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Research on strategy of green electricity acquisition transaction of park-level energy internet by using STP

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In order to save resources and reduce air pollution, human beings have begun to pay attention to the production and use of photovoltaic, wind power and other green power. Due to the difficulty of direct transaction between green power producers and power users, a park-level energy Internet has been proposed and used to connect all kinds of green electricity with power users. Then park users can effectively buy and use green electricity. Taking the park-level energy Internet as the scenario, this paper constructs a transaction model between green power operators and green power producers. The model is a dynamic game of complete and perfect information. The dynamic characteristics of this game model are analyzed by using semi-tensor product method, and corresponding strategies are provided for all players. From the results obtained, it is easy to find that in many cases, the strategy profile of all participants are constantly changing to obtain more profits, rather than stable at some traditional Nash equilibrium.

KEYWORDS

park-level energy internet, green electricity, green power operator, green power producer, game, semi-tensor product of matrices, Nash equilibrium

1 Introduction

Because of the limited resources and the increasingly serious environmental pollution, in recent years, many countries in the world have paid much attention to the production and consumption of renewable energy. For example, China has issued many policy documents on renewable resources, which promoted the rapid development of China's renewable resources. More and more households are trying to produce and use green power, such as photovoltaic and wind power. These households may sell their excess electricity to the grid company or directly to other customers. In the future, the power grid company may be more responsible for power grid operation, maintenance, power transmission, system upgrade and capacity expansion. For both sides of the direct transaction of green power, the power grid company charges an appropriate network fees to ensure sufficient communication capability between the power management system and scheduling agencies (Deng et al., 2019).

On the other hand, since green power transactions involve many technical issues in data processing, security and so on, a kind of energy Internet appears, called park-level energy Internet. Through interconnection of multiple types of distributed energy sources, multiple types of loads, energy storage and information flow, etc., park-level energy Internets can promote a large proportion of renewable energy access and green power market transaction (Huang et al., 2020). And in order to realize the continuous power supply to the users in the park, the park-level energy Internet is connected to the external power grid, which plays a unified role in the allocation of power resources and acts as a backup power source through the dual-main line configuration (Zhang and Tong, 2022).

However, there are various difficulties in the process of direct transaction between green power producers (GPPs) and power users. The current direct trade rules can not guarantee the interests of all parties directly related to the transaction. Therefore, there is usually a green power operator (GPO) in the park. The GPO purchases power from traditional energy generators, renewable energy generators and external grids. And it determines a price at which the GPO sells green electricity to users by referring to the traditional electricity price and the history of transactions.

Many excellent researchers have considered the transaction model between GPOs and park users and have given some results (Sun and Nie, 2015; Pineda and Bock, 2016; Tai et al., 2016; Zhang and Tong, 2022). But they all emphasize the application of block chain technology in energy trading. For example, Zhang used block chain technology to build a bargaining game model of power transaction between GPOs and power users (Zhang and Tong, 2022). However, there is little discussion on how to determine a price at which small-scale GPPs sell green power to GPOs. Taking the park as the application background, we try to model and analyze the transaction process of GPOs and GPPs.

2 Preliminaries

For the sake of simplicity, we introduce some notations.

- δ_n^i: the ith column of the $n \times n$ identity matrix;
- $\Delta_n := \{\delta_n^i \mid i = 1, 2, \ldots, n\}$, namely Δ_n denotes the set of all columns of $n \times n$ identity matrix;
- $\delta_n[i_1, i_2, \ldots, i_s] := [\delta_n^{i_1}\ \delta_n^{i_2} \cdots \delta_n^{i_s}]$, called logical matrix;
- $\mathbb{L}_{m\times n}$: the set of $m \times n$ logical matrices;
- $\mathbb{M}_{m\times n}$: the set of all $m \times n$ real matrices;
- $\mathbb{R}^n$: the set of all n-dimensional real vectors;
- $Col_i(M)(Row_i(M))$: the ith column (row) of a matrix M.

The green power trading model we will establish later is a game model, so we need to give a proper strategic updating rule and analyze its characteristics. The following are two basic concepts of game theory.

Definition 1 [(Cheng et al., 2015; Robert, 1999)]. *A normal game consists of three factors:*

1) *n players $N = \{1, 2, \ldots, n\}$;*
2) *Player i has the strategy set $S_i = \{1, 2, \ldots, k_i\}, i = 1, 2, \ldots, n$, and $S = \Pi_{i=1}^n S_i$ is the set of profiles;*
3) *Payoff functions $c_i : S \to \mathbb{R}, \quad i = 1, 2, \ldots, n$.*

Definition 2 [(Robert, 1999)]. *In the n-player normal game $G = \{S_1, \ldots, S_n; c_1, \ldots, c_n\}$, the strategies $\{s_1^*, \ldots, s_n^*\}$ are a Nash equilibrium if, for each player i, s_i^* is player i's best response to the strategies specified for the $n-1$ other players $\{s_1^*, \ldots, s_{i-1}^*, s_{i+1}^*, \ldots, s_n^*\}$:*

$$c_i\left(s_1^*, \ldots, s_{i-1}^*, s_i^*, s_{i+1}^*, \ldots, s_n^*\right) \geq c_i\left(s_1^*, \ldots, s_{i-1}^*, s_i, s_{i+1}^*, \ldots, s_n^*\right) \tag{1}$$

For a dynamical game, it has been proved in (Cheng et al., 2015) that the game can be determined as a logical dynamic system, as long as its strategy updating rule is assigned. By using a new mathematical tool, called semi-tensor product of matrices (STP), we are able to convert a logical system into its algebraic form (Cheng and Qi, 2009; Cheng and Qi, 2010). Then it is convenient to study logical system under an algebraic framework. In the following, we recall STP and some basic results.

Definition 3 [(Cheng and Qi, 2010)]. *Let $A \in \mathbb{M}_{m\times n}, B \in \mathbb{M}_{p\times q}$, and denote the least common multiplier of n and p by $l = l\,cm\,(n, p)$. Then the STP of A and B is defined as*

$$A \ltimes B := \left(A \otimes I_{\frac{l}{n}}\right)\left(B \otimes I_{\frac{l}{p}}\right), \tag{2}$$

where I_k is the $k \times k$ identity matrix, $\otimes$ is the Kronecker product of matrices.

Remark 1. *STP is a natural generalization of the traditional matrix product, since all fundamental properties of the traditional matrix product are retained. Especially, STP coincides with the traditional matrix product when $n = p$. So the matrix products used in this paper can be thought of as STP and the symbol $\ltimes$ is usually omitted. Some important properties of STP are listed in the following. We refer to (Cheng et al., 2011) for more details.*

1) A $mn \times mn$ matrix

$$W_{[m,n]} = \delta_{mn}[1, m+1, 2m+1, \ldots, (n-1)m+1, 2, m+2, 2m+2, \ldots, (n-1)m+2, \ldots, m, 2m, 3m, \ldots, nm].$$

is called swap matrix. For any two column vectors $x \in \mathbb{R}^m$ and $y \in \mathbb{R}^n$, we have

$$W_{[m,n]}xy = yx.$$

2) A $2^{2n} \times 2^n$ logical matrix Φ_n is defined as

$$\Phi_n = \delta_{2^{2n}}\left[1, 2^n + 2, 2 \times 2^n + 3, \ldots, (2^n - 2)2^n + 2^n - 1, 2^{2n}\right].$$

For any $\delta_{2^n}^i \in \Delta_{2^n}$, we have $\delta_{2^n}^i \ltimes \delta_{2^n}^i = \Phi_n \delta_{2^n}^i$.

Example 1.

1) *Let* $A = \begin{bmatrix} 3 & 1 & 3 & 0 \\ 1 & 3 & 2 & 2 \end{bmatrix}$, $B = \begin{bmatrix} 1 & -2 \\ 2 & 0 \end{bmatrix}$. *According to Definition* 3, *we have*

$$\begin{aligned} &A \ltimes B \\ &= \begin{bmatrix} \begin{bmatrix} 3 & 1 \end{bmatrix} \times 1 + \begin{bmatrix} 3 & 0 \end{bmatrix} \times 2 & \begin{bmatrix} 3 & 1 \end{bmatrix} \times (-2) + \begin{bmatrix} 3 & 0 \end{bmatrix} \times 0 \\ \begin{bmatrix} 1 & 3 \end{bmatrix} \times 1 + \begin{bmatrix} 2 & 2 \end{bmatrix} \times 2 & \begin{bmatrix} 1 & 3 \end{bmatrix} \times (-2) + \begin{bmatrix} 2 & 2 \end{bmatrix} \times 0 \end{bmatrix} \\ &= \begin{bmatrix} 9 & 1 & -6 & -2 \\ 5 & 7 & -2 & -6 \end{bmatrix} \end{aligned}$$

2) *Let* $x = \begin{bmatrix} 2 & 3 & 8 & 1 \end{bmatrix}^T$, $y = \begin{bmatrix} -3 & 0.5 & 2 \end{bmatrix}^T$. *Then*

$$x \ltimes y = \begin{bmatrix} -6 & 1 & 4 & -9 & 1.5 & 6 & -24 & 4 & 16 & -3 & 0.5 & 2 \end{bmatrix}^T$$

3 Model

3.1 Problem analysis

Normally, a small-scale GPP can only sell its green electricity to GPOs, but a GPO may choose to buy traditional electricity outside the park when the electricity price of surrounding GPPs is too high. A GPO usually has multiple GPPs as its neighborhoods. Similarly, each GPP often has multiple GPOs nearby to trade with. Therefore, there is not only competition among operators, but also among nearby GPOs, and none of them can dominate the market alone. To sum up, when the traditional electricity price is lower than the green electricity price, the green power acquisition transaction is regarded as a game model, where the neighbors of a GPP are only GPOs, and the GPO's neighbor has only GPPs, too.

The GPO usually exists in the form of a company or enterprise, and the majority of GPPs are households. So GPPs have no opportunity to bargain directly with GPOs. The transaction process of GPOs and GPPs is roughly as follows:

- *Step1*. It is required by the third-party platform that all GPPs participating in trading activities, must give their quoted price before the official quotation of the GPO on the same day.
- *Step2*. The GPO quotes once a day based on the current market conditions.
- *Step3*. If a GPP agrees to the quotation, then a green electricity transaction between them takes place. Otherwise, the transaction fails and they look forward to next deal.

It is noted that in Step 1, no GPO knows these prices before its quotation. In other words, only after the GPO makes a quotation can it learn of the price of each GPP from the third-party platform, and use it as the reference data for its next quotation. GPOs will make appropriate strategic adjustments according to the previous historical transaction data. Roughly speaking, when the previous transaction price is low, the quotation is still not high and then many GPPs are reluctant to sell green electricity to GPOs. When the transaction volume decreases to a certain extent, or even threatens to be insufficient to maintain the green power supply of GPOs to park users, the quoted price is raised but still not higher than the traditional electricity price.

Similar to the study of general game problems, we assume that.

1) All players are rational and choose the appropriate decisions in order to make more profits every time;
2) GPOs cannot make profits in partnership and must quote independently, and the same to GPPs;
3) GPPs can only sell green power to GPOs nearby, and any one of GPOs has the ability to accept all the renewable electricity in the vicinity.

3.2 Strategy updating rule

As analyzed in **Section 3.1**, the transaction process of GPOs and GPPs is regarded as a game. We adopt Unconditional Imitation (Nowak and May 1992) as the strategy updating rule. Precisely speaking, if

$$j^* = \arg\max_{j \in U(i)} c_j(x(t)), \tag{3}$$

then

$$x_i(t+1) = x_{j^*}(t). \tag{4}$$

where $x(t) = (x_1(t), \ldots, x_i(t), \ldots, x_n(t))^T$, $x_i(t)$ is the strategy of player i at time t, $U(i)$ is the neighborhood of player i (here, meaning those players that can trade with player i).

When there are two different subscripts j_1^* and j_2^*, satisfying

$$c_{j_1^*}(x(t)) = c_{j_2^*}(x(t)) = \max_{j \in U(i)} c_j(x(t)), \tag{5}$$

We describe the strategy in two cases. One is that when the player i is GPP, we set

$$x_i(t+1) = \max\left\{x_{j_1^*}(t), x_{j_2^*}(t)\right\}. \tag{6}$$

Another is that when the player i is GPO, we choose

$$x_i(t+1) = \min\left\{x_{j_1^*}(t), x_{j_2^*}(t)\right\}. \tag{7}$$

3.3 Payoff Bi-matrix

The traditional electricity price of the external network is used as a reference of GPOs. The general cost C_g of a GPO includes two parts: the cost C_1 of purchasing green power from GPPs, the cost C_2 of operation and maintenance of the GPO, namely

$$C_g = C_1 + C_2. \tag{8}$$

According to Assumption 1, only when the green electricity price sold to park users is not higher than the traditional electricity price outside the park, these users are willing to buy green electricity instead of traditional electricity. Therefore, in order to retain these users, the price P_{users} at which GPO sells green power to users, should be less than the traditional electricity price $P_{traditional}$, namely

$$P_{users} \leq P_{traditional}. \tag{9}$$

For any GPO, the following inequality holds to ensure the investment profit in green power

$$P_{quotation} + P_{operation} \leq P_{users}, \tag{10}$$

where $P_{quotation}$ is GPO's quotation for green electricity from GPPs; $P_{operation}$ is the cost price of GPO$'$ operation and maintenance, i.e., the average operating cost of GPO.

Combing (**Eqs. 9**, **10**), we have

$$P_{quotation} + P_{operation} \leq P_{users} \leq P_{traditional}. \tag{11}$$

Hence we get

$$P_{quotation} \leq P_{traditional} - P_{operation} \tag{12}$$

That is, when purchasing green power from GPPs, GPO's quotation should not be higher than the difference between the traditional electricity price and the cost price of GPO$'$ operation and maintenance.

For any GPP, it is also necessary to ensure its profit, so that the GPP is willing to make a green electricity deal with a GPO. Therefore, $P_{quotation}$ should not be lower than the cost price $P_{produce}$ of the GPP.

$$P_{produce} \leq P_{quotation} \tag{13}$$

From (**Eqs. 11–13**), we have

$$P_{produce} \leq P_{traditional} - P_{operation} \tag{14}$$

Let $P_{produce} = A$ and $P_{traditional} - P_{operation} = B$. We divide interval $[A, B]$ into $n+2$ grades: A, $A + \frac{B-A}{n+1}, A + \frac{2(B-A)}{n+1}, \ldots, A + \frac{n(B-A)}{n+1}$ and B. From Assumption 1, no player (i.e. GPO and GPP) wants to choose extreme strategy A or strategy B. Assume that there are m GPPs and GPOs. We set

$$S_1 = S_2 = \cdots = S_m = \left\{A + \frac{B-A}{n+1}, A + \frac{2(B-A)}{n+1}, \ldots, A + \frac{n(B-A)}{n+1}\right\}$$

We simply denote $A + \frac{i(B-A)}{n+1}$ as $i, i = 1, 2, \ldots, n$. Using Unconditional Imitation as the strategy updating rule, we get the payoff bi-matrix as in **Table 1**.

TABLE 1 Payoff bi-matrix.

GPP \ GPO	1	2	$\cdots$	$n-1$	n
1	$(1,n)$	$(2,n-1)$	$\cdots$	$(n-1,2)$	$(n,1)$
2	$(0,0)$	$(2,n-1)$	$\cdots$	$(n-1,2)$	$(n,1)$
$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$
$n-1$	$(0,0)$	$(0,0)$	$\cdots$	$(n-1,2)$	$(n,1)$
n	$(0,0)$	$(0,0)$	$\cdots$	$(0,0)$	$(n,1)$

Remark 2.

1) *The profit of green power is divided into $n+1$ shares on average. The number of shares to win, except for extreme strategies, is considered as a strategy for each player to act in our model.*
2) *From **Table 1**, it is easy to find that the payoff bi-matrix is an asymmetry and upper triangular matrix. This characteristic is determined by the transaction process of GPOs and GPPs, which is shown in **Section 3.1**.*

According to Theorem 3.1 of (Cheng et al., 2015), the strategy dynamics of each player can be expressed as a n-valued logical dynamic system. Now we identify δ_n^k with $k, k = 1, 2, \ldots, m$, then each strategy profile $(k_1, k_2, \ldots, k_m)^T$ is equivalent to $\delta_{n^m}^r$, where

$$\delta_{n^m}^r = \delta_n^{k_1} \ltimes \delta_n^{k_2} \ltimes \cdots \ltimes \delta_n^{k_m} = \delta_{n^m}^{(k_1-1)n^{m-1} + (k_2-1)n^{m-2} + \cdots + (k_{m-1}-1)n + k_m}$$

Namely,

$$r = (k_1 - 1)n^{m-1} + (k_2 - 1)n^{m-2} + \cdots + (k_{m-1} - 1)n + k_m.$$

We use $x_i(t)$ to express the strategy of player i at time step t. Define $x(t) = \ltimes_{i=1}^m x_i(t) \in \Delta_{n^m}$. Then based on STP (Cheng and Qi, 2010), enable us to equivalently transform the above green power transaction model into a linear form as in (**Eq. 15**).

$$x(t+1) = Mx(t), \tag{15}$$

where $M \in \mathbb{L}_{n^m \times n^m}$ is called the structure matrix of system.

Theorem 1. *Assume that there are m_1 GPOs and m_2 GPPs nearby, and denote $m = m_1 + m_2$. For the green power transaction model provided above, a strategy profile $(s_1^*, s_2^*, \ldots, s_m^*)$ is a*

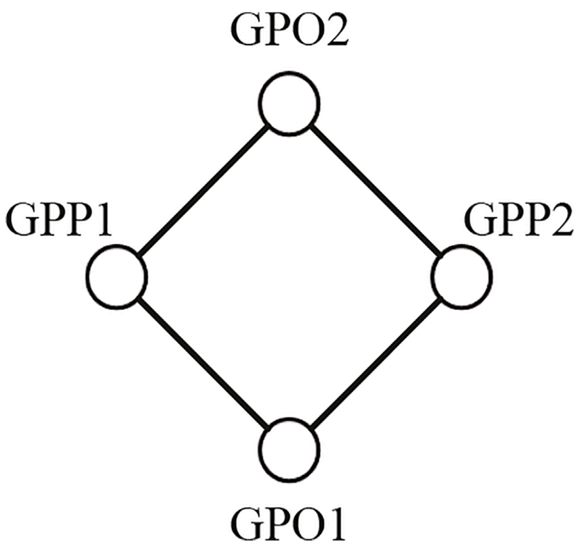

FIGURE1
The topology diagram of two GPOs and two GPPs.

Nash equilibrium, if and only if $Row_r(Col_r(M)) = 1$, *where* $r = (s_1^* - 1)n^{m-1} + (s_2^* - 1)n^{m-2} + \cdots + (s_{m-1}^* - 1)n + s_m^*$.

Froof. *For a strategy profile* $(s_1^*, s_2^*, \ldots, s_m^*)$, *if* $Row_r(Col_r(M)) = 1$, *where* $r = (s_1^* - 1)n^{m-1} + (s_2^* - 1)n^{m-2} + \cdots + (s_{m-1}^* - 1)n + s_m^*$, *then* $x = \delta_{n^m}^r$ *is a fixed point of system* (15), *since it satisfies* $\delta_{n^m}^r = M\delta_{n^m}^r$. *According to the strategy updating rule, each player adopt the best strategy from his neighborhoods. So the fixed point shows that player i still choose the same strategy as before, as long as the strategies of all other players remain unchanged. From Definition 2,* $(s_1^*, s_2^*, \ldots, s_m^*)$ *is a Nash equilibrium. The above analysis process can be deduced backwards. Therefore, the proof is completed.*

4 Illustrative example

For the convenience of showing the method itself, we assume that there are two GPOs and two GPPs nearby. The topology diagram is given as in Figure 1.

Set $n = 2$ and divide interval $[A, B]$ into 4 grades: $A, A + (B - A)/3, A + 2(B - A)/3$ and B. According to the above analysis, four players consisting of two GPPs and two GPOs, definitely not choose extreme strategies A or B. We denote $A + (B - A)/3$ and $A + 2(B - A)/3$ by 1 and 2, respectively. From Table 1, the payoff bi-matrix is given as in Table 2.

In the following, we illustrate how to use the payoff bi-matrix and the strategy updating rule, introduced above, to establish the dynamic characteristics for each player. For example, let $x_1(t) = x_4(t) = 2, x_2(t) = x_3(t) = 1$. For GPP1, it has two neighborhoods: GPO 1 and GPO 2. Then we get

TABLE 2 Payoff bi-matrix for the case of $n = 2$.

GPP \ GPO	1	2
1	(1, 2)	(2, 1)
2	(0, 0)	(2, 1)

$$\begin{aligned}
&c_{1,2}(x_1(t), x_2(t)) = 0, c_{1,4}(x_1(t), x_4(t)) \\
&\quad = 2 \Rightarrow c_1(t) = \max(c_{1,2}, c_{1,4}) = 2 \Rightarrow x_1(t+1) = x_4(t) = 2; \\
&c_{2,1}(x_2(t), x_1(t)) = 0, c_{2,3}(x_2(t), x_3(t)) \\
&\quad = 2 \Rightarrow c_2(t) = \max(c_{2,1}, c_{2,3}) = 2 \Rightarrow x_2(t+1) = x_3(t) = 1; \\
&c_{3,2}(x_3(t), x_2(t)) = 1, c_{3,4}(x_3(t), x_4(t)) \\
&\quad = 2 \Rightarrow c_3(t) = \max(c_{3,2}, c_{3,4}) = 2 \Rightarrow x_3(t+1) = x_4(t) = 2; \\
&c_{4,1}(x_4(t), x_1(t)) = 1, c_{4,3}(x_4(t), x_3(t)) \\
&\quad = 1 \Rightarrow c_4(t) = \max(c_{4,1}, c_{4,3}) = 1 \Rightarrow x_4(t+1) = x_3(t) = 1.
\end{aligned}$$

We use the same argument for each profile $(x_1(t), x_2(t), x_3(t), x_4(t))^T$, and can compute next action for each player as in Table 3.

Identify action k with δ_2^k, $k = 1, 2$. From Table 3, it is verified for each player' strategy that its dynamic characteristics is

$$x_i(t+1) = M_i x(t), \quad i = 1, 2, 3, 4, \tag{16}$$

where $x_i(t) \in \triangle_2, x(t) = \ltimes_{i=1}^4 x_i(t)$, and

$$\begin{aligned}
M_1 &= \delta_2[1,2,1,2,2,2,2,2,1,2,1,2,2,2,2,2], \\
M_2 &= \delta_2[1,1,1,1,1,1,1,1,1,1,2,2,1,1,2,2], \\
M_3 &= \delta_2[1,2,1,2,2,2,2,2,1,2,1,2,2,2,2,2], \\
M_4 &= \delta_2[1,1,1,1,1,1,1,1,1,1,2,2,1,1,2,2].
\end{aligned}$$

By using properties of STP, we obtain

$$\begin{aligned}
x(t+1) &= x_1(t+1)x_2(t+1)x_3(t+1)x_4(t+1) \\
&= M_1x(t)M_2x(t)M_3x(t)M_4x(t) \\
&= M_1W_{[2,16]}M_2x(t)x(t)M_3x(t)M_4x(t) \\
&= M_1W_{[2,16]}M_2\Phi_4x(t)M_3x(t)M_4x(t) \\
&= M_1W_{[2,16]}M_2\Phi_4W_{[2,16]}M_3x(t)x(t)M_4x(t) \\
&= M_1W_{[2,16]}M_2\Phi_4W_{[2,16]}M_3\Phi_4x(t)M_4x(t) \\
&= M_1W_{[2,16]}M_2\Phi_4W_{[2,16]}M_3\Phi_4W_{[2,16]}M_4x(t)x(t) \\
&= M_1W_{[2,16]}M_2\Phi_4W_{[2,16]}M_3\Phi_4W_{[2,16]}M_4\Phi_4x(t) \\
&= Mx(t)
\end{aligned}$$

where

$$\begin{aligned}
M &= M_1W_{[2,16]}M_2\Phi_4W_{[2,16]}M_3\Phi_4W_{[2,16]}M_4\Phi_4 \\
&= \delta_{16}[1,11,1,11,11,11,11,11,1,11,6,16,11,11,16,16].
\end{aligned}$$

TABLE 3 Strategy updating for the case of two GPOs and two GPPs.

Profile	**1111**	**1112**	**1121**	**1122**	**1211**	**1212**	**1221**	**1222**
$c_1(t)$	1	2	1	2	2	2	2	2
$c_2(t)$	2	2	2	2	1	1	1	1
$c_3(t)$	1	2	0	2	2	2	2	2
$c_4(t)$	2	1	2	1	2	1	2	1
$x_1(t+1)$	1	2	1	2	2	2	2	2
$x_2(t+1)$	1	1	1	1	1	1	1	1
$x_3(t+1)$	1	2	1	2	2	2	2	2
$x_4(t+1)$	1	1	1	1	1	1	1	1

Profile	2111	2112	2121	2122	2211	2212	2221	2222
$c_1(t)$	0	2	0	2	2	2	2	2
$c_2(t)$	2	2	0	0	1	1	1	1
$c_3(t)$	1	2	0	2	2	2	2	2
$c_4(t)$	2	1	0	1	2	1	0	1
$x_1(t+1)$	1	2	1	2	2	2	2	2
$x_2(t+1)$	1	1	2	2	1	1	2	2
$x_3(t+1)$	1	2	1	2	2	2	2	2
$x_4(t+1)$	1	1	2	2	1	1	2	2

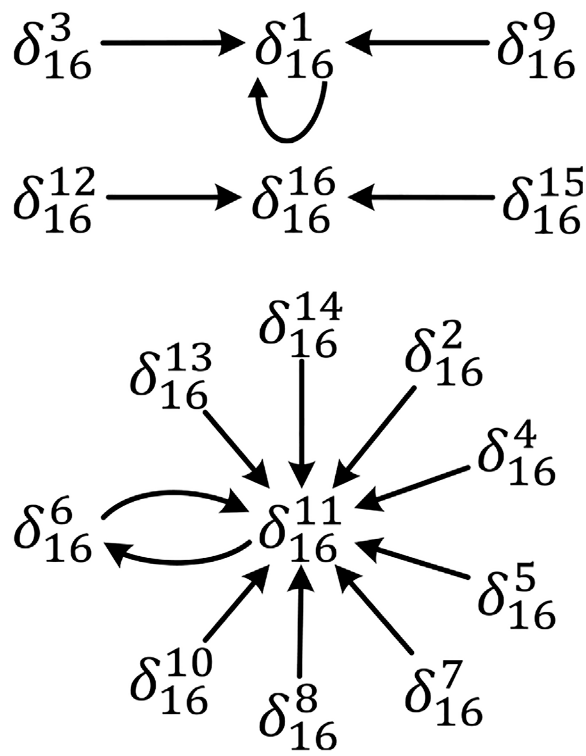

FIGURE 2
The state transition diagram of system (16).

It is easy to find two elements on the diagonal of matrix M. So there are only two equilibrium points in this game: δ_{16}^{1} and δ_{16}^{16}, namely Nash equilibriums. In addition, by a simple computation we get a limit cycle $C: \delta_{16}^{6} \to \delta_{16}^{11} \to \delta_{16}^{6}$. And their attraction domains are

$$
\begin{aligned}
D(\delta_{16}^{1}) &= \{\delta_{16}^{1}, \delta_{16}^{3}, \delta_{16}^{9}\} \sim \{(1,1,1,1),(1,1,2,1),(2,1,1,1)\} \\
D(\delta_{16}^{16}) &= \{\delta_{16}^{12}, \delta_{16}^{15}, \delta_{16}^{16}\} \sim \{(2,1,2,2),(2,2,2,1),(2,2,2,2)\} \\
D(C) &= \{\delta_{16}^{2}, \delta_{16}^{4}, \delta_{16}^{5}, \delta_{16}^{6}, \delta_{16}^{7}, \delta_{16}^{8}, \delta_{16}^{10}, \delta_{16}^{11}, \delta_{16}^{13}, \delta_{16}^{14}\} \\
&\sim \{(1,1,1,2),(1,1,2,2),(1,2,1,1),(1,2,1,2), \\
&\quad (1,2,2,1),(1,2,2,2),(2,1,1,2),(2,1,2,1), \\
&\quad (2,2,1,1),(2,2,1,2)\}
\end{aligned}
$$

The state transition diagram of system 16) is given in Figure 2. From Figure 2 and Theorem 1, we know that only when the initial state is taken from $D(\delta_{16}^{1})$ and $D(\delta_{16}^{16})$, system (16) will be stable at the Nash equilibrium δ_{16}^{1} (meaning strategy profile (1, 1, 1, 1)) and δ_{16}^{16} (meaning strategy profile (2, 2, 2, 2)), respectively.

Remark 3. The results obtained above show that the strategy profile depends on its initial state, and finally be stable at one of three attractors. We explain it in three cases.

- *If player i chooses an initial strategy profile from* $\{(1,1,1,1),(1,1,2,1),(2,1,1,1)\}$, *then the strategy profile will reach* (1, 1, 1, 1) *and be stable at this point in order to make as much profit as possible.*
- *If the player adopts an initial strategy profile from* $\{(2,1,2,2),(2,2,2,1),(2,2,2,2)\}$, *then the strategy profile will be stable at* (2, 2, 2, 2).
- *For other initial strategy profiles, they change every time. That is, they are unstable.*

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding authors.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Conflict of interest

Authors ZZ, YC, YL and XJ were employed by Beijing Smartchip Microelectronics Technology Company Limited.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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