Academic Journal of Management and Social Sciences
ISSN: 2958-4396 | Vol. 11, No. 2, 2025

Research on Decision-Making Behavior of Oligopolistic Competitive Enterprises under Initial Unit Carbon Emission Level

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Abstract: This article studies the decision-making behavior of various oligopolistic competitive enterprises based on the initial unit carbon emission level by establishing a game model. Research has shown that under this allocation mechanism, the output of low emission enterprises is always greater than that of high emission enterprises, but their emission reduction level is always lower than that of high emission enterprises. Secondly, the profits of enterprises are closely related to the potential market demand. When the potential market demand is strong, the profits of low emission enterprises are greater than those of high emission enterprises; When the potential demand in the market is low, high emission enterprises can obtain higher profits from lower emission enterprises.

Keywords: Carbon Quota Allocation; Carbon Trading; Carbon Emissions; Carbon Emission Reduction; Oligopolistic Competition.

1. Introduction

Energy-related emissions are worsening environmental degradation, the report of the Intergovernmental Panel on Climate Change (IPCC) of the United Nations points out that the greenhouse gas emissions generated by social activities are the main cause of global warming and the frequent occurrence of extreme weather. According to survey statistics, from 1970 to 2015, the global annual carbon emissions increased from 16 Gt to 36 Gt (Xu et al., 2018). Global climate warming has attracted high attention from the international community, and the development of a low-carbon economy has become a global consensus. Therefore, to cope with climate change, countries around the world have successively formulated various policies and regulations to control carbon emissions. For example, The United States passed "the Clean Energy Security Act" in 2009 to limit domestic greenhouse gas emissions, and in March 2021, the United States launched the "Trade Policy Agenda", which plans to include carbon border adjustment taxes in its trade agenda. France began imposing huge tariffs on imports from countries with weak environmental legislation in January 2010. To further establish a domestic carbon trading market, since 2013, China carried out pilot carbon emission trading in seven provinces and cities (Beijing, Tianjin, Shanghai, Chongqing, Guangdong, Hubei, and Shenzhen), and promulgated "the Administrative Measures for Carbon Emissions Trading (Trial)" at the end of 2020. The European Union (EU) established an emissions trading mechanism in July 2021 and put forward a series of environmental proposals, including the establishment of a carbon border adjustment mechanism, which is planned to be implemented by January 1, 2023, at the latest. According to the World Bank, there have been 64 carbon pricing mechanisms implemented worldwide, covering 21% of global greenhouse gas emissions as of May 2021. Meanwhile, 35 carbon tax systems have been successively introduced, covering 27 countries and regions across all continents.

The initial allocation of carbon allowances plays an important role in the establishment and operation of carbon trading markets. The scarcity of allowances will form a market price after establishing the carbon emission trading system. Therefore, the allocation of quotas is essentially the allocation of property rights, and the method of quota allocation determines the cost of participating in carbon emission trading systems (Green & Yatchew, 2012). Furthermore, the emission abatement technology of enterprises is continuously progressing and improving, and it is improper to assume that enterprises are merely able to cope with carbon emissions by regulating production. In pursuing profit maximization, firms are allowed to compete in the traditional sense of production, as well as in emission reduction (Fan et al., 2023). This means that firms can achieve carbon emission limits by cutting production or increasing emission reductions.

2. Model Framework

There are significant differences in the initial carbon emission levels of enterprises due to their historical and practical development. According to the difference of initial carbon emission level, enterprises are categorized into two types, i.e. low emission enterprises and high emission enterprises, based on low initial carbon emission level and high initial carbon emission level. It is assumed that there are m low-emission enterprises and $(n-m)$ high-emission enterprises in the market, where $0 < m < n$.

2.1. Demand Functions

Firm i, for $i = 1,2 \dots\dots n$, orients to a common consumer market, produce products with identical functions and substitutability, meanwhile, competing in output. Suppose the inverse demand function is as follows:

$$p_i = a - bq_i - \gamma bQ_{-i} \quad (1)$$
$$i = 1,2 \dots\dots n$$

Where p_i is the resultant price, which is affected by the total output, q_i represents the production of firm i, Q_{-i} represents the output of all firms except firm i, a is the total market capacity, b is the coefficient of the impact of output on prices, and $a > 0, b > 0$, the parameter γ captures the degree of substitution between products, reflects the degree of competition between products, and $0 < \gamma < 1$.

2.2. Carbon Reduction

To increase the flexibility of enterprise production and solve the situation that enterprises have surplus carbon quotas, the carbon trading market is introduced. In the carbon trading market, enterprises can freely trade carbon emission permits. When the government's free allocation of carbon quotas is insufficient to meet the production needs of enterprises, enterprises can purchase carbon emission permits in the carbon trading market. Conversely, when the government's free allocation of carbon quotas meets the production needs of enterprises and there is a surplus, enterprises can sell carbon emission permits in the carbon trading market.

In response to low-carbon policies and environmental protection, companies have formulated their emission reduction plans to invest in emission reduction, and enterprises need to pay a certain amount of emission reduction costs while reducing carbon emissions. The existing literatures normally assume that emission reduction cost is a convex-increasing function of emission reduction, referring to Nault (1996), Levi and Nault (2004) assuming that the emission reduction cost function is $C = k_i(e_i q_i)^2$, which k_i represents the emission reduction cost coefficient, $k_i > 0$, $k_l > k_h$.

2.3. Carbon Trading

$g\big((\delta_1 - \tau_i) - (\tau_i - e_i)\big)q_i$ represents the cost or benefit of a company purchasing or selling carbon quotas when the government allocates carbon quotas based on the initial unit carbon emission level. When $(\delta_1 - \tau_i) - (\tau_i - e_i) > 0$, it indicates that the carbon quota allocated by the government to enterprises has a surplus after meeting the production requirements of the enterprise. The enterprise can take the remaining carbon quota $\big((\delta_1 - \tau_i) - (\tau_i - e_i)\big)q_i$ to the carbon trading market for sale and obtain a profit of $g\big((\delta_1 - \tau_i) - (\tau_i - e_i)\big)q_i$. On the other hand, when $(\delta_1 - \tau_i) - (\tau_i - e_i) < 0$, it means that the carbon quota allocated by the government to enterprises cannot meet their production needs. In the case, enterprises need to purchase a certain amount of carbon quota $\big((\tau_i - e_i) - (\delta_1 - \tau_i)\big)q_i$ in the carbon trading market, which requires a certain cost $g\big((\tau_i - e_i) - (\delta_1 - \tau_i)\big)q_i$, where g represents the price in the carbon trading market.

3. Model

Profit expression for firm i:

$$\max_{q_i > 0, 0 \le e_i \le \tau_i} \pi_{i1}(q_i, e_i | Q_{-i}, g) = q_i p_i - k_i(e_i q_i)^2 + g\big((\delta_1 - \tau_i) - (\tau_i - e_i)\big)q_i \tag{2}$$

Structure the Lagrangian function and use Kuhn Tucker's condition to solve for:

$$L_{i1} = q_i(a - bq_i - \gamma b Q_{-i}) - k_i(e_i q_i)^2 + g\big((\delta_1 - \tau_i) - (\tau_i - e_i)\big)q_i + \eta_i e_i - \mu_i(e_i - \tau_i) \tag{3}$$

Derive the first-order partial derivatives of q_i, e_i, respectively:

$$\frac{\partial L_i}{\partial q_i} = a - \gamma b Q_{-i} - 2q_i(b + k_i e_i^2) + g\big((\delta_1 - \tau_i) - (\tau_i - e_i)\big) = 0 \tag{4}$$

$$\frac{\partial L_i}{\partial e_i} = (g - 2k_i e_i q_i)q_i + \eta_i - \mu_i = 0 \tag{5}$$

By (4) and (5), we solve for $q_i = \frac{a - \gamma b Q + g(\delta_1 - \tau_i) - g\tau_i}{2b - \gamma b}$, $e_i = \frac{g}{2k_i q_i}$

Combined with $Q = mq_l + (n - m)q_h$, we can solve for q_i, e_i

$$q_l = \frac{(((2(n-m-1)\tau_l + 2(m-n)\tau_h + \delta_1)g + a)\gamma + (4\tau_l - 2\delta_1)g - 2a)}{(\gamma-2)b(2+(n-1)\gamma)} \tag{6}$$

$$q_h = \frac{((((2m-2)\tau_h + 2m\tau_l + \delta_1)g + a)\gamma + (4\tau_h - 2\delta_1)g - 2a)}{(\gamma-2)b(2+(n-1)\gamma)} \tag{7}$$

$$e_l = \frac{g(\gamma-2)b(2+(n-1)\gamma)}{2k_l((((2(n-m-1)\tau_l + 2(m-n)\tau_h + \delta_1)g + a)\gamma + (4\tau_l - 2\delta_1)g - 2a))} \tag{8}$$

$$e_h = \frac{g(\gamma-2)b(2+(n-1)\gamma)}{2k_h(((((2m-2)\tau_h + 2m\tau_l + \delta_1)g + a)\gamma + (4\tau_h - 2\delta_1)g - 2a))} \tag{9}$$

Proposition 1

Under the initial unit carbon emission level allocation mechanism, if the condition $(2 - \gamma + n\gamma)d > \frac{3g}{2}$ is satisfied, then the optimal decision variables and optimal social welfare can be obtained as follows:

$$q_l^* = \frac{((-4\gamma(\tau_h-\tau_l)n^2 + ((4m+3)\tau_h - \gamma(4m+4)\tau_l - 6\tau_h + 8\tau_l)n + 3m(\tau_h-\tau_l)(2-\gamma))g - an(2-\gamma))d + 6g^2(n-m)(\tau_h-\tau_l)}{2n((2-\gamma+n\gamma)d - \frac{3g}{2})(\gamma-2)b} \tag{10}$$

$$q_h^* = \frac{(((4n-3)(\tau_h-\tau_l)m - n\tau_h)\gamma + (6(\tau_h-\tau_l)m + 2n\tau_h)g - an(2-\gamma))d - 6g^2 m(\tau_h-\tau_l)}{2n((2-\gamma+n\gamma)d - \frac{3g}{2})(\gamma-2)b} \tag{11}$$

$$e_l^* = \frac{gn((2-\gamma+n\gamma)d - \frac{3g}{2})(\gamma-2)b}{k_l(((-4\gamma(\tau_h-\tau_l)n^2 + ((4m+3)\tau_h - \gamma(4m+4)\tau_l - 6\tau_h + 8\tau_l)n + 3m(\tau_h-\tau_l)(2-\gamma))g - an(2-\gamma))d + 6g^2(n-m)(\tau_h-\tau_l))} \tag{12}$$

$$e_h^* = \frac{2n((2-\gamma+n\gamma)d - \frac{3g}{2})(\gamma-2)bg}{k_h((((4n-3)(\tau_h-\tau_l)m - n\tau_h)\gamma + (6(\tau_h-\tau_l)m + 2n\tau_h)g - an(2-\gamma))d - 6g^2 m(\tau_h-\tau_l))} \tag{13}$$

Conclusion 1

To derive the difference in output and emission reduction between low-emitting and high-emitting firms under the initial unit carbon emission level allocation mechanism, Eqs. (10) and (11) are made differential:

$$\Delta q_{h-l}^{*} = q_h^{*} - q_l^{*} = -\frac{2g(\tau_h-\tau_l)}{b(2-\gamma)} < 0 \tag{14}$$

Eqs. (14) and (15) are made differential:

$$\Delta e_{h-l}^{*} = e_h^{*} - e_l^{*} = \frac{g(k_l q_l^{*} - k_h q_h^{*})}{k_l k_h q_h^{*} q_l^{*}} > 0 \tag{15}$$

Since $k_l > k_h$, $q_h^{*} < q_l^{*}$, so $\Delta e_{h-l}^{*} > 0$

When allocated based on the initial unit carbon emission level, low-emission firms always produce more than high-emission firms, the reason is that low-emission firms are allocated more allowances due to their low initial unit carbon emission levels, so they can produce more products under the limit of allowances. Nevertheless, low-emission firms are reluctant to actively reduce their emissions due to the higher abatement costs, while high-emission firms have been making efforts to reduce their emissions to reduce carbon trading costs, thereby the low-emission firms lagging behind high-emission firms in terms of emission reduction levels.

Based on the above analysis, the government should continue to incentivize high-emission firms to reduce emissions. And for firms' pressure to reduce emissions, the government can consider giving some subsidy support. It can also consider promoting technical communication between high-emission firms and low-emission firms to improve the overall emission reduction level.

Proposition 2

The profits of low-emission firms:

$$\pi_l^{*} = b{q_l}^2 + k_l {e_l}^2 {q_l}^2 = \frac{X_1+X_2+X_3+X_4}{16k_l n^2(\gamma-2)^2 b\left((n\gamma-\gamma+2)d-\frac{3g}{2}\right)^2} \tag{16}$$

Where

$$\begin{aligned} X_1 = &\big((144(\tau_l-\tau_h)^2 k_l + 9b(\gamma-2)^2)n^2 \\ &- 288mk_l(\tau_l-\tau_h)^2 n \\ &+ 144m^2 k_l(\tau_l-\tau_h)^2\big)g^4 \end{aligned}$$

$$\begin{aligned} X_2 = -192d\Bigg(&\left((\tau_l-\tau_h)^2 k_l + \frac{b(\gamma-2)^2}{16}\right)\gamma n^3 \\ &+\Bigg(-2\left(\left(\left(-m-\frac{3}{8}\right)\tau_h + \tau_l\left(m+\frac{1}{2}\right)\right)\gamma \right.\\ &\left. - \tau_l + \frac{3\tau_h}{4}\right)(\tau_l-\tau_h)k_l - \frac{b(\gamma-2)^3}{16}\Bigg)n^2 \\ &+ k_l(\tau_l \\ &- \tau_h)\left(\left(\left(-m-\frac{3}{2}\right)\tau_h + \tau_l\left(m+\frac{7}{4}\right)\right)\gamma \right.\\ &\left. - \frac{7\tau_l}{2} + 3\tau_h\right)mn \\ &- \frac{3m^2 k_l(\tau_l-\tau_h)^2(\gamma-2)}{4}\Bigg)g^3 \end{aligned}$$

There exists

$$\begin{aligned} a_1^{*} = \frac{1}{8dnk_h k_l(\gamma-2)(\tau_h-\tau_l)}\Bigg(\Bigg(\Bigg(&(16(\tau_l - \tau_h)^2 k_l + b(\gamma-2)^2)k_h - bk_l(\gamma-2)^2)\gamma dn^2 + \\ &\Bigg(-32(\tau_l-\tau_h)\left(\left(\left(\left(-m-\tfrac{1}{4}\right)\tau_h + \tau_l\left(m+\tfrac{1}{2}\right)\right)\gamma - \tau_l + \tfrac{\tau_h}{2}\right)d + \tfrac{3g(\tau_l-\tau_h)}{4}\right)k_l - (\gamma-2)^2 b\left((\gamma-2)d+\tfrac{3g}{2}\right)\Bigg)k_h + \\ &(\gamma-2)^2 bk_l\left((\gamma-2)d+\tfrac{3g}{2}\right)\Bigg)n + 24(\tau_l-\tau_h)^2((\gamma - 2)d + 2g)k_l k_h m\Bigg)g\Bigg) \end{aligned}$$

, when $a > a_1^{*}$, then $\pi_h^{*} < \pi_l^{*}$; conversely, when $a < a_1^{*}$, then $\pi_h^{*} > \pi_l^{*}$.

$$\begin{aligned} X_3 = 48d\Bigg(\Bigg(&4\left((\tau_l-\tau_h)^2 k_l + \frac{b(\gamma-2)^2}{16}\right)\gamma^2 n^4 \\ &- 8\gamma\Bigg((\tau_l-\tau_h)\left(\left(\left(-m-\frac{3}{4}\right)\tau_h + \tau_l(m+1)\right)\gamma \right.\\ &\left. - 2\tau_l + \frac{3\tau_h}{2}\right)k_l + \frac{b(\gamma-2)^3}{16}\Bigg)n^3 \\ &+\Bigg(\Bigg(\Bigg(\left(\frac{3}{4}+\frac{4}{3}m^2+4m\right){\tau_h}^2 \\ &- \frac{8\tau_l\left(m+\frac{1}{4}\right)(m+3)\tau_h}{3} \\ &+ \frac{4{\tau_l}^2\left(m^2+\frac{7}{2}m+1\right)}{3}\Bigg)\gamma^2 \\ &+\Bigg((-3-8m){\tau_h}^2 + \tau_l\left(\frac{52m}{3}+8\right)\tau_h \\ &- \frac{28{\tau_l}^2\left(\frac{4}{7}+m\right)}{3}\Bigg)\gamma + \frac{16\left(\tau_l-\frac{3\tau_h}{4}\right)^2}{3}\Bigg)k_l \\ &+ \frac{b(\gamma-2)^4}{12}\Bigg)n^2 \\ &- 2k_l(\tau_l-\tau_h)(\gamma \\ &- 2)m\left(\left(\left(-m-\frac{3}{4}\right)\tau_h + \tau_l(m+1)\right)\gamma - 2\tau_l \right.\\ &\left. + \frac{3\tau_h}{2}\right)n + \frac{3m^2 k_l(\gamma-2)^2(\tau_l-\tau_h)^2}{4}\Bigg)d \\ &+ ank_l(\gamma-2)(-n+m)(\tau_l-\tau_h)\Bigg)g^2 \end{aligned}$$

$$X_4 = -32k_l n\Bigg(-\gamma(\tau_l-\tau_h)n^2 + \Bigg(\bigg(\Big(-m-\frac{3}{4}\Big)\tau_h + \tau_l(m+1)\bigg)\gamma - 2\tau_l + \frac{3\tau_h}{2}\Bigg)n - \frac{3m(\gamma-2)(\tau_l-\tau_h)}{4}\Bigg)(\gamma - 2)d^2ag + 4a^2d^2n^2k_l(\gamma-2)^2$$

The profits of high-emission firms:

$$\pi_h^* = bq_{h1}{}^2 + k_h e_h{}^2 q_h{}^2 = \frac{Y_1+Y_2}{16k_h n^2(\gamma-2)^2 b\left((n\gamma-\gamma+2)d-\frac{3g}{2}\right)^2} \quad (17)$$

$$Y_1 = (9bn^2(\gamma-2)^2 + 144m^2k_h(\tau_l-\tau_h)^2)g^4 - 192\Bigg(\frac{b\gamma n^3(\gamma-2)^2}{16} - \frac{n^2(\gamma-2)^3 b}{16} + k_h(\tau_l-\tau_h)m\bigg(\Big((\tau_l-\tau_h)m + \frac{\tau_h}{4}\Big)\gamma - \frac{\tau_h}{2}\bigg)n - \frac{3m^2k_h(\tau_l-\tau_h)^2(\gamma-2)}{4}\Bigg)dg^3$$

$$Y_2 = 48\Bigg(\Bigg(\Bigg(\frac{n^4(\gamma-2)^2\gamma^2 b}{12} - \frac{n^3(\gamma-2)^3\gamma b}{6} + \Bigg(\frac{b\gamma^4}{12} - \frac{2b\gamma^3}{3} + \Bigg(\frac{4\left((\tau_l-\tau_h)m+\frac{\tau_h}{4}\right)^2 k_h}{3} + 2b\Bigg)\gamma^2 + \Bigg(-\frac{4\left((\tau_l-\tau_h)m+\frac{\tau_h}{4}\right)\tau_h k_h}{3} - \frac{8b}{3}\Bigg)\gamma + \frac{4b}{3} + \frac{\tau_h{}^2 k_h}{3}\Bigg)n^2 - 2k_h(\tau_l-\tau_h)(\gamma - 2)m\bigg(\Big((\tau_l-\tau_h)m+\frac{\tau_h}{4}\Big)\gamma - \frac{\tau_h}{2}\bigg)n + \frac{3m^2k_h(\gamma-2)^2(\tau_l-\tau_h)^2}{4}\Bigg)d + amnk_h(\gamma-2)(\tau_l-\tau_h)dg^2\Bigg) - 32k_h n(\gamma - 2)\Bigg(\bigg(\Big((\tau_l-\tau_h)m+\frac{\tau_h}{4}\Big)\gamma - \frac{\tau_h}{2}\bigg)n - \frac{3m(\gamma-2)(\tau_l-\tau_h)}{4}\Bigg)d^2ag + 4a^2d^2n^2k_h(\gamma-2)^2$$

Conclusion 2 illustrates that the profits of low-emitting firms and high-emitting firms are closely related to potential market demand. The profit of low-emission enterprises is greater than that of high-emission enterprises when the market demand is booming, conversely, high-emitting firms can earn higher corporate profits than low-emitting firms when market demand is low. This is because under the carbon limit, if a company has production needs, it must have carbon emission permits as support. Having more carbon emission permits means having more production freedom. Low-emission firms receive more free carbon allowances because of their low initial carbon emissions, therefore, they can produce more, so low-emission firms are always higher than high-emission firms in terms of production volume, which allows low-emission firms gaining a greater production advantage and getting greater corporate profits. When consumer demand is limited, low emission and high production are no longer considered as an advantage, at the same time, if too many products are produced, they must bear the significant production costs and the risk of unsold products. When market demand is low, high-emission enterprises occupy an advantageous position due to their higher emission reduction levels. The higher the emission reduction level, the lower the cost of purchasing carbon emission rights paid by high-emission enterprises. because of cost reduction, lower-emission enterprises gain higher corporate profits.

4. Literature Review

Subramanian et al. (2007) point out that different quotas can affect the emission reduction efforts of different industries. While Steenberghe (2005), Zheng and Chen (2011) point out that a "fair" quota allocation is not beneficial for all countries or industries, and better allocation mechanisms should be designed based on balance and regional differences. Groenenberg and Blok (2002) study the applicability of different quota allocation methods from the perspective of industry characteristics and regional development, they point out that the "grandfather method" and the "benchmark method" should be implemented separately for different enterprises, and at the same time, the allocation should be gradually transitioned from free to auction allocation. Bode (2006), and Zhang et al. (2018) explore the approaches to carbon emission allocation in the power industries. Morrell (2007) compares the impact of auctions, historical emissions laws, and baselines on the aviation industry. Zhang and Hao (2016) explore the allocation of carbon emission quotas in China's industrial sector by using the comprehensive index method combined with different weighting methods and ZSG-DEA models based on the principles of fairness and efficiency.

5. Summary

Research has shown that under this allocation mechanism, the output of low emission enterprises is always greater than that of high emission enterprises, but their emission reduction level is always lower than that of high emission enterprises. Secondly, the profits of enterprises are closely related to the potential market demand. When the potential market demand is strong, the profits of low emission enterprises are greater than those of high emission enterprises; When the potential demand in the market is low, high emission enterprises can obtain higher profits from lower emission enterprises.

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