Carbon tax effect difference on net-zero carbon emissions target and social welfare level promotion

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ABSTRACT
This research aims to find the best carbon tax regime for the achievement of net-zero carbon emissions and promotion of social welfare level. We discuss two regimes in this study, including carbon tax on total social welfare level (CTTW) and carbon tax on single social welfare level (CTSW). Findings show that the best regime depends on product substitution and product price elasticity of demand. Industrial transformation not only causes changes in product substitution and product price elasticity of demand, but also makes these two regimes have different effects on the achievement of net-zero carbon emissions and promotion of social welfare level.

KEYWORDS
Net-zero carbon emissions; carbon tax; social welfare level

Introduction
The International Panel on Climate Change (IPCC) states that climate change will not stop if net-zero emissions cannot be achieved. Net-zero carbon emissions mean that the net emissions of carbon dioxide (CO2) must be reduced to zero in order to stabilize global temperatures. The Paris Agreement has set the target of net-zero carbon emissions by 2050. In general, a carbon tax is one of various available methods to achieve this aim.

It is widely known that a carbon tax can effectively eliminate the environmental externality to mitigate global warming and climate change. The Pigouvian tax, named after English economist Arthur Cecil Pigou, is a famous theory to correct the negative externality. Baumol [1] systematically collects and arranges Pigou’s works in modern economics. Based on the viewpoints of Borzuei et al. [2] and Moosavian et al. [3], the Pigouvian tax effectively reduces environmental damage and maximizes the social welfare level.

Information by Energy & Climate Intelligence Unit [4] shows that 127 countries in total have enacted a net-zero carbon emissions strategy. Moreover, many global enterprises have formed a team of “Transform to Net Zero,” including Microsoft, Apple, Nike, Starbucks, Mercedes-Benz, etc., to realize the net-zero carbon emissions target together. A government's carbon tax policy and enterprises’ volunteer actions can strongly support the realization of net-zero carbon emissions. However, a government policy, such as a carbon tax imposed on enterprises, will influence producers’ and consumers’ behaviors.

Tax shift is one effect from a tax levy. The tax shift effect may release a producer’s carbon tax imposed by the authority and increase consumers’ tax loading. One wonders whether the tax shift effect weakens the motivation of a firm to engage in product differentiation and thus becomes an obstacle to industrial transformation in the trend of “Transform to Net Zero.”

The European Union (EU) officially announced the Carbon Border Adjustment Mechanism (CBAM) in July 2021. CBAM levies a carbon tax on high-carbon products by equalizing the price of carbon between domestic products and imports to make sure the EU’s climate objectives are achieved. The EU has ensured that the carbon tax revenue will be used to enhance decarbonization technology.

This study therefore compares different carbon tax regimes and their effects on the achievements of a net-zero emission target and social welfare level promotion. There are two carbon tax regimes in this study: one is a carbon tax on single social welfare level (CTSW), which refers to CBAM specifically treating carbon emissions; the other is a carbon...
tax on total social welfare level (CTTW). This study looks to find the best carbon tax regime to achieve the net-zero emission target.

**Literature review**

Environmental economics concerns an externality impact on social welfare and how to remove this externality for environmental target achievement and social welfare maximization. With the initiation of net-zero carbon emissions, a carbon tax is seen as one of the most powerful tools to help countries limit carbon emissions and reach net-zero targets. Early studies discuss a tax in environmental economics through an environmental tax, but environmental tax research has shifted to a carbon tax in the trend of net-zero carbon emissions.

The tax not only impacts market competition, but also social welfare. Shaffer [5] and Lee [6] investigate the environmental tax effect in oligopolistic markets, and Garcia et al. [7] and Leal et al. [8] analyze the environmental tax effects on a firm’s activity and on the social welfare level. Liu et al. [9] find that a carbon tax has a negative influence on social welfare. However, the tax shift is a critical problem when the government pushes tax policy. The environmental tax or carbon tax is always used by a government to control a firm policy. The environmental tax or carbon tax is critical when the government pushes tax on social welfare. Shaffer [5] and Lee [6] analyze the environmental tax effects on a firm's activity and on the social welfare level. Liu et al. [9] find that a carbon tax has a negative influence on social welfare. However, the tax shift is a critical problem when the government pushes tax policy. The environmental tax or carbon tax is always used by a government to control a firm's pollution behavior. Anand and Giraud-Carrier [10] indicate that the primary consideration for enacting an environmental tax should be on consumers rather than firms, because firms may use the government’s tax regulation to collude by reducing production (pollution at the same time) to upgrade their profits. We expect that if an environmental tax causes firms’ collusion or the tax levied on producers shifts to consumers, then this tax damages consumer surplus so that social welfare is not maximized.

The size of the tax shift is very much close to product price elasticity of demand. Wang et al. [11] find the price elasticity of demand in China's cement market is so large that the environmental tax imposed upon the cement industry exhibits a negative impact on firms' revenue and profit. Kotlán et al. [12] examine the European Green Deal and conclude that a high environmental tax negatively affects economic activities and also limits the implementation of sustainable development policies. Moosavian et al. [3] indicate that a carbon tax can effectively reduce energy consumption and pollutant emissions, while it can also present incentives to create new jobs by simultaneously lowering the labor tax. Hence, the tax effect generates a comprehensive influence on many economic tiers.

Different from an environmental tax, the aim of a carbon tax is to remove greenhouse gas (GHG) emissions by internalizing an externality causing GHG emissions. Wang et al. [13] classify the functions of carbon tax and environmental tax in their study in which they set the carbon tax to reduce carbon emissions and the environmental tax to reduce air pollutant emissions. A carbon tax can help stabilize global warming and hinder climate change. Pradhan et al. [14] and Quarton and Samsatli [15] discuss net-zero carbon emissions from the viewpoint of a carbon tax. In academia the carbon tax has been studied from different direction. Bachus et al. [16] study the effect of a carbon tax levied on energy products, Ouchida and Goto [17] model the tax in a product’s manufacturing process, and Nie et al. [18] discuss the carbon tax in a monopoly market. In practice, Millot et al. [19] indicate that France introduced the carbon tax in 2014 at a rate of €7/tCO2 in its Energy Transition for Green Growth Act with the objective to reach €100/tCO2 in 2030.

Achieving the goal of net-zero carbon emissions, a low-carbon economy through industrial transformation is a pathway, and the carbon tax is one type of tool. Industrial transformation is seldom discussed in the literature on carbon tax analysis, however, we find that many studies focus on the carbon tax and its industrial influence, such as Cheng et al. [20] on supply chain, Liu et al. [9] on industrial energy structure, and Nilsson et al. [21] on energy and emissions intensive industries. The carbon tax and its industry development influence is important, but the most important issue is whether it effectively promotes industrial transformation. By observing the industrial transformation process, we can understand the influences of carbon emissions, consumer surplus, producer surplus, and social welfare.

A carbon tax comprehensively affects the fields of environment, emission reduction, firms' market competition, consumers' well-being, and industrial transformation. In order to examine the carbon tax effect, two carbon tax regimes are investigated and compared, including a carbon tax on single social welfare level and a carbon tax on total social welfare level. The former takes net-zero carbon emissions as a main target and then maximizes the social welfare level. The
latter considers not only to achieve the target of net-zero carbon emissions, but also to maximize the social welfare level.

**Model set-up**

We consider a duopoly market with two firms that produce differentiated products. We follow the viewpoint of Singh and Vives [22] who provide the format of a linear demand function in a differentiated duopoly market as follows: \( p_1 = a - bq_1 - rq_1 \) and \( p_2 = a - bq_2 - rq_2 \), where the parameter \( a \) means market size. Based on the two firms’ linear demand functions in Eq. (1), the absolute value of product price elasticity of demand is \( |e_{p}^d| = \frac{1}{b} \), where the parameter \( b \) is defined as the slope of the demand function. The product’s cross-elasticity of demand is \( e_{q} = -\frac{1}{r} \), where the parameter \( r \) \((0, 1)\) denotes the product’s substitute between \( q_1 \) and \( q_2 \). Here, \( r = 1 \) \((r = 0)\) means \( q_1 \) and \( q_2 \) are perfect substitutes (independent). According to the two firms’ linear demand functions, the consumer surplus (CS) used to measure the consumer benefits is:

\[
CS = \frac{1}{2}(bq_1^2 + bq_2^2 - 2rq_1q_2)
\]  

(2)

The product during its manufacturing process in general may generate some by-products. Hence, it is reasonable to assume that one unit of output causes one unit of carbon emissions in our model analysis. Following the quadratic form setting on the environmental damage (ED) function by Buccella et al. [23] and one unit of product causing one unit of carbon emissions, we have the environmental damage function as:

\[
ED = \frac{g}{2}(q_1 + q_2)^2,
\]  

(3)

where the parameter \( g > 0 \) stands for the product’s carbon emissions coefficient.

Based on a consideration of net-zero carbon emissions, the authority levies a carbon tax on products; hence, the two firms’ carbon tax burdens are \( T_1 = \frac{t}{2}q_1^2 \) and \( T_2 = \frac{t}{2}q_2^2 \), where the authority’s carbon tax revenue is also a quadratic form that is the same as the form of the environmental damage function. Since the authority uses the carbon emissions tax revenue to clean up the environmental damage caused by carbon emissions, we have \( T = T_1 + T_2 = ED \). A firm’s profit comes from its revenue minus its carbon tax burden, and so the profit functions of the two firms are:

\[ \pi_1 = p_1q_1 - (t/2)q_1^2 \] and \[ \pi_2 = p_2q_2 - (t/2)q_2^2 \].

(4)

Producer surplus (PS) used to measure the sum of all firms’ profits is:

\[
PS = \pi_1 + \pi_2 = p_1q_1 + p_2q_2 - \frac{t}{2}(q_1^2 + q_2^2).
\]  

(5)

Since the social welfare level (W) is measured by the sum of consumer surplus, producer surplus, carbon tax revenue by government, and environmental damage, it is presented as:

\[
W = CS + PS + T - ED = \frac{1}{2}(bq_1^2 + bq_2^2 - 2rq_1q_2)
\]

\[
+ p_1q_1 + p_2q_2 - \frac{g}{2}(q_1 + q_2)
\]

where the consumer surplus, producer surplus, and carbon tax revenue present a positive promotion of the social welfare level, and environmental damage has a negative effect on the same level.

One can generally refer to the works of Buccella et al. [23], Lambertini et al. [24], and Xu et al. [25] for the formula of social welfare in Eq. (6). When we comprehensively consider consumer surplus, producer surplus, carbon tax, and environmental damage in the social welfare function, we find that the optimal product quantity not only affects the scale of social welfare, but also the scales of consumer surplus, producer surplus, carbon tax, and environmental damage. The optimal quantity has a connection to consumer surplus and producer surplus. In more detail, if the product’s environmental damage is large (small), then the optimal quantity is less (more), which deteriorates (enhances) consumer surplus and producer surplus.

The other point on the setting of the social welfare function in Eq. (6) needs to be illustrated in the relationship between carbon tax and environmental damage. The former is a social cost treatment, and the latter is a loss of social welfare. The environmental damage to social welfare depends on the product’s total quantity and marginal environmental damage per product. In order to correct the environmental damage caused by a product’s manufacturing, the government always levies a tax on the manufacturer. The Pigouvian tax used to correct the negative externality caused by market activity means that the tax rate is equal to the product’s marginal environmental damage. Through the concept of the Pigouvian tax, environmental damage can use the social cost to connect. For this topic, one may refer to the literature of Eichner and Pethig [26], Fullerton [27], and Metcalf [28].

In our model the two firms’ competitive behaviors and the authority’s action can be described as
a two-stage game in which the authority sets a carbon tax rate levied on the firms in the first stage, and then the two firms act out quantity competition in the second stage. We obtain the subgame perfect Nash equilibrium (SPNE) solutions through the backward induction approach in which we first solve the solution in the second stage and then the solution in the first stage.

The solutions in the two-stage game are an optimization problem whereby we employ calculus to obtain them. In more detail, we individually obtain the firm’s reaction function, which is a derivative of its profit function with respect to its product quantity. Next, we obtain the two firms’ output quantities by utilizing their reaction functions in a simultaneous equation. Here, a firm’s output quantity is still a function of carbon tax. Since the government has complete information on the two firms’ output quantities, it can set the optimal carbon tax to reduce CO2 emissions caused by the product’s manufacturing for maximizing social welfare. Finally, we take the optimal carbon tax by the government by replacing it to the firm’s output quantity and then obtaining the optimal output quantity and the optimal firm’s profit.

**Model analysis**

We here compare two regimes in which the carbon tax on the single social welfare level is the first regime, and the carbon tax on the total social welfare level is the second regime.

**Carbon tax on the single social welfare level**

In this regime the authority uses a carbon emissions tax to clean up all environmental damages caused by carbon emissions before maximizing the social welfare level. According to Eq. (4), the two firms maximize their profits at stage 2, and we obtain the solution as $q_1^* = q_2^* = a/(r + 2b + t)$. In order to find the optimal carbon tax rate, we replace the solution $q_1^* = q_2^* = a/(r + 2b + t)$ at stage 2 into Eq. (6), and then the authority maximizes the social welfare function, but subject to $T = ED$. The constraint $T = ED$ means an achievement of a net-zero carbon emissions target by using the carbon tax revenue to eliminate all environmental damages caused by carbon emissions. Hence, the objective function in this regime is $W = CS + PS + T - ED$, but subject to $T = ED$. Based on the Lagrange approach, the optimal solution at stage 1 is:

$$t^* = 2g,$$  \hspace{1cm} (7)

where “***” means the optimal solution in the CTSW regime, and $t^*$ is the optimal carbon tax rate on the single social welfare level. Taking the optimal CTSW tax rate ($t^*$) back to stage 2, the optimal solutions are:

$$q_1^* = q_2^* = a/(r + 2b + 2g) > 0,$$ \hspace{1cm} (8a)

$$\pi_1^* = \pi_2^* = a^2(b + g)/(r + 2b + 2g)^2 > 0,$$ \hspace{1cm} (8b)

$$PS^* = 2a^2(b + g)/(r + 2b + 2g)^2 > 0,$$ \hspace{1cm} (8c)

$$CS^* = 2a^2(b - r)/(r + 2b + 2g)^2 > 0 \text{ when } b > r,$$ \hspace{1cm} (8d)

$$T^* = ED^* = 2ga^2(r + 2b + 2g)^2 > 0,$$ \hspace{1cm} (8e)

$$W^* = a^2(3b - r + 2g)/(r + 2b + 2g)^2 > 0 \text{ when } 3b + 2g > r.$$ \hspace{1cm} (8f)

The variables $q^*, \pi^*, PS^*, CS^*, T^* , ED^*$, and $W^*$ are respectively the optimal solutions for a firm’s output quantity, its profit, producer surplus, consumer surplus, carbon tax revenue, environmental damage, and social welfare level in the CTSW regime.

**Carbon tax on the total social welfare level**

In this regime the carbon tax’s purpose is not only to maximize the social welfare level, but also to eliminate environmental damage caused by carbon emissions. A carbon tax on the total social welfare level is a carbon tax with a comprehensive consideration on all social welfare factors, including consumer surplus, producer surplus, carbon tax revenue, and environmental damage. In other words, when it maximizes social welfare, it is not necessary to eliminate all environmental damages like a carbon tax on the single social welfare level. Hence, the model’s objective function in this regime is $W = CS + PS + T - ED$ and is not subject to $T = ED$. The solution at stage 2 is $q_1 = q_2 = a/(r + 2b + t)$.

Taking the solution in stage 2 into Eq. (6), we have the optimal carbon tax at stage 1 as:

$$t^{**} = -b + 2r + 2g > 0 \text{ when } r + g > b/2,$$  \hspace{1cm} (9)

where “****” means the optimal solution in the regime of a carbon tax on the total social welfare level, and $t^{**}$ satisfies the second condition of the maximized social welfare function. Taking the optimal CTTW tax rate ($t^{**}$) back to the solutions at stage 2, we have the optimal solutions in this regime as:

$$q_1^{**} = q_2^{**} = a/(3r + b + 2g) > 0,$$ \hspace{1cm} (10a)
\[
\pi_1^{**} = \pi_2^{**} \\
= a^2(2r + b + 2g)/(2(3r + b + 2g))^2 > 0,
\]

(10b)

\[
PS^{**} = a^2(2r + b + 2g)/(3r + b + 2g)^2 > 0 \quad \text{(10c)}
\]

\[
CS^{**} = 2a^2(b - r)/(3r + b + 2g)^2 > 0 \quad \text{when } b > r,
\]

(10d)

\[
T^{**} = a^2(2r - b + 2g)/(3r + b + 2g)^2 > 0 \quad \text{when } 2r - b + 2g > 0,
\]

(10e)

\[
ED^{**} = 2ga^2/(3r + b + 2g)^2 > 0 \quad \text{(10f)}
\]

\[
W^{**} = a^2/(3r + b + 2g) > 0 \quad \text{(10g)}
\]

where \(q^{**}, \pi^{**}, PS^{**}, CS^{**}, T^{**}, ED^{**}, \) and \(W^{**}\) respectively mean the optimal solutions on a firm’s output quantity, its profit, producer surplus, consumer surplus, carbon tax revenue, environmental damage, and social welfare level in the CTTW regime.

**Equilibrium comparisons on social welfare level and environmental damage**

The difference between the optimal social welfare level in the CTSW regime in Eq. (8f) and that in the CTTW regime in Eq. (10g) is:

\[
W^{**} - W^* = (a^2(2b - b)^2)/(3r + b + 2g)(r + 2b + 2g)^2 \geq 0
\]

(11)

Equation (11) shows that the optimal social welfare level in the CTTW regime is always larger than or equal to that in the CTSW regime. This result implies that if the authority adopts the CTTW regime, then society necessarily receives a higher social welfare level than that in the CTSW regime. This outcome results in CTTW presenting a more total consideration on social welfare level promotion than CTSW. The former not only removes environmental damage, but also prompts consumer surplus and producer surplus, while the latter mainly focuses on environmental damage elimination.

The difference in the tax shift effects on CTTW and CTSW also influences the social welfare level. The evidence is that when the price elasticity of demand turns larger and larger (i.e. the parameter \(b\) becomes smaller and smaller), then the difference between \(W^*\) and \(W^{**}\) increases; in other words, the CTTW regime presents a smaller tax shift effect than the CTSW regime since a large tax shift effect will degrade the social welfare level. We can also say that the CTTW regime creates a smaller social welfare distortion than the CTSW regime. The evidence is that the CTTW regime creates a higher social welfare level than the CTSW regime. Based on this line, we have the first proposition as follows.

**[Proposition 1]**

A carbon tax on the total social welfare level is better than a carbon tax on the single social welfare level.

**[Proof]** This proposition can be proved by Eq. (11) as:

\[
W^{**} - W^* = \left[\frac{a^2(2b - b)^2}{(3r + b + 2g)(r + 2b + 2g)^2}\right] \geq 0
\]

For Proposition 1, one can refer to Khastar et al. [29] who find a carbon tax policy in Finland reduces carbon emissions, but it exhibits negative effects on social welfare. Therefore, they suggest that the optimal carbon price or carbon tax system revision could be considered in the future.

Based on an observation of Eqs. (8) and (10), the environmental damage difference in the two regimes is:

\[
ED^{**} - ED^* = 2ga^2/(3r + b + 2g)^2 - 2ga^2/(r + 2b + 2g)^2 < 0, \text{ when } r > b/2
\]

(12)

In Eq. (12), if \(b \to 0\) (i.e. \(e_p^d \to \infty\)), then \(ED^{**} < ED^*\), which implies that the CTTW regime causes a smaller environmental damage than the CTSW regime when a product’s price elasticity of demand is large; on the contrary, if \(b \to \infty\) (i.e. \(e_p^d \to 0\)), then \(ED^{**} > ED^*\), which implies that the CTSW regime causes a smaller environmental damage than the CTTW regime when a product’s price elasticity of demand is small.

We next investigate the product’s substitution effect on environmental damage and find that when \(r = 0\) (i.e. two products are independent), then \(ED^{**} > ED^*\), which implies that the CTSW regime makes a smaller environmental damage than the CTTW regime when the two products’ substitution is small; on the contrary, if \(r = 1\) (i.e. two products are full substitution), then \(ED^{**} < ED^*\), which means that the CTTW regime is a benefit to the CTSW regime to incur a small environmental damage when the two products’ substitution is large.

A summary of Eq. (12) is that the CTTW (CTSW) regime levies a carbon tax on a product with high (low) substitution and that a large (small) product...
price elasticity of demand can cause low environmental damage. An interesting finding is that the CTSW regime can use carbon tax revenue to eliminate all environmental damages, but its environmental damage is not necessarily lower than that in the CTTW regime. The reason is that the CTSW regime does not use the tax rate to restrain a firm’s production; instead, it uses tax revenue to remove all environmental damages. Hence, the quantity of product under the CTSW regime may be higher than that under the CTTW regime. On the contrary, the CTTW regime needs to care about the total social welfare level, including the two sides of the economy and environment, so that it may restrain the product quantity and further restrain the environmental damage caused by any by-product in the manufacturing process. Based on this discussion, we have the next proposition as follows.

[Proposition 2]

The function of a carbon tax on the single welfare level is to eliminate all environmental damages by means of carbon tax revenue, but the environmental damage of a carbon tax on the single welfare level is not necessarily lower than that of a carbon tax on the total social welfare level.

[Proof]

This proposition can be proved by Eq. (12) as: 
$$ED^{**} - ED^* = 2ga^2/(3r + b + 2g)^2 - 2ga^2/(r + 2b + 2g)^2 < 0,$$
when $r > b/2$.

Proposition 2 is similarly supported by Pató et al. [30] who conclude that a carbon border adjustment mechanism will harm the development of the EU power sector and increase greenhouse gas emissions, because the carbon border adjustment mechanism is not an awkward tax system.

Equilibrium comparisons on social welfare level and carbon tax rate

According to Eqs. (7) and (9), we find that the carbon tax on a product with high product substitution and large product price elasticity of demand will result in $t^{**} > t^*$. In addition, we conclude in Proposition 1 that the social welfare level in the CTTW regime is always higher than that in the CTSW regime. Hence, an interesting finding in the CTTW regime is that a high tax rate does not necessarily cause a low social welfare level. The result arises, because a market with high product substitution and large product price elasticity of demand causes greater product quantity than that in a market with low product substitution and small product price elasticity of demand; hence, a high tax rate in the CTTW regime can restrain the product quantity and further reduce environmental damage. In addition, a high tax rate in the CTTW regime also creates a small market distortion and further prompts consumer surplus and producer surplus. Based on the discussion above, we have the third proposition as follows.

[Proposition 3]

In the regime of a carbon tax on the total social welfare level, a high carbon tax rate may cause a high social welfare level.

[Proof]

This proposition can be proved by Eq. (7) with $t^* = 2g$ and Eq. (9) with $t^{**} = -b + 2r + 2g > 0$ when $r + g > b/2$. If $t^{**} > t^*$, then $2r > b$. Given the result in Eq. (11) with $W^{**} - W^* = (a(2r-b)^2/(3r+b+2g)(r+2b+2g)^2) > 0$, if there is a bigger gap between $t^{**}$ and $t^*$, then $W^{**}$ also has a larger gap than $W^*$.

For Proposition 3, one can refer to Liu et al. [31] who find that the carbon tax can generate comprehensive effects on promoting economic development, reducing carbon emissions, and improving social welfare, because a high carbon tax not only accelerates industrial market competition, but also promotes emission reduction.

Based on the observation of Eqs. (7) and (9), we also find that the carbon tax rate in a market with low product substitution and small product price elasticity of demand exhibits $t^{**} < t^*$. Equation (11) further shows that the social welfare level in the CTTW regime is always higher than that in the CTSW regime. This result tells us that the firm in a market with low product substitution and small product price elasticity of demand will provide a small quantity of product for maximizing its profit. At this time, the authority using a low carbon tax in the CTTW regime can spur the product quantity and further reduce environmental damages caused by carbon emissions. However, the disadvantage for using CTTW in a market with low product substitution and small price elasticity of demand is that it may not eliminate all environmental damages.

Net-zero carbon emissions analysis

Because carbon tax revenue can be used to remove all environmental damages and the
function of the CTSW regime is to eliminate all environmental damages, the CTSW regime must go the way of net-zero carbon emissions. The CTTW regime also has the function to remove environmental damage. Hence, it is possible to achieve the net-zero carbon emissions target.

This subsection investigates a net-zero carbon emissions effect by comparing the sizes of carbon emissions tax revenue and environmental damage caused by carbon emissions. The CTSW regime uses carbon emissions tax revenue to remove all environmental damages, which means that \( T^* - ED^* = 0 \). However, the CTTW regime comprehensively considers to maximize the social welfare level, in which it not only eliminates environmental damage, but also prompts consumer surplus and producer surplus so that the CTTW regime does not necessarily move along the path of net-zero carbon emissions. In other words, the net-zero carbon emissions target in the CTTW regime may be impacted by other market factors such as product substitution and product price elasticity of demand investigated in our paper.

The carbon emissions path \( (E_m) \) in the CTTW regime can be presented as:

\[
E_{m}^{**} = T^{**} - ED^{**} = a^2(2r - b + 2g)/(3r + b + 2g)^2 - 2ga^2/(3r + b + 2g)^2 \geq 0, \text{ when } r \geq b/2.
\]

Equation (13) shows that the CTTW regime may possibly achieve the net-zero carbon emissions target (i.e. \( T^{**} - ED^{**} = 0 \)), which is conditional on \( r = b/2 \). Even the carbon emissions tax revenue presents a surplus when the net-zero carbon emissions target is achieved in the CTTW regime (i.e. \( T^{**} - ED^{**} > 0 \)). This is conditional on \( r > b/2 \) in which product substitution is high and product price elasticity of demand is large.

According to the result in Eq. (12), the environmental damage in the CTTW regime \( (ED^{**}) \) is smaller than that in CTSW regime \( (ED^*) \) when the condition \( r > b/2 \) is satisfied. This result tells us that when product substitution is high and product price elasticity of demand is large (i.e. \( r > b/2 \)), the CTTW regime achieves four advantages: (i) net-zero carbon emissions achievement; (ii) a carbon emissions tax revenue surplus; (iii) environmental damage in the CTTW regime is lower than that in the CTSW regime; and (iv) the social welfare level in the CTTW regime is higher than that in the CTSW regime. Based on this discussion, we have the next proposition as follows.

[Proposition 4] In a market with high product substitution and large product price elasticity of demand, the regime of a carbon tax on the total social welfare level can achieve multiple targets, including net-zero carbon emissions, carbon tax revenue surplus, small environmental damage, and high social welfare level.

[Proof] Given high product substitution and large product price elasticity of demand (i.e. \( 2r > b \)), then \( E_{m}^{**} = T^{**} - ED^{**} = a^2(2r - b + 2g)/(3r + b + 2g)^2 - 2ga^2/(3r + b + 2g)^2 \geq 0, \text{ when } r \geq b/2 \) in Eq. (13), and \( W^{**} - W^* = (a(2r-b))2/(3r+b+2g)(r+b+2g) \geq 0 \) in Eq. (11) are achieved. It implies the achievements on net-zero carbon emissions \( (E_m^{**} = 0) \), carbon tax revenue surplus \( (T^{**} > ED^{**}) \), small environmental damage \( (ED^{**} < T^{**}) \), and high social welfare level \( (W^{**} > W^*) \).

Proposition 4 denotes that an appropriate carbon tax regime conditional on the market’s and product’s characteristics can accomplish multiple targets. For example, Liu et al. [32] conclude that an effective carbon tax policy can achieve the win-win goal of carbon reduction and GDP growth.

When the market exhibits \( r < b/2 \) (i.e. product substitution is low and product price elasticity of demand is small), the CTTW regime cannot achieve the net-zero carbon emissions target, but the CTSW regime does, and it causes lower environmental damage than the CTTW regime; i.e. \( ED^{**} > ED^* \). The CTSW regime presents many advantages in the \( r < b/2 \) scenario, but its social welfare level is still lower than that in CTTW regime. Based on the targets of net-zero carbon emissions, low environmental damage, and high social welfare level, the CTSW regime can realize the first two targets and the CTTW regime can realize the third one only in the \( r < b/2 \) scenario. We summarize the results in this subsection in the following table in which we compare the effects of the CTTW and CTSW regimes on net-zero carbon emissions, environmental damage, and social welfare level based on a product’s characteristics.

| Industrial transformation and carbon tax regime |
|------------------------------------------------|

Business transaction and digital transaction are two terms relative to industrial transformation. The banking industry is an example of industrial transformation and has started to push digital transactions, which digitize all traditional banking services in order to substitute the physical banks’ services
with digital ones. In fact, Table 1 also exhibits the industrial transformation process in which product substitution is from high to low and product price elasticity of demand is from large to small in the beginning stage of industrial transformation since the product is differentiating. When the product goes into a mature stage, product substitution is from high to low and product price elasticity of demand is from small to large, which is the late stage in industrial transformation. Figure 1 shows the carbon tax regime in each industrial transformation stage with the change in product characteristics.

In the beginning stage of industrial transformation with \( r \geq b/2 \), the CTTW regime has an absolute advantage on three targets: achievement of net-zero carbon emissions target, small environmental damage, and high social welfare level. However, in the beginning stage of industrial transformation with \( r < b/2 \), the CTSW regime can achieve the targets of net-zero carbon emissions and small environmental damage, and the CTTW regime can realize a high social welfare level. In the late stage of industrial transformation with \( r < b/2 \), the CTSW regime has two advantages on achieving net-zero carbon emissions and small environmental damage, and the CTTW regime has only one advantage on high social welfare level. In the late stage of industrial transformation with \( r \geq b/2 \), the CTTW regime presents an absolute advantage to reach three targets: net-zero carbon emissions, small environmental damage and high social welfare level. It is no doubt that an authority will adopt the CTTW regime in the beginning and late stages of industrial transformation when product substitution and product price elasticity of demand are large in order to realize three targets. There is, though, an alternative choice for the authority to adopt the CTSW regime for achievements of net-zero carbon emission target and small environmental damage or choose the CTTW regime for a high social welfare level in the beginning and late stages of industrial transformation when product substitution and product price elasticity of demand are small.

### Table 1. A comparison of the CTTW and CTSW regimes.

| Targets/product’s character | Low product substitution | High product substitution |
|-----------------------------|--------------------------|----------------------------|
| Net-zero carbon emissions   | CTSW                     | CTTW                       |
| Small environmental damage  | CTSW                     | CTTW                       |
| High social welfare level   | CTTW                     | CTTW                       |

### Comparative static analysis

This section presents a comparative static analysis on social welfare level and carbon tax rate with respect to product characteristics.

#### Social welfare level and carbon tax rate

From the previous section we conclude that the social welfare level in the CTTW regime is always higher than that in CTSW regime. However, a comparative static analysis on the social welfare level in the CTSW regime is still necessary since the authority may take net-zero carbon emissions as the target instead of seeking a high social welfare level by adopting the CTSW regime in the industrial transformation stage with \( r < b/2 \); i.e. a market with small product substitution and low price elasticity of demand. Comparative static analysis on the optimal social welfare level with respect to product substitution and product price elasticity of demand goes as follows:

\[
\frac{\partial W^*}{\partial r} = a^2(r - 8b + 6g)/(r + 2b + 2g)^3 < 0 \quad \text{when} \quad r < 8b + 6g, \quad (14a)
\]

\[
\frac{\partial W^*}{\partial r} = -3a^2/(3r + b + 2g)^2 < 0, \quad (14b)
\]

\[
\frac{\partial W^*}{\partial b} = a^2(7r - 6b - 2g)/(r + 2b + 2g)^3 < 0 \quad \text{when} \quad b > (7r - 2g)/6, \quad (14c)
\]

\[
\frac{\partial W^*}{\partial b} = -a^2/(3r + b + 2g)^2 < 0 \quad (14d)
\]

Equation (14a) shows that the social welfare level in the CTSW regime increases (decreases) when product substitution becomes small (large), which is conditional on a large product carbon emissions coefficient \( g \). Equation (14b) shows that the change of social welfare level in the CTTW regime has the same result, but it does not matter to the size of product carbon emissions coefficient. Equation (14c) shows that the social welfare level in the CTSW regime increases (decreases) when...
product price elasticity of demand becomes large (small), which is conditional on a large product carbon emissions coefficient. Equation (14d) shows that the change of the social welfare level in the CTTW regime also has the same result, but it also does not matter to the size of product carbon emissions coefficient. We here find that the influence of a change in product characteristics on social welfare change in the CTSW regime matters to the product carbon emissions coefficient, which results in the aim of the CTSW regime being to eliminate all environmental damage caused by carbon emissions. Nonetheless, the scale of environmental damage is relative to the size of the product carbon emissions coefficient.

Product substitution and product price elasticity of demand in general have a relationship whereby high (low) product substitution is relative to large (small) price elasticity of demand. However, their influences on the social welfare level present a trade-off effect in which when product substitution becomes high (low) to push up (lower) the social welfare level high (down), the product price elasticity of demand becomes large (small) and decreases (increases) the social welfare level. This result is caused by the carbon emissions tax being involved in the analysis of the social welfare level, so that one factor (i.e. the product substitution for an example) pushes the social welfare level, and the other factor (the product price elasticity of demand) cuts down the social welfare level after considering the environmental damage restraint.

We next show the comparative static analysis on the optimal carbon tax rate with respect to product substitution and product price elasticity of demand as follows:

\[
\frac{\partial t^*}{\partial r} = 0 \quad (15a) \\
\frac{\partial t^{**}}{\partial r} = 2 > 0, \quad (15b) \\
\frac{\partial t^*}{\partial b} = 0, \quad (15c) \\
\frac{\partial t^{**}}{\partial b} = -1 < 0. \quad (15d)
\]

Equations (15a) and (15c) show that the optimal carbon tax rate in the CTSW regime does not change by any economic factor, including product substitution and product price elasticity of demand as discussed in this paper, because the aim of the CTSW regime is to eliminate all environmental damages caused by carbon emissions. However, the aim of the CTTW regime is to consider a total social welfare level not only on environmental damage reduction, but also on the promotion of consumer surplus and producer surplus. Here, Eqs. (15b) and (15d) present that if product substitution or product price elasticity of demand becomes large (small), then the optimal carbon tax rate in the CTTW regime soars (falls).

The results in Eqs. (15b) and (15d) can be explained by the large product substitution and price elasticity of demand causing more product quantity, which also causes more serious environmental damage. In order to prevent the environmental damage caused by carbon emissions, a high carbon tax rate needs to be levied on a per product basis, so that the carbon tax revenue in the CTTW regime cleans up environmental damage and makes up for the losses of consumer surplus and producer surplus caused by a high carbon tax rate. A high carbon tax rate distorts the side of market production, but it corrects the side of environmental damage. In addition, high carbon emissions tax revenue recovers the distortion on market production, including the losses to consumer surplus and producer surplus. On the contrary, a low carbon tax rate is appropriate to the market with small product substitution and price elasticity of demand in which a low carbon tax rate can decrease distortion on the production side by promoting product quantity and also has a function to eliminate environmental damage.

**Comparative static analysis in industrial transformation**

The beginning stage of industrial transformation can be characterized by product substitution and product price elasticity of demand becoming small; i.e. the parameter \( r \) becomes small and the parameter \( b \) becomes large. In the late stage of industrial transformation, product substitution and product price elasticity of demand become large; i.e. the parameter \( r \) becomes large and the parameter \( b \) becomes small. In other words, product quantity goes from more to less in the beginning stage of industrial transformation, and then it runs from less to more in the late stage of industrial transformation. We arrange the effects of comparative static analysis in the industrial transformation process on the social welfare level and carbon tax rate in Table 2 and use them to illustrate the changes in optimal social welfare level and optimal carbon tax rate during the stages of industrial transformation.

Based on the information in Table 2, we find that the CTSW regime needs to be discussed by classifying into two scenarios in which one is the case of small carbon emissions coefficient and the
other one is the case of large carbon emissions coefficient. Since the aim of the CTSW regime is to eliminate all environmental damages caused by carbon emissions, the carbon emissions tax rate does not change no matter for the carbon emissions coefficient size and no matter in the beginning stage or the late stage of industrial transformation. In the case of the CTSW regime with a small carbon emissions coefficient, the product substitution becoming small (large) in the beginning (late) stage of industrial transformation makes the social welfare level decrease (increase), but product price elasticity of demand becoming small (large) in this stage makes the social welfare increase (decrease). Hence, the net change on social welfare level is uncertain in this case. In the case of the CTSW regime with a high carbon emissions coefficient, the product substitution becoming small (large) in the beginning (late) stage of industrial transformation causes the social welfare level to increase (decrease), and the product price elasticity of demand becoming small (large) in this stage causes social welfare level to decrease (increase). Thus, the net change on social welfare level is also uncertain in this scenario.

Concerning the CTTW regime, Table 2 tells us that the carbon tax rate becomes low (high) in the beginning (late) stage of industrial transformation with the product substitution and product price elasticity of demand becoming small (large). On the other hand, the product substitution becoming small (large) in the beginning (late) stage of industrial transformation causes the social welfare level to increase (decrease). However, the product price elasticity of demand becoming small (large) in this stage of industrial transformation causes the social welfare level to decrease (increase). Thus, the net change on social welfare level is uncertain in the CTTW regime.

From the analysis in this section, we summarize some key findings as follows. First, the carbon tax rate in the CTSW regime does not change with a change of product characteristic since its aim is to eliminate all environmental damages. Second, the carbon tax rate in the CTTW regime falls (soars) in the beginning (late) stage of industrial transformation in which the product substitution and product price elasticity of demand are small (large). Third, no matter for the CTSW and CTTW regimes, there is an inverse effect on social welfare level promotion in which the change in product substitution promotes (lowers) the social welfare level, and the change in product price elasticity of demand lowers (promotes) the social welfare level. This result denotes that the carbon emissions tax rate considers not only a product quantity increase, but also environmental damage reduction in order to maintain the optimal social welfare level.

### Conclusion

Net-zero carbon emissions are the best way to combat global warming and climate change, and an effective carbon tax regime can help to realize their target. This study examines the carbon tax regime from two viewpoints: one is a carbon tax on the single social welfare level and the other one is a carbon tax on the total social welfare level. The former maximizes the social welfare level, but is subject to eliminating all environmental damages caused by carbon emissions, while the latter maximizes the social welfare level and eliminates environmental damages at the same time. In more detail, the common target for the two carbon tax regimes is to maximize the social welfare level, but the former is conditional on eliminating all carbon emissions, whereas the latter does not necessarily eliminate all carbon emissions.
emissions. In fact, the regime of a carbon tax on single social welfare in this study refers to the EU’s carbon border adjustment mechanism, which takes net-zero carbon emissions as a target. We examine the regime of a carbon border adjustment mechanism in this study and find its advantages and disadvantages.

Based on the investigation, we summarize the findings as follows. (i) A carbon tax with the consideration of comprehensive economic factors can create a high social welfare welfare level. (ii) Even if the carbon tax function recovers all environmental damages by using carbon tax revenue, this carbon tax regime cannot guarantee to generate the smallest environmental damage. (iii) A high carbon emissions tax rate does not necessarily cause a low social welfare level when the carbon tax comprehensively considers the social welfare level. (iv) In a market with high product substitution and large product price elasticity of demand, the carbon tax with a comprehensive consideration on the social welfare level not only achieves the target of net-zero emissions, but also receives high social welfare. Based on the results above, the EU’s carbon border adjustment mechanism seems to have room for reconsideration on its implementation method. After all, we find that this regime runs opposite to that in Overland and Sabyrbekov [33].

Industrial transformation causes some changes to economic factors. In general, product substitution and product price elasticity of demand become small in the beginning stage of industrial transformation in which the product is in a product differentiation stage and become large in the late stage of industrial transformation in which the product has entered a mature stage. Our study concludes that no matter in the beginning or late stage of industrial transformation, and no matter for any carbon tax regime, the changes in product substitution or product price elasticity of demand have a trade-off effect on the social welfare level change, which results in an uncertain change to the social welfare level. This result means the authority can use an appropriate carbon tax regime to eliminate environmental damage caused by carbon emissions, spurring consumer demand and benefitting firms at the same time. Hence, the authority should consider the industrial and market characteristics to adopt an appropriate carbon tax regime.

Net-zero carbon emissions and maximized social welfare level are two targets for the relevant authority. We summarize three outcomes for a carbon emissions tax as follows. (i) No matter for product substitution or product price elasticity of demand, a carbon tax on the single social welfare level can achieve the target of net-zero carbon emissions, but cannot maximize the social welfare level. (ii) A carbon tax on the total social welfare level can simultaneously achieve the net-zero carbon emissions target and maximize the social welfare level, conditional on the market having high product substitution and large product price elasticity of demand. (iii) Given low product substitution and small product price elasticity of demand, the authority either chooses the regime of a carbon tax on the total social welfare level to maximize the social welfare level, but sacrifices the target of net-zero carbon emissions, or chooses the regime of a carbon tax on the single social welfare level to achieve the target of net-zero carbon emissions, but cannot maximize the social welfare level. One management implication from this point is that there should be different mechanisms of carbon tax regimes for the authority to adopt under different market types.

This study establishes the framework under a subgame perfect Nash equilibrium and a dynamic game with complete information. Referring to Gibbons [34], complete information means all information in the game, including feasible strategy, player’s action timing, and payoffs as common knowledge. In other words, all variables in the game are known so that the government can set the optimal CO2 emissions tax rate, and the firm can also decide the optimal strategy based on the government’s policy and its rival’s action. However, a game with uncertain variables is another research avenue that can refer to a game with incomplete information. Moreover, different from game theory analysis whereby we use a partial equilibrium analysis for discussing industrial transformation, the computable general equilibrium (CGE) model is able to investigate the impact on all macroeconomic markets, including capital market, labor market, foreign exchange market, and so on. The carbon event study by the CGE approach appears in the works by Zhou et al. [35], Lin and Jia [36], Liu et al. [9], and Jia et al. [37]. The constructions of complete information and partial equilibrium analysis in this study are the research limitations, but we can replace them by incomplete information and general equilibrium analysis in a future study.

Data availability statement
Data in this study are available upon request from the author.
No potential conflict of interest was reported by the author.

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