_1 - C_1' - C2 - C_2')$$
$$+y(1-z)(R_0 - C_1 + R_2 - C_1' - C_2')$$
$$+(1-y)z(R_0 - C_1 - C_2 - C_1' + R_2')$$

$$+yz(R_0 - C_1 + R_2 - C_1' + R_2')$$
$$= R_0 - C_1 - C_1' - (1-y)C_2 - (1-z)C_2' + yR_2 + zR_2'.$$

The expected benefits of getting Electricity value-added services, considering both scenarios of government incentivization and non-incentivization, are:

$$\overline{U}_{gov} = (1-x)U_{gov}^{(0)} + xU_{gov}^{(1)}$$

Establish a replicator dynamic equation to examine the game-changing path of the probability of the government adopting incentive policies.

$$\frac{dx}{dt} = x(U_{gov}^{(1)} - \overline{U}_{gov}) = x(1-x)(U_{gov}^{(1)} - U_{gov}^{(0)})$$
$$= x(1-x)\left[-C_1 - C_1' + y(R_2 - R_1) + z(R_2' - R_1')\right] \triangleq F_{gov}(x,y,z). \quad (1)$$

To determine the stable state after a sufficiently long duration of the game, according to the theory of stability analysis [27], let $F_{gov}(x,y,z) = 0$, to obtain the stable state:

(i) $x = 0$;

(ii) $x = 1$;

(iii) $y(R_2 - R_1) + z(R_2' - R_1') = C_1 + C_1'$

Because $y, z \in [0,1]$, then $0 < C_1 + C_1' \le R_2 - R_1 + R_2' - R_1'$.

Expected revenue of power grid company under different circumstances

Next, analyze the benefits for the grid company when the government and park customers implement different schemes, as detailed in Table 4.

Table 4. Expected benefits of power grid Company in different situations

Power Grid Company	Government	Park customers	Earnings
Not implemented, With a probability of *1-y*	No excitation, *1-x*	Not accepted, *1-z*	I_0
	Motivate *x*	Do not accept, *1-z*	I_0
	Do not motivate, *1-x*	Accept, *z*	I_0
	Motivate *x*	Acceptance, *z*	I_0
Implementation of value-added service project with probability *y*	No incentive, *1-x*	Do not accept, *1-z*	$I_0 - S_1$
	Motivate *x*	Do not accept, *1-z*	$I_0 + I_1 - S_1$
	Do not motivate, *1-x*	Accept, *z*	$I_0 + I_2 - S_1$
	Motivate *x*	Acceptance, *z*	$I_0 + I_1 + I_2 - S_1$

(a) The expected benefits for the grid company not implementing getting Electricity value-added services are:

$$U_{grid}^{(0)} = I_0$$

(b) The expected benefits of the grid company implementing getting Electricity value-added services are:

$$U_{grid}^{(1)} = (1-x)(1-z)(I_0 - S_1) + x(1-z)(I_0 + I_1 - S_1)$$
$$+(1-x)z(I_0 + I_2 - S_1) + xz(I_0 + I_1 + I_2 - S_1)$$
$$= I_0 + xI_1 + zI_2 - S_1$$

The expected benefits of getting Electricity value-added services, considering both scenarios where the grid company implements and does not implement, are:

$\overline{U}_{grid} = (1-y)U_{grid}^{(0)} + yU_{grid}^{(1)}$

Similarly, establish a replicator dynamic equation to examine the game-changing path of the grid company adopting the probability y of implementing incentive policies.

$$\frac{dy}{dt} = y(U_{grid}^{(1)} - \overline{U}_{grid}) = y(1-y)(U_{grid}^{(1)} - U_{grid}^{(0)})$$
$$= y(1-y)\left[xI_1 + zI_2 - S_1\right] \triangleq F_{grid}(x,y,z). \quad (2)$$

In order to find the stable state after a sufficiently long period, based on stability analysis theory, let $F_{grid}(x,y,z) = 0$, to obtain the stable state:

(i) $y = 0$;

(ii) $y = 1$;

(iii) $xI_1 + zI_2 = S_1$.

Because $x, z \in [0,1]$, then, $0 < S_1 \le I_1 + I_2$

Expected returns of park customers under different circumstances

Then, analyze the benefits for park customers when the government and grid companies implement different schemes, as detailed in Table 5.

Table 5. Expected returns of park customers under different circumstances

Park customers	Government	Grid Company	Earnings
Not accepted, With a probability of *1-z*	No excitation, *1-x*	Do not implement, *1-y*	D_0
	Motivate *x*	Not implemented, *1-y*	D_0
	Do not motivate, *1-x*	Implement, *y*	D_0
	Motivate *x*	Implementation, *y*	D_0
Acceptance of value-added service projects with probability *z*	No excitation, *1-x*	Do not implement, *1-y*	D_0
	Motivate *x*	Not implemented, *1-y*	D_0
	Do not motivate, *1-x*	Implement, *y*	$D_0 + D_2 + D_3 - F_1$
	Motivate *x*	Implementation, *y*	$D_0 + D_1 + D_2 + D_3 - F_1$

(a) The expected benefits for park customers not accepting getting Electricity value-added services are:

$U_{user}^{(0)} = D_0$.

(b) The expected benefits for park customers accepting getting Electricity value-added services are:

$$U_{user}^{(1)} = (1-x)(1-y)D_0 + x(1-y)D_0$$
$$+(1-x)y(D_0 + D_2 + D_3 - F_1)$$
$$+xy(D_0 + D_1 + D_2 + D_3 - F_1)$$

$= D_0 + xyD_1 + y(D_2 + D_3 - F_1)$.

The expected benefits of getting Electricity value-added services for park customers, considering both scenarios of acceptance and non-acceptance, are:

$$\overline{U}_{user} = (1-z)U_{user}^{(0)} + zU_{user}^{(1)}$$

Similarly, establish a replicator dynamic equation to examine the game-changing path of the probability z of park customers accepting incentive policies.

$$\begin{aligned}\frac{dz}{dt} &= z(U_{user}^{(1)} - \overline{U}_{user}) = z(1-z)(U_{user}^{(1)} - U_{user}^{(0)}) \\ &= yz(1-z)(xD_1 + D_2 + D_3 - F_1) \triangleq F_{user}(x,y,z).\end{aligned} \quad (3)$$

In order to find the stable state after a sufficiently long period, based on stability analysis theory, let $F_{user}(x,y,z) = 0$, to obtain the stable state:

(i)$y = 0$;

(ii)$z = 0$;

(iii)$z = 1$;

(iv)$x^* = \dfrac{F_1 - D_2 - D_3}{D_1}$.

Since$x^* \in (0,1)$, then$0 < F_1 - D_2 - D_3 < D_1$, for all z belong to the stable state.

Stability analysis and dynamic evolution of Three-way game

Based on the above discussion, the following conditions need to be considered in the three-way game are summarized:

(a) $0 < F_1 - D_2 - D_3 < D_1$,

(b) $0 < S_1 \le I_1 + I_2$,

(c) $0 < C_1 + C_1' \le R_2 - R_1 + R_2' - R_1'$,

(d) $R_2 > R_1, R_2' > R_1'$.

The differential equation system satisfied by the government, power grid Company and park customers is

$$\begin{cases} \dfrac{dx}{dt} = x(1-x)[y(R_2 - R_1) + z(R_2^{'} - R_1^{'}) - C_1 - C_1^{'}] \\ \dfrac{dy}{dt} = y(1-y)[xI_1 + zI_2 - S_1] \\ \dfrac{dz}{dt} = yz(1-z)(xD_1 + D_2 + D_3 - F_1) \end{cases} \quad (4)$$

Given the constraints based on the aforementioned parameters, to explore the dynamic evolution process of grid companies, park customers, and the government under initial probability conditions, a MATLAB numerical solution program for differential equation dynamical system (4) is developed, with parameter values as follows:

$R_1 = 0.5,\ R_2 = 1.0, R_1' = 0.5, R_2' = 1.0, C_1 = 0.3, C_1' = 0.3, I_1 = 1.0, I_2 = 1.0,$

$S_1 = 1.2, D_1 = 0.8 = 7, D_2 = 0.2, D_3 = 0.2, F_1 = 0.8,$

The initial probability of the three parties is$x_0 = 0.75, y_0 = 0.55, z_0 = 0.55.$, and the dynamic evolution process of the three-way game is shown in Figure2(a). The spatial variation curve of three-way game is shown in Figure 2(b).

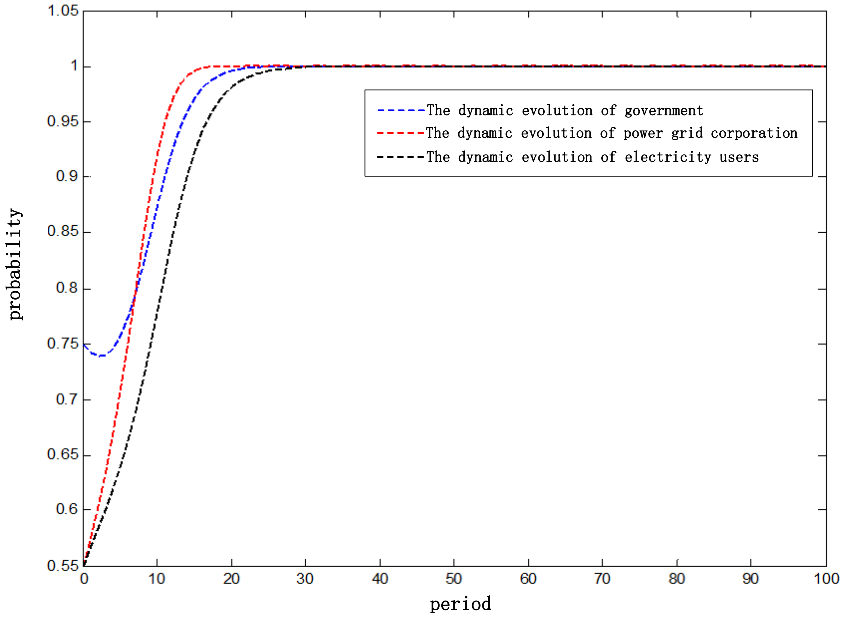


Figure 2. (a) The dynamic evolutionary process of the three-way game when the initial state is x_0=0.75, y_0=0.55, z_0=0.55

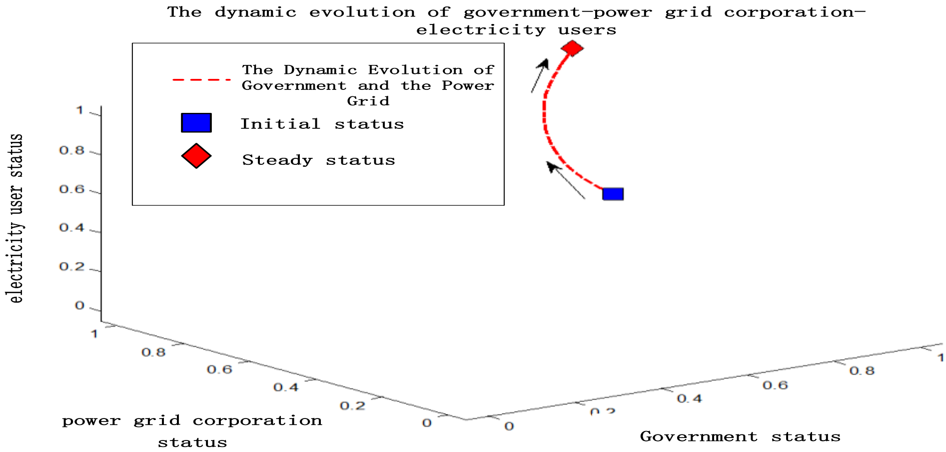


Figure 2. (b) Spatial variation curves of the three-way game

From Figure 2(a) and Figure 2(b), it can be seen that following the initial state meeting the set conditions, the grid companies, park customers, and government can ultimately achieve a state of (1,1,1), meaning that grid companies implement the getting electricity value-added services, park customers accept the getting electricity value-added services, and the government incentivizes the getting electricity value-added services.

THE REALIZATION PATH OF TRIPARTITE INTEREST COORDINATION UNDER DIFFERENT INVESTMENT INTERFACE EXTENSION STANDARDS

Accordingly, there are four main necessary conditions for achieving stable cooperation and operation of the "government--- grid companies--- park customers " in the extension of the Getting Electricity investment interface services, ensuring a coordinated and win-win situation for all three parties.

The Implementation Path for Adjusting the Initial Intentions of the Three Parties

Based on the dynamic evolution and stability analysis of the game among the government, grid companies, and park customers, it is known that the evolutionary trend of the tripartite cooperation relationship is related to their initial intentions and the corresponding stability regions.

When x_0, y_0, z_0 takes different values, the dynamic evolutionary process of the government and park customers is shown in Figure 3.

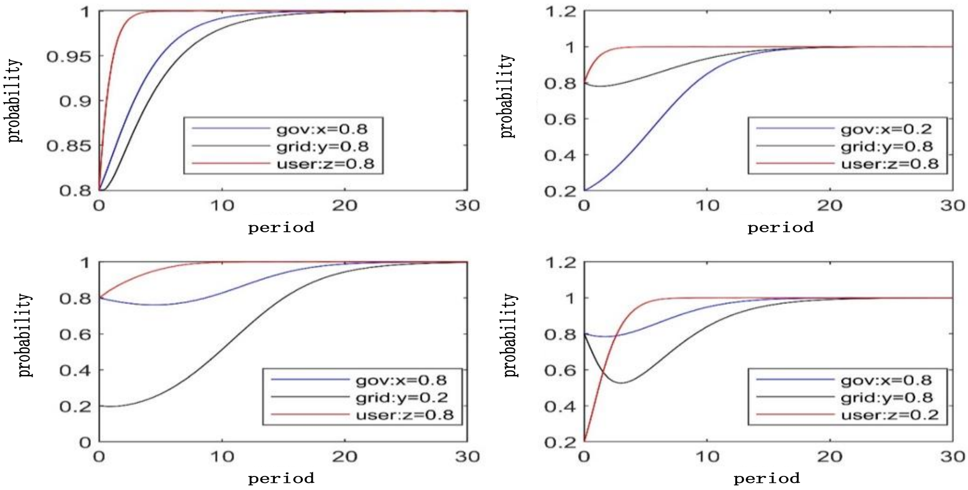
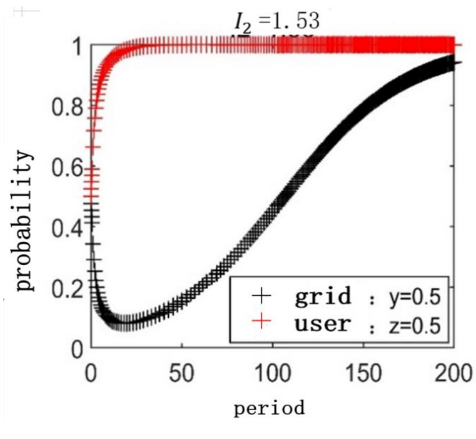


Figure 3. The dynamic evolutionary process of the three-way game under different initial intentions

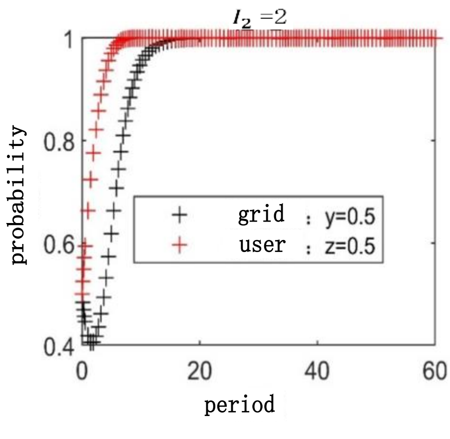
As shown in Figure 3, when the initial intentions of all three parties are relatively high ($x_0, y_0, z_0 = 0.8$), the three parties quickly tend to move towards a cooperative model state within this dynamic system. When the initial intention of either the government, the power grid, or the park customers is relatively low, it initially has some impact, but eventually, all three parties also tend to move towards a cooperative model state.

Implementation Path for Cost Control of Investment Interface Extension Service Projects by Power grid Company

The various costs incurred by grid companies in implementing investment interface extension service projects (planning, construction, operation, etc.) must be strictly less than the sum of the following two items ($0 < S_1 \leq I_1 + I_2$). As shown in Figure 4.



1) Dynamic evolution process of power grid Company and park customers (I_2=1.53)



2) Dynamic evolution process of power grid Company and park customers (I_2=2)

Figure 4. I_2 **(Equivalent System Benefits for Power Grid Company) influence on the cooperation status of both parties**

As shown in Figure 4, if the equivalent benefits created by the extension of the power grid investment interface (I_2=1.53), the government and the power grid initially lack the willingness to participate. However, after a period of evolutionary game, the three parties can form a cooperative model state. Additionally, the larger this part of the equivalent benefits (I_2=1.8), the shorter the duration of negative intentions in the strategy evolution process of the power grid enterprises and the government, which is more conducive to the three parties achieving a win-win cooperation situation sooner.

Implementation Path of the Government's Cost Control of Incentive Policies for Power Grid Company and Park Customers

For the government, the sum of the costs of incentivizing grid companies and park customers, under the conditions of park customers accepting the investment interface extension service and grid companies implementing service projects, must be strictly less than the social and environmental benefits when the government incentivizes - the social and environmental benefits in the scenario where park customers accept the investment interface extension service and grid companies implement service projects, and the government does not incentivize. That is, the corresponding condition is: $0 < C_1 + C_1' \leq R_2 - R_1 + R_2' - R_1'$.

Implementation Path for Adjusting the Government's Participation Degree (1-α)

If the grid companies invests 80% and the government invests 20%, the game cycle between the two parties can be shortened by 2/3; when the grid companies invests 60% and the government invests 40%, the game cycle can be shortened by 4/5. This shows that government participation in investment interface extension services has a positive impact on the formation of cooperative operating models between grid companies and park customers. As shown in Figure 5.

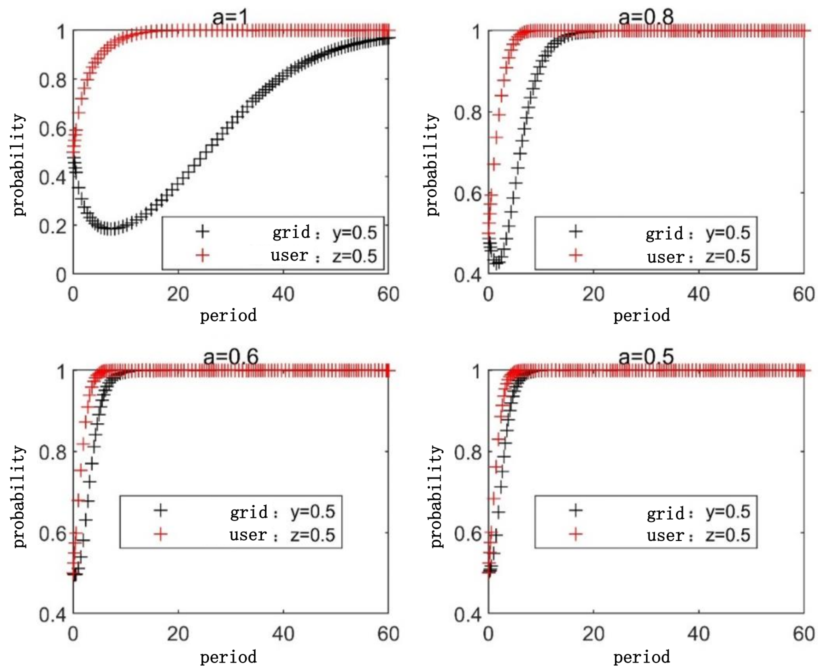


Figure 5 Dynamic evolution of power grid Company and park users under different levels of government involvement

CONCLUSION AND DISCUSSION

By constructing an evolutionary model for the cooperative operation mechanism of the power grid enterprises, park customers, and the government in the "Getting Electricity" investment interface strategy, this paper analyzes the equilibrium stability and influencing factors under different game situations. This includes an equilibrium stability analysis of the government, power grid enterprises, and park customers in the scenario of value-added electricity services for key parks in the Hainan Free Trade Port. Based on this, from the perspective of project implementation, the paper provides pathways for coordinating the interests of the three parties under different standards of investment interface extension. It addresses some fundamental issues of the "Getting Electricity" investment interface extension strategy for the Hainan power grid. Furthermore, case analysis shows that when the power grid invests 60% and the government invests 40%, the game cycle between the two parties can be shortened by 4/5, making it easier to achieve stable linkage and value enhancement in the cooperative operation of "Getting Electricity" supply services aimed at optimizing the business environment in the Hainan power grid. This also aligns with related research conclusions [21].

To support the construction of a high-level free trade port in Hainan, Hainan Power Grid Co., Ltd. can further expand the scope and range of the "Getting Electricity" investment extension policy execution. This involves considering the connection of key parks to electricity, the use of electricity, and the inclusion of value-added electric power into the entire system. By analyzing the historical electricity usage behavior characteristics of high-voltage park customers, the evolutionary features of the tripartite dynamic game model can be further refined. Based on quantitative analysis, targeted at different customer types, as well as phased and step-by-step " Getting Electricity " investment extension strategies can be developed. This facilitates the formulation of targeted free trade port energy construction support policies, continuously improving the level of electricity access in the Hainan Free Trade Port.

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