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# The Impact of Government Subsidies on the Alliance Mechanism Between Microgrids and Shared Energy Storage Under A Three-Party Evolutionary Game

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**Abstract:** Aggregating distributed renewable energy (RE), flexible loads, and energy storage (ES) in microgrids (MGs) is a feasible option for optimizing energy structures and facilitating the low-carbon transformation of power systems. The shared energy storage (SES) model, as an emerging business model, can reduce the resource waste issues caused by the ES configuration of individual MGs, and connect multiple MGs to achieve energy sharing among different MGs. However, the cooperation between MGs and SES is influenced by government subsidies. The transition to a sustainable energy system requires a strong policy and regulatory framework to support the deployment of RE MGs and ES systems. This paper addresses the cooperation between MGs and SES. Firstly, considering the limited rationality of participants, it proposes an evolutionary game approach to analyze the impact of government subsidies on their alliance mechanism. Secondly, it demonstrates the stability of the equilibrium points in the aforementioned game model, discusses the equilibrium stability of the system under different gaming scenarios and their influencing factors, and further analyzes the dynamic behavioral characteristics of trilateral evolution. Finally, the impact of different initial strategy states, subsidy costs, penalty amounts, and profit statuses on the behavior of each party is discussed. The results confirm the validity of the proposed model.

**Keywords:** Evolutionary game, shared energy storage (SES), microgrids (MGs), government subsidies.

## INTRODUCTION

Energy reliance on fossil fuels plays a significant role in the escalating global greenhouse gas (GHG) emissions. To address global energy issues, renewable energy (RE) generation is rapidly increasing worldwide [1]. RE microgrids (MGs) achieve centralized management by aggregating distributed RE, flexible loads, and energy storage (ES) to meet load demands and provide flexible responses. This has become the most viable option to bridge the gap between energy supply and demand and to tackle the global challenges of climate change [2], [3], [4]. However, the intermittent and variable output of RE represented by wind power and photovoltaic can affect the power and energy balance of the microgrid cluster [5]. Configuring systems with ES characteristics within the MGs can transfer the surplus electricity generated by RE to the remaining periods of electricity shortage. This smooths out the output curve of RE generation, addresses the issue of wind curtailment, and alleviates the burden on the grid. Therefore, ES plays an important role in managing the randomness and intermittency of RE, and it is a key technology in the transition to a low-carbon economy and the energy revolution [6], [7].

In 2018, Qinghai Province in China proposed the “shared energy storage (SES)” business model, which refers to independent ES operators gathering user demand, investing in the construction of ES power stations, and providing SES services [8]. In the SES scheme, multiple energy consumers can use a shared ES device [9]. Therefore, multiple MGs can be connected through an SES model, enabling energy sharing between different MGs and reducing the issues of resource waste and high costs that may arise from a single MG’s storage configuration [10]. However, the adoption and widespread implementation of RE MGs and ES systems are largely influenced by the surrounding policy and regulatory frameworks [11]. Sani et al. [12] reviewed global policies for the development of the ES industry and concluded that subsidies and market conditions are significant factors in the growth of the ES sector. Yuan et al. [13], Zhu et al. [14], and Liu et al. [15] analyze the ES policies of the European Union, the United Kingdom, and Australia, providing a detailed discussion on the influences of technological research and development, financial subsidies, and market entities on the growth of the ES industry. The government can promote the advancement of ES technologies through policies that encourage industrial development. Currently, multiple regions in China are successively implementing policies for the integration of ES and RE [16]. The government vigorously advocates for investment and construction of SES stations, using policy subsidies to incentivize the supporting infrastructure or the implementation of shared models for new ES projects in RE generation, further promoting SES. However, the deployment of RE MGs and storage systems may face significant obstacles in the absence of sound policies and regulations, including high initial costs, technical and operational challenges, as well as regulatory uncertainties [11]. Paul et al. [11] argue that it is necessary to study the policies and regulatory frameworks that support the adoption of RE MGs and storage systems. Understanding these frameworks can provide insights into best practices and lessons learned across regions, highlight challenges and barriers related to implementation, and offer recommendations for developing more effective and adaptive policies.

The current research on shared ES and microgrid fields has become quite extensive. Ren et al. [17] and Zhang et al. [18] studied the optimal scale of ES in MG system configuration, maximizing the utilization of ES while also enhancing the absorption rate of RE. Kandari et al. [19] provide a review of research on ES in MG configurations, analyzing that compared to simple battery storage systems, hybrid ES systems can enhance the stability and reliability of microgrid operations. Wang et al. [20] proposed a blockchain-based collaborative economic dispatch method for MGs to address privacy and security issues, enhancing the safety, economy, and reliability of the microgrid clusters. In the literature mentioned above, under the mode where a single MG is independently configured with an ES system, the MG experiences a significant phenomenon of RE abandonment due to limited scheduling capability. The investment cost for independently configuring ES in the MG is relatively high, and the scheduling behavior within the MG is chaotic, leading to low ES efficiency.

Under the development of the SES model, MGs can lease ES capacity from ES stations to replace their current practice of independently configuring ES devices. At the same time, by interconnecting MGs through SES, the large scale of the ES systems based on the shared storage model can further accommodate RE within the region. At this point, the electricity of each MG is uniformly charged and discharged by the SES station, enhancing the economic efficiency and stability of the system operation.

In the research on the operation of MGs and SES alliances, Cao et al. [21] propose a model for multiple MGs that incorporates hybrid storage and energy sharing, where multiple MGs collaboratively share energy through a hybrid ES system.

Shi et al. [22] propose an optimization strategy for planning MGs consisting of shared hydrogen storage systems, demonstrating that the complementarity between MGs and hydrogen ES configurations can eliminate power outage phenomena and reduce the dependence of MGs on the grid. Diaz et al. [23] evaluate the feasibility of using hydrogen energy as an ES system in MGs. Xu et al. [24] describe the design of a dual-layer alternating direction multiplier method to solve the energy coordination optimization scheduling problem between SES and multiple MGs. In the above studies, the collaboration between MGs and SES can effectively coordinate ES and utilization. However, most of the aforementioned studies assume that participants are fully rational, meaning that ES entities can accurately decide whether to share storage capacity and how much to share and that ES providers can make rational decisions about whether to lease storage capacity and how much to lease. In reality, the ES service transaction behaviors of different stakeholders exhibit strong randomness and unpredictability, making it necessary to propose an optimization method based on bounded rationality game theory to analyze this situation.

Game theory has two fundamental research methods: classical game theory based on the assumption of fully rational individuals and evolutionary game theory based on the assumption of boundedly rational individuals. Classical game theory focuses on studying how fully rational participants in a game make decisions to maximize their game payoffs or utility, while the advantage of evolutionary game theory is that it does not require all members of the game to be fully rational, nor does it require the ability to have complete information [25]. WER has developed an evolutionary game approach that takes into account the limited rationality of participants for ES providers, SES operators, and ES users. This approach employs a mechanism of natural selection, without strict rationality assumptions, making it closer to reality and better reflecting the spontaneous evolution of strategies among different stakeholders.

This article uses evolutionary game theory to study the evolutionary process of strategy frequencies among different stakeholders in the context of whether the government provides subsidies. The government acts as the dominant party and can provide incentives through subsidy policies for the investment and construction of SES stations and the participating MGs, in response to national policies promoting the development of SES. SES can generate revenue through the price differential between peak and off-peak electricity sales. MGs can reduce their electricity purchasing costs and also earn revenue by transferring excess electricity to SES. Overall, cooperation among the three parties is significant for promoting the consumption of RE. The specific contributions are as follows:

(1) This article analyzes the cooperative behavior between ES entities and MGs, where multiple MGs are interconnected through SES stations to achieve the consumption and coordinated scheduling of RE.

(2) It examines the impact of government subsidy behavior on the cooperation between ES entities and MGs.

(3) By employing evolutionary game theory with limited rationality, it illustrates how the participation behaviors of the government, ES entities, and MGs evolve, discusses the complex balance stability among the three different parties, and analyzes

the complete dynamics of the system. The article also analyzes the effects of factors such as the initial state of strategies, subsidy costs, penalty amounts, and profit states on the behaviors of each party.

## EVOLUTIONARY GAME MODELLING

### Model assumption

Assumption 1: The three participants in the game are assumed to possess finite rationality within a natural environment, without considering any external constraints. They make strategic decisions based on the principle of maximizing benefits while operating under conditions of asymmetric information. Each participant continuously adjusts their strategies through observation, learning, and imitation.

Assumption 2: In the game, the three participants are the government, the SES, and the MGs. The government offers subsidies for SES and MGs to encourage cooperation between the two parties and increase the adoption of RE. SES in cooperation with MGs can generate revenue through the peak-to-valley price difference between the purchase and sale of electricity. MGs can reduce their electricity purchasing costs and additionally profit by transmitting excess electricity to shared storage for resale.

Assumption 3: During the game, the government can choose whether or not to provide subsidies for SES and MGs with the set of strategies (subsidy, no subsidy). SES can choose whether to cooperate with local MGs based on cost and revenue, with a set of strategies (cooperation, no cooperation). MGs can choose whether to cooperate with SES based on their own needs, with the set of strategies (cooperation, no cooperation).

Assumption 4: When the government selects the "subsidy" strategy, it sets the subsidy factors $\alpha$ for both the SES entities and $\beta$ represents the subsidy factor for microgrid cluster entities. Based on the total input cost $C$ of the demonstration project, the government subsidizes the SES cost as $\alpha C$ and the MGs cost as $\beta C$. The government also implements regulatory measures to monitor potential cheating by the other participants concerning the subsidy, with the regulatory cost denoted as $Q$. The total revenue from the operation of the SES is $E_1$, while the total revenue from the operation of the MGs is $G_1$.

Assumption 5: Define $R_1$ as the benefits obtained when the government chooses the "subsidy" strategy, and $b$ as the proportion of the benefits gained under the government chooses the "no subsidy" strategy relative to those under the "subsidy" strategy. In this context, the benefits obtained when the government chooses the "no subsidy" strategy are $bR_1$, where $b$ takes a value between 0 and 1. When the SES chooses the "cooperation" strategy and the MGs also choose the "cooperation" strategy, the SES benefits from the peak-valley price difference $E_2$ and the government subsidy $\alpha C$, while the MGs benefit from reduced electricity purchasing costs $G_2$ and the government subsidy $\beta C$.

Assumption 6: If the SES adopts a "no cooperation" strategy, or if the MGs adopt a "no cooperation" strategy, the government will impose a penalty on the non-cooperating party, with a total penalty amounting to $D$. The penalty coefficients for the SES and the MGs are $d_1$ and $d_2$, so the amount of fines for these two subjects are $d_1D$ and $d_2D$ respectively. Under the government's "no subsidy" strategy, if the MGs tend to adopt the "no cooperation" strategy, the SES will likely adopt the "cooperation" strategy to gain $k_1E_2$. Conversely, if the SES tends to adopt the "no cooperation" strategy, the MGs will gain $k_2G_2$ by cooperating with other ES equipment vendors. In this scenario, the values of $k_1$ and $k_2$ both lie within the range of 0 to 1.

### Game matrix construction

In the model, the government, SES, and the MGs each choose their strategies independently. Denote $x$ as the probability that the government selects the "subsidy" strategy, and 1-$x$ as the probability of choosing the "no subsidy" strategy. Similarly, define $y$ as the probability that the SES chooses the "cooperation" strategy, and 1-$y$ as the probability of choosing the "no cooperation" strategy. For the MGs, represent $z$ as the probability of choosing the "cooperation" strategy, and 1-$z$ as the probability of choosing the "no cooperation" strategy. Based on these assumptions, the payment matrix for the government, SES, and the MGs can be constructed. Table 1 shows the payment matrices of the three-way evolutionary game under government subsidy and no-subsidy strategies, respectively. The values of x,y, and z above all range from 0 to 1.

Table 1. Matrix of returns on the combination of behavioral strategies of the various subjects.

| | | | Government | |
|---|---|---|---|---|
| | | | Subsidy ($x$) | No subsidy (1-$x$) |
| SES | Cooperation ($y$) | MGs Cooperation ($z$) | $R_1$-$C$-$Q$ | $bR_1$ |
| | | | $\alpha C+E_1+E_2$ | $E_1+E_2$ |
| | | | $\beta C+G_1+G_2$ | $G_1+G_2$ |

| | | | | |
|---|---|---|---|---|
| | | MGs No cooperation (1-$z$) | $R_1$-$C$-$Q$+$d_2D$ | $bR_1$ |
| | | | $\alpha C$+$E_1$+$k_1E_2$ | $E_1$+$k_1E_2$ |
| | | | $\beta C$+$G_1$-$d_2D$ | $G_1$ |
| | No cooperation (1-$y$) | MGs Cooperation ($z$) | $R_1$-$C$-$Q$+$d_1D$ | $bR_1$ |
| | | | $\alpha C$+ $E_1$-$d_1D$ | $E_1$ |
| | | | $\beta C$+$G_1$+$k_2G_2$ | $G_1$+$k_2G_2$ |
| | | MGs No cooperation (1-$z$) | $R_1$-$C$-$Q$+$D$ | $bR_1$ |
| | | | $\alpha C$+$E_1$-$d_1D$ | $E_1$ |
| | | | $\beta C$-$d_2D$+$G_1$ | $G_1$ |

## ANALYSIS OF EVOLUTIONARY GAME MODELS

### Analysis of the stability of the strategies of the subjects of the three-way evolutionary game

(1)Analysis of the stability of the government's strategy

Define the government's expected return with subsidy as $U_{11}$, without subsidy as $U_{12}$, and the average expected return as $\overline{U}_1$. Based on Table 1, the expressions for the expected returns under the different strategies chosen by the government can be obtained as follows:

$$\begin{aligned} U_{11} &= yz\left(R_1 - C - Q\right) + y\left(1-z\right)\left(R_1 - C - Q + d_2D\right) + \\ &\left(1-y\right)z\left(R_1 - C - Q + d_1D\right) + \left(1-y\right)\left(1-z\right)\left(R_1 - C - Q + D\right) \end{aligned} \tag{1}$$

$$U_{12} = yzbR_1 + y\left(1-z\right)bR_1 + \left(1-y\right)zbR_1 + \left(1-y\right)\left(1-z\right)bR_1 \tag{2}$$

$$\begin{aligned} \overline{U_1} &= xU_{11} + (1-x)U_{12} = bR_1 + Dx - Qx + R_1x - Cx - bR_1x - Dxy - Dxz + \\ &Dxyz + d_2Dxy + d_1Dxz - d_1Dxyz - d_2Dxyz \end{aligned} \tag{3}$$

A strategy was employed to characterize the species by simulating the dynamic adjustment process, based on the kinetic properties of the replication factors. It reveals evolutionary patterns in population size or proportions and can be described by a dynamic differential equation that describes the probability that a particular pure strategy will be adopted in a population. This dynamic differential equation is known as the replicator Dynamics system (RDS) equation. In an RDS equation, the growth rate of a player's chosen strategy is equal to its 50% gain minus each player's population average 50% gain. The RDS equation for government replication is:

$$F(x) = \frac{dx}{dt} = x(U_{11} - \overline{U_1}) = x(x-1)(Q - D - R_1 + C + bR_1 + Dy + Dz - d_2Dy - d_1Dz) \tag{4}$$

$$F'(x) = (2x-1)(Q - D - R_1 + C + bR_1 + Dy + Dz - d_2Dy - d_1Dz) \tag{5}$$

The principles of the replication RDS equations for the other subjects are the same as above and will not be repeated later.

According to the stability theorem of the differential equation, the probability of the government choosing to subsidize is in a steady state must be satisfied:

$$\begin{cases} F\left(x\right) = 0 \\ \dfrac{dF\left(x\right)}{dx} < 0 \end{cases} \tag{6}$$

Proposition 1: Define $y^* = \dfrac{R_1 - Q - C - bR_1 + D - d_2Dz}{d_1D}$. When $y > y^*$ no subsidy is the stabilization strategy of the government. When $y < y^*$, the subsidy is the stabilization strategy of the government, and when $y = y^*$, the stabilization strategy of the government cannot be determined.

Proof: Let $P(y) = Q - D - R_1 + C + bR_1 + Dy + Dz - d_2Dy - d_1Dz$, and get $y^* = \dfrac{R_1 - Q - C - bR_1 + D - d_2Dz}{d_1D}$ from $P(y) = 0$.

From $\frac{\partial P(y)}{\partial y} > 0$, 1) $P(y) > 0$ when $y > y*$, which gives $F(x)|_{x=0} = 0$ and $F'(x)|_{x=0} < 0$. Thus $x = 0$ is stable. 2) $P(y) < 0$ when $y < y*$, which gives $F(x)|_{x=1} = 0$ and $F'(x)|_{x=1} < 0$. Thus $x = 1$ is stable. 3) When $y = y*$, $F(x) = 0$ and $F'(x) = 0$, no stable strategy can currently be explicitly determined, and any $x \in [0,1]$ is a steady state.

Proposition 1 suggests that governments are increasingly reluctant to subsidize SES subjects, as these are more likely to operate within MGs.

(2) Analysis of the stability of the SES's strategy

Let the expected return of SES be $U_{21}$ when it tends to the "cooperation" strategy, $U_{22}$ when it chooses the "no cooperation" strategy, and $\overline{U_2}$ when it averages the expected return, and the expressions are as follows:

$$\begin{aligned} U_{21} &= xz(\alpha C + E_1 + E_2) + x(1-z)(\alpha C + E_1 + k_1 E_2) + \\ &(1-x)z(E_1 + E_2) + (1-x)(1-z)(E_1 + k_1 E_2) \end{aligned} \tag{7}$$

$$U_{22} = xz(\alpha C + E_1 - d_1 D) + x(1-z)(\alpha C + E_1 - d_1 D) + (1-x)zE_1 + (1-x)(1-z)E_1 \tag{8}$$

$$\overline{U_2} = yU_{21} + (1-y)U_{22} = E_1 - d_1 Dx + \alpha Cx + k_1 E_2 y + E_2 yz - k_1 E_2 yz + d_1 Dxy \tag{9}$$

The RDS equation for SES replication is:

$$F(y) = \frac{dy}{dt} = y(U_{21} - \overline{U_2}) = y(1-y)(k_1 E_2 + E_2 z + d_1 Dx - k_1 E_2 z) \tag{10}$$

$$F'(y) = (1-2y)(k_1 E_2 + E_2 z + d_1 Dx - k_1 E_2 z) \tag{11}$$

Proposition 2: Define $z* = \frac{-k_1 E_2 - d_1 Dx}{(1-k_1)E_2}$. When $z > z*$ adopting a "cooperation" strategy is a stabilization strategy for SES. Conversely, when $z < z*$, a "no cooperation" strategy is a stable strategy for SES. and when $z = z*$ the stabilization strategy of the SES cannot be determined.

Proof: Let $P(z) = k_1 E_2 + E_2 z + d_1 Dx - k_1 E_2 z$, and get $z* = \frac{-k_1 E_2 - d_1 Dx}{(1-k_1)E_2}$ from $P(z) = 0$.

From $\frac{\partial P(z)}{\partial z} > 0$, $P(z)$ is an increasing function. 1) When $z < z*$, which gives $F(y)|_{y=0} = 0$ and $F'(y)|_{y=0} < 0$. SES favors a "no cooperation" strategy at this time. 2) When $z > z*$, which gives $F(y)|_{y=1} = 0$ and $F'(y)|_{y=1} < 0$. SES favors a "cooperation" strategy at this time. 3) When $z = z*$, $F(y) = 0$ and $F'(y) = 0$, no stable strategy can currently be explicitly determined.

Proposition 2 suggests that SES subjects tend to cooperate with MGs as the willingness of MGs to participate in cooperation increases.

(3) Analysis of the stability of the MGs' strategy

Define the expected return of the MGs as $U_{31}$ when it cooperates, $U_{32}$ when it does not cooperate, and $\overline{U_3}$ for the average expected return. The expressions are as follows:

$$\begin{aligned} U_{31} &= xy(\beta C + G_1 + G_2) + (1-x)y(G_1 + G_2) + \\ &x(1-y)(\beta C + G_1 + k_2 G_2) + (1-x)(1-y)(G_1 + k_2 G_2) \end{aligned} \tag{12}$$

$$\begin{aligned} U_{32} &= xy(\beta C + G_1 - d_2 D) + (1-x)yG_1 + \\ &x(1-y)(\beta C + G_1 - d_2 D) + (1-x)(1-y)G_1 \end{aligned} \tag{13}$$

$$\overline{U_3} == zU_{31} + (1-z)U_{32} = G_1 - G_1 z - d_2 Dx + \beta Cx + k_2 G_2 z + G_1 xz + G_1 yz + G_2 yz - k_2 G_2 yz - G_1 xyz + d_2 Dxz \quad (14)$$

The RDS equation for MGs replication is:

$$F(z) = z(1-z)(k_2 G_2 - G_1 + G_1 x + G_1 y + G_2 y + d_2 Dx - k_2 G_2 y - G_1 xy) \quad (15)$$

$$F'(z) = (1-2z)(k_2 G_2 - G_1 + G_1 x + G_1 y + G_2 y + d_2 Dx - k_2 G_2 y - G_1 xy) \quad (16)$$

Proposition 3: Define $x^* = \frac{k_2 G_2 - G_1 + G_1 y + G_2 y - k_2 G_2 y}{G_1 y - d_2 D - G_1}$. When $x < x^*$, MGs tend not to cooperate with SES. Conversely, when $x > x^*$, MGs tend to choose the strategy of working with SES, and when $x = x^*$, the game cannot get stable strategies.

Proof: Let $P(x) = k_2 G_2 - G_1 + G_1 x + G_1 y + G_2 y + d_2 Dx - k_2 G_2 y - G_1 xy$, and get $x^* = \frac{k_2 G_2 - G_1 + G_1 y + G_2 y - k_2 G_2 y}{G_1 y - d_2 D - G_1}$ from $P(x) = 0$.

From $\frac{\partial P(x)}{\partial x} > 0$, $P(x)$ is an increasing function. 1) When $x < x^*$, which gives $F(z)|_{z=0} = 0$ and $F'(z)|_{z=0} < 0$. The MGs tend to avoid cooperating with SES. 2) When $x > x^*$, which gives $F(z)|_{z=1} = 0$ and $F'(z)|_{z=1} < 0$. The MGs tend to cooperate with SES at this time. 3) When $x = x^*$, $F(z) = 0$ and $F'(z) = 0$, no stable strategy can currently be explicitly determined.

Proposition 3 suggests that with the implementation of government subsidy policies, MGs tend to cooperate with SES.

**Analysis of stabilization strategies in a three-way evolutionary game**

From Eqs. (4), (10), and (15), the replicated power equations for the government, SES, and MGs are given as:

$$\begin{cases} F(x) = x(x-1)\begin{pmatrix} Q - D - R_1 + C + bR_1 + \\ Dy + Dz - d_2 Dy - d_1 Dz \end{pmatrix} \\ F(y) = y(1-y)(k_1 E_2 + E_2 z + d_1 Dx - k_1 E_2 z) \\ F(z) = z(1-z)\begin{pmatrix} k_2 G_2 - G_1 + G_1 x + G_1 y + \\ G_2 y + d_2 Dx - k_2 G_2 y - G_1 xy \end{pmatrix} \end{cases} \quad (17)$$

The evolutionary stability strategy (ESS) for the system of differential equations can be derived from the local stability analysis of the Jacobian matrix of the system, which can be obtained according to Eq. (17):

$$J = \begin{pmatrix} \frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} & \frac{\partial F(x)}{\partial z} \\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} & \frac{\partial F(y)}{\partial z} \\ \frac{\partial F(z)}{\partial x} & \frac{\partial F(z)}{\partial y} & \frac{\partial F(z)}{\partial z} \end{pmatrix} = \begin{pmatrix} (2x-1)\begin{pmatrix} Q - D - R_1 + C + bR_1 + \\ Dy + Dz - d_2 Dy - d_1 Dz \end{pmatrix} & x(x-1)(D - d_2 D) & x(x-1)(D - d_1 D) \\ y(1-y) d_1 D & (1-2y)(k_1 E_2 + E_2 z + d_1 Dx - k_1 E_2 z) & y(1-y)(E_2 - k_1 E_2) \\ z(1-z)(G_1 + d_2 D - G_1 y) & z(1-z)(G_1 + G_2 - k_2 G_2 - G_1 x) & (1-2z)\begin{pmatrix} k_2 G_2 - G_1 + G_1 x + G_1 y + \\ G_2 y + d_2 Dx - k_2 G_2 y - G_1 xy \end{pmatrix} \end{pmatrix} \quad (18)$$

In Eq. (18), defining $F(x) = F(y) = F(z) = 0$, multiple local equilibrium points can be obtained as $T_1$ (0,0,0), $T_2$ (0,1,0), $T_3$ (0,0,1), $T_4$ (1,0,0), $T_5$ (1,1,0), $T_6$ (1,0,1), $T_7$ (0,1,1) and $T_8$ (1,1,1) respectively.

According to evolutionary game theory, if all eigenvalues of the Jacobian matrix are negative, the equilibrium point at this point is the ESS of the system [26].

Substituting each of the eight equilibrium points into the Jacobi matrix (Eq. (18)), the eigenvalues of the Jacobi matrix corresponding to the equilibrium points can be obtained separately as shown in Table 2.

Table 2. Eigenvalues of Jacobi matrix

| Equilibrium point | Eigenvalue $\lambda_1$ | Eigenvalue $\lambda_2$ | Eigenvalue $\lambda_3$ | Stability | Situations |
|---|---|---|---|---|---|
| $T_1$(0,0,0) | $k_1E_2$ | $k_2G_2-G_1$ | $D-C-Q+R_1-bR_1$ | - | - |
| $T_2$(0,1,0) | $G_2$ | $-k_1E_2$ | $R_1-Q-C+d_2D-bR_1$ | - | - |
| $T_3$(0,0,1) | $E_2$ | $G_1-k_2G_2$ | $R_1-Q-C+d_1D-bR_1$ | - | - |
| $T_4$(1,0,0) | $d_1D+k_1E_2$ | $d_2D+k_2G_2$ | $C-D+Q-R_1+bR_1$ | - | - |
| $T_5$(1,1,0) | $-d_1D-k_1E_2$ | $G+d_2D$ | $C+Q-R_1-d_2D+bR_1$ | - | - |
| $T_6$(1,0,1) | $-d_2D-k_2G_2$ | $E_2+d_1D$ | $C+Q-R_1-d_1D+bR_1$ | - | - |
| $T_7$(0,1,1) | $-E_2$ | $-G_2$ | $R_1-Q-C-bR_1$ | ESS | Situation 1 |
| $T_8$(1,1,1) | $-E_2-d_1D$ | $-G_2-d_2D$ | $C+Q-R_1+bR_1$ | ESS | Situation 2 |

Situation 1: $R_1-Q-C<bR_1$, in which the system has a stabilisation point (0, 1, 1) and the corresponding evolutionary strategies are (no subsidy, cooperation, cooperation).

Situation 2: $R_1-Q-C>bR_1$, in which the system has a stability point (1, 1, 1), corresponding to an evolutionary strategy of (subsidy, cooperation, cooperation). That is, the government prefers to adopt the subsidy policy when the benefits of adopting the subsidy are higher than all its paid costs and the benefits of not subsidizing it.

## CASE STUDY

### Simulation and Analysis of Strategic Games

Based on the actual situation, the parameters set in this paper are assigned: $\alpha$=0.7， $\beta$=0.3， $C$=2, $Q$=0.2, $E_1$=1.2, $G_1$=0.5, $R_1$=3, $b$=0.1, $E_2$=1.7, $G_2$=0.8, $d_1$=0.8, $d_2$=0.2, $D$=2, $W$=1.4, $S$=0.6. Due to $R_1-Q-C<bR_1$, based on situation 2 of Table 2, the system has a stabilization point (1, 1, 1).

The values were simulated 125 times to obtain the system equilibrium point (1, 1, 1), which is consistent with the previous analysis in situation 2.

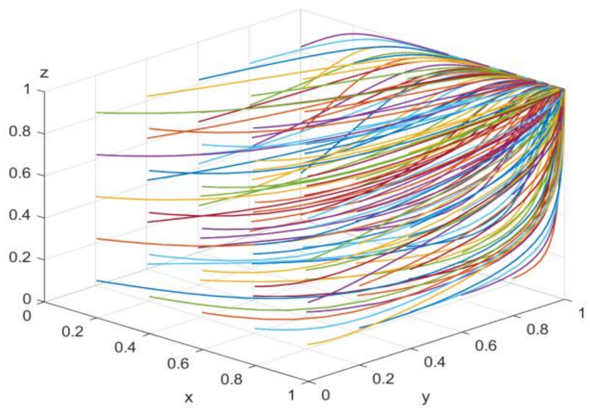


Figure 1. The knot of 125 evolutions of situation 2

Matlab software is used to simulate and analyze the game process of behavioral choices of government, SES, and MGs in different initial situations.

(1)Government's initial strategy of "no subsidy"

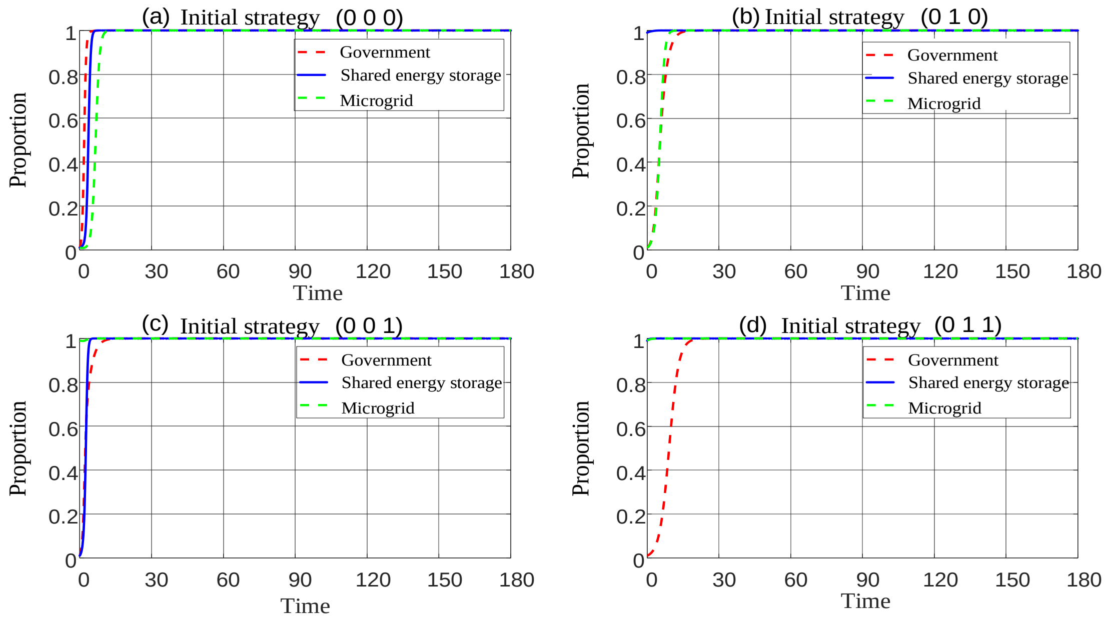


Figure 2. The evolutionary game process when the government initially chooses "no subsidy" situation 2

In case (a), when the initial strategy of the government does not subsidize, the initial strategy of SES does not build stations, and the initial strategy of MGs does not cooperate, because the initial alliance intention of SES and MGs is not strong, to promote the cooperation between the two sides, the government tends to subsidize at first, so that the cooperation between ES power stations and MGs can be reached faster based on SES mode.

In the three cases (b), (c), and (d), the government chooses "subsidy" because the income obtained by the government under the "subsidy" strategy is 0.8, which is much larger than that under the "no subsidy" strategy, so choosing "subsidy" strategy can be more conducive to the government to obtain income.

(2) Government's initial strategy of "subsidy"

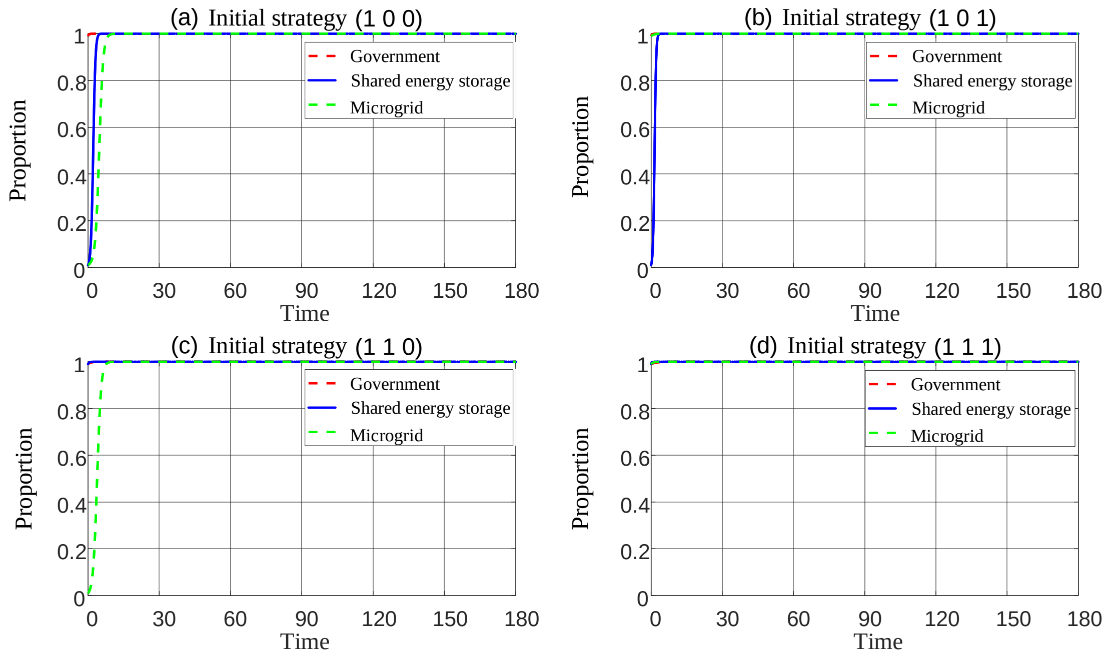


Figure 3. Evolutionary game process when the government initially chooses "subsidy" in situation 2

When the government chooses "subsidy" as the initial strategy, the three scenarios (a), (b), and (c) are more favorable for SES choosing the "cooperation" strategy and MGs choosing the "cooperation" strategy. The government adopts the policy of "subsidy" which is conducive to the government achieving higher revenue, so the government will not end the subsidy to the two parties because the SES and MGs have reached cooperation, and the final evolution of the game equilibrium is (subsidy, cooperation, cooperation) as shown in scenario (d) of Fig. 3.

In the following, the effects of different parameters on the choice of government, SES and MGs strategies are considered, and the actual data are fine-tuned to further assign a second set of values: $\alpha$=0.7, $\beta$=0.3, $C$=2, $Q$=0.2, $E_1$=1.2, $G_1$=0.5, $R_1$=2, $b$=0.1, $E_2$=1.7, $G_2$=0.8, $d_1$=0.8, $d_2$=0.2, $D$=2, $W$=1.4, $S$=0.6. Since $R_1 - Q - C > bR_1$, from the previous situation 1, the system has a stability point (0, 1, 1). The values are simulated 125 times to obtain the system equilibrium point (0, 1, 1) as shown in Fig. 4. This verifies the analysis of situation 1.

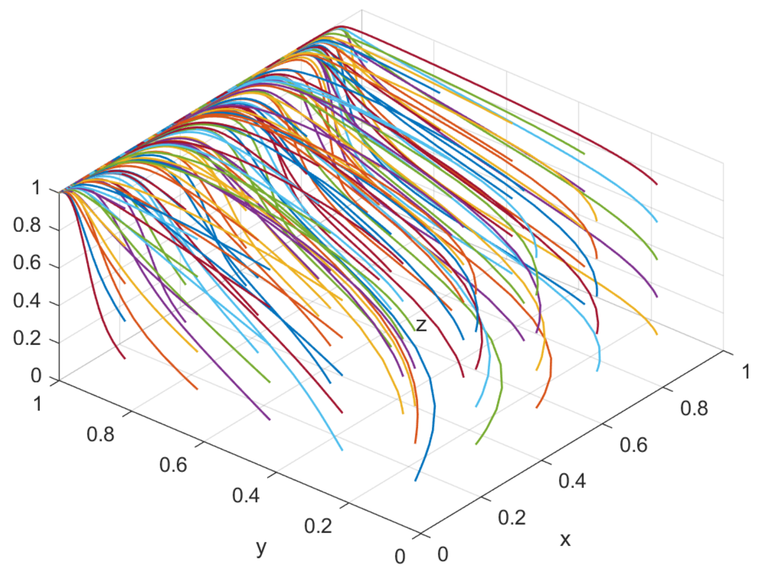


Figure 4. The knot of 125 evolutions of situation 1

(1)Government's initial strategy of "no subsidy"

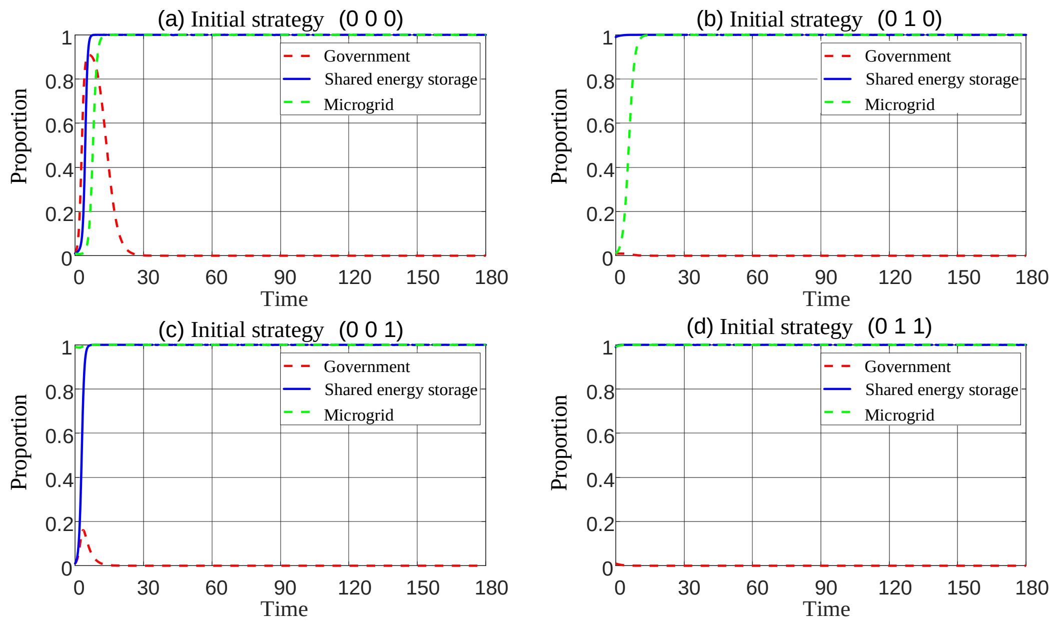


Figure 5. Evolutionary game process when the government initially chooses "no subsidy" in situation 1

In scenario (a), when the government's initial strategy chooses "no subsidy", the SES's initial strategy chooses "no cooperation", and the MGs' initial strategy chooses "no cooperation", due to the SES and MGs' initial alliance willingness is not strong, to promote the two sides to reach cooperation, the government initially favors the “subsidy” strategy, which makes SES plants and MGs reach cooperation more quickly, and when the two sides reach the willingness to cooperate because the government’s adoption of “subsidy” strategy is too low, the government will gradually withdraw the subsidy. In scenarios (b) and (c), the probability of cooperation between the two parties is greatly increased because there is already SES choosing “cooperation” or MGs choosing “cooperation” at the beginning, so the government chooses the “no subsidy” strategy. Therefore, the government chooses the “no subsidy” strategy to reduce the subsidy and regulatory costs of investment.

In scenario (d), the government chooses “no subsidy” because the MGs and the SES have already reached cooperation. According to Figure 5, only in scenario (d) do the strategies of each party remain unchanged, proving that equilibrium has been reached, and the equilibrium point in this case is (0, 1, 1).

(2) Government’s initial strategy of “subsidy”

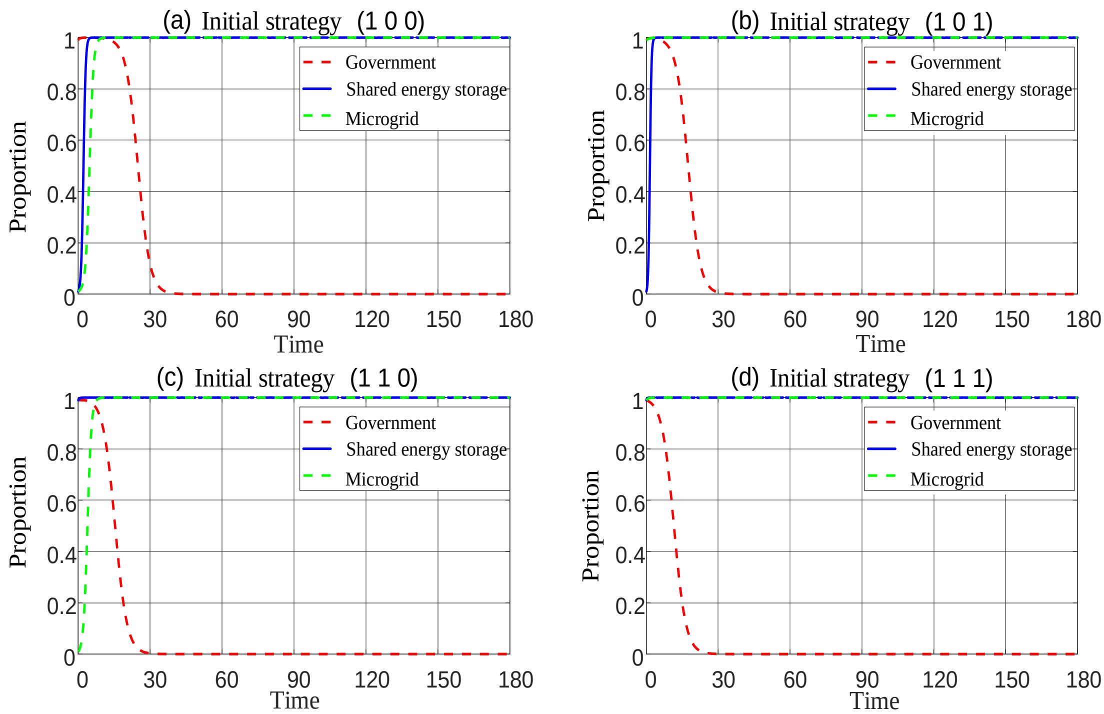


Figure 6. The evolutionary game process when the government initially chooses “subsidy” in situation 1

The government chooses the “subsidy” strategy at the beginning, the SES and microgrid subjects in scenarios (a), (b) and (c) all quickly reach cooperation because of the government’s subsidy. Due to the high proportion of government subsidies to SES, under the guidance of policies, SES has a stronger willingness to cooperate than MGs. The goal of “cooperation” is reached more quickly. However, with the cooperation between the two parties, the government gradually withdrew from the subsidy policy because of the low income. The sooner the cooperation between SES and MGs is reached, the faster the government’s subsidy withdrawal will be.

**Sensitivity analysis**

(1) The effect of subsidy costs on evolutionary paths when governments choose a “subsidy” strategy

Both SES and MGs will eventually converge to the alliance cooperation strategy, but the two sides tend to have different convergence speeds in the cooperation process. This sensitivity analysis mainly analyses the impact of subsidy costs on the convergence speed. Therefore, only the initial strategy (subsidy, no cooperation, no cooperation) is selected for the analysis.

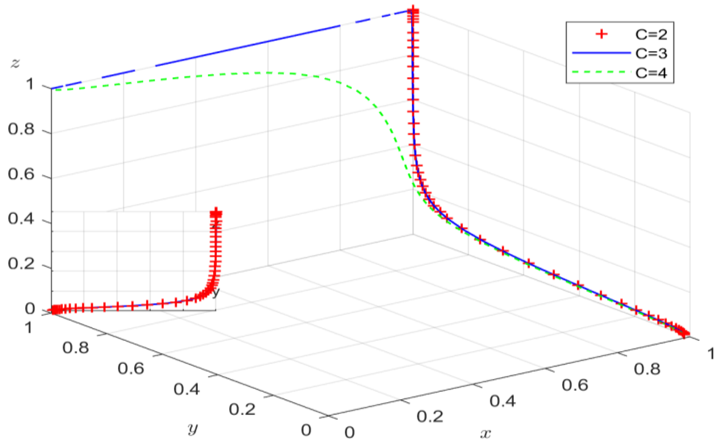


Figure 7. Effect of subsidy cost *C* on evolutionary paths

Figure 7 shows a three-dimensional plot of the effect of subsidy cost *C* on the evolutionary path. As can be seen from Figure 7, when the government's subsidy cost $C = 2$, the government's subsidy cost is small, and the SES and MGs converge to the coalition under the government's subsidy behavior more and more quickly. Since the government's benefit in situation 2 is higher than that of the "no subsidy" strategy, the government will eventually tend to choose the "subsidy" strategy. At this point, the stabilization strategy evolves from (subsidy, no cooperation, no cooperation) to (subsidy, cooperation, cooperation).

When the government's subsidy cost $C = 3$, the government's gain is slightly lower than the gain when it does not subsidize, so when the SES and MGs tend to ally, the government immediately stops the subsidy policy to reduce the loss. When $C$=4, at this point, the government's gain from subsidizing is less than the gain from not subsidizing, and the government gradually converges to the "no subsidy" strategy to reduce the loss, which is consistent with situation 1, and thus finally reaches the stabilization point (0, 1, 1), and the stabilization strategy evolves from (subsidy, no cooperation, no cooperation) to (no subsidy, cooperation, cooperation).

(2) The effect of penalty amount on evolutionary paths when governments choose a "subsidy" strategy

When the government's initial strategy chooses subsidy, the SES and MGs will only be penalized if at least one of their initial strategies chooses not to cooperate, so the three scenarios of initial strategies that can be chosen for this sensitivity analysis are (subsidy, no cooperation, no cooperation), (subsidy, no cooperation, cooperation) and (subsidy, cooperation, no cooperation). Since the mechanism of the effect of penalty *D* on the decision-making of SES and MGs is the same in all three scenarios, the (subsidy, no cooperation, no cooperation) is chosen to be analyzed as the initial strategy representative of the evolutionary game.

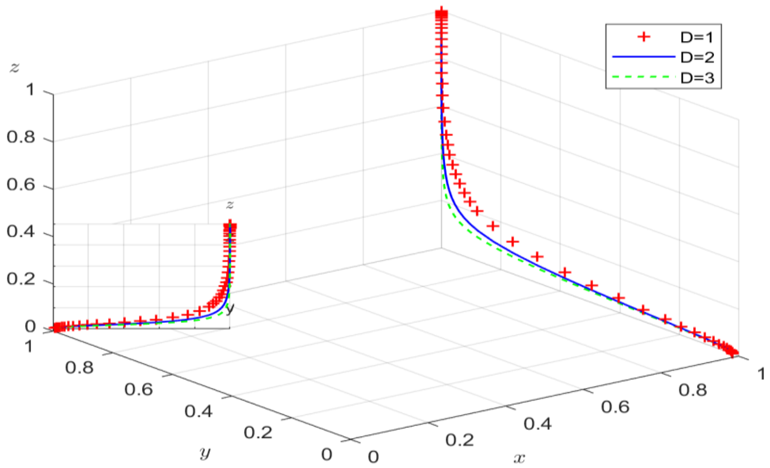


Figure 8. Effect of penalty amount *D* on evolutionary paths

Figure 8 shows the three-dimensional diagram of the influence of penalty amount *D* on the evolutionary path. It can be found through the analysis that the trend of the influence of the penalty amount *D* on the decision-making of SES and MGs is similar. The larger the penalty amount *D* is, the faster the convergence of SES and MGs towards cooperative strategies. Therefore, under the government's choice of "subsidy" strategy, the penalty can be appropriately increased to promote cooperation between SES and MGs to achieve a win-win situation.

(3) The effect of the SES revenue share $k_1$ on the evolutionary path when the government chooses a "no subsidy" strategy

When the government's initial strategy is "no subsidy", the evolutionary game chooses the initial strategy (no subsidy, no cooperation, no cooperation) for analysis. $k_1$ represents the proportion of revenue when only one party of SES is committed to promoting cooperation with the MGs. From Figure 9, it can be seen that when the value of $k_1$ is smaller, the pace of the cooperative alliance between the two parties is slower. Conversely, the speed of the two parties' cooperation is faster. That is to say, when the SES is with multiple MGs the higher the benefit, the easier the two sides to reach cooperation.

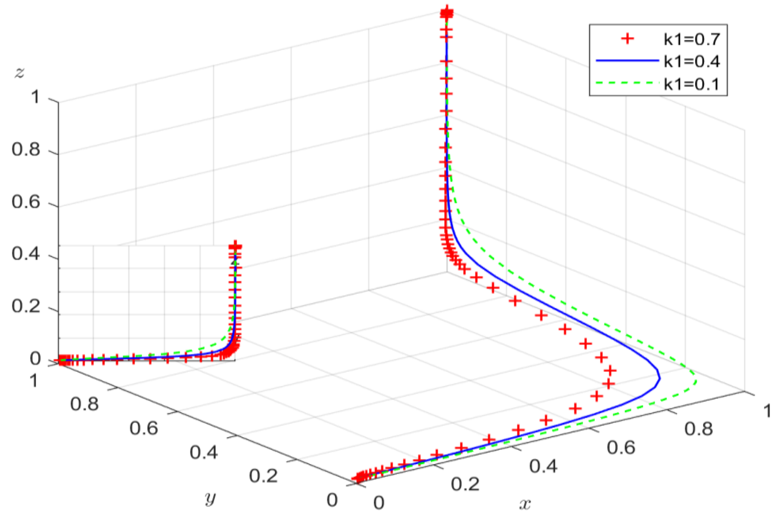


Figure 9. Effect of SES revenue share $k_1$ on evolutionary paths

(4) The effect of the MGs' revenue share $k_2$ on the evolutionary path when the government chooses a "no subsidy" strategy

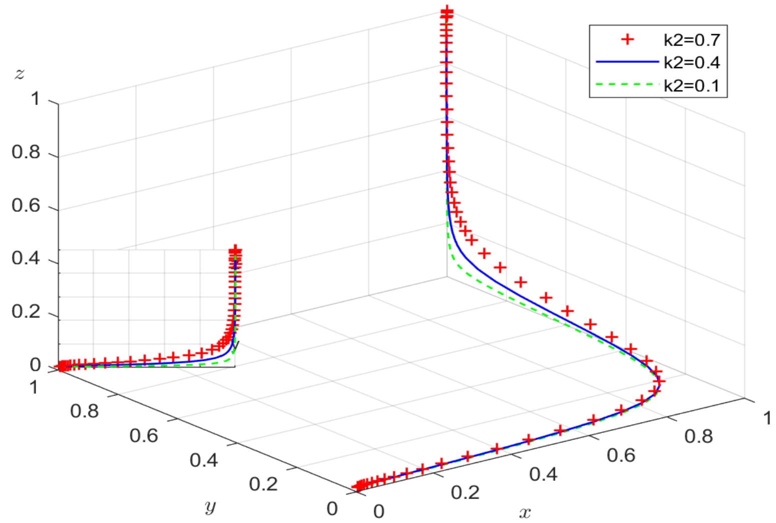


Figure 10. Effect of MGs' revenue share $k_2$ on evolutionary paths

When the government's initial strategy is to choose no subsidy, the initial strategy of (no subsidy, no cooperation, no cooperation) is chosen for analysis. $k_2$ indicates the proportion of gains when only one side of the MGs is committed to promoting alliance cooperation. From Figure 10, it can be seen that when the value of $k_2$ is smaller, the speed of the two sides to reach a cooperative alliance is faster, and when the value of $k_2$ is larger, the speed of the two sides to reach cooperation is slower. So the microgrid group unilaterally seeks the smaller ES cooperation gains. That is to say, when the MGs find it difficult to obtain ES revenue through other channels except leasing ES equipment to SES, the more the MGs tend to lease ES equipment to the main body of SES, the easier it is to reach cooperation between the SES and MGs.

## CONCLUSION

This paper takes the finite rationality of each game party as the premise and uses the evolutionary game theory to establish the alliance game payment matrix of the government, SES, and MGs. Systematically analyses the decision-making evolution process among the three participants, and combines numerical analyses to examine the alliance strategy behaviors of the government, SES, and MGs and their influencing factors. This paper draws the following conclusions:

(1) An appropriate increase in the cost of subsidies by the government can promote the formation of cooperation between SES and MGs, but too high a cost will reduce government revenue, so the cost of subsidies needs to be appropriate.

(2) The larger the penalty amount *D* of the government for the SES and MGs, the faster the convergence of the SES and MGs towards the alliance strategy. Therefore, under the government's choice of subsidy strategy, an appropriate increase in the amount of punishment can promote alliance formation.

(3) In addition to the influence of government subsidies, enhancing the benefits of cooperation between SES and MGs is also an effective way to promote their cooperation.

(4) Regardless of government subsidies, SES and MGs tend to cooperate under existing circumstances. This is because when multiple MGs fail to find other alternative ES modes to reduce the cost of SES. SES can connect MGs and unify RE consumption. This not only reduces the cost of independently configuring ES systems for MGs but also increases the revenue of MGs to some extent. In addition, it expands the commercial cooperation opportunities for SES, creating a win-win situation for both parties.

In this paper, we only consider the commercial cooperation between SES and MG groups under the government subsidy behavior. In the future, the cost and benefit impacts on other MGs, caused by one MG using and crowding out ES capacity, can be further explored when SES cooperates with a cluster of MGs.

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