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Analysis of Enterprise Behavior Game under the Condition of Carbon Taxes and New Energy Subsidies

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Analysis of Enterprise Behavior Game under the Condition of Carbon Taxes and New Energy Subsidies

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Abstract: In this paper, a dynamic game model of duopoly firms between the traditional electric power enterprises and new energy enterprises was established for analyzing the behaviors of electric power enterprises under different government carbon taxes policies and the corresponding Nash equilibrium. This goal of the model was set to maximize the total social welfare while considering the economic, social and environmental benefit. This model was further used to calculate the optimal carbon tax rate and optimal government subsidy level for both traditional electric power enterprises and new energy enterprises. The results showed that a reasonable carbon tax rate and return mode can optimize the structure of Chinese power industry, encouraging the high-carbon enterprises to reduce emission, promote the development of low carbon enterprises, and reduce the overall carbon dioxide emission from the power industry.

Keywords: Carbon emission reduction; carbon tax; power sector; dynamic game model

1. INTRODUCTION

With the continuous deterioration of global climate in recent years, ecological environment has become a matter of the world's concern. Both domestic and foreign scholars have done research into the effect of reduction in carbon dioxide emissions. Among them, Whalley and Wigle estimated the impact of carbon tax on global carbon dioxide emissions, suggesting that carbon tax collection could reduce carbon dioxide emissions [1]. Christoph et al. used CGE and studied the change of social welfare in an open economy when there was a difference in carbon tax [2]; Wang Jinnan et al. argued that a low tax rate could obviously slow down the increase in CO2 emissions, but it just had a limited effect on China's macro economy, so it was merely a feasible carbon tax policy [3]. Wei Taoyuan et al. quantitatively analyzed the influence of carbon tax collection on China's economy and greenhouse gas emission using China computable general equilibrium (CNACGE) model. When analyzing international carbon tax design, Michael pointed out that there was a proper unified carbon tax rate that could realize an emission distribution extremely close to social optimum, and then built a dynamic game model, concluding that a unified tax rate could help realize a Pareto optimum [4]. When studying carbon tax-based carbon emission reduction, Wolfram et al. held that differentiated carbon taxes should be levied on production departments. They also presented a condition for the implementation of carbon tax differentiation [5]. Zhang and Baranzini argued that carbon tax rate should be constantly increased with time going by to reflect the increase in the marginal abatement cost caused by the rise of carbon dioxide content in the atmosphere [6]. Li Huan et al. built a three-phrase model for the game between the government and enterprises, suggesting that differentiated carbon taxes should be levied in China at the present stage [7].

In conclusion, the research of government policies on carbon emission reduction and carbon tax has drawn wide attention from the scholars both at home and abroad, and achieved great results. But most of the existing literatures involve just the effects of carbon taxes on macro-economy, and some quantitatively put forward suggestions on the determination of a carbon tax rate by building a game model, while very few are focused on

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the carbon tax policies for power sector. According to statistics, among all sectors, the power sector sees the highest proportion of carbon dioxide emissions nationwide. On the previous studies, by building a three-phase model for the game between the government, traditional power enterprises and new energy enterprises, this paper made a discussion on the power enterprises' countermeasures against the carbon tax policy, as well as the carbon tax rate and subsidies made by the government, providing theoretical suggestions and data support for the formulation of government policies on carbon taxation.

2. BUILDING OF A CARBON TAX POLICY-BASED GAME MODEL FOR ENTERPRISE BEHAVIOR CHOICES

It is assumed in this model that the participants include the government department that participates in the setting of carbon tax rate and two representative power enterprises (Enterprise 1 and Enterprise 2), of which Enterprise 1 represents the traditional power enterprises that use coal as the main fuel, while Enterprise 2 represents the new energy enterprises that adopt photovoltaic material, hydroelectricity or nuclear power as the main fuel. And then a dynamic game model [8] is established, aimed at researching the optimal decision problem of the power system consisting of the government departments and duopoly firms.

In particular, there are two optional government policies for carbon tax collection and subsidy distribution: 1) levying a carbon tax on the traditional power enterprises, while subsidizing the new energy enterprises, called tax and subsidy model for short; 2) levying a carbon tax on the traditional power enterprises, which also actively develop emission reduction technologies, while the new energy enterprises aren't subsidized, called subsidy-free tax collection & emission reduction model for short. The following is a comparative analysis on the game behavior orientations and results growing out of both policies.

2.1 Variable and Parameter Setting

(1) enterprise 1 and enterprise 2 form a duopolistic power market. Suppose the gross output q of the power sector exactly meets the market demand, and power price is denoted by inverse demand function $p(Q) = a - bQ(a > 0, b > 0)$. Where, a denotes a ceiling price acceptable to the market, and q_i denotes the production of enterprise i, then $Q = \sum_{i=1}^{2} q_i$.

(2) Suppose the average production cost of per unit product is $c_i(i = 1,2)$, since new energy enterprises have to import key production components, and that the operation and maintenance cost is high, $c_1 < c_2$.

(3) There are differences in carbon emission between both types of power enterprises. Suppose Enterprise i emits e_i of carbon dioxide per unit product, since the production in the new energy enterprise is characterized by cleanness and environmental protection, $e_1 > e_2$, Enterprise I emits $e_i q_i$ of carbon dioxide in practical production.

(4) The government levies a carbon tax on enterprises according to quantity. Suppose carbon tax at t yuan is levied per unit carbon emission.

(5) The amount of loss caused by carbon dioxide emission can be denoted by environmental damage function U_e . See Literature [9] for the details of the damage function, which can be assumed as $U_e = \frac{k(e_1 q_1 + e_2 q_2)^2}{2}$, where $k > 0$, representing the degree of the state's attention to climate.

(6) A simplified model is set up for new energy enterprises owing to the very low carbon emission.

Let $e_2 = 0$ in all the following model solutions.

(7) Considering the high initial investment cost and long payoff period for Enterprise 2, the government gives it financial subsidies in accordance with its fixed output. Suppose s yuan is given to Enterprise 2 for per unit of product.

2.2 Three-phase Dynamic Taxation & Subsidy Model and Analyses

2.2.1 Model Building

The cost function for Enterprise 1: $C_1 = c_1 q_1 + t e_1 q_1$

Profit function:

$$\Pi_1^1 = (a - bq_1 - bq_2)q_1 - c_1 q_1 - t e_1 q_1 \tag{1}$$

The cost function for Enterprise 2: $C_2 = c_2 q_2 - s q_2$

Profit function:

$$\Pi_2^1 = (a - bq_1 - bq_2)q_2 - c_2 q_2 + s q_2 \tag{2}$$

The social total welfare function U in this paper is comprised of power enterprise profit, consumer surplus, carbon tax revenue, subsidy loss, and the environmental loss caused by carbon emission. Function U is shown as follows:

$$\begin{aligned} U_1 &= \Pi_1^1 + \Pi_2^1 + U_0 + t e_1 q_1 - s q_1 - U_e \\ &= (a - bq_1 - bq_2 - c_1)q_1 + (a - bq_1 - bq_2 - c_2)q_2 + \frac{1}{2} b(q_1 + q_2)^2 - \frac{1}{2} k(e_1 q_1)^2 \\ &= (a - c_1)q_1 + (a - c_2)q_2 - \frac{1}{2} b(q_1 + q_2)^2 - \frac{1}{2} k(e_1 q_1)^2 \end{aligned} \tag{3}$$

2.2.2 Model Analysis

Converse solution method is adopted since this model is built on complete information hypothesis.

Step 1: as a follower, the new energy enterprise chooses an optimal output level for itself

Take the derivative of q_2 by (2) and get: $\frac{\partial \Pi_2^1}{\partial q_2} = a - bq_1 - 2bq_2 - c_2 + s$

Let $\frac{\partial \Pi_2^1}{\partial q_2} = 0$ and get that when Enterprise 1 chooses q_1, Enterprise 2 actually selects $s_2(q_2)$

$$s_2(q_2) = \frac{a - c_2 - bq_1 + s}{2b} \tag{4}$$

Take the derivative of Formula (2-4), identifying the influence of the output of Enterprise 1 and the amount of subsidies on Enterprise 2.

$$\frac{\partial q_2}{\partial q_1} < 0, \frac{\partial q_2}{\partial s} > 0 \tag{5}$$

Conclusion: The distribution of subsidies leads to an increase in the output of Enterprise 2, and thus encourages Enterprise 2 to develop, to achieve the goal of optimizing the industrial structure. The output of Enterprise 2 decreases with the output of Enterprise 1 increasing, and this is the inevitable outcome of oligarch competition in the market.

Step 2: as a leader, the traditional power enterprise selects an optimal output level for itself at a given tax rate level and subsidy level

Substitute (4) into (1) and identify the profit made by Enterprise 1:

$$\Pi_1^1 = \frac{a + c_2 - 2c_1 - 2te_1 - s}{2} q_1 - \frac{b}{2} q_1^2$$

Take the derivative of q_1 and get:

$$\frac{\partial \Pi_1^1}{\partial q_1} = \frac{a - 2bq_1 + (c_2 - 2c_1) - 2e_1 t - s}{2}$$

$$q_1 = \frac{a + (c_2 - 2c_1) - 2e_1 t - s}{2b} \tag{6}$$

Meanwhile substitute (6) into (4) and get:

$$q_2 = \frac{a + (2c_1 - 3c_2) + 2e_1 t + 3s}{4b} \tag{7}$$

Take the derivative of (7) and identify the effect of carbon taxation and subsidy level on Enterprise 1.

$$\frac{\partial q_1}{\partial t} < 0, \frac{\partial q_1}{\partial s} < 0 \tag{8}$$

Conclusion: The introduction of carbon taxes and subsidies reduces the output of Enterprise 1, and this will help control carbon emissions in the power sector, so as to urge the traditional power enterprises to further reduce emissions.

Step 3: the government levies a carbon tax on the power enterprise at the rate of t^* and subsidizes the new energy enterprise at the level of s^*

Take the derivative of t by (3) and get:

$$\frac{\partial U_1}{\partial t} = (a - c_1)\frac{\partial q_1}{\partial t} + (a - c_2)\frac{\partial q_2}{\partial t} - b(q_1 + q_2)\frac{\partial (q_1 + q_2)}{\partial t} - ke_1^2 q_1 \frac{\partial q_1}{\partial t}$$

Then, take the derivative of s by (2-3) and get:

$$\frac{\partial U_1}{\partial s} = (a - c_1)\frac{\partial q_1}{\partial s} + (a - c_2)\frac{\partial q_2}{\partial s} - b(q_1 + q_2)\frac{\partial (q_1 + q_2)}{\partial s} - ke_1^2 q_1 \frac{\partial q_1}{\partial s}$$

The optimum carbon tax rate t^* and subsidy level s^* should satisfy condition

$$t_1^* = \frac{(c_2 - c_1)(2ke_1^2 - b)}{2ke_1^3}, s^* = (a - c_2) - \frac{b(c_2 - c_1)}{ke_1^2} \tag{9}$$

Conclusion: Carbon tax rate is positively correlated to the cost of power generation by the new energy enterprise and traditional power enterprise, as well as to the subsidies to new energy enterprise and the carbon emission intensity in Enterprise 1.

2.3 Subsidy-free Tax Collection & Emission Reduction Model and Analyses

2.3.1Model Building

On the premise of model hypothesis in 2.1, Enterprise 1 actively introduces emission reduction equipment and technology to purify carbon dioxide emissions. At this point, Enterprise 2 is not subsidized. Let emission purification level be r, which represents the decrement in carbon emission after the purification of per unit emission. Suppose the cost of purification treatment equals $c(r)$ at purification level r, $c(r)$ is a monotonic increasing concave function. Refer to Literature [10]- [16] and let $c(r)=\frac{\delta r}{1-r}$, where, δ denotes purification cost coefficient, and is affected by the emission reduction technology adopted at that time.

The profit function for Enterprise 1:

$$\Pi_1^2 = (a - bq_1 - bq_2)q_1 - c_1q_1 - \frac{\delta r}{1-r}e_1q_1 - t(1-r)e_1q_1 \tag{10}$$

The profit function for Enterprise 2:

$$\Pi_2^2 = (a - bq_1 - bq_2)q_2 - c_2q_2$$

The social welfare function:

$$\begin{aligned} U_2 &= \Pi_1^2 + \Pi_2^2 + U_0 + t(1-r)e_1q_1 - U_e \\ &= (a - c_1 - \frac{\delta r}{1-r}e_1)q_1 + (a - c_2)q_2 \\ &- \frac{1}{2}b(q_1 + q_2)^2 - \frac{1}{2}k(1-r)^2(e_1q_1)^2 \end{aligned} \tag{11}$$

2.3.2 Model Analysis

Three-phase dynamic analysis is adopted for model analysis.

Step 1: as a follower, the new energy enterprise chooses an optimal output level for itself

Take the derivative of q_2 by (11) and get:

$$\frac{\partial \Pi_2^2}{\partial q_2} = a - bq_1 - 2bq_2 - c_2$$

Let $\frac{\partial \Pi_2^2}{\partial q_2} = 0$ and conclude that when Enterprise 1 selects q_1, Enterprise 2 actually chooses $s_2(q_2)$

$$s_2(q_2) = \frac{a - c_2 - bq_1}{2b} \tag{12}$$

Take the derivative of Formula (12), $\frac{\partial q_2}{\partial q_1} < 0$

Conclusion: The output of Enterprise 2 is merely related to the output of Enterprise 1, and decreases with the output of Enterprise 1 increasing.

Step 2: as a leader, the traditional power enterprise selects an optimal output level for itself at a given tax rate level and subsidy level.

Take the derivative of r by Formula (10) and get:

$$\frac{\partial \Pi_1^2}{\partial r} = -\frac{\delta}{(1-r)^2}e_1q_1 + te_1q_1 \tag{13}$$

Let $\frac{\partial \Pi_1^2}{\partial r} = 0$ and get: $r = 1 - \sqrt{\frac{\delta}{t}}$

Take the derivative of Formula（13）, $\frac{dr}{dt} > 0$,

Conclusion: With carbon tax rate increasing, the enterprises become more proactive in reducing emissions, but acceleration drops off.

Then substitute (12) and (10) into (10), revealing the profit of Enterprise:

$$\Pi_1^2 = [\frac{a + c_2 - 2c_1}{2} - (2\sqrt{t\delta} - \delta)e_1]q_1 - \frac{b}{2}q_1^2$$

Take the derivative of F q_1 in the above formula and get:

$$\frac{\partial \Pi_1^2}{\partial q_1} = \frac{a + c_2 - 2c_1}{2} - (2\sqrt{t\delta} - \delta)e_1 - bq_1$$

Let $\frac{\partial \Pi_1^2}{\partial q_1} = 0$ and get: $q_1 = \frac{a + c_2 - 2c_1 - 2e_1(2\sqrt{t}\delta - \delta)}{2b}$ (14)

Then substitute (2-14) into (2-12) and get:

$$q_2 = \frac{a + 2c_1 - 3c_2 + 2e_1(2\sqrt{t\delta} - \delta)}{4b} \quad (15)$$

Take the derivative of (15) $\frac{\partial q_1}{\partial t} < 0$,

Conclusion: The introduction of carbon tax decreases the output of Enterprise 1, and this will help control carbon emissions in the power sector, so as to urge the traditional power enterprises to further reduce emissions.

Step 3: the government levies a carbon tax on the power enterprise at the rate of t^*

Substitute (13) into (11) and get the following social total welfare function:

$$U_2 = (a - c_1 - \sqrt{t\delta}e_1 + \delta e_1)q_1 + (a - c_2)q_2 - \frac{1}{2}b(q_1 + q_2)^2 - \frac{\delta}{2t}k(e_1 q_1)^2$$

The optimum carbon tax rate satisfies:

$$t^* = \arg \underset{t}{Max}\ U_2 \quad (16)$$

3. DATE SIMULATION ANALYSIS

3.1 Parameter Estimation

The related data of power enterprises' cost, demand, emission, and loss function comes mainly from the relevant data of Chinese power sector in 2014. (1) The average cost of 1kwh power, including that in traditional power enterprises and new energy enterprises, is calculated. (2) The inverted demand curve of power products is estimated according to domestic research achievements [11], denoted by $p = 1.5 - 0.004Q$.(3) According to the data of carbon emission recorded in China Energy Statistical Yearbook, the traditional power enterprises emit 0.96 kg of carbon when producing 1kwh power, namely $e_1 = 0.96$. (4) Refer to foreign research achievements [9] and let pollution loss coefficient $k = 0.005$.

3.2 Numerical Simulation Result and Analysis

Suppose the purification cost coefficient δ of Enterprise 1 is a constant, let $\delta = 0.2$. In Model 2, since purification level $r > 0$, $t \geq 0.2$. By reference to the policies implemented by the countries in which a carbon tax has begun to be collected, considering China's concrete national conditions, here the initial value of carbon tax rate is set equal to 0.2, and increases gradually. The enterprise's production decision, social welfare and equilibrium outcome are shown as follows.

Table 1. The Optimum Carbon Tax Rate in Model 1

Carbon Tax Rate t_1 (yuan/kg co_2)	Subsidy s (yuan/kg co_2)	q_1	q_2	CO2 Emissions (Ten THS Tons)	Π_1	Π_2	U_1
0.118	0.826	43.43	206.535	416.93	3.766	170.598	166.078

Table 2. The Influence of Changes in Carbon Tax Rate

t_2	r	q_1	q_2	CO2 Emissions (Ten THS Tons)	Π_1	Π_2	U_2
0.20	0	127	61.5	1219.20	32.258	15.129	105.674
0.22	0.047	122.314	63.843	1119.57	29.922	16.304	108.829
0.24	0.087	117.837	66.081	1032.67	27.771	17.467	111.014
0.26	0.123	113.543	68.228	956.01	25.784	18.620	112.494
0.28	0.155	109.411	70.294	887.71	23.942	19.765	113.450
0.30	0.184	105.424	72.288	826.36	22.229	20.902	114.013
0.32	0.209	101.569	74.216	770.85	20.632	22.032	114.276
0.33	0.222	99.686	75.157	745.01	19.875	22.594	114.318
0.34	0.233	97.831	76.084	720.31	19.142	23.155	114.310
0.36	0.254	94.202	77.899	674.06	17.748	24.273	114.166
0.38	0.275	90.673	79.663	631.50	16.443	25.385	113.885
0.40	0.293	87.235	81.382	592.17	15.220	26.492	113.496
⋮							
1.08	----	----	125.042	----	----	62.542	93.7343

From **Table** we can get:

(1) With carbon tax t increasing, the social total welfare function first increases and then decreases. With carbon tax t increasing, the output of Enterprise 1 keeps decreasing, and when $t = 1.08$, Enterprise 1 stops production. Enterprise constantly increases its output, and Enterprise 1 earns an increasingly lower profit, while Enterprise 2 sees an increase in its profit.

(2) With carbon tax t increasing, carbon emission drops off, suggesting that an increase in carbon tax rate can effectively reduce carbon dioxide emissions in the power sector. But with carbon tax t increasing, the purification level of Enterprise 1 increases slowly, and thus it becomes less proactive in reducing emissions.

(3) When $t_2 > t_1$, the carbon tax rate in Model 2 is higher than that in Model 1.

4. CONCLUSIONS

On the premise of carbon tax collection, for the decision-making behaviors of the government and power enterprises, this paper built an oligarchic game and competition model, and quantitatively analyzed the optimal decisions respectively made by the government and enterprises, identifying an optimum carbon tax rate and an optimum output, with a numerical simulation conducted on them. It then compared the optimal decisions under these two models, coming to the following conclusions:

First, when the state levies a carbon tax, for a traditional power enterprise, being proactive in reducing emissions is the best measure. So, the government should make a proper carbon tax policy, and then on the premise of guaranteeing social total welfare optimization, encourage and instruct the traditional power enterprises to purify carbon emissions to enhance their market competitiveness.

Second, for a new energy enterprise, it can maximize its profit when it's subsidized by the government. But Enterprise 2 cannot supply electricity steadily or bid for electric network easily. Its high cost at present cannot enable it to replace Enterprise 1 in spite of subsidies. So, the government should set a rational carbon tax rate and then steer the power sector in a low-carbon direction.

Third, currently, power sector has become China's largest source of carbon dioxide emissions, since Chinese power generation structure is dominated by coal, while new energy just occupies a very small proportion.

Therefore, the power generation structure must be optimized. To this end, we must encourage the production of new energy, and meanwhile strengthen the efforts to reduce emissions in the traditional power enterprises.

Fourth, an analysis based on the practical situation indicates that to achieve the emission reduction target, the government usually tends to directly subsidize clean energy enterprises in the short term, but this practice will dampen the traditional power enterprises' enthusiasm for emission reduction, and thus undermine the stability of the power sector. For long-term steady development of the power sector, the government needs to set a rational carbon tax rate to support high-carbon enterprises in emission reduction, and encourage new energy enterprises to develop.

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