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The assessment of “Electrified Changji Project” based on evolutionary game theory

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Abstract. The consumption of renewable energies has become a priority task in energy-rich areas such as Changji, Xinjiang Province, China. Changji government has proposed a project to replace the traditional heating devices into electrical heating devices, known as electrified changji project. This paper focuses on the promotion of the plan and assesses the economic benefit of this plan using evolutionary game theory. The results of the optimization show greater benefit can be achieved by appropriate compromising from both the participators.

1. Introduction

The utilization of renewable energy has become an international topic in the past decades due to the climate change and environmental pollution caused by traditional fossil fuels[1-3]. Therefore, the development of renewable energies has increased rapidly in many countries such as China[4-6], US, UK[7-8]and so on. Many renewable power stations have been built in these countries, causing a quick increase of local power supplies. However, those renewable power cannot always be consumed locally due to the common unbalance source-load distribution. Moreover, those renewable power cannot be connected directly to the grid due to their unstable frequency. Power storage facilities can solve the connection problem, but they also increase the investment significantly, making the promotion of renewable energies highly reliable on the government funding support. Recently, due to the reduction of government funding, the abandon of renewable energies facilities has become a common phenomenon in China.

Therefore, the promotion of renewable energies has become the priority topic in China. The main researches are carried out in two proposes: expanding the users of renewable energies and reducing the investment of renewable energies. Articles[9-11] utilizes the renewable energies (mostly wind) to produce thermal energies. It consumes the abundant wind energy, reduces the emission and pollution caused by traditional coal-based heating system and provides thermal energies to the customer. Articles [12-14] use the renewable energies to generate hydrogen, which can be sell to coal/petroleum chemical industries.



2. Electrified Changji Project

Due to the Mid-latitude steppe and desert climate in Xinjiang province, China, heating supply is necessary for a considerable amount of time in winter. As studied in [15], the heat supply should cover between 152 days to 161 days, which consume a considerable amount of energies[16]. Another study indicates the pollution and emission level has increased significantly during the heat seasons[17]. Therefore, a clean heating system is urgently required in the Xinjiang province.

The government proposes a project named "Electrified Xinjiang Project", which uses the renewable energies as the heating source. By replacing the coal-based heating system with the electricity-based heating system, the redundant renewable energies are consumed, and the emissions caused by the traditional coal-based heating system are saved[18]. It has significant benefits to the strategic transformation of energy structure and provides a valid solution to the consumption of renewable energies. However, the modification of this 'clean' electrical heating system would cost a large amount of investment.

On one hand, local electricity company has limited amount of funding available for this modification. On the other hand, the government objective of energy-saving and emission reduction should be satisfied as much as possible. Therefore, compromises should be established between the government emission objective (represented as the area of installing clean heating system) and the investment of the power companies. This paper focuses on the development plan of "Electrified Changji project" and assess the overall benefits of the project based on evolutionary game theory.

3. Evolutional game theory

Game theory is a common optimization method used widely in economics, sociology and psychology analysis. This theory studies the interaction among the participators involved in the game (known as the player). The participators are faced with a series of action and gain certain benefits or lost based on their choice. Based on different rules and hypothesis, game theory can not only provide the best solution (i.e. the overall benefits of all subjects reach maximum) but also the most possible solutions (i.e. the interest of each subject is satisfied but the overall benefits are not the optimum value).

Traditional game theory asks each participator in the game to be purely rational. They should fully understand the opponent's decision and their probability, the rules of the game, the payoff structure as well as the ability to deduct the best strategy. However, the participators in real life are often bounded rationality. Therefore, the best response strategy is often achieved by trial and experiment rather than complex calculation. The participator selects their choice based on the experience of their ancestors. They also learn and duplicate others' choice. This situation is more common and realistic in real life optimization problem. Therefore, it is used in the analysis of electrified Changji Project.

4. Optimization of electrical heating system construction plan based on the evolutionary game theory

4.1. Players of the game theory

Two players participating in this game are the government and electricity company.

4.2. Hypothesis

All the participators in this game are bounded rational.

4.3. Action

The pure strategies of the government are to promote the clean heating system and not promote. The pure strategies of the electricity company are to fully invest in the clean heating system and invest nothing in the clean heating system. However, since they are bounded rational, they can adjust the proportion of strategies. For example, the government can promote the clean heating system in $X\%$ of the total areas in Changji while the $(100-X)\%$ remains the same. The electricity company can invest $Y\%$

of the total modification funding required to fully apply the clean heating system in Changji, while (100-Y) % of the investment would be saved for the future development.

4.4. Basic parameters and their physical meanings

The payoff of every player is influenced by a lot of parameters. Before calculating the payoff, the parameters and their physical meanings are explained in Table. 1.

Table 1. Parameters and their physical explanation.

| Constant | Explanation |
|----------|--|
| B_E | The saving cost of environmental protection |
| T_i | Government funding of this project |
| P_u | Economic tax |
| P_u' | The cost of environmental protection |
| A | Coving area of the electrical heating system |
| P | Heating price |
| F_E | The average cost of the heating system |
| C | Modification cost of the power grid |

4.5. Pay-off matrix

The player's payoff when using pure strategies is shown in Table. 2.

Table 2. Payoff matrix.

| | | Government | |
|------|-----------------|---|--|
| | | Fully electrical heating system | No electrical heating system |
| Grid | Full investment | $(r_{1E} = T_i - C + AF_E P, r_{1G} = B_E - T_i)$ | $(r_{2E} = -C + AF_E P, r_{2G} = -P_U')$ |
| | No investment | $(r_{3E} = -P_U, r_{3G} = -P_U')$ | $(r_{4E} = -P_U, r_{4G} = -P_U')$ |

4.6. Construction of replicator dynamic equations and its solution

By using the payoff matrix and the hypothesis that all players are bound rational. The mean payoff for each player is shown in Table.3.

Table 3. Mean payoff estimation.

| | Grid | Government |
|---------------|--|---|
| Fully apply | $\pi_E^1 = Y(T_i - C + AF_E P) + (1 - Y)(-C + AF_E P)$ | $\pi_G^1 = X(B_E - T_i) + (1 - X)(-P_U')$ |
| No apply | $\pi_E^2 = -P_U$ | $\pi_G^2 = -P_U'$ |
| Partial apply | $\bar{\pi}_E = X(YT_i + -C + AF_E P) + (1 - X)(-P_U)$ | $\bar{\pi}_G = YX(B_E - T_i) + [(1 - X)Y + (1 - Y)](-P_U')$ |

In the evolutionary game theory, the decision is assumed to be made based on others' decision. Therefore, it is called the replicator dynamic. This equation is expressed mathematically by:

$$\frac{dx_i}{dt} = x_i[f_i(x) - \phi(x)], \phi(x) = \sum_{j=1}^n x_j f_j(x) \quad (1)$$

In this equation, x_i is the proportion of type i in the population $x = (x_1, \dots, x_n)$, $f_i(x)$ is the fitness of type i , and $\Phi(x)$ is the average population fitness.

Therefore, the duplicator's dynamic equation is shown as:

Grid:

$$\begin{aligned}\frac{dX}{dt} &= X(\pi_E^1 - \overline{\pi_E}) \\ &= X(1-X)(YT_i - C + AF_E P + P_U)\end{aligned}\quad (2)$$

Government:

$$\begin{aligned}\frac{dY}{dt} &= Y(\pi_G^1 - \overline{\pi_G}) \\ &= Y(1-Y)(XB_E - XT_i - 2P_U' + XP_U')\end{aligned}\quad (3)$$

Assume $\frac{dX}{dt} = 0$ and $\frac{dY}{dt} = 0$, the possible best solution can be in the following points:

$$E_1(0,0) \quad E_2(0,1) \quad E_3(1,0) \quad E_4(1,1) \quad , E_5\left(\frac{2P_U'}{B_E + P_U' - T_i}, \frac{-C + AF_E P + P_U}{-T_i}\right)$$

4.7. Evolutional stability check

Assume $F = \frac{dX}{dt}$ $G = \frac{dY}{dt}$, the Jacobi matrix of the equation is shown as:

$$\begin{aligned}J &= \begin{bmatrix} N_{11} = \frac{\partial F}{\partial X} & N_{12} = \frac{\partial F}{\partial Y} \\ N_{21} = \frac{\partial G}{\partial X} & N_{22} = \frac{\partial G}{\partial Y} \end{bmatrix} \\ &= \begin{bmatrix} N_{11} = (1-2X)(YT_i - C + AF_E P + P_U) & N_{12} = X(1-X)T_i \\ N_{21} = Y(1-Y)(B_E - T_i + P_U') & N_{22} = (1-2Y)[X(B_E - T_i + P_U') - 2P_U'] \end{bmatrix}\end{aligned}\quad (4)$$

By checking the Det and Tr of the Jacobian matrix, the stability of the matrix is judged by table.4.

Table 4. Mean payoff estimation.

| Possible best points | Det(J) | Tr(J) |
|----------------------|---|---------------------------------------|
| $E_1(0,0)$ | $(AF_E P + P_U - C)(-2P_U')$ | $AF_E P + P_U - C - 2P_U'$ |
| $E_2(0,1)$ | $(T_i - C + AF_E P + P_U)(-2P_U')$ | $T_i - C + AF_E P + P_U - 2P_U'$ |
| $E_3(1,0)$ | $(C - AF_E P - P_U)(B_E - T_i - P_U')$ | $C - AF_E P - P_U + B_E - T_i - P_U'$ |
| $E_4(1,1)$ | $(C - AF_E P - P_U)(-B_E + T_i + P_U')$ | $C - AF_E P - P_U - B_E + T_i + P_U'$ |
| E_5 | Equ(5) | Equ(6) |

The det(J) in E_5 is shown as:

$$\frac{2P_U'(B_E - P_U' - T_i)(C + AF_E P + P_U)(T_i + C + AF_E P + P_U)}{(B_E + P_U' - T_i)^2 T_i^2} \quad (5)$$

The Tr(J) in E_5 is shown as:

$$-\frac{2P_U'(B_E - P_U' - T_i)}{(B_E + P_U' - T_i)^2} - \frac{(C + AF_E P + P_U)(T_i + C + AF_E P + P_U)}{T_i^2} \quad (6)$$

By checking the positivity and negativity of the corresponding value, the best point is selected based on the following conditions:

If $Det(J) > 0, Tr(J) > 0$, the point is considered unstable.

If $\begin{cases} Det(J) < 0, Tr(J) < 0 \\ Det(J) < 0, Tr(J) > 0 \\ Det(J) > 0, Tr(J) < 0 \end{cases}$, the point is considered stable.

5. Case study and results discussion

Changji is in the north of Xinjiang Province. The local temperature is between -20°C - 11°C degree during the winter season, which is usually 15th Oct to 15th Apr. Therefore, the average heating days are 180-185 days. The aimed temperature using the traditional heating system is 20°C , with the heating price at 22.5 yuan/ m^2 . Electrified Changji Project plans to convert 1.043 million m^2 of the traditional heating areas into the electrical heating area. The electricity price is expected to be 0.39 Yuan/kMh. By analyzing the climate conditions in Changji, the parameters are given by changji electricity corporation and shown in the table. 5.

Table 5. Parameters and their physical explanation.

| Constant | Explanation | Value (Million Yuan) |
|----------|---|----------------------|
| B_E | The economic benefit of electrified Changji project | 66 |
| T_i | Government funding of this project | 17.73 |
| P_u | Economic tax | 1.55 |
| P_u' | The cost of environmental protection | 14.6 |
| F_E | The average cost of the heating system | 30.244514 |
| C | Modification cost of the power grid | 32.5448 |

By putting these numbers into the payoff matrix, the payoff matrix is given in Table.6:

Table 6. Payoff matrix.

| | | Government | |
|------|-----------------|--------------------------------|------------------------------|
| | | Full electrical heating system | No electrical heating system |
| Grid | Full investment | (15243000, 48269000) | (-2308000, -14600000) |
| | No investment | (-1550000, -14600000) | (-1550000, -14600000) |

By solving the Jacobi matrix and the duplicators' dynamic equations, possible solutions and their mean estimations are given by Table 7.

3 points are founded stable. However, E5 is the obviously the best solution for this optimization, since it is the only stable point with positive gains in all situations. The X and Y, in this case, are 0.46 and 0.6. This means the best case for both the government and the electricity company is: When 479.78 thousand m^2 area is promoted and 19. 52688 million yuan is used in the modification of the grid. In this case, the mean benefit of government is 1,220,044 Yuan. The mean benefit of the electricity company is 2,996,548 Yuan.

As discussed, considering the benefits of both players, each player should make compromise on its plan. By adopting the plan above, the cost of the electricity company is reduced while most of the government plan are finished. Therefore, the overall benefit can be achieved in this optimization.

Table 7. Mean payoff estimation

| Possible best points | Det(J) | Tr(J) | Stability |
|----------------------|--------|-------|-----------|
| $E_1(0,0)$ | - | + | Stable |
| $E_2(0,1)$ | + | - | Unstable |
| $E_3(1,0)$ | + | - | Unstable |
| $E_4(1,1)$ | - | + | Stable |
| $E_5(0.46,0.6)$ | + | - | Stable |

6. Conclusions

This paper searches the promotion plan of the electrical heating system based on the evolutionary game theory by maximizing the benefits of both the government and the electricity function. A new game theory optimization model of this project is proposed and simulated based on the statistic results in Changji area. The optimization model provides good compromising results with consideration of both participators' benefits, which is considered effective in such problem. However, due to the benefits of the users are ignored in this case, the model is too simplified and incomplete. This model would be improved and compared with the operational data from the Electrified Changji Project in the future studies.

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