Research on renewable energy incentive policy based on evolutionary game

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Abstract. In view of the current policy design, which is created to influence the growth of the renewable energy sector, the status quo of different subjects' role orientation and behaviour mechanism is neglected. This paper constructs the evolutionary game model of the three parties in the renewable energy industry involved: government, enterprise and consumer. The results show that the initial stage of government incentive policies should increase subsidies to enterprises and increase price incentives for consumers. At the same time, enterprises must actively respond to the call of the state. With the further advancement of the policy, the government should reduce subsidies to enterprises appropriately, and urge enterprises to develop production technologies for renewable energy vigorously to reduce the operation of enterprises' cost. The results can provide theoretical reference and realistic support for the government.

1. Introduction
The report of the 19th National Congress of the Communist Party of China proposes to transform the national energy sector into a low-carbon clean, safe and efficient one. Against the background of new requirements, research into how to generate clean and low-carbon energy subject to national and regional conditions, whilst at the same time ensuring high-quality economic development, is currently the focus of political and academic circles. In support of economic and social sustainable development, the Chinese government is promoting a green development strategy, and plans to generate 75% of the total electricity consumption from renewable energy by 2050. This shows that the uptake of renewable energy is growing.

At present, the Chinese government implements incentives such as installed stickers, green certificates, taxes, and fixed on-grid tariffs to promote the development of the renewable energy industry. These policies guarantee the economic benefits of investing in renewable energy and can effectively stimulate demand for renewable energy in the short-term [1,2]. However, due to either, “lack of” or “poor consideration of”, the inherent needs and laws required to ensure the sustainable development of renewable energy, these policies may bring problems such as “policy failure”, “inefficiency” and “unsustainable subsidies”.

Renewable energy incentives can be divided into economic incentives and price incentives. Economic incentives play a key role in the early development of the energy system. Their functions are mainly: encouraging research and development, promoting basic technology development, and
project investment [3,4]. At the same time, regional energy development policy region homogeneity phenomenon is serious, so it is unable to form regional complementary, the virtuous cycle of energy development system, which can lead to enterprise high cost of energy [5,6]. There is rich academic research on price incentives, including the formulation of standards related to the development and operation of the energy system, the design of operational mechanisms, and regional distribution. The research perspective is based mainly on the development of matching policies at market level. In most cases, as the main body of policy implementation, the cost and effectiveness of policy implementation needs to be expressed from the enterprise level. The beneficiary body of energy policy is also a game process with many subjects [7].

Evolutionary game theory has been used widely to study the energy sector, trade, behavioural decision analysis, etc. by means of a replication dynamic mechanism [8,9]. This paper uses the evolutionary game method to analyse the development of the renewable energy industry, constructs an evolutionary game model between government, enterprises and consumers, explores the game relationship between the groups, and tries to construct the optimal strategy of the groups in different periods. The aim is to determine the collection, which enables the optimal state for the development of the renewable energy sector.

2. Model assumption

This paper assumes that the participants in the renewable energy industry are the government, enterprises and consumers. The three parties are bounded and rational, all aim to maximize their benefits, like government is more care about social benefits, the enterprises more concerned in economic benefits and the consumers pay more attention to well-being. The model-related parameters are illustrated in Table 1 and specific assumptions are as follows:

Hypothesis 1: In the evolution model based on government, enterprises, and consumers, the probability of government implementing incentive policies is x, the probability of enterprises developing renewable energy is y, and the probability of consumers choosing to use renewable energy is z. Where x, y, z ∈ [0,1] are all functions of time t.

Hypothesis 2: When the government implements incentive policies, it needs to pay other costs A (including taxation and land support for enterprises), and the government will subsidize B consumers who use renewable energy. When developing renewable energy, the government department gives it a subsidy. When consumers choose “traditional energy”, the government will face losses K, such as a reduction in social welfare.

Hypothesis 3: After the government implements the incentive policy, it can alleviate the long-standing environmental pollution problems caused by traditional energy sources and the lack of traditional energy and raw materials. It can also share the growing tensions caused by the increasing supply of energy. Pressure has increased the overall social welfare, so the government can get the environmental benefits R. At the same time, the government's implementation of renewable energy incentives will gain income P, referring mainly to consumers' affirmation of the government's positive behaviour, thus improving the government's image and credibility [10].

Hypothesis 4: Under the government's incentive policy, when enterprises choose to research and develop vigorously, they will receive government subsidies S. When consumers use renewable energy, enterprises will obtain operating income Rf. In addition, enterprises will also obtain potential income R2; for example, after the company develops renewable energy, it obtains taxation, land, and other government support, policy preferences such as bank loans, and social positive evaluation of its corporate image. Enterprises that choose not to develop renewable energy vigorously under incentive policies are required to pay a fine F to the government.

Hypothesis 5: When a company chooses the strategy of “not developing renewable energy”, the company has neither operating income R1 nor cost C for developing renewable energy and developing new technologies, so both are zero.

Hypothesis 6: The utility that consumers obtain when using renewable energy is U1, the utility obtained when using traditional energy is U2, and the loss T suffered by consumers when using
traditional energy, refers mainly to the reduction of welfare, the negative externalities of traditional energy.

### Table 1. Model-related parameters and meaning.

| Parameter | Meaning |
|-----------|---------|
| P         | The government's incentives for implementing renewable energy incentives. Consumers affirm the positive behaviour of the government, thereby increasing the government's image and credibility. |
| R         | The environmental benefits that the government receives when consumers use renewable energy. |
| K         | Losses government incurs when solving environmental pollution problems and the lack of raw materials when consumers choose traditional energy sources. |
| S         | When the government implements incentive policies and enterprises develop renewable energy vigorously, the government gives investment subsidies to enterprises. |
| A         | The government's incentives for implementing renewable energy, other than investment subsidies, such as the preferential tax costs for enterprises. |
| B         | The government’s subsidies for consumers using renewable energy when the government implements incentives. |
| R₁        | The operating income of a company that is developed vigorously and that consumers use renewable energy. |
| R₂        | The potential benefits of the company's efforts to develop renewable energy, including taxation, government support such as land, policy tilts in bank loans, and social positive evaluation of corporate image. |
| C         | The cost of implementing a new renewable energy technology and developing new ones. |
| F         | The fines that companies must pay when they do not develop renewable energy under incentive policies. |
| U₁        | The utility that consumers receive when using renewable energy. |
| U₂        | The utility that consumers get when using traditional energy sources. |
| T         | The loss that consumers experience when using traditional energy sources refers mainly to the reduction of welfare and the negative externalities of traditional energy sources. |

### 3. Stability and evolution path analysis

#### 3.1. Dynamic analysis of replication of government decisions

The expected benefits of the government group's choice of “implementation” and “non-implementation” incentives $E(x_1)$ and $E(x_2)$ are:

$$ E(x_1) = y \times z \times (R + P - S - A - B) + y \times (1 - z) \times (P - S - K - A) + (1 - y) \times z \times (F + P) + (1 - y) \times (1 - z) \times (F + P - K) $$

$$ E(x_2) = y \times z \times R + y \times (1 - z) \times (-K) + (1 - y) \times z \times 0 + (1 - y) \times (1 - z) \times (-K) $$

The replication dynamic equation for government decision-making is:

$$ F(x) = \frac{dy}{dt} = x(1 - x) \times (E_{x_1} - E_{x_2}) = x(1 - x) \times [-y \times (z \times B + S + A + F) + P + F] $$  (1)

According to the stability theorem of the replication dynamic equation, the x of the stability
strategy needs to satisfy $F(x)=0$ and $F'(x)<0$.

- If $y = \frac{P+F}{B\times z+S+A+F}$, then $F(x) = 0$, at this time, the probability $x$ that the government chooses to implement the incentive policy, no matter what, will make the game reach a stable state and will not change with the change of time.

- If $y \neq \frac{P+F}{B\times z+S+A+F}$. Let $F(x)=0$, and obtain two quasi-evolutionary stable points of $x=0$ and $x=1$. Deriving $F(x)$ leads to: $F'(x) = (1-2x) \times [-y \times (z \times B + S + A + F) + P + F]$

  - When $0 < y < \frac{P+F}{B\times z+S+A+F}$, $F'(x) | x = 0 > 0$, $F'(x) | x = 1 < 0$, at this time, $x=0$ is a stable evolution point, that is, when the proportion of enterprises adopting the strategy of "developing renewable energy vigorously" is lower than $\frac{P+F}{B\times z+S+A+F}$, the government will tend to choose "implementation incentive policy".

  - When $\frac{P+F}{B\times z+S+A+F} < y < 1$, then, $F'(x) | x = 0 < 0$, $F'(x) | x = 1 > 0$, at this time, $x=0$ is a stable evolution point, that is, when adopting "deep development" When the proportion of enterprises with renewable energy strategy is higher than that of $\frac{P+F}{B\times z+S+A+F}$ at this time, most enterprises choose to develop renewable energy, and the government will choose not to implement the incentive policy considering the cost and social utility of implementing the incentive policy of renewable energy.

3.2. Dynamic analysis of replication of enterprise decision-making

The expected returns $E(y_1)$ and $E(y_2)$ of the enterprise's "deep development" and "not vigorous development" decisions are:

$$E(y_1) = x \times z \times (R_1 + R_2 + S - C) + x \times (1-z) \times (R_1 - C) + (1-x) \times z \times (R_2 + S - C) + (1-x) \times (1-z) \times (-C)$$

$$E(y_2) = x \times z \times (-F) + x \times (1-z) \times 0 + (1-x) \times z \times (-F) + (1-x) \times (1-z) \times 0$$

The replication dynamic equation for enterprise development decisions is:

$$F(y) = \frac{dy}{dt} = y \times (1-y) \times (E_{y_1} - E_{y_2}) = y \times (1-y) \times [z \times R_1 + x \times (F + S + R_2) - C]$$

- If $z = \frac{C-x(R_2+S+F)}{R_1}$, then $F(y) = 0$, We can see that the probability of companies developing renewable energy is fixed and does not change over time.

- If $z \neq \frac{C-x(R_2+S+F)}{R_1}$, let $F(y) = 0$, get $y = 1$ two quasi-evolutionary stable points. Deriving $F(y)$ gives: $F'(y) = (1-2x) \times [z \times R_1 + x \times (R_2 + \beta \times C + F) - C]$.

  - When $0 < z < \frac{C-x(R_2+S+F)}{R_1}$, $F'(y) | y=0 < 0$, $F'(y) | y=1 > 0$, at this time, $y=0$ is a stable evolution point, that is, when the proportion of consumers adopting the strategy of "using renewable energy" is lower than, the enterprise chooses the strategy of "not vigorously developing renewable energy" as the evolutionary stability strategy.

  - When $\frac{C-x(R_2+S+F)}{R_1} < z < 1$, $F'(y) | y=0 > 0$, $F'(y) | y=1 < 0$, at this time, $y=1$ is a stable evolution point, that is, when the proportion of consumers adopting the strategy of "using renewable energy" is higher than $\frac{C-x(R_2+S+F)}{R_1}$, the enterprise chooses the strategy of "vigorously developing renewable energy" as the evolutionary stability strategy.

3.3. Dynamic analysis of copying of consumer decision-making

The expected benefits $E(z_1)$ and $E(z_2)$ for consumers to choose "use" and "not to use" renewable energy are:
\[ E(z_1) = x \times y \times (U1 + B) + x \times (1 - y) \times 0 + (1 - x) \times y \times (U1) + (1 - x) \times (1 - y) \times 0 \]
\[ E(z_2) = x \times y \times (U2 - T) + x \times (1 - y) \times (U2 - T) + (1 - x) \times y \times (U2 - T) + (1 - x) \times (1 - y) \times (U2 - T) \]

The dynamic equation for copying consumer decisions is:

\[ F(z) = \frac{dz}{dt} = z \times (1 - z) \times (E_{z1} - E_{z2}) = z \times (1 - z) \times [y \times (x \times B + U_1) + T - U_2] \tag{3} \]

- If \( y = \frac{T+U_2}{xB+U_1} \), then \( F(z) = 0 \), meaning that it is stable for any \( z \) value; that is, the consumer chooses any use decision to be an evolutionary stability strategy, and the proportion of the strategy does not change with time.
- If \( y \neq \frac{T+U_2}{xB+U_1} \), let \( F(z) = 0 \), and obtain two quasi-evolutionary stable points of \( z = 0 \) and \( z = 1 \). Deriving \( F(z) \) gives:

\[ F'(z) = (1 - 2z) \times [y \times (x \times B + U_1) + T - U_2] \]

- When \( 0 < y < \frac{T+U_2}{xB+U_1} \), \( F'(z) \mid_{z=0} < 0, F'(z) \mid_{z=1} > 0 \), at this time, \( x=0 \) is a stable evolution point.

That means when the proportion of enterprises with energy “strategy” is lower than \( \frac{T+U_2}{xB+U_1} \), consumers choose “no renewable energy” strategy as an evolutionary stability strategy.

- When \( \frac{T+U_2}{xB+U_1} < y < 1 \), \( F'(z) \mid_{z=0} > 0, F'(z) \mid_{z=1} < 0 \), at this time, \( x=1 \) is a stable evolution point.

That means when the proportion of companies with energy “strategies” is higher than \( \frac{T+U_2}{xB+U_1} \), consumers choose “renewable energy” strategies as an evolutionary stability strategies.

4. The simulation analysis

Based on the previous analysis, the results of evolutionary stability of the system depend on the initial conditions and changes of related parameters. More intuitively reflect the behaviour of the subject's evolutionary path and parameter selection on the result of evolution stability, involving investment subsidies are the key parameters of \( S \), other costs \( A \), research and development costs \( C \), and renewable energy utility \( U_1 \), initial values for the parameters which aim to keep the analysis simple: \( P=5, B=0.8, R_1=10, R_2=6, U_2=10, T=4, S=2, A=2, C=9, F=3, U_1=7 \). At the beginning, the proportion of government, enterprises and consumers' behaviour decisions is set as 0.5.

4.1. Impact of investment subsidies and other costs on system evolution

**Figure 1.** Simulation diagram of system state evolution when \( S=2 \) and \( A=3 \).

**Figure 2.** Simulation diagram of system state evolution when \( S=3 \) and \( A=2 \).

When investment subsidy \( S \) and other costs \( A \) are set, the simulation diagram of system state evolution
is shown in figures 1 and 2. When the investment subsidy S and other costs A are large, as shown in figure 1, the probability of the government implementing the renewable energy incentive policy increases at the beginning, but with the passage of time, the government's decision will gradually evolve to the non-implementation of renewable energy, and finally reach the state D7, at which time the evolution time is relatively fast. When the value of investment subsidy S or other costs A is reduced, as shown in figures 1 and 2, the government will tend to implement the incentive policy of renewable energy at the beginning, however eventually it will evolve towards the state D7 as time goes by, but the rate of evolution is slower than that when the investment subsidy S and other costs A are both large.

4.2. The impact of R & D costs and penalties on system evolution
In the simulation analysis of R & D costs, in order to avoid the influence of the irrelevant variable utility $U_1$ of renewable energy, the amount of utility $U_1$ of renewable energy is set to 5. When R & D costs C and penalty F are respectively set as (21,0.5), (21,3), (9,0.5) and (9,3), which are easy and reasonable to analyze the simulation diagrams of system state evolution are shown in figures 3-6. Under the condition that the enterprise's R & D costs C is large and the penalty F is small, as shown in figure 3, the enterprise's spontaneous choice will tend towards not develop renewable energy vigorously. When the R & D cost of enterprises is kept unchanged and the penalty is reduced, as shown in figure 4, the gap between the penalty and R & D cost is still large, and enterprises would rather pay the penalty than choose to vigorously develop renewable energy. This shows that only changing the penalty has little impact on the decision-making of enterprises.
4.3. The effect of renewable energy on system evolution
The utility $U_1$ of renewable energy is set to 5 and 7 respectively which can show a clear trend, and the system state evolution simulation diagram obtained is shown in figures 5 and 6. In the case of a large utility setting of renewable energy, after a certain period of time, consumers' strategic choice will evolve to the use of renewable energy, which means that the value of renewable energy utility plays a decisive role in consumers' strategy selection when other parameters remain unchanged. Therefore, in order to make the system evolve to an ideal state, the government should increase price incentives for consumers, and enterprises should vigorously develop renewable energy, so as to increase the utility $U_1$ obtained by consumers from renewable energy.

5. Conclusions
In this paper, government, enterprises and consumers are presented as three parties involved in an evolutionary game model. The model is solved by using a replicated dynamic equation, including the government's subsidies to the enterprise, the government's penalties, the development cost of enterprise and consumer use of renewable energy utility. Subsequently, key parameters, such as the different evolution of stable state of the system were analysed. At the beginning of the incentive policy, government should use economic measures to encourage enterprises to vigorously develop renewable energy and improve the enthusiasm of traditional enterprises to vigorously develop renewable energy. With the development trend of replacing traditional energy with renewable energy all over the world, enterprises should vigorously develop renewable energy to achieve sustainable development, and in the process of developing renewable energy, enterprises should invest strongly on developing the renewable energy production technology to reduce operating costs. At the same time, consumers need to be actively involved in promoting the renewable energy industry.

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