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The Impact of Consumer Utility on Duopoly Competition Markets Decision-Making Under Constraints of Carbon Cap Policies

Abstract. *This study analyses the optimal pricing and competition decisions in a duopoly market under carbon emission cap policies, based on the carbon emission-dependent markets of traditional energy, electricity, oil, and chemicals. It validates the research findings through numerical analysis and confirms the proposed theoretical propositions. This study verifies the relevant conclusions through numerical analysis. First, the research results indicate that, in the context of consumer utility and under the constraints of carbon emission cap policies in a competitive market, there exists an equilibrium solution for the pricing and output decisions of two oligopolists. Second, under the constraints of carbon emission limits, the optimal market price of products is influenced by production capacity, carbon emissions per unit of product, consumer preferences, and preference costs. Third, under the constraints of carbon emission limits, as the carbon emissions per unit of product decrease and production capacity increases, the market price of the product declines. Finally, under the condition of fixed production capacity, the higher the consumer preference for low-carbon*

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products, the higher the market price; conversely, the lower the preference cost, the lower the market price.

Keywords: *carbon cap, consumer utility, price-output competition, corporate decision-making.*

JEL Classification: C61, C62, C70.

1. Introduction

Global carbon emissions levels continue to rise, leading to climate change and global warming. By the end of 2023, global carbon emissions have reached 37.4 billion tons, an increase of 52% over the past 30 years. Taking proactive measures to reduce carbon emissions has become a consensus in the international community (IEA, 2024). For example, from the Kyoto Protocol in 1997, the Copenhagen Accord in 2009, to the Paris Agreement in 2015, countries have actively participated in climate governance. To effectively achieve the carbon neutrality goals set forth in the Paris Agreement, countries have agreed to formulate comprehensive and customised long-term strategies based on their individual circumstances. The relevant strategic deployments at the national level outline the overall framework for carbon reduction. However, as the main contributors to carbon emissions, enterprises have a significant influence on the implementation of carbon reduction measures (Choi et al., 2021). Therefore, enterprises face pressure from various aspects, including society, the economy, and regulations, making the development of low-carbon operations an inevitable trend.

Currently, global efforts to reduce carbon emissions fall primarily into three main categories: emission caps, carbon taxes, and cap-and-trade systems. The emission cap policy involves the government's implementation of specific limits on carbon dioxide emissions for various industries or entities. These companies must not exceed the specified limits; otherwise, they will face severe penalties from the government. In addition, in practice, it falls under the carbon emission cap policy implemented by the state, aligning in management approach with administrative supervision and enforcement. The advantage of carbon emission cap policies lies in their ability to quickly and effectively achieve carbon reduction targets (Linghu et al., 2022). Undoubtedly, it has a direct impact on the evaluation of the maximum thresholds for carbon emission ceilings and penalty requirements by policymakers and regulators, therefore shaping the economic landscape in which firms function. Hence, the evaluation of firms' determinations regarding product pricing and production within the framework of the carbon emission cap policy holds great significance for both enterprises and government officials. Indeed, the implementation of carbon emission caps can offer enterprises enduring motivations to mitigate financial risks linked to environmental penalties, thus counterbalancing the operating expenses of organisations and ultimately attaining the simultaneous advantages of environmental management and profit maximisation (Adu et al., 2023). Furthermore, changing consumer preferences for environmentally friendly products serve as a significant motivating factor for enterprises to reduce their carbon emissions. For instance, the level of consciousness among consumers about environmental preservation is consistently growing, and their capacity to voice their concerns and exert impact through their buying choices is accordingly increasing. In addition, a public opinion survey conducted by Nielsen shows that approximately 81% of respondents worldwide believe that companies should contribute to improving the environment (Nielsen, 2020). In addition, about 40% of American consumers are participating in the $300 billion low-carbon consumption market. The above results indicate that companies reducing carbon emissions to environmentally friendly levels may influence consumers' purchasing decisions, especially among environmentally conscious consumers (Muñoz et al., 2017).

A few significant suppliers dominate the primary product supply in the generally established and stable markets of the energy, electricity, oil, and chemical sectors. The suppliers exert a decisive and considerable influence on pricing, but the extent of product variety is restricted. The production processes in these industries generate a large amount of carbon dioxide emissions, indicating that they belong to typical carbon emission-dependent markets. Furthermore, these industries have high energy consumption and low added value, which poses significant obstacles to achieving comprehensive carbon peaking and carbon neutrality. Given the continuous progress in carbon reduction efforts and environmental legislation, corporations in these sectors are now confronted with unparalleled pressures to conserve energy and reduce their emissions. Furthermore, apart from evaluating the environmental expenses linked to carbon reduction efforts, these corporations must consider price, production constraints, and other strategic aspects to successfully negotiate the competitive market. These carbon reduction policies deviate from traditional business practices, leading to increased operational costs for companies. Moreover, although market forces significantly influence corporate decision-making, there is little research on how market structure affects carbon emission limits. And the impact of oligopolistic structures on the efficiency of regulatory policies is particularly noteworthy. Therefore, how to make effective corporate decisions under the constraints of carbon reduction policies, in order to cope with the severe pressure of carbon reduction while simultaneously achieving optimal profitability, has become a common concern for both businesses and scholars.

To address these issues, this study constructs a game theory model to examine how carbon emission cap policies and consumer utility influence the pricing and production decisions of firms in a duopoly market. In the proposed basic model, it is assumed that the market consists of two competing oligopolistic firms, each with its own distribution.

2. Literature review

With the increasing political and social emphasis on a low-carbon economy, research on carbon emission has become a hot topic. Specifically, carbon emission refers to the efficient use of energy or resources in the manufacturing process. In the rapid emergence of the literature on corporate development under carbon reduction conditions, two types of literature are particularly relevant to this study: the impact of carbon emission cap policies on corporate competitive strategies and the influence of consumer utility on corporate competitive strategies. Therefore, the literature review of this study focusses mainly on these two types of research, thereby outlining the direction of this study.

To efficiently regulate the carbon emission practices of companies, numerous researchers have examined the correlation between carbon emission cap regulations and corporate growth. At the corporate decision-making level, Giraud-Carrier (2014) examined the operational decision-making procedures of manufacturing firms while considering three different types of carbon reduction policy limitations. The analysis suggests that imposing any form of carbon reduction policy restriction will result in a decline in the overall production efficiency of manufacturing firms. Furthermore, Toptal et al. (2014) investigated the joint decision-making problem of inventory replenishment and green technology investment for retailers operating within the limitations of three primary carbon reduction policies. Du et al. (2015a) investigated the coordination challenge of a two-tier supply chain that is comprised of suppliers who possess carbon emission rights and emission-dependent manufacturing enterprises, subject to the limitations of carbon trading policies. With non-cooperative game theory, they developed a supply chain coordination mechanism and identified that carbon emission rights significantly influence the sustainable production of emission-dependent manufacturing enterprises. In addition, Ma et al. (2015) brought out green technology and studied the impact of different carbon emission reduction policies on the output of firms. They found that for those firms investing in green technology, production capacity can be enhanced expectably output rising profits under a carbon-constrained and carbon tax policy. In the study by He et al. (2016) research was done on how constraints of various carbon emission reduction policies affect carbon emissions under market-determined scenarios. They found that, with a government-adopted policy of capping carbon through trade, firms can optimise profits. In addition, Ma et al. (2016) examined the production decision-making issues of carbon-sensitive product manufacturing enterprises under carbon cap policies, solving for optimal output and expected profit in both deterministic and stochastic demand scenarios. Additionally, Xu et al. (2017) investigated the production and pricing challenges of a make-to-order supply chain that consists of manufacturers and retailers that produce two products within the confines of carbon trading policies. Moreover, Ma et al. (2017) expanded the newsvendor model by incorporating green technology investment and investigated the intertemporal production decision problem of manufacturing enterprises with a two-period production cycle under the constraints of a carbon trading policy. He et al. (2018) considered the manufacturing firm's production decision problem that produces two types of products: common ones and green/low-carbon products, and in the decision-making model integrated green technology inputs so as to achieve optimal production to the manufacturing firms which are a composition of carbon emission policy constraints. Moreover, Jian et al. (2019) studied the pricing issues of competitive and cooperative products in an oligopolistic market under carbon cap policies, and derived the optimal pricing for both competitive and cooperative scenarios based on an extension of Bertrand competition. Olatunji et al. (2019) took a UK car manufacturing company as an example to discuss how to sustain a competitive advantage within a low-carbon supply chain. A case study comparison between various companies identifies the need for the uptake of carbon-reducing strategies in the expansion of business and presents influencing factors and barriers related to them for automotive manufacturing supply chains. According to Ma et al. (2020), the decision model for low-carbon production in manufacturing firms operating under carbon cap regulations revealed the presence of an optimal output for these companies. Moreover, the activity of trading carbon emissions has a direct influence on the growth of corporations, and allocating resources towards green technology yields favourable outcomes in terms of carbon emission reduction and enhanced corporate profitability. Ma et al. (2022) examine how government carbon trading initiatives affect manufacturing firms. They emphasise the importance of firms changing their production processes, participating in carbon trading, and increasing investment in sustainable technologies to overcome the challenges posed by regulatory carbon reduction policies. This study by Ma et al. (2023) investigates the influence of government-imposed carbon emission regulations on the decision-making processes of enterprises. The researchers derived the most efficient production mix for manufacturing companies that operate under carbon emission allowances and demonstrated that engaging in carbon emission trading can result in increased company earnings.

This research model assumes that after meeting carbon emission limit constraints, the demand from environmentally conscious consumers will also influence the competitive decisions of enterprises. Some empirical studies indicate that consumer utility positively affects the production and competition strategies of companies. Du et al. (2015b) initially studied the impact of low-carbon consumption preferences on emissions-related supply chains. By designing an emissions-sensitive demand function, they verified that consumers' low-carbon consumption preferences influence companies' production decisions. Ma et al. (2016) further explored the impact of consumer utility on the production strategies of carbon-sensitive product manufacturers under deterministic and stochastic demand, finding that when demand is certain, company profits are higher. He et al. (2016) studied supplier sales-oriented strategies that stimulate downstream orders through repurchase contracts to meet consumer utility and increase market demand. Under the quota and trading system, Xia et al. (2018) studied the impact of consumer utility on the production strategies of manufacturers of carbon-sensitive products, finding that incorporating social preferences and consumers' low-carbon awareness into the supply chains of manufacturers and retailers demonstrated that an increase in consumers' low-carbon awareness creates an incentive mechanism. These incentives motivate members in the supply chain to put more efforts into emission reduction and promotion and earn more profits in the process. Also, He et al. (2018) explore the manufacturers' processes of producing green and/or conventional products and find out that firms can use green technologies to capture consumers' environmental sensibilities and increase sales and further profit. Yenipazarli (2019) examined how consumer preferences, competitor behaviour, and regulatory schemes shape manufacturers' competitive R&D and pricing strategies. Consumers prefer to purchase greener products, as one of the reasons is the low carbon practice. At the government level, Zhang et al. (2020) developed a Stackelberg game-focused model with a government subsidy element to determine how consumer preference affects firm strategy in the carbon trading framework. With the increase in the subsidy, they observed a decreasing trend in the retail price of the product as the consumer preference for low-carbon products started to decline. Hu et al. (2022) analysed the influence of static carbon taxes and subsidies on the level and dynamics of interactions between the government, manufacturers, and consumers using the framework of an evolutionary game theory. Wang et al. (2022) addresses the evolution of behavioural strategies and their mutual interplay, with a particular emphasis on the low-carbon consumer orientation in regulating manufacturers' market shares. Their survey on the dual aspects of low-carbon preference held by consumers stresses its effect on the willingness to pay for products and on CSR preferences at the firm level. They demonstrate how these preferences affect the competitive and cooperative strategic investments of manufacturers. Also, Huo et al. (2022) applied evolutionary game theory to study the phenomena of firms in secondary supply chains with the help of numerical simulation methods. It has been shown that low carbon reduction investment behaviour in the supply chain firm is influenced by consumers low carbon preference and environmental regulations. At value changer prices and constant social carbon credits, Wang et al. (2023) analysed the relationship and interactions of factors of price decision-making in carbon emission reduction on the supply chain employing the dual channel evolutionary game theory. The findings of the study revealed that more low-carbon choices preferable by the consumers encouraged the manufacturers to mitigate carbon emissions and increase profitability among the members of the supply chain. In addition, Xu et al. (2023) further calculated which investment alternatives performed the best for manufacturers in targeting emission cuts. They also analysed how the carbon emissions trading system and consumer preferences for low-carbon products affect these strategies. A strong consumer preference for low-carbon products leads to higher levels of emission reductions, more orders, and higher manufacturing profits. Finally, Shi et al. (2023) examined the impact of consumer utility on the production strategies of new energy vehicle manufacturing companies from a supply chain perspective, constructing an evolutionary game model among the government, consumers, and manufacturers. Government subsidies and consumer utility will promote the adoption of new energy vehicles.

A large number of studies have explored the impact of carbon emission reduction policies and consumer utility on corporate decision-making under various constraints, primarily focussing on the joint decisions of individual firms or upstream and downstream companies. However, in the actual market, there are many industries where two or more companies have similar production functions, such as the traditional energy, electricity, oil, and chemical markets. Companies in these markets not only need to cope with the restrictions of carbon reduction policies, but also face competition from their peers within the market. Therefore, this study will focus on competition in a duopoly market, exploring how carbon-dependent companies can make price-quantity decisions to achieve carbon reduction goals under carbon cap policies while considering consumer utility.

3. Model specification

Oligopoly is a dominant market structure in traditional energy, electricity, petroleum, chemical, and associated industries. Prominent corporations such as ExxonMobil and Shell mostly control the energy sector, while PetroChina, Sinopec, and BP dominate the petroleum sector. The State Grid and the Southern electrical Grid wield significant dominance over the electrical sector, whilst DuPont of the United States and BASF of Germany dominate the chemical industry. Furthermore, because of their heavy reliance on conventional oil and coal as raw materials, their carbon dioxide emissions are substantial.

The present study examines a market that is contingent upon carbon emissions, encompassing conventional energy, power, oil, chemical, and associated sectors. An oligopolistic monopoly system arises when two major oligopolistic firms dominate the supply of items in the market. The two primary oligarchs possess different distribution networks, resulting in highly competitive pricing of products in the market. They each produce a single product, which is not completely homogeneous; the differentiation of the products comes from the different carbon dioxide emissions per unit of their respective products. During the production process, both major oligopolies are subject to a government-mandated maximum carbon emission limit, denoted as the carbon emission cap K_i (>0), where i=1, 2.

At the same time, due to the deepening of low-carbon and environmental protection concepts, low-carbon products such as high-octane, eco-friendly gasoline are becoming increasingly competitive in the market compared to high-carbon products. Additionally, with the development of green low-carbon technologies, the manufacturing costs of low-carbon products are continuously decreasing. Furthermore, with the ongoing introduction of policies such as government subsidies, the prices of low-carbon products often do not exceed those of high-carbon products. Therefore, when making price-quantity decisions, oligopolies must also consider the issue of consumer preferences for low-carbon or high-carbon products, namely, the issue of consumer utility. To facilitate discussion and expression, the parameters adopted in the model are assigned the following descriptions (see details in Table 1).

Table 1. Parameters and Descriptions

Parameter	Description	Parameter	Description
Q_0	Market demand	U	Consumer utility

Parameter	Description	Parameter	Description
q_1	Production quantity of the Oligopoly1	t_u	The preference cost of consumer on purchase low carbon products and high carbon products
q_2	Production quantity of the Oligopoly2	λ	The extent of consumer's preference on low carbon products and high carbon products
p_1	The market price per unit product of the oligopoly1	K_1	Government-imposed carbon caps on Oligopoly1
p_2	The market price per unit product of the Oligopoly2	K_2	Government-imposed carbon caps on Oligopoly2
e_1	The carbon emissions per unit product of the Oligopoly1	$S_1(\chi)$	The distance from which any consumer purchases Product 1
e_2	The carbon emissions per unit product of the Oligopoly2	$S_2(\chi)$	The distance from which any consumer purchases Product 2
c_1	The cost per unit product of the Oligopoly1	π_1	Expected profit of Oligopoly1
c_2	The cost per unit product of the Oligopoly2	π_2	Expected profit of Oligopoly2

Source: Authors' own creation.

The aforementioned parameters must meet the following conditions for the constructed model to have practical significance, thereby, the assumptions are:

(1) Oligopoly i has the common sense of the carbon emissions per unit product, where i=1, 2, and $e_1 < e_2$;

(2) $\frac{K_i}{e_i}$ is defined as the maximum production of suppliers under the carbon limit constraint, where $Q_0 \geq \frac{K_i}{e_i} + \frac{K_j}{e_j}$, and i=1, 2;

(3) The extent of consumer preference for low-carbon products and high-carbon products, referred to as consumer preference λ, where the interval of parameter is [0, 1];

(4) The extent of cost preference of consumers toward low-carbon products and high-carbon products, referred to as cost preference t_u, where the interval of parameter is [0, 1];

(5) Assume that the oligopoly must be able to maintain normal but rational production while balancing the benefits and costs generated by carbon emission rights trading.

4. Results and discussion

4.1 Basic Model

Consumers differ in their preferences for low- and high-carbon products. The Hotelling model assumes that products have the same material properties but differ in their carbon emissions per unit. Assigning low-carbon and high-carbon products to the ends of a 1-unit length line segment results in a uniform distribution of customers in the interval [0,1] with a density of 1. Within this range, we denote the location of the consumer as y, with the low-carbon product located at x = 0 and the high-carbon product located at x = 1. Thus, the spatial separation between the consumer and the low-carbon product is denoted as x, and the spatial separation from the high-carbon product is denoted as 1-x. The spatial separation between consumers and products is denoted as 1-x. The distance between consumers and products is proportional to the carbon cost incurred by purchasing products with different carbon emissions.

The cost of consumers purchasing each unit of a product is represented as t_u. Assuming that the total output of the two major oligopolistic firms is sufficient to meet market demand without the constraints of carbon reduction policies, it follows that $q_1 + q_2 = 1$, which $q_1 = s_1(x) = x$, $q_2 = s_2(x) = 1 - x$. At the same time, the model that is not constrained by carbon emissions describes a competitive market scenario between two major oligopolistic firms, where the production activities of the two oligopolies are not hindered by carbon reduction policies.

The profits of the two oligopolistic firms (π_i^{NC}) can be expressed as:

$$\pi_i^{NC} = (p_i - c_i)q_i;\ \ i = \{1,2\} \tag{1}$$

In addition, when considering the impact of consumer utility on demand, consumer utility (U_i^{NC}) can be expressed as:

$$U_i^{NC}(x) = 1 - t_u s_i(x) - p_i + \lambda\left(e_j - e_i\right); i = \{1,2\}; j = 3 - i \tag{2}$$

The random demand $x_{12}^{NC} \equiv (t_u + p_2 - p_1)/(2t)$ is the point at which customers become indifferent over the purchase of things. Within this particular situation, two oligopolistic products exert complete control over the whole market, with the primary goal being the maximum of profits. This paper presents the optimal decisions made by the two oligopolists.

$$\begin{cases} p_1^{*NC} = \frac{3t_{ii}+2c_1+c_2-2\lambda(e_1-e_2)}{3} \\ p_2^{*NC} = \frac{3t_{ii}+c_1+2c_2-2\lambda(e_2-e_1)}{3} \\ q_1^{*NC} = \frac{-c_1+c_2+3t_{ii}-2e_1\lambda+2e_2\lambda}{6t_{ii}} \\ q_2^{*NC} = \frac{c_1-c_2+3t_{ii}+2e_1\lambda-2e_2\lambda}{6t_{ii}} \\ \pi_1^{*NC} = \frac{(-c_1+c_2+3t_{ii}-2e_1\lambda+2e_2\lambda)^2}{18t_{ii}} \\ \pi_2^{*NC} = \frac{(c_1-c_2+3t_{ii}+2e_1\lambda-2e_2\lambda)^2}{18t_{ii}} \end{cases} \tag{3}$$

Thus, in a market controlled by two dominant oligopolies, taking into account consumer benefit, if the two oligopolies are not limited by carbon reduction measures during production, there is an ideal price that meets market demand and an optimal price ascertained by output that maximises profits.

4.2 Carbon Cap Policy Constraint Model

An essential objective of this scenario is to optimise financial gains. A carbon emission cap policy is applicable in a market characterised by competition between two oligopolistic firms. Each oligopolistic firm is subject to a government-imposed maximum carbon emission cap, denoted as the carbon emission cap K_i (>0), where i=1, 2. If the carbon emission cap of any oligopolistic firm proves inadequate or excessive, they will be rendered unable to engage in the purchase or sale of carbon credits. Thus, the net benefit of oligopoly can be expressed as:

$$\begin{cases} \pi_1^{CX} = (p_1 - c_1)q_1 \\ s.t. e_1 q_2 \le K_1 \end{cases} \tag{4}$$

The profitability of oligopoly 2 can be expressed as:

$$\begin{cases} \pi_2^{CX} = (p_2 - c_2)q_2 \\ s.t. e_2 q_2 \le K_2 \end{cases} \tag{5}$$

Consumer Utility (U_i^{NC}) can be formalised as:

$$U_i^{CX}(x) = 1 - t_u s_i(x) - p_i + \lambda(e_j - e_i);\ i = \{1,2\}; j = 3 - i \tag{6}$$

Proposition 1. In two oligopolistic competitive markets limited by carbon emission cap regulations, the government establishes the carbon emission cap as K_i (i=1, 2), such that the two oligopolists have a distinct optimal output pricing option, taking into account consumer value.

Proof: In the absence of carbon emission cap regulations, the absence of carbon emission permits prevents any oligopoly from attaining optimal output, resulting in a decrease in market size. This phase is characterised by oligopolistic decision-making that focusses on complying with carbon emission restrictions while simultaneously retaining the highest market share and earnings. At this point, the market demand function (d_i^{CX}) for the oligopoly i's products can therefore be elaborated as:

$$d_i^{CX} = \left[1 - p_i + \lambda\left(e_j - e_i\right)\right]/t_u, i = \{1,2\}; j = 3 - i \tag{7}$$

where d_i^{CX} represents the market demand derived from the consumer utility function. Oligopoly i's output equals the market demand and complies with the carbon cap constraint, thus:

$$q_i^{cx} = d_i^{cx}, e_i q_i \leq K_i, i = \{1,2\}.$$

Construct the Lagrangian function $L_i\left(p_i, \gamma_i^{CX}\right)$ for oligopoly i, whereγ_i^{CX} is the Lagrangian multiplier, $\gamma_i^{CX} > 0, i = \{1,2\}$.

$$L_i\left(p_i, \gamma_i^{CX}\right) = (p_i - c_i)(1 - p_i)/t + \gamma_i^{CX}\left[e_i\left((1 - p_i)/t_u\right) - K_i\right]$$

The Lagrange multipliers obtained through first-order optimality conditions are:

$$\gamma_i^{CX} = -1 + c_i + \frac{2K_i t_u}{e_i} + e_i\lambda - e_j\lambda,\ \ i = \{1,2\}; j = i - 3$$

The first-order optimal conditions are derived by combining equations (4), (5), and (7):

$$\begin{cases} 1 + c_i - \gamma_i^{CX} - 2p_i - e_i\lambda + e_j\lambda = 0 \\ -\frac{K_i}{e_i} + \frac{1 - p_i - e_i\lambda + e_j\lambda}{t_u} = 0 \end{cases} \tag{8}$$

Solving this system of equations, the optimal output-pricing decision for the two oligopolies are listed below:

$$\begin{cases} p_1^{*CX} = 1 - \frac{K_1 t_u}{e_1} - e_1\lambda + e_2\lambda \\ p_2^{*CX} = 1 - \frac{K_2 t_u}{e_2} - e_2\lambda + e_1\lambda \\ q_1^{*CX} = \frac{K_1}{e_1} \\ q_2^{*CX} = \frac{K_2}{e_2} \\ \pi_1^{*CX} = \frac{K_1}{e_1}(1 - c_1 + e_2\lambda - e_1\lambda - \frac{K_1}{e_1} t_u) \\ \pi_2^{*CX} = \frac{K_2}{e_2}(1 - \frac{k_2 t_u}{e_2} - e_2\lambda + e_1\lambda - c_2) \end{cases} \quad (9)$$

Hence, taking consumer utility into account, in the competitive market between two oligopolies constrained by the carbon cap policy, when the government sets the carbon cap as K_i (i=1, 2), there exists a unique optimal output-pricing decision for the two oligopolies. **The proof has been confirmed.**

Corollary 1. Take into account consumer utility, in the competitive market characterised by two oligopolies and constrained by the carbon cap policy, when $\frac{K_2}{e_2} \geq \frac{K_1}{e_1}$ and $e_1 \geq e_2$, $p_1^{*CX} \geq p_2^{*CX}$;and when $\frac{K_2}{e_2} < \frac{K_1}{e_1}$ and $e_1 < e_2$, $p_1^{*CX} < p_2^{*CX}$. Notably, the $\left(p_1^{*CX} - p_2^{*CX}\right)$ exhibits a positive correlation with the increase in both $t_{u.}$ and λ.

Proof:

Because $\sqrt[n]{a^n} = \begin{cases} p_1^{*CX} = 1 - \frac{K_1 t_u}{e_1} - e_1\lambda + e_2\lambda \\ p_2^{*CX} = 1 - \frac{K_2 t_u}{e_2} - e_2\lambda + e_1\lambda \end{cases}$,

then $p_1^{*CX} - p_2^{*CX} = t_u\left(\frac{K_2}{e_2} - \frac{K_1}{e_1}\right) + 2\lambda(e_1 - e_2)$

Hence, when $\frac{K_2}{e_2} \geq \frac{K_1}{e_1}$ and $e_1 \geq e_2$, then $p_1^{*CX} \geq p_2^{*CX}$; and when $\frac{K_2}{e_2} < \frac{K_1}{e_1}$ and $e_1 < e_2$, then $p_1^{*CX} < p_2^{*CX}$. Thus, take account of consumer utility in the competitive market characterised by two oligopolies and constrained by the carbon cap policy, when $\frac{K_2}{e_2} \geq \frac{K_1}{e_1}$ and $e_1 \geq e_2$, $p_1^{*CX} \geq p_2^{*CX}$; and when $\frac{K_2}{e_2} < \frac{K_1}{e_1}$ and $e_1 < e_2$, $p_1^{*CX} < p_2^{*CX}$. Notably, the $(p_1^{*CX} - p_2^{*CX})$ exhibits a positive correlation with the increase in both $t_u$and λ. **The proof has been confirmed.**

The aforementioned propositions and inferences indicate that, when considering consumer utility under carbon emission cap constraints, there exists an equilibrium solution for the price and output decisions of the two major oligopolistic firms in a competitive market. The optimal market price of a product is influenced by factors such as the production capacity constrained by carbon emission limits, carbon emissions per unit of product, consumer preferences, and the cost of those preferences. In particular, the market price of the product decreases as a result of an increase in production capacity within the carbon constraints, which is a result of a reduction in carbon emissions per unit of product. Furthermore, the market price of low-carbon products will rise in proportion to the increase in consumer demand, provided that production capacity remains constant. Consequently, this would result in a decrease in market prices for manufactured products and an increase in preference costs.

5. Numerical Analysis

Taking into account consumer utility, the impact of carbon emission cap policies on the decisions of two major oligopolistic firms was evaluated. Through numerical examples, this study intuitively illustrates the trends in market prices, output, and profits of the two major oligopolistic firms, providing a reference for the government to improve carbon reduction policies. The parameter values are as follows:

The market capacity is $Q_0 = 1$; the production cost and unit product carbon emissions for Oligopoly 1 are $c_1 = 0.2$, $e_1 = 0.2$; the production cost and unit product carbon emissions for Oligopoly 2 are $c_1 = 0.2, e_1 = 0.2$. The carbon emission caps set by the government and the unit carbon tax are both $K_1 = K_2 = 0.1$,. Consumer's preference on the carbon emissions per unit of the two products are denoted as $\lambda \in [0,1]$, and the preference cost of purchasing each unit of the product is denoted as $t \in [0,1]$. When considering the impact of consumers' preference on the carbon emissions per unit of the two products on the oligopoly's decision-making, $t = \frac{2}{3}$; conversely, when considering the impact of consumers' preference cost per unit of product on the oligopoly's decision-making, $\lambda = \frac{2}{3}$.

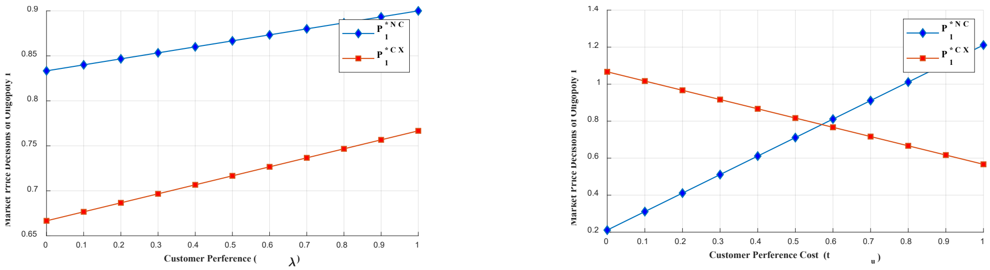

Figure 1 Market Pricing Decision by Oligopoly 1
Source: Authors' own creation.

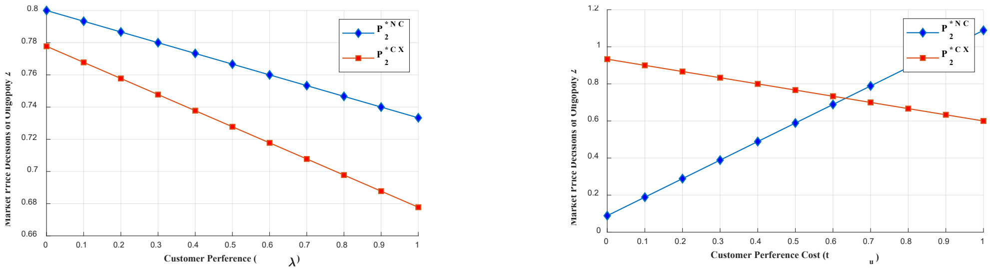

Figure 2: Market Price Decisions of Oligopoly 2
Source: Authors' own creation.

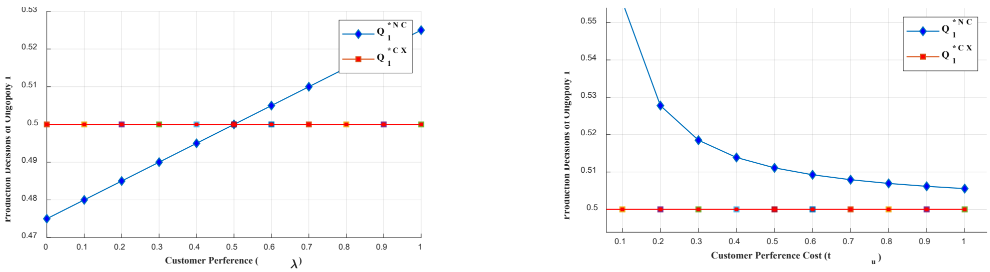

Figure 3: Production Decisions of Oligopoly 1
Source: Authors' own creation.

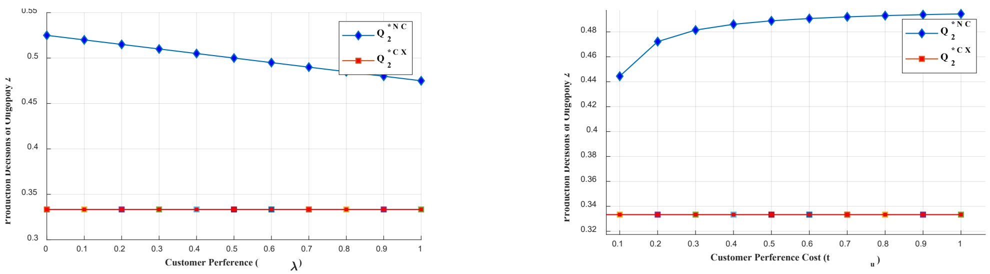

Figure 4: Production Decisions of Oligopoly 2
Source: Authors' own creation.

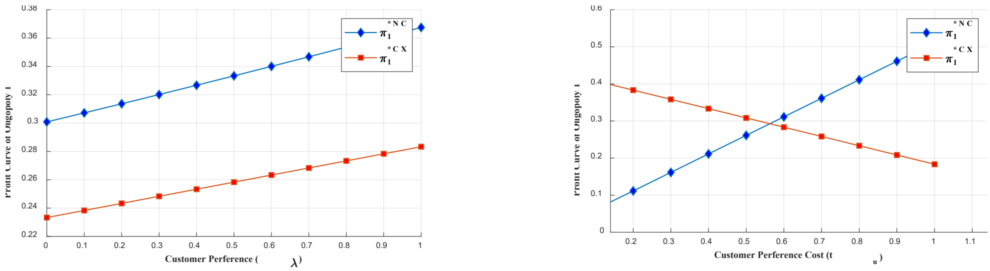

Figure 5: Profit Curve of Oligopoly 1
Source: Authors' own creation.

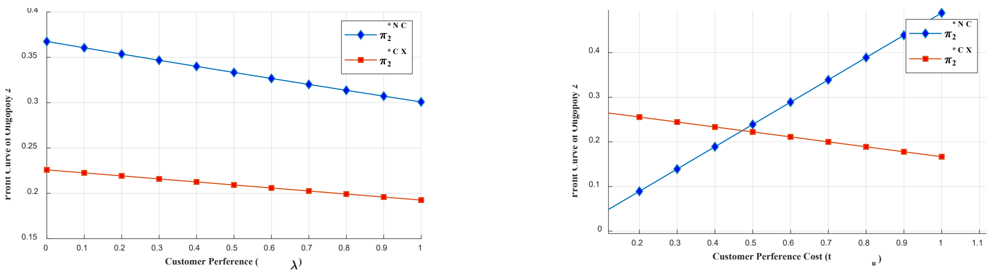

Figure 6: Profit Curve of Oligopoly 2
Source: Authors' own creation.

5.1 Basic Model Scenario

The basic model scenario describes a market where two oligopolistic firms compete, taking into account consumer utility, but where the production process is not affected by carbon reduction policies. In Figures 1 to 6, the superscript NC^* on the right side indicates the basic model scenario. According to formula (3), it is possible to derive the market price decisions, output decisions, and profit curves of two oligopolistic firms when considering consumer utility.

In this scenario, as consumer preference (λ) increases, the market price, output, and profit of oligopoly 1 rise, while the market price, output, and profit of oligopoly 2 decrease. On the contrary, as the cost paid by consumers (t) increases, the market prices and profits of the two oligopolistic firms rise simultaneously, while output remains almost unchanged.

5.2 Carbon Cap Policy Constraint Scenario

In a scenario constrained by carbon emission cap policies, in a market with competition between two major oligopolistic firms, considering consumer utility, the production processes of both oligopolistic firms are subject to government-mandated maximum carbon emission limits. In Figures 1 to 6, CX^* as a superscript on the right indicates the scenario of carbon emission cap policy constraints. According to formula (9), when considering consumer utility, we can derive the market price decisions, output decisions, and profit curves of the two major oligopolistic firms under the constraints of carbon emission cap policies. Through numerical analysis, the following observations can be made:

In this scenario, when consumer preferences (λ) increase, the market price and profits of oligopoly 1 increase, while the market price and profits of oligopoly firm 2 decrease. The output of the two oligopolies remains constant.

As the cost (t) borne by customers rises, the market prices of the two oligopolistic entities fall while output remains constant, leading to a loss of profits for both parties.

6. Discussions and Conclusions

This study specifically examines markets that are significantly impacted by carbon emissions, namely in conventional industries such as energy, electricity, oil, and industrial chemicals. This study investigates the decision-making process of two prominent companies in determining the most effective pricing and competitive strategies, while also compliance with carbon emission restrictions. The conclusions are later validated by numerical statistical analysis. First of all, the analysis indicates that in a carbon emission cap competition market that takes consumer utility into account, there exists an equilibrium solution for the pricing and production decisions of the two major oligopolists. In addition, the analysis also indicates that the optimal market price of the product is influenced by various factors, including the company's production capacity, carbon emission limits, carbon emissions per unit of product, consumer preferences, and preference costs, among others. In addition, the analysis indicates that under carbon emission cap constraints, a lower carbon emission per unit of product can lead to higher production capacity, thereby reducing the market price of the product. Furthermore, with production capacity remaining unchanged, the market price of low-carbon items increases in proportion to the customer demand for such products. Conversely, the market price of low-carbon products decreases when the cost of preference for such things increases.

Therefore, consumers' purchasing behaviour is influenced by their preferences and the costs of choosing low-carbon products, which in turn affects the market prices of those products. Oligopolistic enterprises should prioritise the promotion of low-carbon product characteristics to increase consumers' propensity to purchase, in light of the constraints imposed by carbon emission quota policies. Simultaneously, consumers not only exhibit a preference for low-carbon products but also the inclination and capacity to acquire them as their awareness of environmental protection increases. Finally, it is equally important that in future research, the government, when implementing carbon emission cap policies, can find a balance based on the results of this study, optimising social welfare while minimising carbon emissions.

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