# Mitigating Size Bias for Carbon Pricing in Small Asia-Pacific Countries: Increasing Block Carbon Tax

Yunfei An[a], Dequn Zhou[b,c], Qunwei Wang [b,c,**], Xunpeng Shi[d,e *], Farhad Taghizadeh-Hesary[f]

*[a] School of Business, Henan University, Jinming Avenue, Kaifeng 475004, China*
*[b] College of Economics and Management, Nanjing University of Aeronautics and Astronautics, 29 Jiangjun Avenue, Nanjing 211106, China*
*[c] Research Centre for Soft Energy Science, Nanjing University of Aeronautics and Astronautics, 29 Jiangjun Avenue, Nanjing 211106, China*
*[d] Australia-China Relations Institute, University of Technology Sydney, Ultimo, NSW, 2007, Australia*
*[e] Center of Hubei Cooperative Innovation for Emissions Trading System, Hubei University of Economics, Wuhan 430205, China*
*[f] Tokai University, Tokyo, Japan*

**Abstract:** While the popularity of emission trading schemes (ETS) has exceeded that of carbon taxes, ETS is not applicable to all countries. This paper investigates the increasing block carbon tax (IBCT), which is a modified carbon tax based on the increasing block tariffs theory. The IBCT considers the size bias in emission reduction, and this paper discusses whether it is suitable for small Asia-Pacific countries (SAPCs). Both theoretical analysis and numerical simulation were used to compare the impacts of IBCT and flat carbon tax (FCT) on the emission reduction behavior of manufacturers in both purely competitive and co-opetitive market environments. This study demonstrates that the IBCT is better than the prevailing FCT, and the results indicate that this could be a better choice for SAPCs. The implementation of the IBCT policy in SAPCs can protect domestic manufacturers and decrease the risk of carbon leakage. The IBCT promotes low-carbon production when the manufacturers expand their scale, which can lead to a win-win situation for social welfare and environmental development. We suggest that the IBCT should be implemented in high-carbon

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[*] Corresponding author. Tel: +86 2584896261
*E-mail address: xunpeng.shi@uts.edu.au (Xunpeng Shi); wqw0305@126.com (Qunwei Wang)*

industries; its formulation needs more market details than FCT. Besides the policy, the development of reduction technologies also cannot be ignored.

**Keywords:** Increasing block carbon tax; Carbon emission reduction; Small Asia-Pacific country; Game theory

## 1 Introduction

The Paris Agreement has encouraged countries around the world to restrain climate change, and a majority of countries successively introduced corresponding policies to reduce greenhouse gas emissions (Ding et al., 2019; World Bank, 2021). By the end of 2020, 61 countries and regions have implemented or planned to implement carbon pricing mechanisms, including 31 carbon emission trading schemes (ETS) regions and 30 carbon tax regions; many regions, involving 1,482 administrative jurisdictions with 820 million residents, have declared a climate emergency in 2019 (Word Bank, 2020).

While the Asia-Pacific region is a key region for combating climate change, many countries have yet to develop their carbon pricing policies. Over the past 50 years, the Asia-Pacific region has witnessed rapid development, which is also accompanied by the rapid growth of energy consumption and carbon emissions (Niu et al., 2011; Song and Zhang, 2019). Several large countries in the Asia-Pacific region either implement carbon pricing policies or prepare to control carbon emissions with carbon pricing policies, such as Japan, Indonesia (World Bank, 2021); however, few SAPCs are involved. Although any single SAPC currently accounts for a low share of global carbon emissions, their total emitted amount is considerable. The lack of carbon pricing policies may cause carbon leakage risks given the lack of implementation of the carbon border adjustment mechanism (CBAM) (Branger and Quirion, 2014; Eicke et al., 2021). In this case, designing clever carbon pricing mechanisms for SAPCs will not only help them to shape a low-carbon and sustainable future, but will also reduce the carbon leakage risk.

Since the number of manufacturers that participate in ETS in these countries is insufficient, carbon tax policies may be more applicable, but require further modification. Most implemented carbon tax policies adopt uniform prices, i.e., a flat carbon tax (FCT), which has made the implementation of a carbon tax controversial (Lin and Li, 2011). One of the major challenges associated with the FCT is the identification of an appropriate carbon tax rate. Most manufacturers in SAPCs are small-scale, and their abilities to resist external risks are poor (Gomes-Casseres, 1997). A high carbon tax limits the manufacturers' production, while a low carbon tax diminishes the ability to control excessive carbon emissions (Zhang and Baranzini, 2004).

The recently proposed increasing block carbon tax (IBCT) (Zhou et al., 2019), may be applicable to SAPCs. IBCT has been inspired by the increasing block tariffs (IBTs), which have been applied in many fields to achieve social fairness, cost recovery, and efficiency, as well as to tackle environmental problems (Filipović and Tanić, 2008). Its implementation can effectively overcome the contradiction between satisfying basic needs and punishing excessive waste via resource pricing, thus achieving a more reasonable resource allocation (Wu et al., 2017). The IBCT is a form of carbon tax with increasing marginal tax. Under an IBCT framework, smaller firms can obtain preferential treatment, i.e., a lower carbon tax rate, and will therefore not be disadvantaged by a carbon tax. Furthermore, a relatively high tax rate can push large firms with relatively low marginal abatement costs to reduce further their emissions than under an FCT. Therefore, the IBCT policy can promote both manufacturing development and low carbon growth.

Clarifying the effects of an IBCT on the behavior of manufacturers is necessary to validate the proposed carbon tax policy and formulate related policies in SAPCs. Since the IBCT has a progressive marginal tax, its effects on the decisions of manufacturers at both the strategic and operational levels are significantly different from those of the FCT. However, only few academic studies on the IBCT explored its feasibility from a macroscopic perspective (Zhou et al., 2019; An and Zhai, 2020). But the impacts of this modified carbon pricing policy on the behaviors of manufacturers have not been examined to date.

To explore the impacts of the IBCT on the carbon emissions of manufacturers from fossil energy use, this study examined two competing manufacturers that apply different emission reduction strategies under two different carbon tax regimes. Using both non-cooperative and cooperative games, the emission reductions were analyzed under both policy scenarios. The impacts of the IBCT were compared with those from the FCT and its characteristics were distinguished. A comparative study was also developed in both purely competitive and co-opetitive environments. Based on this, this paper discusses whether the IBCT policy is applicable to SAPCs.

The main contributions of this paper are twofold: First, the effects of an IBCT policy on the behaviors of manufacturers were explored, embodied in two dimensions. Second, the feasibility of carbon policies for SAPCs is discussed and it was clarified whether increasing the marginal carbon tax is beneficial for SAPCs.

The remainder of this paper is organized as follows: Section 2 reviews the related literature. Section 3 introduces the model formulation and assumptions. The influence of an IBCT on the emission reduction behavior of manufacturers in purely competitive and co-opetitive scenarios is analyzed. Section 4 applies numerical examples to specify the analysis results and discussions. The main conclusions of the study are summarized in Section 5.

## 2 Literature review

In this section, we perform a literature review to validate the importance and originality of the current research. Considering only few studies for carbon policies in SAPCs, our study relates to three broader streams of research: manufacturer's pricing and production behavior within a carbon tax policy, the application of IBTs, and exploration of the IBCT.

The first relevant stream of literature studies the manufacturer's pricing and production behavior within a carbon tax policy. Chen et al. (2015) showed that a carbon tax has a greater negative impact on resource-rich regions. Besides, Yang, Luo, and Wang (2017) explored the government's optimal carbon tax, which encourages manufacturers to reduce emissions as much as possible. He et al. (2018) argued that a low rate of carbon tax will have little control to reduce emissions, whereas a high rate will force manufacturers to give up their technology upgrade plans. Ma et al. (2018b) proposed an optimal scheme for selecting suppliers and ordering quantity to overcome the influence of a carbon tax. Besides, many studies apply game theory to research carbon tax (Li et al., 2015; Chen and Hao, 2015; Yi and Li, 2018; Meng et al., 2018). Therefore, we choose it as a research method.

The second relevant stream of literature studies the application of IBTs. The content relates primarily to three aspects: IBTs prices in water (Rinaudo, Neverre, and Montginoul, 2012; von Hirschhausen, Flekstad, and Meran 2017), electric (Chen and Yang, 2009; Lin and Jiang, 2012), and gas (Gong et al., 2016; Liu and Lin, 2018) sectors. In the literature, IBTs are demonstrated to be better than the flat price policy (Hung and Huang 2015) in terms of resource-saving, cost minimization, and social equity, leading to an increase in policy efficiency. Rinaudo et al. (2012) simulated an increasing block water price in Southern France and argued that increasing block water prices are better in balancing the relationship between environmental protection, cost recovery, and equity. von Hirschhausen (2017) believed that increasing the block water price is a policy tool widely used to support poor people's access to drinking water and thus promote equity. Lin and Jiang (2012) put forward a residential electricity price with increasing block pricing. These various IBT concepts improve social equity and efficiency. Liu and Lin (2015) designed an increasing block gas price plan and found that more price blocks in combination with a higher price gap in each block can optimize the subsidy redistribution and improve social fairness, efficiency, and consciousness of energy saving. Gong et al. (2016) designed an increasing block gas price in China and showed that this pricing method can achieve both an income guarantee for operators, as well as protection of natural gas resources. When carbon emissions are given a price, they will also have properties similar to these resources. Similar to the pricing of water, electricity, and gas, applying IBTs to carbon tax is expected to produce better policy effects.

The third relevant stream of literature is related to the exploration of the IBCT. Both Zhou et al. (2019) and Wu et al. (2017) have proposed to apply the IBT framework to carbon tax but only Zhou et al. (2019) explicitly proposed the concept of IBCT. Zhou et al., (2019) demonstrated that the application of IBTs in the carbon emission will also achieve similar results to other applications of the IBTs and the IBCT regime is better than the prevailing FCT. More recently, An and Zhai (2020) applied IBCT to China's coal-fired power industry. Their results showed that the IBCT can reduce the burden on the coal-fired power industry and achieve the same abatement effect as IBT. The IBCT regime is better than the prevailing FCT in that can reduce compliance costs because of its flexible marginal carbon price. However, no previous studies have ever investigated firms' behavior under such an IBCT regime.

In this paper, quite different from the literature reviewed above, we focus on how the increasing blocking carbon tax affects the manufacturers' emission reduction behaviors, and whether the IBCT policy applies to SAPCs is explored. To solve the problem, a model with a carbon tax using the game theory is set up. Based on this, the emission reduction behaviors for the IBCT and FCT are analyzed.

## 3 Modelling

### *3.1 Assumptions and variables*

In this section, the possible effects of the IBCT implementation are theoretically analyzed, and whether this tax scheme suits for SAPCs is discussed. Due to small number of firms in SAPC, we consider only two competing manufacturers. To eliminate the interference of production factors, the manufacturers are assumed to produce the same products. The parameters and variables used to represent them in the model are presented in Table 1 (Yalabik and Fairchild, 2011; Choudhary et al., 2015; Luo et al., 2016; Cao et al., 2017; Xun et al., 2017).

**Table 1. Market parameter list**

| Notation | Descriptions |
|---|---|
| $q_1$ , $q_2$ | Production quantity or customer demand of Manufacturer 1 and 2 respectively |
| $P(q_1,q_2)$ | Unit retail price of manufacturers |

| | |
|---|---|
| $\alpha$ | The market potential, $\alpha > 0$ |
| $\beta$ | Self-price elasticity, $\beta > 0$ |
| $c$ | Unit production cost, $c < \alpha$ |
| $e_0$ | Initial unit carbon emissions of Manufacturer 1 and 2, $e_0 > 0$ |
| $e_1, e_2$ | Unit carbon emissions after reduction of Manufacturer 1 and 2, respectively, $0 < e_1 \le e_0$ and $0 < e_2 \le e_0$ |
| $s$ | An investment parameter of emission reduction efficiency of manufacturer |
| $I_i = s(e_0 - e_i)^2$ | The investment of emission reduction of manufacturer $i$, $i = 1,2$ |
| $k$ | Growth factor for carbon tax |
| $a$ | Marginal coefficient for carbon tax |
| $\pi_1, \pi_2$ | The profit of Manufacturer 1 and 2 respectively |

We assume that the relationship between demand and price in the market is linear. The price function is represented by: $P(q_1,q_2) = \alpha - \beta(q_1 + q_2)$. Due to the small size of home-market in SAPCs, the market can achieve market clearing, quickly equalizing the supply and demand of products. Therefore, there is neither rationing and idle resources nor excess supply or demand (Cao et al. 2017).

The green technology investment is assumed as a disposable (one-off) investment to improve the production process, which turns raw material into product. The unit product needs fixed raw material, however, carbon emissions from the unit product in the production process could be reduced through the use of green technology. The two manufacturers aim to reduce initial unit carbon emissions from $e_0$ to $e_i\ (i = 1,2)$, respectively, to reduce the carbon tax cost. The investment is represented by: $I_i = s(e_0 - e_i)^2$ (Yalabik and Fairchild 2011; Choudhary et al. 2015).

A carbon tax set by the government aims to ensure that carbon emissions reach an expected value. The two kinds of carbon tax policies (IBCT and FCT) can be used. Generally, an IBCT is a discrete model. However, when the block is infinitesimal, the limit of the discrete model is the continuum model (Xun et al. 2017). Furthermore, the most essential difference between the increasing block tax and the flat tax is that the increasing block tax has an increasing marginal tax rate, while the flat tax remains unchanged (Chen and Yang 2009). Therefore, we express the IBCT as a continuum model to simplify the research process without affecting the results. We assume that the carbon tax is represented by: $t = kE_i^a = k(e_i q_i)^a$ $(a = 0,1)$. When $a = 0$, the tax $t$ becomes an FCT. When $a = 1$, the tax $t$ becomes an IBCT. Between the two forms of the carbon tax, we can find the IBT has a uniform carbon tax $k$, while the IBCT has a changing marginal tax, which is related to the manufacturers' overall carbon emissions $e_i q_i$. As such, the most essential difference between IBT and IBCT can be reflected by our defined form.

Manufacturers' revenues come from sale revenues, and the costs of manufacturers include manufacturing costs, green technology investments, and carbon tax costs. According to the existing research of other scholars (Luo et al., 2016), we assume that the two manufacturers have the same unit production cost $c$ and green technology investment parameter $s$.

Based on the above description and assumptions, Manufacturer 1's profit, denoted by $\pi_i(q_i, e_i)$, $i = 1,2$, is given by Equation (1).

$$\pi_i(q_i, e_i) = (\alpha - \beta \sum q\ )q_i - cq_i - s(e_0 - e_i)^2 - e_i q_i \cdot k(e_i q_i)^a \tag{1}$$

In Equation (1), the first term is the sale revenue. The second term is the manufacturing cost, while the third term is the green technology investment. The fourth term is the carbon tax cost.

### *3.2 Comparative analysis of the two carbon taxes in a purely competitive market*

In a purely competitive market, the two manufacturers make their decisions separately to achieve maximum profit. That is, the manufacturer's decision problem is given by Equation (2).

$$\begin{aligned} &\max \quad \pi_i(q_i, e_i) \\ &s.t. \quad \pi_i(q_i, e_i) > 0 \end{aligned} \tag{2}$$

Each manufacturer chooses the profit-maximizing strategy to produce the products in a purely competitive market in any case. The constraint condition means that the two manufacturers would not produce products if their profit turns out negative.

Taking the first order conditions of Equation (1) with respect to $q_1$ and $q_2$ produce the solutions to $(q_1, q_2)$, which are given by Equations (3) and (4).

$$\frac{\partial \pi_1}{\partial q_1} = \alpha - 2\beta q_1 - \beta q_2 - c - (a+1)ke_1^{a+1}q_1^{a} = 0 \tag{3}$$

$$\frac{\partial \pi_2}{\partial q_2} = \alpha - 2\beta q_2 - \beta q_1 - c - (a+1)ke_2^{a+1}q_2^{a} = 0 \tag{4}$$

The variables $q_1^{nf}$ and $q_2^{nf}$ represent the Manufacturer 1's equilibrium output and Manufacturer 2's equilibrium output in a purely competitive market within an FCT policy (a=0), which can be solved using Equations (3) and (4).

$$q_1^{nf} = \frac{\alpha - c - 2k_0e_1 + k_0e_2}{3\beta} \tag{5}$$

$$q_2^{nf} = \frac{\alpha - c - 2k_0e_2 + k_0e_1}{3\beta} \tag{6}$$

Using Equations (5) and (6), the output of each manufacturer changes and can be solved as Equations (7) and (8).

$$\frac{\partial q_1^{nf}}{\partial e_1} = -2k_0 / 3\beta \tag{7}$$

$$\frac{\partial q_2^{nf}}{\partial e_1} = k_0 / 3\beta \tag{8}$$

The variables $q_1^{nb}$ and $q_2^{nb}$ represent Manufacturer 1's equilibrium output and Manufacturer 2's equilibrium output in a purely competitive market within an IBCT policy ($a = 1$), which can be solved using Equations (3) and (4).

$$q_1^{nb} = \frac{\beta(\alpha - c) + 2k_1(\alpha - c){e_2}^2}{3\beta^2 + 4\beta k_1{e_2}^2 + {e_1}^2(4{k_1}^2{e_2}^2 + 4\beta k_1)} \tag{9}$$

$$q_2^{nb} = \frac{\beta(\alpha - c) + 2k_1(\alpha - c)e_1^{\,2}}{3\beta^2 + 4\beta k_1 e_2^{\,2} + (4k_1^{\,2} e_2^{\,2} + 4\beta k_1)e_1^{\,2}} \tag{10}$$

The output of each manufacturer changes because of Manufacturer 1's reduction can be solved using Equations (9) and (10).

$$\frac{\partial q_1^{nb}}{\partial e_1} = -\frac{(8e_2^{\,2}k_1^{\,2}e_1 + 8\beta k_1 e_1)(\beta + 2e_2^{\,2}k_1)(\alpha - c)}{(3\beta^2 + 4\beta e_1^{\,2}k_1 + 4\beta e_2^{\,2}k_1 + 4e_1^{\,2}e_2^{\,2}k_1^{\,2})^2} < 0 \tag{11}$$

$$\frac{\partial q_2^{nb}}{\partial e_1} = \frac{4\beta^2 e_1 k_1(\alpha - c) + 8\beta e_1 e_2^{\,2}k_1^{\,2}(\alpha - c)}{(3\beta^2 + 4\beta e_1^{\,2}k_1 + 4\beta e_2^{\,2}k_1 + 4e_1^{\,2}e_2^{\,2}k_1^{\,2})^2} > 0 \tag{12}$$

**Proposition1: Compared with the FCT, an IBCT can help Manufacturer 1 obtain greater profits by reducing their carbon emissions and this market boost effect is more significant for a larger manufacturer.**

When the market implements an FCT policy ($a = 0$), the relationship between Manufacturer 1's profit and carbon emissions per unit product can be solved by taking the first order of Equation (1) with respect to $e_1$ (see Equation (13)).

$$\frac{\partial \pi_1^{nf}}{\partial e_1} = 2e_0 s - 2se_1 - k_0 q_1 \tag{13}$$

Equation (13) shows that $\pi_1$ is inversely proportional to $e_1$ when $e_1 > e_0 - \frac{k_0 q_1}{2s}$, whereas $\pi_1$ is proportional to $e_1$ when $e_1 < e_0 - \frac{k_0 q_1}{2s}$.

When the market implements an IBCT policy ($a = 1$), the relationship between Manufacturer 1's profit and carbon emissions per unit product can be solved by taking the first order conditions of Equation (1) with respect to $e_1$ (see Equation 14).

$$\frac{\partial \pi_1^{nb}}{\partial e_1} = 2se_0 - (2k_1 q_1^{\,2} + 2s)e_1 \tag{14}$$

Eq. (14) shows that $\pi_1$ is inversely proportional to $e_1$ when $e_1 > \frac{se_0}{k_1 q_1^{\,2} + s}$, whereas $\pi_1$ is proportional to $e_1$ when $e_1 < \frac{se_0}{k_1 q_1^{\,2} + s}$.

Eq. (13) and (14) indicate that the carbon emissions per unit product of

Manufacturer 1 has an extreme point within both the FCT and IBCT. The emissions reduction can bring more profits for Manufacturer 1 due to the low cost of emission reductions in the low reduction phase. However, the marginal cost of emissions reduction is incremental. When the emissions reduction exceeds the extreme point, the emissions reduction behavior of Manufacturer 1 will result in negative profit growth.

When $\frac{\partial \pi_1^{nf}}{\partial e_1} - \frac{\partial \pi_1^{nb}}{\partial e_1} < 0$, the marginal profit of Manufacturer 1's carbon emissions reduction per unit product within an IBCT policy becomes greater than an FCT policy, which is represented by the Inequality (15).

$$q_1 > \frac{k_0}{2k_1 e_1} \tag{15}$$

Inequality (15) will be satisfied when $q_1$ is large (Pang, 2018), which indicates that the marginal profit of the manufacturer's emissions reduction within an IBCT is higher than that within an FCT. Therefore, IBCT is conducive to stimulate manufacturers to implement emissions reduction behaviors to obtain greater profits.

**Proposition 2: In a dynamic game market of a purely competitive market under an IBCT regime, Manufacturer 1's continuous increases in emission reductions cause an incremental marginal equilibrium output within an interval. The less sensitive to price is the manufacturer's product, the larger will be the interval.**

The equilibrium output of Manufacturer 1 in the purely competitive market is given by: $q_1^{nf} = \frac{\alpha - c - 2ke_1 + ke_2}{3\beta}$ within an FCT. Taking the first order condition of $q_1^{nf}$ with respect to $e_1$ produces $\frac{\partial q_1^{nf}}{\partial e_1} = -2k/3\beta < 0$. This means that Manufacturer 1's equilibrium quantity $q_1^{nf}$ decreases in its unit carbon emissions $e_1$, and every unit $e_1$ decrease causes $2k/3\beta$ units of $q_1^{nf}$ increase.

The equilibrium output of Manufacturer 2 in the purely competitive market is given by: $q_2^{nf} = \dfrac{\alpha - c - 2ke_2 + ke_1}{3\beta}$ within an FCT. Taking the first order condition of $q_2^{nf}$ with respect to $e_1$ gives: $\dfrac{\partial q_2^{nf}}{\partial e_1} = k / 3\beta$. This means that Manufacturer 2's equilibrium quantity $q_2^{nf}$ increases in Manufacturer 1's unit carbon emissions $e_1$, and every unit $e_1$ decrease causes $k / 3\beta$ units of $q_1^{nf}$ decrease.

The equilibrium output of Manufacturer 1 in the purely competitive market is given by: $q_1^{nb} = \dfrac{\beta(\alpha - c) + 2k_1(\alpha - c)e_2{}^2}{3\beta^2 + 4\beta k_1 e_2{}^2 + e_1{}^2(4k_1{}^2 e_2{}^2 + 4\beta k_1)}$ within an FCT. Taking the first order condition of $q_1^{nb}$ with respect to $e_1$ produces: $\dfrac{\partial q_1^{nb}}{\partial e_1} = -\dfrac{(8e_2{}^2 k^2 e_1 + 8\beta k e_1)(\beta + 2e_2{}^2 k)(\alpha - c)}{(3\beta^2 + 4\beta e_1{}^2 k + 4\beta e_2{}^2 k + 4e_1{}^2 e_2{}^2 k^2)^2} < 0$. This means that Manufacturer 1's equilibrium quantity $q_1^{nf}$ decreases in its unit carbon emissions $e_1$ and every unit $e_1$ decrease causes marginal changes to $q_1^{nf}$. Particularly, every unit $e_1$ decrease causes marginal increments of $q_1^{nf}$ when $e_1 \in [\sqrt{\dfrac{\beta}{3k_1} - \dfrac{\beta^2}{12k_1(k_1 e_2{}^2 + \beta)}}, e_0]$. Furthermore, every unit $e_1$ decrease causes marginal reductions of $q_1^{nf}$ when $e_1 \in [0, \sqrt{\dfrac{\beta}{3k_1} - \dfrac{\beta^2}{12k_1(k_1 e_2{}^2 + \beta)}}]$ (see Appendix A.1). The inflection point emissions are given by: $e_{nt} = \sqrt{\dfrac{\beta}{3k_1} - \dfrac{\beta^2}{12k_1(k_1 e_2{}^2 + \beta)}}$.

The equilibrium output of Manufacturer 1 in a purely competitive market is given by: $q_2^{nb} = \dfrac{\beta(\alpha - c) + 2k_1(\alpha - c)e_1{}^2}{3\beta^2 + 4\beta k_1 e_2{}^2 + e_1{}^2(4k_1{}^2 e_2{}^2 + 4\beta k_1)}$ within an FCT. Taking the first order condition of $q_2^{nb}$ with respect to $e_1$ produces: $\dfrac{\partial q_2^{nb}}{\partial e_1} = \dfrac{4\beta^2 e_1 k_1(\alpha - c) + 8\beta e_1 e_2{}^2 k_1{}^2(\alpha - c)}{(3\beta^2 + 4\beta e_1{}^2 k_1 + 4\beta e_2{}^2 k_1 + 4e_1{}^2 e_2{}^2 k_1{}^2)^2} > 0$. This means that Manufacturer 2's equilibrium quantity $q_2^{nb}$ increases in Manufacturer 1's unit carbon emissions $e_1$ and every unit $e_1$ decrease causes marginal changes to $q_2^{nb}$. Particularly, every unit $e_1$ decrease causes marginal increments of $q_2^{nb}$ when $e_1 \in [\sqrt{\frac{\beta}{3k_1} - \frac{\beta^2}{12k_1(k_1 e_2{}^2 + \beta)}}, e_0]$. Furthermore, every unit $e_1$ decrease causes marginal reductions of $q_1^{nf}$ when $e_1 \in [0, \sqrt{\frac{\beta}{3k_1} - \frac{\beta^2}{12k_1(k_1 e_2{}^2 + \beta)}}]$ (see Appendix A.2). The inflection point emissions are given by: $e_{nt} = \sqrt{\frac{\beta}{3k_1} - \frac{\beta^2}{12k_1(k_1 e_2{}^2 + \beta)}}$. The inflection point emissions $e_{nt}$ are increasing in $\beta$ (see Appendix A.3). This means that the inflection point corresponding to Manufacturer 1's unit carbon emissions has a positive correlation with the price elasticity of demand for the product.

In a purely competitive market within an IBCT, Manufacturer 1's reduction in carbon emissions per unit of product can increase its equilibrium quantity. There is an inflection point in the ascent. At the beginning of the reduction, Manufacturer 1's marginal equilibrium output increases in its emission reductions. As Manufacturer 1's emissions decrease to the inflection point, Manufacturer 1's marginal equilibrium output decreases in its emission reductions. In addition, compared to Manufacturer 1, Manufacturer 2 experiences the opposite situation due to the influence of Manufacturer 1's emissions reduction.

The inflection point corresponding to Manufacturer 1's unit carbon emissions has a correlation with the price elasticity of demand for product. Less is the flexible demand for product, lower will be the inflection point corresponding to Manufacturer 1's unit carbon emissions. This is because emission reductions mean less spent on paying the carbon tax, whereas the initial marginal cost of emission reductions is lower. Therefore, a manufacturer which reduces its emissions has higher positive marginal profits to devote towards producing more products. However, when the prices of products are more flexible, the manufacturer produces more products, and this results in much lower prices. Therefore, the profits of the manufacturer are affected, which leads to an increase in the unit carbon emissions at the inflection point. Generally, the price flexibility of non-necessities is large, and there are many alternatives. Therefore, these non-necessities should be replaced by green products having low carbon emissions. Necessities have less price flexibility and fewer alternatives, due to which, a carbon tax is needed to control their emissions.

Compared with the FCT, initial stage emission reductions cause the manufacturer to have an incremental marginal equilibrium output. This makes it more effective for the manufacturer to increase the investment in emission reductions to expand market equilibrium production. This is especially true for the manufacturer who either does not have emissions reduction or has low emissions reduction. However, the scope of increase is limited. In excess of the limit, the opposite result will be produced due to an incremental emission reduction.

### *3.3 Comparative analysis of the two carbon taxes in a co-opetitive model market*

In the co-opetition situation, Manufacturer 1 and Manufacturer 2 aim to maximize their total profits. They make decisions together and share the emission reduction technology. The situation is represented using Equations (16) and (17).

$$q_c = q_1 + q_2 \tag{16}$$

$$e_c = e_1 = e_2 \tag{17}$$

where $q_c$ represents the two manufacturers' equilibrium total output and $e_c$ is their unit carbon emissions after investing in the green technology. Their profit $\pi_{cf}$ is given by Equation (18).

$$\begin{aligned} \max\ & \pi_c(q_c, e_c) = (q_1 + q_2)(\alpha - \beta(q_1 + q_2) - c) - 2s(e_0 - e_c)^2 - k_1 e_c{}^2 (q_1{}^{a+1} + q_2{}^{a+1}) \\ s.t.\ \ & \pi_1(q_1, e_c) > 0 \\ & \pi_2(q_2, e_c) > 0 \end{aligned} \tag{18}$$

where $q_1^{cf}$ and $q_2^{cf}$ are the Manufacturer 1's equilibrium output and

Manufacturer 2's equilibrium output in a co-opetition market within an FCT policy (a=0), and which can be solved using Equation (18).

The function $\pi_{cf}(q_1,q_2,e_c)$ of $q_1$ and $q_2$ may not be a concave function (see Appendix A.4). However, we can find an optimal value of $q_1+q_2$, as given by Equations (19) and (20).

$$\frac{\partial\pi_{cf}(q_1,q_2,e_c)}{\partial(q_1+q_2)}=\alpha-2\beta(q_1+q_2)-c-k_0e_c=0 \tag{19}$$

$$q^{cf}=q_1+q_2=\frac{\alpha-c-k_0e_c}{2\beta} \tag{20}$$

Therefore, the two manufacturers maximize their total profits when their total output is given by: $\frac{\alpha-c-k_0e_c}{2\beta}$.

where $q_1^{cb}$ and $q_2^{cb}$ are Manufacturer 1's and Manufacturer 2's equilibrium outputs in a co-opetition competition market within an IBCT policy (a=1), respectively, and which can be solved using Equation (18).

$$\frac{\partial\pi_{cb}(q_1,q_2,e_c)}{\partial q_1}=-2\beta q_1-2\beta q_2+a-c-2k_1{e_c}^2q_1 \tag{21}$$

$$\frac{\partial\pi_{cb}(q_1,q_2,e_c)}{\partial q_2}=-2\beta q_2-2\beta q_1+a-c-2k_1{e_c}^2q_2 \tag{22}$$

Therefore, the two manufacturers maximize their total profits when their total output is (see Appendix A.5) given by Equation (23).

$$q_1^{cf}=q_2^{cf}=\frac{a-c}{2(k_1{e_c}^2+2\beta)} \tag{23}$$

The two manufacturers' total output $q^{cb}$ and total profit $\pi^{cb}$ are given by Equations (24) and (25).

$$q^{cb}=q_1^{cf}+q_2^{cf}=\frac{a-c}{k_1{e_c}^2+2\beta} \tag{24}$$

$$\pi_{cb}(q_1,q_2,e_c)=\frac{(\alpha-c)^2}{2(ke_c{}^2+2\beta)}-2s(e_0-e_c)^2 \qquad (25)$$

**Proposition 3: Compared with the FCT, an IBCT can incentivize the co-operative manufacturers to obtain greater profits by reducing their carbon emissions further. This incentive is stronger for larger manufacturers.**

When the market implements an FCT policy ( $a=0$ ), the relationship between the co-operative manufacturers' profits and carbon emissions per unit product can be solved by taking the first order conditions of Equation (18) with respect to $e_c$:

$$\frac{\partial \pi^{cf}}{\partial e_c}=2(2e_0 s-2se_c-k_0 q_c) \qquad (26)$$

Eq. (26) shows that $\pi^{cf}$ is inversely proportional to $e_c$ when $e_c > e_0-\frac{k_0 q_c}{2s}$, whereas $\pi^{cf}$ is directly proportional to $e_c$ when $e_c < e_0-\frac{k_0 q_c}{2s}$.

When the market implements an IBCT policy ( $a=1$ ), the relationship between the co-operative manufacturers' profits and carbon emissions per unit product can be solved by taking the first order conditions of Equation (18) with respect to $e_c$:

$$\frac{\partial \pi^{cb}}{\partial e_c}=4se_0-4se_c-2k_1 q_1{}^2 e_c-2k_1 q_2{}^2 e_c \qquad (27)$$

Eq. (27) shows that $\pi^{cf}$ is inversely proportional to $e_c$ when $e_c > \frac{4se_0}{4s+k_1 q_c{}^2}$,

whereas $\pi^{cf}$ is directly proportional to $e_c$ when $e_c < \frac{4se_0}{4s+k_1 q_c{}^2}$.

Similar to the purely competitive market, Eq. (26) and (27) indicate that the unit carbon emissions of co-operative manufacturers have extreme values within both the IBCT and FCT. At the initial stage of emission reduction, it can result in more total profits for the co-opetition manufacturers because of low cost. However, the marginal cost of emission reduction increases with the increase in unit emission reduction. Therefore, when the emission reduction exceeds the extreme point, the emission reduction behavior of co-operative manufacturers will bring negative total profit growth.

When $\frac{\partial \pi^{cb}}{\partial e_c} - \frac{\partial \pi^{cf}}{\partial e_c} < 0$, the marginal profit of co-operative manufacturers within the IBCT is higher than the FCT. This is represented by Inequality (28).

$$q_c > \frac{2k_0}{k_1 e_c} \tag{28}$$

The condition in Inequality (28) will be satisfied when $q_c$ is large (Pang, 2018). This means that the marginal profit of co-operative manufacturers' emission reduction within an IBCT is higher than that within an FCT. Therefore, an IBCT is conducive to stimulate co-operative manufacturers to implement emission reduction behaviors to obtain greater profits.

**Proposition 4: In a co-operative market within an IBCT policy, co-operative manufacturers continuously increase their emission reductions, thus causing an incremental marginal equilibrium output until the turning point. The opportunities before the turning point, or the increasing interval, will be larger for those products that are less sensitive to price.**

The equilibrium output of Manufacturer 1 in the co-opetitive market is given by: $q^{cf} = \frac{\alpha - c - k_0 e_c}{2\beta}$ within an FCT. Taking the first order condition of $q_1^{nf}$ with respect to $e_1$ produces: $\frac{\partial q^{cf}}{\partial e_c} = -k_0 / 2\beta < 0$. This means that the co-operative manufacturer's equilibrium quantity $q_1^{nf}$ decreases in its unit carbon emission $e_c$, and every unit $e_c$ decrease always causes $k_0 / 2\beta$ units of increase in $q^{cf}$.

The equilibrium output of Manufacturer 1 in the co-opetitive market is given by: $q^{cb} = q_1^{cb} + q_2^{cb} = \frac{a - c}{k_1 e_c{}^2 + 2\beta}$ within an FCT. Taking the first order condition of $q^{cb}$ with respect to $e_c$ produces $\frac{\partial q^{cb}}{\partial e_c} = -\frac{2k_1 e_c}{(k_1 e_c{}^2 + 2\beta)^2} < 0$. This means that

Manufacturer 1's equilibrium quantity $q^{cb}$ decreases in its unit carbon emission $e_c$ and every unit $e_c$ decrease causes marginal changes in $q^{cb}$. Notably, every unit $e_c$ decrease causes a marginal increment in $q^{cb}$ when $e_c \in [\sqrt{\frac{2\beta}{3k_1}}, e_0]$. Furthermore, every unit $e_c$ decrease causes marginal reduction in $q^{cb}$ when $e_c \in [0, \sqrt{\frac{2\beta}{3k_1}}]$ (see Appendix A.6). The inflection point emissions are given by: $e_{ct} = \sqrt{\frac{2\beta}{3k_1}}$.

The carbon tax will inhibit the production of manufacturers and reduce their optimal production, due to which, they will fail to reach the maximum profit without the restriction of carbon tax (Tian et al., 2017). In a co-opetitive market within an IBCT policy, manufacturers continue to reduce emissions, which causes an incremental marginal equilibrium output. This makes it more effective for manufacturers to increase their investment in emission reduction to expand the market equilibrium production, especially for the manufacturer who either does not have emissions reduction or has low emissions reduction. However, the scope of the increase is limited. In excess of the limit, the opposite result will be produced due to an incremental emission reduction.

## 4 Numerical simulations

We have theoretically analyzed the IBCT and the FCT in different markets. An IBCT takes different carbon costs in different emission intervals, thereby enhancing the manufacturer's energy conservation and emission reduction. In this section, two markets are developed for numerical analyses. They are the pure competition market and co-opetition market. We attempt to present simple numerical examples evaluating the differences between the IBCT and FCT in each market for SAPC. In numerical analyses, we use the control variables method to more significantly distinguish the results of the decision made by a manufacturer under the two carbon tax policy regimes. Since the two manufacturers are assumed to be identical, only the behavior and results of Manufacturer 1 are emphasized as a representative in this section.

### *4.1 Pure competition market*

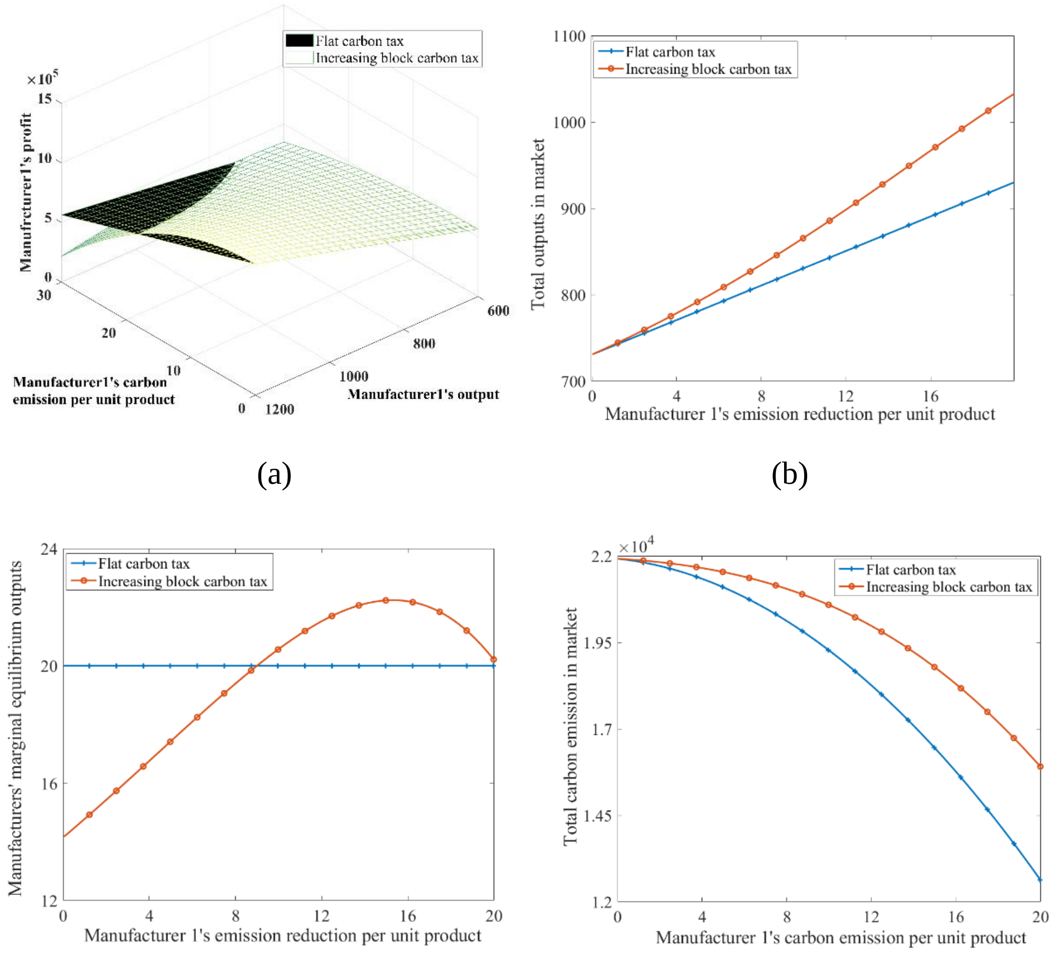
A carbon tax for SAPC should constrain large-scale production with high carbon emissions. Considering the characteristics of SAPC market and the purpose of carbon reduction policy, we set up a purely competitive duopoly market with lower price elasticity $\beta$, larger market capacity $\alpha$, larger unit production cost $c$, and larger initial carbon emissions per unit production. Therefore, referring to the research of other scholars, we specified that: $\beta = 0.05$, $\alpha = 1000$, $c = 2$, $e_0 = 30$, and $s = 5$ (Luo et al., 2016; Zhou et al., 2019). The rate of emission reductions will not exceed 66.7% with the current technological level. We set an IBCT and an FCT with the same binding effects, which means that the total carbon emissions emitted by the SAPC market can be constrained to the same desired value of 10960 when $e_0 = 30$. The IBCT parameters in the purely competitive market are: $k_1 = 0.000684307$, and $a_1 = 1$.

A carbon tax for SAPC should restrict large-scale production with high carbon emissions. Considering the characteristics of SAPC market and the purpose of carbon reduction policy, we set up a purely competitive duopoly market with lower price elasticity $\beta$, larger market capacity $\alpha$, larger unit production cost $c$, and larger initial carbon emissions per unit production. Following the literature (Luo, Chen, and Wang 2016; Zhou et al., 2019), we specified that: $\beta = 0.05$, $\alpha = 1000$, $c = 2$, $e_0 = 30$, and $s = 5$. The rate of emission reductions will not exceed 66.7% with the current technological level. We set an IBCT and an FCT with the same binding effects, which means that the total carbon emissions emitted by the SAPC market can be capped to the same desired value of 10960 when $e_0 = 30$. The IBCT parameters in the purely competitive market are: $k_1 = 0.000684307$, and $a_1 = 1$. The FCT parameters in the purely competitive market are: $k_0 = 15$, and $a_0 = 0$. In the absence of a carbon tax constraint, the equilibrium total output of the market is 1330.6667 and the total emissions are 39920. In the case of an IBCT or FCT, the equilibrium output of the SAPC market is 730.6667, whereas the total emissions are 21920. At this point, both Manufacturer 1 and Manufacturer 2 produced 365.3333 units.

In Scenario 1, Manufacturer 1 changed the production and emission reduction strategies, while Manufacturer 2 did not make timely adjustments. The output of Manufacturer 2 is set at 365.3333. The different production output and emission reduction adopted by Manufacturer 1 are shown in Figure 1(a).

Figure 1(a) shows that, in most of the cases, Manufacturer 1 makes more profit based upon the IBCT rather than the FCT policy. The IBCT has a low tax amount in the low carbon emission intervals. Due to this reason, Manufacturer 1 can save more tax costs than in the case of the FCT. However, when implementing the IBCT, Manufacturer 1 with high unit carbon emissions and high output would have much lower profits than that within the FCT. The main reason is that the IBCT has a high tax amount in the high carbon emissions interval, which leads to a high carbon tax cost for high carbon manufacturers. The manufacturer’s marginal profit is less than zero, causing a rapid decline in profits. A high tax amount for a high emission interval is a punishment for a manufacturer’s excessive emissions. For a high carbon emission manufacturer in a competitive market, the IBCT is conducive to its voluntary emissions reduction. The emissions reduction is a better way to save costs, which improves the manufacturer’s profit. This result is consistent with those obtained in Proposition 1.

In Scenario 2, we assume that the production of Manufacturer 2 is dynamically adjusted with Manufacturer 1’s decision. When Manufacturer 1 reduces its carbon emissions, the market equilibrium is changed, as shown in Figure 1(b)-(d).



(a) (b)

(c) (d)

**Figure 1. Impact of manufacturer 1's emission reduction behavior in a purely competitive market**

Figure 1(b) illustrates that the marginal equilibrium output of Manufacturer 1 increases gradually with the increase in its reduced emissions in the case of the IBCT, while in the case of the FCT, it remains constant. The initial emission reduction causes less increase in production within the IBCT. However, when the emission reduction is greater than 9, the marginal equilibrium output exceeds the FCT in the case of the IBCT. When the emission reduction increases to 15, the rate of increase for the marginal equilibrium output gradually slows down. This result is consistent with that obtained in Proposition 2.

Figure 1(c) and 1(d), respectively, illustrate the total production and total carbon emissions from the perspective of the whole market. Figure 1(c) shows the relationship between the total output and the unit emission reduction of Manufacturer

1. The total market output within the IBCT is higher than that within the FCT. Generally, more production means more social welfare (Chen and Nie, 2016). Therefore, emission reductions will create more products and social benefits in the market with the IBCT. Figure 1(d) shows the relationship between the total carbon emissions and the unit emission reduction of Manufacturer 1. Regardless of the type of tax, the total carbon emissions of the market show a downward trend with the increase in the unit emissions of Manufacturer 1. Although in the case of the IBCT, higher emissions are observed, the SAPC market's carbon emissions are not higher than the expected value of 21920. The FCT may impose too much constraint on the market, which leads to low social welfare. Therefore, both of the carbon tax policies meet the requirements, though the increasing block carbon would be more advantageous for SAPC.

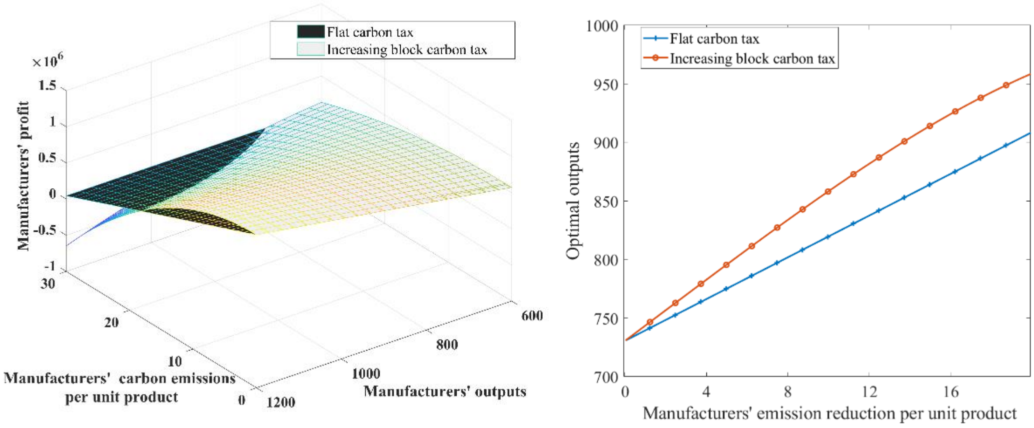
### *4.2 Co-opetitive market*

Similar to the purely competitive market for SAPC discussed in Sub-section 4.1, in a co-operative market, we specify that $\beta = 0.05$, $\alpha = 1000$, $c = 2$, $e_0 = 30$, and $s = 5$. Furthermore, the rate of emission reduction shall not exceed 66.7%. In the co-operative market, the manufacturer adopts the same reduction technology and gains joint profits. Based upon the study of Zhou et al. (2019), we set an IBCT and an FCT with the same binding effect, which means that the total carbon emissions emitted by the SAPC market do not exceed 21960 when the unit product emission is given by: $e_0 = 30$. The IBCT parameters in the co-operative market are given by: $k_1 = 0.00040653$, and $a_1 = 1$. The FCT parameters in the co-operative market are given by: $k_0 = 8.911116667$, and $a_0 = 0$. In the absence of a carbon tax constraint, the equilibrium output of the co-operative manufacturer is 998, and the total emissions are 29820. In the case of a stepped carbon tax or fixed carbon tax, the equilibrium output is 730.6667, whereas the total emissions emitted by the SAPC market are 21920.

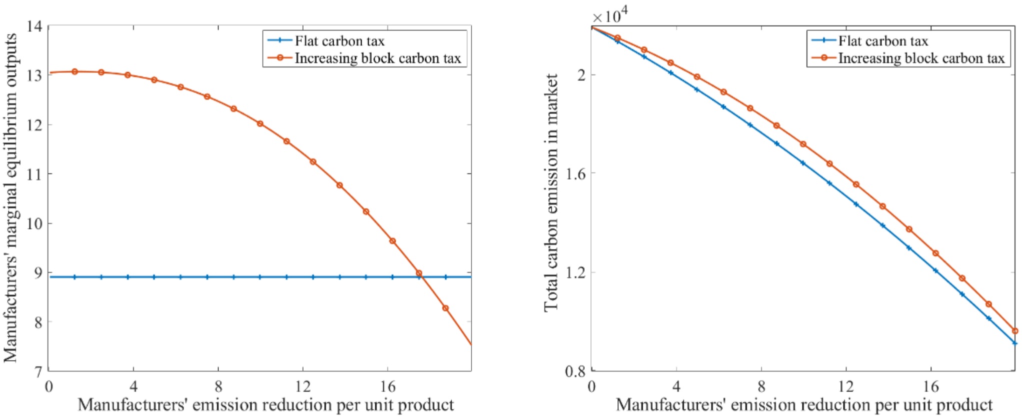
In Scenario 3, we show the impact of co-operative manufacturers' emission reductions and outputs on their profits within different carbon taxes, as shown in Figure 2(a).

Figure 2(a) shows that, generally speaking, the co-operative manufacturers make more profits in the case of the IBCT than in the FCT case. The IBCT has a lower tax amount in the low carbon emission intervals. Therefore, the co-operative manufacturers can save more tax costs than within the FCT. However, when implementing the IBCT, the co-operative manufacturers with high unit carbon emissions and high output would have much lower profits than with the FCT. The main reason is that the IBCT has a high tax amount in the high carbon emissions interval, which leads to a high carbon tax cost for high carbon production. Emissions reduction is a better way to save costs, which also improves manufacturers' profits. This result is consistent with that obtained in Proposition 3.

In Scenario 4, we set the production of co-operative manufacturers as dynamically adjusted with the co-operative manufacturers' decisions. Based on optimum profits, they also aim to expand their scale of production. When co-operative manufacturers reduce their carbon emissions, the market equilibrium is changed, as shown in Figure 2 (b)-(d).



(a) (b)



(c) (d)

**Figure 2. Impact of the co-operative manufacturers' emission reduction behavior**

Figure 2(b) illustrates the relationship between the emission reduction of co-operative manufacturers and their equilibrium production within the two carbon taxes. As the emission reduction increases, the output of the co-operative manufacturers under the two carbon tax policies gradually increases. On the contrary, in the case of the IBCT, the rate of increase is higher at the initial stage and has a short increasing interval.

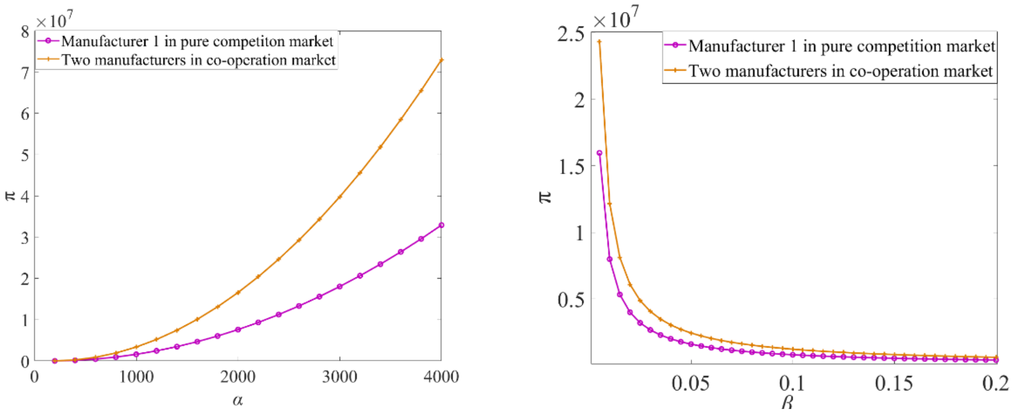
Figure 2(c) illustrates that the co-operative manufacturers have a high marginal equilibrium output at the initial stage in the case of the IBCT. The marginal equilibrium output increases with emission reduction from 0 to 1.35 and decreases after the short increasing interval. The result is consistent with that obtained in Proposition 4. However, in the co-operative market settings with an increasing carbon tax, the inflection point of the unit carbon emission is higher than that in the purely competitive market (see Appendix A.7). This means that the IBCT causes a less marginal increase in the equilibrium output by increasing the reduction. However, the initial marginal equilibrium output is high and is often higher than the IBCT, which is conducive to production-oriented co-operative manufacturers' voluntary emissions reductions.

In addition, Figure 2(d) shows that the relationship between the total carbon emissions and the unit emission reduction of the co-operative manufacturers is similar.

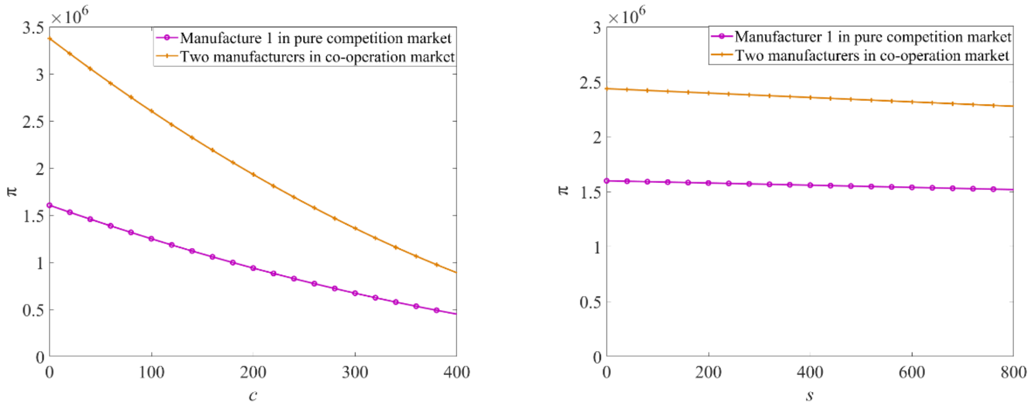
Regardless of the IBCT or the FCT, the total carbon emissions of the SAPC market show a declining trend with the increase in unit emission reduction of the co-operative manufacturers. Although the case of the IBCT has more total emissions, the carbon emissions in the market are not higher than the expected value of 21920. The FCT may impose too much constraint on the market, which leads to low social welfare in SAPC. Therefore, while both carbon tax policies meet the requirements, the IBCT would have more advantages.

After exploring the relationship between the manufacturers' emission reduction with different carbon tax policies for SAPC, we develop sensitivity analyses on the market-determined parameters in the model.

According to the model description, in the SAPC market within the flat carbon tax, we specify that $\beta = 0.05$, $\alpha = 1000$, $c = 2$, $s = 5$, $k_0 = 15$, $a_0 = 0$, $e_0 = 30$, $e_1 = 20$, $e_2 = 30$. And we also specify that $\beta = 0.05$, $\alpha = 1000$, $c = 2$, $s = 5$, $k_1 = 0.0004$, $a_1 = 1$, $e_0 = 30$, $e_1 = 20$, $e_2 = 30$ as the parametric values in the SAPC market within the increasing block carbon tax. On a separate note, we attempt to explore the effect of $\beta$, $\alpha$, $c$ and $s$ on the profit of the manufacturers under the static condition of other parameters.



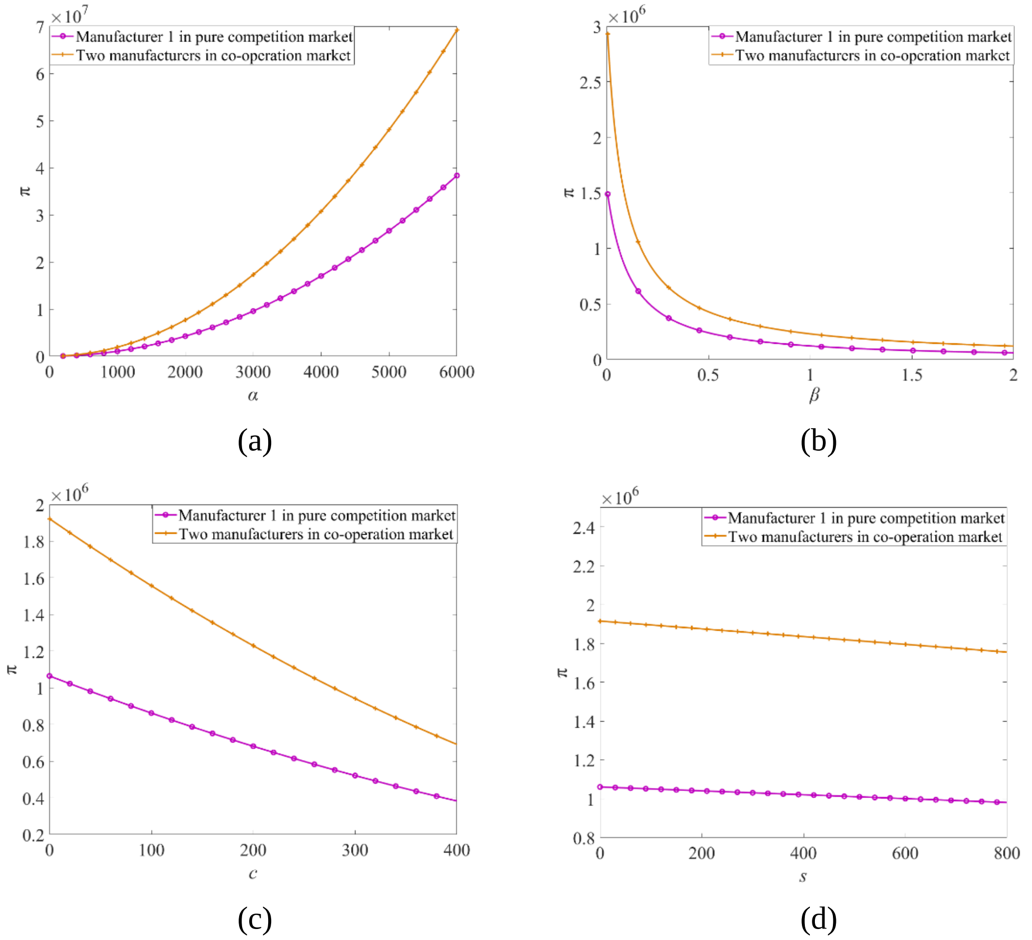
(a) (b)



(c) (d)

**Figure 3 Sensitivity analysis of the parameters for the FCT**

The results of the two markets for the FCT are shown in Figure 3, while those for the IBCT are shown in Figure 4.



(a) (b)

(c) (d)

**Figure 4 Sensitivity analysis of the parameters for the IBCT**

Figure 3(a) and Figure 4(a) show the changes in manufacturers' profit in response to the changing parameters pertaining to market potential $\alpha$. The four curves have a positive slope, meaning that the manufacturers' profit increases with the increase in the market potential. Large $\alpha$ indicates the presence of more buyers in the market, due to which, manufacturers can sell more products and gain more profits.

Figure 3(b) and Figure 4(b) show the simulated results of manufacturers' profits in response to the changes in parameters related to the self-price elasticity of production $\beta$. The four curves have a negative slope, indicating that as $\beta$ increases, the decline of manufacturers' profit is huge, which gradually slows down. This means that higher $\beta$ represents the situation where customers are highly affected by the change in price, which makes a shrinking demand that dampens the production.

Figure 3(c) and Figure 4(c) show the relationship between the manufacturers' profits and the unit production costs $c$. The four curves slope downwards. However, the downward trend of manufacturers' profit with the increase in $c$ becomes slower and slower. This is due to the fact that a high unit cost reduces the unit profit.

Figure 3(d) and Figure 4(d) illustrate the negative relationship between the manufacturers' profit and investment parameters of emission reduction efficiency of manufacturer $s$. The four descending lines show the manufacturers' profit in response to the changes in parameters related to $s$. High $s$ represents the low efficiency of manufacturers' investment for emission reduction, causing a high reduction cost.

### *4.3 Discussion*

Quantitative analysis demonstrated that the IBCT has better effects in both a purely competitive market and a co-opetitive market setting. The advantages of IBCT make it more suitable for SAPCs than FCT. This is embodied in three aspects, presented in the following:

Firstly, compared with the FCT, the IBCT results in higher profits for manufacturers in both a purely competitive market and a co-opetitive market setting. High-carbon manufacturers who do not adopt a strategy of emission reductions are the exception. This is in line with the goals of a carbon tax. Furthermore, the IBCT further alleviates the adverse impacts of a carbon tax on the profit of the manufacturer, which lowers the manufacturers' carbon tax burden. For SAPCs with more small-scale manufacturers, IBCT can reduce the carbon tax burden of enterprises to a certain extent. Moreover, the current carbon leakage is generally caused by high carbon emission manufacturers who transfer their production spatially to reduce the costs associated with their own carbon emissions. The high marginal carbon tax of IBCT for the high carbon emission range can effectively prevent the occurrence of such carbon leakage. Therefore, the IBCT policy can not only protect the interests of domestic manufacturers but also lower the risk of carbon leakage.

Secondly, in both a purely competitive market and a co-opetitive market setting, the manufacturer's emission reduction yields an increasing marginal equilibrium output with an IBCT, while it remains constant for an FCT. However, the marginal equilibrium output is low at the initial stage of emission reductions, while the progressive increasing interval is large in a purely competitive market. The implementation of IBCT in SAPCs can guide the development direction of their manufacturers. A scale expansion without carbon reduction is not advisable under the IBCT policy. Therefore, manufacturers must take carbon emission reductions into account while expanding; otherwise, they will face more strict carbon tax penalties.

Thirdly, in both a purely competitive market and a co-opetitive market setting, the emission reduction of manufacturers yields more output with the IBCT, which means that emission reduction would yield more social welfare. Furthermore, the emissions also remain within the required levels. Overall, under the IBCT policy, the effect of improving social welfare induced by emission reduction has been significantly enhanced. Therefore, both for SAPCs and other countries, an IBCT policy can contribute to a win-win situation and improve both social welfare and environmental development.

## 5 Conclusion and Policy Implications

This paper examined the emission reduction behavior of manufacturers under the IBCT, which differs from FCT policies. IBCT was identified as a feasible policy for the regulation of carbon emissions in SAPCs. Both non-cooperative and co-operative games were used to develop competition and co-opetition models. The advantages of IBCT implementation in SAPCs were also clarified. Based on the results, the following conclusions can be drawn:

First, the implementation of the IBCT policy in SAPCs not only protects their domestic manufacturers but also diminishes the risk of carbon leakage. The IBCT encourages manufacturers with high emissions to decrease their emissions while reducing the carbon tax burden of small-scale manufacturers. This result is in line with the objectives of a carbon tax policy, thus suggesting that the IBCT is better than the FCT alternative.

Second, the implementation of an IBCT in SAPCs can guide a low-carbon development direction for their manufacturers. The manufacturers must consider carbon emission reductions while expanding; otherwise, they will face more strict carbon tax penalties. The manufacturers’ emission reduction behavior under an IBCT would lead to an increasing marginal equilibrium output. However, there is a turning point, at which the increasing trend stops. The increasing interval is large when the price elasticity of the produced products is low. The output boosting factor acts as an incentive for manufacturers to reduce emissions under an IBCT regime.

Third, the IBCT policy will contribute to achieving a win-win situation for improving both social welfare and environmental development in SAPCs or other countries. With the same emission reduction effect, the emission reduction of manufacturers yields more output with the IBCT, which means that emission reduction would yield more social welfare. This indicates that the social welfare improvement effect induced by emission reduction has been significantly enhanced.

Based on these conclusions, a number of suggestions for formulating IBCT policies in SAPCs are presented in the following.

First, SAPCs should formulate IBCT policies so that these restrict manufacturers in high-carbon emission industries. Since the IBCT regime divides the marginal tax based on the total amount of carbon emissions of a manufacturer, industries with little carbon emissions will cause this difference to become insignificant thus, failing to obtain its advantages. Therefore, the target of policy formulation should be industries with actual or potentially high carbon emissions. Even though such industries are generally rare in SAPCs, such a policy is still useful to provide a stable expectation for investors.

Second, to apply IBCT, governments need to fully investigate the emission characteristics of domestic enterprises, including their total emissions, marginal abatement costs, and emission reduction potential. IBCT is more flexible than FCT, but its formulation is also more complicated and requires more market details. Policymakers should therefore reasonably coordinate the relationship between carbon emission reduction and economic development based on these specific characteristics.

Third, governments can stimulate the development of new energy industries through subsidies, and substitute fossil fuels with clean and renewable energy. IBCT encourages manufacturers to implement energy-saving and emission-reduction measures; however, as manufacturers continue to expand their production scale, an increase in total carbon emissions is still inevitable. The incremental effect of marginal abatement costs will also increase the burden on manufacturers, which implies that single energy-saving technologies for emission reduction are limited.

Considering the complexities of the market characteristics and the actual application of a carbon tax, this study may have several limitations. Firstly, this study represents a theoretical model of reality. The proposed model reflects the objective laws of manufacturers, and to simplify and clarify this research, only key factors were considered. Nevertheless, these limitations constitute the direction for future research. Additionally, future studies should examine the empirical effects of the IBCT implementation in SAPCs. Furthermore, the relationship between the increasing costs of implementing a downscale strategy for manufacturers and the associated carbon tax charges should be further examined. Since the marginal tax rate increases as the total carbon emissions increase, a large manufacturer may opt to split into a number of smaller manufacturers.

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## References

An, Y., and X. Zhai. 2020. "SVR-DEA model of carbon tax pricing for China's thermal power industry." Science of The Total Environment:139438. doi.org/10.1016/j.scitotenv.2020.139438

Branger, F., and P. Quirion. 2014. "Would border carbon adjustments prevent carbon leakage and heavy industry competitiveness losses? Insights from a meta-analysis of recent economic studies." In *Ecological Economics*, 29-39. doi.org/10.1016/j.ecolecon.2013.12.010

Cao, K., X. Xu, Q. Wu, and Q. Zhang. 2017. "Optimal production and carbon emission reduction level under cap-and-trade and low carbon subsidy policies." *Journal of Cleaner Production* 167:505-13. doi:10.1016/j.jclepro.2017.07.251

Chen, H., and Z. Yang. 2009. "Residential water demand model under block rate pricing: a case study of Beijing, China." *Communications in Nonlinear Science and Numerical Simulation* 14 (5):2462-8. doi:10.1016/j.cnsns.2007.12.013

Chen, X., and G. Hao. 2015. "Sustainable pricing and production policies for two competing firms with carbon emissions tax." *International Journal of Production Research* 53 (21):6408-20. doi:10.1080/00207543.2014.932928

Chen, Z., Y. Liu, P. Qin, B. Zhang, L. Lester, G. Chen, Y. Guo, and X. Zheng. 2015. "Environmental externality of coal use in China: Welfare effect and tax regulation." *Applied Energy* 156:16-31. doi:10.1016/j.apenergy.2015.06.066

Choudhary, A., R. Suman, V. Dixit, M. K. Tiwari, K. J. Fernandes, and P. C. Chang. 2015. "An optimization model for a monopolistic firm serving an environmentally conscious market: Use of chemical reaction optimization algorithm." *International Journal of Production Economics* 164:409-20. doi:10.1016/j.ijpe.2014.10.011

Ding, S., M., Zhang, and Y. Song. 2019. "Exploring China's carbon emissions peak for different carbon tax scenarios." *Energy Policy* 129, 1245-1252. doi:10.1016/j.enpol.2019.03.037

Eicke, L., S. Weko, M. Apergi, and A. Marian. 2021. Pulling up the carbon ladder? Decarbonization, dependence, and third-country risks from the European carbon border adjustment mechanism. *Energy Research & Social Science*, 80, 102240. doi:10.1016/j.erss.2021.102240

Filipović, S., and G. Tanić. 2008. "The policy of consumer protection in the electricity market." *Economic Annals* 53 (178-179):157-82. doi:10.2298/eka0879157f

Gomes-Casseres, B. 1997. "Alliance strategies of small firms." *Small Business Economics* 9(1), 33-44. https://link.springer.com/article/10.1023/A:1007947629435

Gong, C., S. Yu, K. Zhu, and A. Hailu. 2016. "Evaluating the influence of increasing block tariffs in residential gas sector using agent-based computational economics." *Energy Policy* 92:334-47. doi:10.1016/j.enpol.2016.02.014

He, S., J. Yin, B. Zhang, and Z. Wang. 2018. "How to upgrade an enterprise's low-carbon technologies under a carbon tax: The trade-off between tax and upgrade fee." *Applied Energy* 227:564-73. doi:10.1016/j.apenergy.2017.07.015

Hung, M., and T. Huang. 2015. "Dynamic demand for residential electricity in Taiwan under seasonality and increasing-block pricing." *Energy Economics* 48:168-77. doi:10.1016/j.eneco.2015.01.010

Li J., L., Y. Qi, J. Dan, and R. Wang. 2015. The duopoly producing strategy under carbon emissions regulation. Paper presented at the 2015 International Conference on Logistics, Informatics and Service Sciences (LISS). doi:10.1109/liss.2015.7369736

Lin, B., and X. Li. 2011. The effect of carbon tax on per capita CO2 emissions. *Energy policy* 39(9), 5137-5146. doi:10.1016/j.enpol.2011.05.050Get

Lin, B., and Z. Jiang. 2012. "Designation and influence of household increasing block electricity tariffs in China." *Energy Policy* 42:164-73. doi:10.1016/j.enpol.2011.11.062

Liu, C., and B. Lin. 2018. "Evaluating design of increasing block tariffs for residential natural gas in China: A case study of Henan province." *Computational Economics* 52 (4):1335-51. doi:10.1007/s10614-017-9674-8

Liu, J., J. Bai, Y. Deng, X. Chen, and X. Liu. 2020. "Impact of energy structure on carbon emission and economy of China in the scenario of carbon taxation." *Science of The Total Environment*:143093. doi.org/10.1016/j.scitotenv.2020.143093

Luo, Z., X. Chen, and X. Wang. 2016. "The role of co-opetition in low carbon manufacturing." *European Journal of Operational Research* 253 (2):392-403. doi:10.1016/j.ejor.2016.02.030

Ma, X., W. Ho, P. Ji, and S. Talluri. 2018. "Coordinated pricing analysis with the carbon tax scheme in a supply chain." *Decision Sciences* 49 (5):863-900. doi:10.1111/deci.12297

Meng, X., Z. Yao, J. Nie, Y. Zhao, and Z. Li. 2018. "Low-carbon product selection with carbon tax and competition: Effects of the power structure." *International Journal of Production Economics* 200:224-30. doi:10.1016/j.ijpe.2018.03.029

Niu, S., Y. Ding, Y. Niu, Y. Li, and G. Luo. 2011. "Economic growth, energy conservation and emissions reduction: A comparative analysis based on panel data for 8 Asian-Pacific countries." *Energy Policy* 39 (4):2121-31. doi.org/10.1016/j.enpol.2011.02.003

Pang, Y. 2018. "Profitable pollution abatement? A worker productivity perspective."

*Resource and Energy Economics* 52:33-49. doi:10.1016/j.reseneeco.2017.12.003

Rinaudo, J., N. Neverre, and M. Montginoul. 2012. "Simulating the impact of pricing policies on residential water demand: a southern France case study." *Water Resources Management* 26 (7):2057-68. doi:10.1007/s11269-012-9998-z

Song, Y., and M. Zhang. 2019. "Research on the gravity movement and mitigation potential of Asia's carbon dioxide emissions." *Energy* 170, 31-39. doi:10.1016/j.energy.2018.12.110

Tian, X., H. Dai, Y. Geng, Z. Huang, T. Masui, and T. Fujita. 2017. "The effects of carbon reduction on sectoral competitiveness in China: A case of Shanghai." *Applied Energy* 197:270-8. doi:10.1016/j.apenergy.2017.04.026

von Hirschhausen, C., M. Flekstad, and G. Meran. 2017. "Clean drinking water as a Sustainable Development Goal: fair, universal access with increasing block tariffs." *DIW Economic Bulletin* 7 (28/29):292-8. https://www.econstor.eu/handle/10419/162887

World Bank . (2020). State and trends of carbon pricing 2020. https://openknowledge.worldbank.org/bitstream/handle/10986/33809/9781464815867.pdf?sequence=4&isAllowed=y

World Bank, (2021). State and Trends of Carbon Pricing 2021. https://openknowledge.worldbank.org/handle/10986/35620

Wu, B., W. Huang, and P. Liu. 2017. "Carbon reduction strategies based on an NW small-world network with a progressive carbon tax." *Sustainability* 9 (10):1747. doi:10.3390/su9101747

Xun, Z., Z. Zhang, Y. Chen, L. Wu, and G. Tang. 2017. "Influences of large height differences and overhangs on the dynamic scaling behavior of discrete models." *Physica A: Statistical Mechanics and its Applications* 471:569-75. doi:10.1016/j.physa.2016.12.042

Yalabik, B., and R. J. Fairchild. 2011. "Customer, regulatory, and competitive pressure as drivers of environmental innovation." *International Journal of Production Economics* 131 (2):519-27. doi:10.1016/j.ijpe.2011.01.020

Yang, H., J. Luo, and H. Wang. 2017. "The role of revenue sharing and first-mover advantage in emission abatement with carbon tax and consumer environmental awareness." *International Journal of Production Economics* 193:691-702. doi:10.1016/j.ijpe.2017.08.032

Yi, Y., and J. Li. 2018. "The effect of governmental policies of carbon taxes and energy-saving subsidies on enterprise decisions in a two-echelon supply chain." *Journal of Cleaner Production* 181:675-91. doi:10.1016/j.jclepro.2018.01.188

Zhang, Z., and A. Baranzini. 2004. "What do we know about carbon taxes? An inquiry into their impacts on competitiveness and distribution of income." *Energy policy* 32(4), 507-518. doi:10.1016/S0301-4215(03)00152-6

Zhou, D., Y. An, D. Zha, F. Wu, and Q. Wang. 2019. "Would an increasing block carbon tax be better? A comparative study within the Stackelberg Game framework." *Journal of Environmental Management*, 235:328-41.

## Appendix A. Mathematical proofs

**(A.1)** Let $A_1 = \beta(\alpha - c) + 2k_1(\alpha - c)e_2^{\ 2} > 0$ , $B_1 = 3\beta^2 + 4\beta k_1 e_2^{\ 2} > 0$ , $C_1 = 4k_1^{\ 2}e_2^{\ 2} + 4\beta k_1 > 0$ .

$$\frac{\partial q_1^{nb}}{\partial e_1} = -\frac{2A_1C_1e_1}{(C_1e_1^{\ 2} + B_1)^2} < 0$$

$$\frac{\partial^2 q_1^{nb}}{\partial e_1^{\ 2}} = \frac{8A_1C_1^{\ 2}e_1^{\ 2}}{(C_1e_1^{\ 2} + B_1)^3} - \frac{2A_1C_1}{(C_1e_1^{\ 2} + B_1)^2} = 0 \text{ , we get } e_1 = \sqrt{\frac{B_1}{3C_1}} \text{ .}$$

When $e_1 = \sqrt{\frac{B_1}{3C_1}}$ , $\frac{\partial^3 q_2^{nb}}{\partial e_1^{\ 3}} \neq 0$ . So $q_1^{nb}(e_1)$ is a convex function when $e_1 \in [0, \sqrt{\frac{B_1}{3C_1}}]$ . Furthermore, $q_1^{nb}(e_1)$ is a concave function when $e_1 \in [\sqrt{\frac{B_1}{3C_1}}, e_0]$ . The inflection point corresponds to unit carbon emissions, and is given by: $e_t = \sqrt{\frac{B_1}{3C_1}} = \sqrt{\frac{\beta}{3k_1} - \frac{\beta^2}{12k_1(k_1e_2^{\ 2} + \beta)}}$ .

**(A.2)**

$$q_2^{nb} = \frac{\beta(\alpha - c) + 2k_1(\alpha - c)e_1^{\ 2}}{3\beta^2 + 4\beta k_1 e_2^{\ 2} + (4k_1^{\ 2}e_2^{\ 2} + 4\beta k_1)e_1^{\ 2}}$$

$$= \frac{\beta(\alpha - c) - \dfrac{2k_1(\alpha - c)(3\beta^2 + 4\beta k_1 e_2^{\ 2})}{(4k_1^{\ 2}e_2^{\ 2} + 4\beta k_1)}}{3\beta^2 + 4\beta k_1 e_2^{\ 2} + (4k_1^{\ 2}e_2^{\ 2} + 4\beta k_1)e_1^{\ 2}} + \frac{2k_1(\alpha - c)(3\beta^2 + 4\beta k_1 e_2^{\ 2})}{(4k_1^{\ 2}e_2^{\ 2} + 4\beta k_1)}$$

$$\beta(\alpha - c) - \frac{2k_1(\alpha - c)(3\beta^2 + 4\beta k_1 e_2^{\ 2})}{4k_1^{\ 2}e_2^{\ 2} + 4\beta k_1}$$

$$= \frac{\beta(\alpha - c)(4k_1^{\ 2}e_2^{\ 2} + 4\beta k_1) - 2k_1(\alpha - c)(3\beta^2 + 4\beta k_1 e_2^{\ 2})}{4k_1^{\ 2}e_2^{\ 2} + 4\beta k_1}$$

$$= \frac{(\alpha - c)\beta k_1[(4k_1e_2^{\ 2} + 4\beta) - 2(3\beta + 4k_1e_2^{\ 2})]}{4k_1^{\ 2}e_2^{\ 2} + 4\beta k_1}$$

$$= -\frac{\beta k_1(\alpha - c)(4k_1e_2^{\ 2} + 2\beta)}{4k_1^{\ 2}e_2^{\ 2} + 4\beta k_1} < 0$$

Let $A_2 = \beta(\alpha - c) - \frac{2k_1(\alpha - c)(3\beta^2 + 4\beta k_1 e_2^{\ 2})}{4k_1^{\ 2}e_2^{\ 2} + 4\beta k_1} < 0$ , $B_2 = 3\beta^2 + 4\beta k_1 e_2^{\ 2} > 0$ ,

$$C_2 = 4k_1^{\,2}e_2^{\,2} + 4\beta k_1 > 0\,,\ \ D_2 = \frac{2k_1(\alpha - c)(3\beta^2 + 4\beta k_1 e_2^{\,2})}{(4k_1^{\,2}e_2^{\,2} + 4\beta k_1)} > 0\,.$$

$$q_2^{nb} = \frac{A_2}{B_2 + C_2 e_1^{\,2}} + D_2$$

$$\frac{\partial q_2^{nb}}{\partial e_1} = \frac{-2A_2C_2e_1}{(B_2 + C_2e_1^{\,2})^2} > 0$$

From $\frac{\partial^2 q_2^{nb}}{\partial e_1^{\,2}} = \frac{-2AC(B - 3Ce^2)}{(B_2 + C_2e_1^{\,2})^3} = 0$, we get $e_1 = \sqrt{\frac{B_2}{3C_2}}$.

When $e_1 = \sqrt{\frac{B}{3C}}$, $\frac{\partial^3 q_2^{nb}}{\partial e_1^{\,3}} \neq 0$. Therefore, $q_2^{nb}(e_1)$ is a concave function when $e_1 \in [0, \sqrt{\frac{B}{3C}}]$. Furthermore, $q_2^{nb}(e_1)$ is a convex function when $e_1 \in [\sqrt{\frac{B}{3C}}, e_0]$. The inflection point corresponds to unit carbon emissions, and is given by: $e_{nt} = \sqrt{\frac{B}{3C}} = \sqrt{\frac{\beta}{3k_1} - \frac{\beta^2}{12k_1(k_1e_2^{\,2} + \beta)}}$.

**(A.3)** From $\frac{\partial(e_t^{\,2})}{\partial\beta} = \frac{3\beta^2 + 6\beta e_2^{\,2}k + 4e_2^{\,4}k^2}{12k(ke_2^{\,2} + \beta)^2} > 0$, $e_{nt}^{\ 2}$ increases with $\beta$. From $e_{nt} > 0$ and $\beta > 0$, $e_{nt}$ and $e_{nt}^{\ 2}$ have the same increase and decrease. Therefore, $e_{nt}$ increases with $\beta$. This means that the inflection point corresponding to Manufacturer 1's unit carbon emissions has a positive correlation with the price elasticity of demand for the product.

**(A.4)** $\frac{\partial \pi_{cf}(q_1, q_2, e_c)}{\partial q_1} = -2\beta q_1 - 2\beta q_2 + a - c - k_0 e_c$

$$\frac{\partial \pi_{cf}(q_1, q_2, e_c)}{\partial q_2} = -2\beta q_1 - 2\beta q_2 + a - c - k_0 e_c$$

From $\frac{\partial^2 \pi_{cf}(q_1, q_2, e_c)}{\partial q_1^{\,2}} = -2\beta$, $\frac{\partial^2 \pi_{cf}(q_1, q_2, e_c)}{\partial q_2^{\,2}} = -2\beta$, $\frac{\partial^2 \pi_{cf}(q_1, q_2, e_c)}{\partial q_1 \partial q_2} = -2\beta$, $\frac{\partial^2 \pi_{cf}(q_1, q_2, e_c)}{\partial q_2 \partial q_1} = -2\beta$, we get $\begin{vmatrix} -2\beta & -2\beta \\ -2\beta & -2\beta \end{vmatrix} = 0$. So, function $\pi_{cf}(q_1, q_2, e_c)$ of $q_1$ and

$q_2$ may not be a concave function.

**(A.5)** $\dfrac{\partial^2 \pi_{cb}(q_1,q_2,e_c)}{\partial {q_1}^2} = -2\beta - 2k_1 {e_c}^2$

$$\frac{\partial^2 \pi_{cb}(q_1,q_2,e_c)}{\partial {q_2}^2} = -2\beta - 2k_1 {e_c}^2$$

$$\frac{\partial^2 \pi_{cb}(q_1,q_2,e_c)}{\partial q_1 \partial q_2} = -2\beta$$

$$\frac{\partial^2 \pi_{cb}(q_1,q_2,e_c)}{\partial q_2 \partial q_1} = -2\beta$$

$\begin{vmatrix} -2\beta - 2k_1 {e_c}^2 & -2\beta \\ -2\beta & -2\beta - 2k_1 {e_c}^2 \end{vmatrix} = 2k_1 {e_c}^2 (4\beta + 2k_1 {e_c}^2) > 0$ , that is the function $\pi_{cb}(q_1,q_2,e_c)$ is a concave function for $q_1$ and $q_2$.

**(A.6)** $\dfrac{\partial^2 q^{cb}}{\partial {e_c}^2} = \dfrac{2k(\alpha - c)(3k{e_c}^2 - 2\beta)}{(k_1 {e_c}^2 + 2\beta)^3}$

From $\dfrac{\partial^2 q^{cb}}{\partial {e_c}^2} > 0$, we get $3k{e_c}^2 - 2\beta > 0$, that is $e_c > \sqrt{\dfrac{2\beta}{3k_1}}$ ; from $\dfrac{\partial^2 q^{cb}}{\partial {e_c}^2} < 0$, we get $3k{e_c}^2 - 2\beta < 0$, that is $e_c < \sqrt{\dfrac{2\beta}{3k_1}}$ 。

**(A.7)** In order to compare the inflection point of marginal equilibrium output between a purely competitive market and a cooperative market, we assume that $e_0 - \sqrt{\dfrac{\beta}{3k_1^{'}} - \dfrac{\beta^2}{12k_1^{'}(k_1^{'}{e_2}^2 + \beta)}} > e_0 - \sqrt{\dfrac{2\beta}{3k_1^{''}}}$.

where $k_1^{'}$ is for a purely competitive market and $k_1^{''}$ is for a cooperative market.

If $e_0 - \sqrt{\dfrac{\beta}{3k_1^{'}} - \dfrac{\beta^2}{12k_1^{'}(k_1^{'}{e_2}^2 + \beta)}} > e_0 - \sqrt{\dfrac{2\beta}{3k_1^{''}}}$ , then $\dfrac{1}{k_1^{'}} - \dfrac{\beta}{4k_1^{'}(k_1^{'}{e_2}^2 + \beta)} < \dfrac{2}{k_1^{''}}$.

From $-\dfrac{\beta}{4k_1^{'}(k_1^{'}{e_2}^2 + \beta)} < 0$, we get $\dfrac{1}{k_1^{'}} < \dfrac{1}{k_1^{'}} - \dfrac{\beta}{4k_1^{'}(k_1^{'}{e_2}^2 + \beta)} < \dfrac{2}{k_1^{''}}$.

Condition $e_0 - \sqrt{\frac{\beta}{3k_1^{'}} - \frac{\beta^2}{12k_1^{'}(k_1^{'}e_2^{\,2} + \beta)}} > e_0 - \sqrt{\frac{2\beta}{3k_1^{''}}}$ will be satisfied when $k_1^{'}$ is not less than half of $k_1^{''}$. This means that the emission reduction corresponding to the inflection point in the cooperative market is usually lower than that in the cooperative market.

# Credit Author Statement

Yunfei An: Writing - Original Draft, Methodology, Software
Dequn Zhou: Supervision, Project administration, Funding acquisition
Qunwei Wang: Writing - Review & Editing, Funding acquisition
Xunpeng Shi: Writing - Review & Editing, Validation
Taghizadeh-Hesary: Writing - Review & Editing

Declaration of Interest Statement

**Declaration of interests**

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: