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Carbon tax or cap-and-trade: Which is more viable for Chinese remanufacturing industry?

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Abstract: The debate between cap-and-trade and carbon tax, two major carbon emission reduction mechanisms to deal with global warming, has been going on for years unsettled. The strategy to implement one of them or both is by far mainly addressed at the national level, and there is a need to customize the policy-making for different sectors, especially the emerging remanufacturing industry that has the great potential to reduce material and energy consumptions. Based on a closed-loop supply chain model, this study analyzes the tradeoffs between carbon tax and cap-and-trade with a series of numerical studies. While keeping carbon emissions under control, cap-and-trade demonstrates a better fit to remanufacturing: its performances on manufacturer profit, social welfare, and consumer surplus surpass carbon tax' in nine, eight, and six out of nine groups respectively. Only when the carbon quota level is too high, the cap-and-trade is possible to lose. In addition, this study examines two government-to-enterprise-subsidy (G-to-E-S) strategies, direct subsidy and policy bias, and find both helpful but almost no difference in their impacts. The findings yield useful insights into the industry-wise design of carbon emission reduction mechanisms for remanufacturing and similar sectors.

Keywords: carbon regulations; carbon tax; cap and trade; remanufacturing industry; greenhouse gas policies.

1 Introduction

Global warming threatens the future of all humanity, and the current international consensus is to reduce the emissions of greenhouse gases, primarily carbon dioxide. The global carbon reduction plan began with the signing of the Kyoto Protocol in December 1997, which stipulates that more than 30 countries will achieve carbon reduction targets of 5.2% or more in 2008-2012. Both the Copenhagen Accord in 2009 and the Paris Agreement in 2015 are pushing countries around the world to adopt quantitative and effective emission reduction plans by 2020. Till the end of 2018, 55 jurisdictions around the world have established carbon taxes and/or emissions trading systems (ETSs), but none of them include all the sectors, leading to a merely 42.5% coverage of carbon emission sources (Haites, 2018).

The European Union (EU) launched Phase III of ETS during 2013-2020. Before that, many EU members had already taken actions: Finland, Poland, and Denmark introduced carbon tax by 1992;

Switzerland established its ETS in 2008, and Iceland adopted carbon tax in 2010. The United States established its regional greenhouse gas initiative in 2008. In Canada, the Alberta greenhouse gas reduction program was introduced in 2007, and the British Columbia carbon tax shift/revenue-neutral carbon tax was enacted in 2008. The two North American countries also explored emission reduction mechanisms together: the two ETS established in California and Quebec in 2013 began joint auctions in November 2014. In Asia, Japan established ETSs in Tokyo (2010) and Saitama (2011) and imposed carbon tax in 2012, while South Korea established an ETS in January 2015 (Haites, 2018).

As the world's factory, China is also actively reducing carbon emission and engaging in sustainable development. In 2009, the Chinese government announced an emission reduction pledge to reduce carbon emission per unit of GDP by 40-45% in 2020 compared with 2005 (Zhang, 2011). After the Paris Agreement, China proposed to reduce carbon emissions per unit of GDP by 60-65% by 2030 compared with 2005 (Kong, Zhao, Yuan et al., 2019). Taking the lead in this new trend, China has explored cap-and-trade since 2013 with several pilots in large cities (Zhou & Li, 2018), which led to a fully-operational nationwide system based in Shanghai (Song, Liang, Liu et al., 2018). This cap-and-trade system features the free allocation of carbon quotas to enterprises, which may sell or purchase extra quotas based on actual emissions (L. W. Liu, Chen, Zhao et al., 2015).

Whereas the cap-and-trade system encourages enterprises to reduce emissions autonomously, the carbon tax provides a supplementary option for companies that are not part of the system (Goulder & Schein, 2013). For this sake, China is to implement both at the national level. So far the cap-and-trade system mainly covers the industries of high carbon emissions (e.g., thermal power), and it is still up to others to decide which one to adopt (Z. Liu, Guan, Douglas et al., 2013). In particular, remanufacturing is an emerging but fast-developing industry that alleviates environmental deterioration and resource depletion with material recycling and reuse (W. J. Liu, Zhang, Jin et al., 2017). To reduce resource consumptions and waste emissions, enterprises dissemble, resemble and/or refurbish used products. The government strongly encourages enterprises to engage in remanufacturing with subsidies and consumers to purchase remanufactured products with financial incentives for trading in old for new. It is believed that cap-and-trade is beneficial to the remanufacturing industry (Chai, Xiao, Lai et al., 2018), but its performance in comparison with carbon tax is still unclear.

Recently, researchers pay attention to the trade-offs between cap-and-trade and carbon tax. Carl and Fedor (2016) investigated the generation of public revenues through cap-and-trade and carbon tax. For the power industry, C. Y. Liu (2017) advocated cap-and-trade due to the fact that carbon-intensive (dirty) energy is heavily subsidized worldwide, making carbon tax relatively ineffective. In order to help policy-makers choose suitable emission-control mechanisms, Wood (2018) elaborated on the pros and cons of cap-and-trade and carbon tax. Kosnik (2018) found that cap-and-trade received more positive media attention than carbon tax in the US over decades. Ritter and Zimmermann (2019) established a two-period, non-cooperative equilibrium of an n-countries policy game, and found that carbon tax outperforms cap-and-trade in terms of carbon leakage. At the industry level, however, there is a lack of research on carbon policy selection, especially for remanufacturing.

From the enterprise perspective, researchers usually focus on the relationship between production decisions and carbon regulations, such as the manufacturing and transportation outsourcing in supply chains under single and multiple carbon regulations (Li, Su, & Ma, 2017), economic order quantity (EOQ) with cap-and-trade and carbon tax (He, Zhang, Xu et al., 2015), and joint production and pricing of multiple products in each scenario (Xu, Xu, & He, 2016). Nevertheless, the impacts of different carbon policies on enterprises are yet to be examined. In particular, it is not clear whether the emerging remanufacturing industry should choose cap-and-trade or carbon tax. This study attempts to answer the question by comparing their effects on this environment-oriented industry along with two government-to-enterprise-subsidy (G-to-E-S) policies: direct subsidy and policy bias. The investigation based on mathematical simulation yields insight into the optimal policy portfolio for the remanufacturing industry.

This study may contribute to the literature in both theory and practice. It establishes a double-closed-loop supply chain model of cap-and-trade and carbon tax in the context of remanufacturing to compare their impacts on manufacturer profit, consumer surplus, social welfare and carbon emissions under different G-to-E-S strategies. The findings from mathematical modeling inform government policies and enterprise decisions to promote the new industry's healthy development. The model setup is based on China's remanufacturing for illustrative purpose, but the method can be easily adapted to other industries and countries.

The rest of this article is organized as follows. It first reviews the extant literature on remanufacturing, government subsidy, and carbon regulation. The understanding leads to the establishment of mathematical models to compare carbon tax and cap-and-trade strategies. Equilibrium analyses reveal their different impacts on economic performance and environmental performance. Theoretical and practical implications of the findings are discussed, followed by the conclusion.

2 Research background

2.1 Remanufacturing

The trade-in and remanufacturing of used products help enterprises gain competitive advantages from consumer recognition, price differentiation, and market niching (Atasu, Sarvary, & Wassenhove, 2008). Based on the Majumder-Groenevelt model (Majumder & Groenvelt, 2001), Ferrer and Swaminathan (2006) compared the optimal production planning and pricing strategies of manufacturers between new products and remanufactured products in monopoly and duopoly situations. On this basis, Ferrer discussed the situation in which the utility and price of remanufactured goods are different from new ones (Ferrer, 2010). In addition, Ferguson and Toktay (2010) set up a double-cycle model and discusses the best recovery strategy of original entrusted manufacturers (OEMs) considering market competition threats from remanufactured products.

Choi, Li, and Xu (2013) examined two modes of closed-loop supply chains in the remanufacturing industry and pointed out that the one led by retailers are more efficient than the other led by recyclers. Yin, Li, and Tang (2015) considered the fact that retailer-led channels involve trade-in for the optimal pricing of two successive-generation products. Zhu, Wang, Wang et al. (2017) also took trade-in into account when comparing two policy options: subsiding donations and subsidizing resales. Yet this essential element has not been incorporated into the modeling of remanufacturing. For instance, Ferguson and Toktay (2010) posited that the purchasing behavior of consumers is affected by remanufacturing without addressing the difference that trade-in policies make. When Choi, Li, and Xu (2013) focused on the channel leadership selection in closed loop supply chains, they did not pay attention to trade-in as well.

Ray, Boyaci, and Aras (2011) suggested that the trade-in strategy affects the purchases of regular customers, and thus has an impact on the profitability of entire remanufacturing supply chains. In 2012, China launched a trade-in subsidy policy, which allows consumers to return used products to their manufacturers and buy new products at favorable prices. Keeping abreast with the current situation in China, this study responds to the call by Ray, Boyaci, and Aras (2011) to consider trade-in policies in remanufacturing closed-loop supply chains.

2.2 Government subsidy

Most existing studies on remanufacturing supply chains, including those in the previous subsection, did not examine the impacts of government subsidies. Mitra and Webster (2008) indicated that government subsidies enhance the marketability of remanufacturing products, as their lower prices make them more competitive than new products. Y. X. Wang, Chang, Chen et al. (2014) compared different subsidy strategies in remanufacturing, and found that initial subsidies are suitable for the start-up development stage, product and R&D subsidies are conducive to the scalability and stability of continuous development, and recycling subsidies help solve the raw material bottleneck. The findings corroborate the analyses by L. Wang and Chen (2013) on the subsidy strategies with end-of-life vehicle (ELV) remanufacturing.

Rahman and Subramanian (2012)'s research indicated that government subsidies have great impacts on the decision-making, performance, and structure of a remanufacturing supply chain. Ma, Zhao, and Ke (2013) pointed out that the subsidies to consumers largely shape the two-channel closed-loop supply chain in remanufacturing. Shu, Peng, Chen et al. (2017) compared the carbon tax approach with the direct subsidy on the effects of trade-in-old-for-new subsidies to enterprises from four aspects: enterprise profit, social welfare, consumer satisfaction, and carbon emission.

In summary, government subsidies have great impacts on the remanufacturing industry from both enterprise and consumer aspects in terms of how they make decisions. In this sense, it is necessary to consider government subsidies in the investigation of the closed-loop supply chain involved in trade-in-old-for-new remanufacturing.

2.3 Carbon regulations

Carbon regulations are rarely considered in existing studies on remanufacturing, though they play indispensable roles in greenhouse gas emission reduction. Montgomery (1972) first proposed the concept of carbon trading, and Laffont and Tirole (1994) discussed the details of setting up a carbon market. In addition, Nordhaus (1992) showed that a proper level of carbon tax is able to slow down global warming. For a better understanding of carbon regulations in the context of remanufacturing, it is helpful to examine and compare cap-and-trade and carbon tax in terms of current status and future development.

In a cross-sectional study on carbon trading markets, Hua, Cheng, and Wang (2011) found that when both order cost and carbon emission are taken into account, the order quantity of an enterprise is likely to be smaller than that of another following the traditional economic order quantity (EOQ) model but larger than that of another targeting the lowest carbon emission. Nong, Meng, and Siriwardana (2017) used the MONASH Green model to evaluate Australia's ETS, and the results showed that ETS facilitates the country’s transition to a low-carbon economy without a significant economic impact. Since the establishment of cap-and-trade pilot projects in China, researchers have examined the system in terms of their design, implementation, and policy (Jiang, Xie, Ye et al., 2016). Du, Ma, Fu et al. (2015) pointed out that the cap-and-trade system enables nonprofit environmental protection organizations to grow and make more contribution to the reduction of carbon emissions.

Carbon tax is a more direct approach to deal with global warming as the policy brings about an immediate reduction of greenhouse gas emissions (Chai, Xiao, Lai et al., 2018; Wittneben, 2009). However, it is somewhat controversial as the dynamic integrated climate economy (DICE) model shows that the dramatic cut-down of production hurts the economy (Nordhaus, 1992). Lin and Li (2011), Kuo, Hong, and Lin (2016), and Allan, Lecca, Mcgregor et al. (2014) analyzed the efficiency of carbon tax in northern Europe, Taiwan, and Scotland, and found that it reduces greenhouse gas emissions to a certain extent but an excessive taxation is economy-unfriendly. Metcalf (2009) proposed the use of carbon tax to reduce greenhouse gas emissions in the United States and offset the existing environmental taxation with the proceeds to strike a balance in tax neutrality. Similarly, (Diamond & Zodrow, 2018) found that carbon tax revenue yields positive impacts on gross domestic production (GDP), investment, consumption, and labor supply in the long run when it is used to reduce payroll tax, but negative impacts when it is used to reduce the national debt or refunded to households. Corradini, Costantini, Markandya et al. (2018) proposed another way of using carbon tax revenue to fund the research and development of new energy technologies, which accelerate the transition to a low-carbon economy at lower social and economic costs.

As cap-and-trade or carbon tax alone is not optimal in all circumstances, the coexistence of both is advocated (Goulder & Schein, 2013). Recent Chinese data showed that optimal carbon tax rate can cut emissions up to 62.5% for some sectors, but not enough for overall reduction as the percentages are only 0.03% for the service sector and 2.02% for the manufacturing sector (Wesseh & Lin, 2018). Whereas carbon tax takes effects quickly, carbon trading is more efficient in the long run in terms of economic benefit and social recognition (Camila, Amalia, Maria et al., 2018). Shi, Yuan, Zhou et al. (2013) made a comparative analysis and concluded that the coexistence strategy strikes a balance between carbon tax and cap-and-trade in terms of emission reduction and enterprise cost. Thus, it is suggested that China implement both, giving cap-and-trade the priority over carbon tax until the country develops a more mature carbon emission reduction capability (Cao & Wang, 2015; Wu, Qian, & Tang, 2014).

Though the dual-track strategy is advantageous at the national level, a single approach, cap-and-trade or carbon tax, should be adopted at the enterprise level to avoid redundant responsibilities (Zeng, 2017). In 2017, China established a national carbon trading market, which only explicitly included the power industry. The Center for Energy and Environmental Policy Research (CEEP) advocated that enterprises with annual carbon dioxide emission over 26000 tons (equivalent to 10,000 tons of standard coal) be included in the carbon market, and the others be levied carbon tax (BJX, 2018). In contrast, the carbon emissions are more evenly-distributed among remanufacturing enterprises, and this study focuses on the industry-wise strategy.

3. Modeling and solution

To examine the effectiveness of cap-and-trade and carbon tax in the remanufacturing closed-loop supply chain, this section establishes mathematical models to compare their impacts on economic and environmental performances considering trade-in and government subsidies. An enterprise in the industry typically produces both new and remanufactured products, which are perceived differently in terms of cost and quality by consumers. Thus, the modeling cannot be based on popular game theory approaches that accommodate two players but focus on one competitive advantage strategy at a time, such as Hotelling model targeting lower cost and Cournot model targeting product differentiation. To handle both price competition and product differentiation between new and remanufactured products in the remanufacturing industry, the models developed in this study assume that there exists one “general” manufacturer for each line of products. This scenario applies to the market segmentation in which consumers have strong product type/brand preferences (e.g., Android vs. Apple phones).

3.1 Basic model

3.1.1Descriptions

There is one manufacturer in the market that produces both new and remanufactured products and recycles used products. The government subsidizes consumers who trade in old for new from the manufacturer with discounted prices. In the basic model, the government adopts the emission permit system, and the manufacturer bears no carbon emission cost. Fig.1 illustrates the closed-loop supply chain in the basic model.

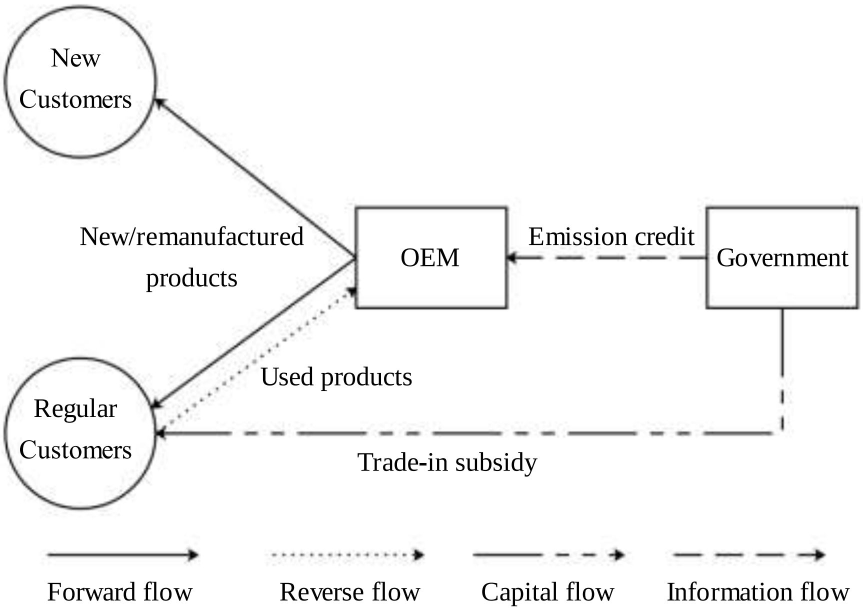

Fig.1. Closed-loop supply chain in the basic model.

Consumers are divided into new customers and regular customers. The new customer had never purchased a manufacturer's product before, the regular customers have purchased products and own the used products. Assume that all customers are fully rational and seek to maximize the utility of expenditure. Table 1 lists the main notations in subsequent mathematical models.

Table 1. Main notations.

Notations	*Definitions*
$B/N/T$	Basic model/model-N/model-T
P_n/P_r	The sale price of new/remanufactured products
v	The recycling price of a used product
C_n/C_r	Manufacturing cost of new/remanufactured products
q_n^i $/q_r^i$	Sales volume of new/remanufactured product that purchased by customers i
q_v	The whole sales including new and remanufactured product
s_t	The government subsidies to consumers who trade in old for new
s_r	The government subsidies to manufacturers engaging in remanufacturing
$\alpha/1-\alpha$	The proportion of new/regular customers
$\theta/t\theta/\delta\theta$	The utility of new/remanufactured/used products for consumers
b	The salvage of the used products
e_n/e_r	Carbon emissions of manufacturing new/remanufactured products
e_t	Carbon emission quotas rate
βe_t	The preferential carbon emission quotas rate
c	Carbon tax rate in model-N/ price of unit carbon emission quota in model-T
ρc	Preferential carbon tax rate
U_n^i/U_r^i	The utility of customer i buying a new/ remanufactured product
π_M	Manufacturer profit
CE	Carbon emission from manufacturing
CS/SW	Consumer surplus/Social welfare

3.1.2 Consumer choices

Before making purchases, consumers compare all the options and choose the ones that maximize the utility. All consumers have three choices: buy new products, buy remanufactured products, or no buy. For regular customers, they can trade in old for new when they buy new or remanufactured products. According to Ferrer and Swaminathan (2006) and Ferrer (2010), the utility that the consumer obtains through buying behavior is as follows:

a) When a new consumer chooses to buy a new product, the utility derived is $U_n^\alpha = \theta - P_n$.

b) When a new consumer chooses to buy a remanufactured product, the utility derived is $U_r^\alpha = t\theta - P_r$.

c) When a new consumer chooses to buy neither, the utility is 0.

d) When a regular consumer chooses to trade in an old product for a new one, the utility derived is $U_n^{1-\alpha} = \theta - P_n + v + s_t - \delta\theta$.

e) When a regular consumer chooses to trade in an old product for a remanufactured one, the utility derived is $U_r^{1-\alpha} = t\theta - P_r + v + s_t - \delta\theta$.

f) When a regular consumer chooses to buy neither, the utility is 0.

This study explores the policy options for reducing carbon emissions of the remanufacturing industry. Other than the remanufacturing sales volume of 0, the sales can then be determined, as summarized in *Lemma 1*.

Lemma 1. When $P_r \le tP_n$ and $(t-\delta)P_n - (1-\delta)P_r + (1-t)(v+S_t) > 0$, the whole sales $q_v = 1 - \frac{\alpha P_r}{t} - (1-\alpha)\frac{P_r - v - s_t}{t-\delta}$, the sales of new products purchased by new customers is $q_n^\alpha = \alpha\left(1 - \frac{P_n - P_r}{1-t}\right)$, the sales of remanufactured products that purchased by new customers are $q_r^\alpha = \alpha\left(\frac{P_n - P_r}{1-t} - \frac{P_r}{t}\right)$, the sales of new products that purchased by regular customers are $q_n^{1-\alpha} = (1-\alpha)\left(1 - \frac{P_n - P_r}{1-t}\right)$, and the sales of remanufactured products that purchased by regular customers are $q_r^{1-\alpha} = (1-\alpha)\left(\frac{P_n - P_r}{1-t} - \frac{P_r - v - s_t}{t-\delta}\right)$.

3.1.3 Optimal enterprise decisions

In the basic model, the manufacturer profit can be formulated as:

$$\pi_M^B = (P_n - C_n)(q_n^\alpha + q_n^{1-\alpha}) + (P_r - C_r)(q_r^\alpha + q_r^{1-\alpha}) - (v - b)(q_n^{1-\alpha} + q_r^{1-\alpha}) \quad (1)$$

The profit of the manufacturer consists of new product revenue, remanufacturing product revenue, and recovery cost. Solving the first-order conditions for the profit-maximizing manufacturer yields the equilibrium prices as summarized by *Lemma 2*.

Lemma 2. In the basic model, when $C_r \le tC_n$ and $(t-\delta)C_n - (1-\delta)C_r + (1-t)(b+S_t) \ge 0$, the equilibrium price for new products is $P_n^{B*} = \frac{1+C_n}{2}$, the equilibrium price for remanufactured products is $P_r^{B*} = \frac{t+C_r}{2}$, and the recovery price for used products is $v^{B*} = \frac{b+\delta-s_t}{2}$.

In $P_r^{B*}=\frac{t+C_r}{2}$, t is positively correlated with P_r^{B*}, the parameter t represents the degree of consumer acceptance of remanufactured products. With the increase of t, the gap between the utility obtained from the remanufactured product and that from the new product decreases. When $t=1$, the utility obtained from the remanufactured product and that from the new product are equal.

In $v^{B*}=\frac{b+\delta-s_t}{2}$, the business also benefits when the government subsidizes consumers. The utility of used products δ is positively correlated with the recycling price. The higher the utility evaluation of the used product, the higher the expected recycling price, and the less likely the consumer is to participate in the recycling. Representing the salvage of the used products, parameter b is also positively correlated with the recycling price. The higher salvage value of used products, the stronger incentive the manufacturer has to recycle them.

On the basis of *Lemma 2*, the equilibrium sales can be determined. A sensitivity analysis is done to make sense of the main parameters, as summarized in Table 2.

Table 2. Sensitivity analysis of main parameters in the basic model.

	$q_n^{\alpha B*}$	$q_r^{\alpha B*}$	$q_n^{(1-\alpha)B*}$	$q_r^{(1-\alpha)B*}$
$C_n\nearrow/C_r\nearrow$	$\searrow/\nearrow$	$\nearrow/\searrow$	$\searrow/\nearrow$	$\nearrow/\searrow$
$s_t\nearrow$	$\longrightarrow$	$\longrightarrow$	$\longrightarrow$	$\nearrow$
$t\nearrow$	$\searrow$	$\nearrow$	$\searrow$	$\nearrow$
$\alpha\nearrow$	$\nearrow$	$\nearrow$	$\searrow$	$\searrow$
$\delta\nearrow$	$\longrightarrow$	$\longrightarrow$	$\longrightarrow$	$\searrow$
$b\nearrow$	$\longrightarrow$	$\longrightarrow$	$\longrightarrow$	$\nearrow$

a) As the $C_n(C_r)$ increases, the sales of remanufactured (new) product increase too. The increase in the manufacturing cost of new (remanufactured) products will lead to the loss of consumers purchasing new (remanufactured) products, who will buy remanufactured (new) products instead.

b) The subsidy to consumers, s_t, is only positively correlated with the volume of remanufactured products purchased by regular customers, $q_r^{(1-\alpha)B*}$. A higher trade-in subsidy enhances the purchase intention of regular customers who originally choose neither new nor remanufactured products. However, it does not change the extant preferences of other regular customers, as the increase shifts the utilities of new and remanufactured products to the same extent. Fig.2 shows the effect of increasing trade-in subsidy on the utility evaluation of regular customers.

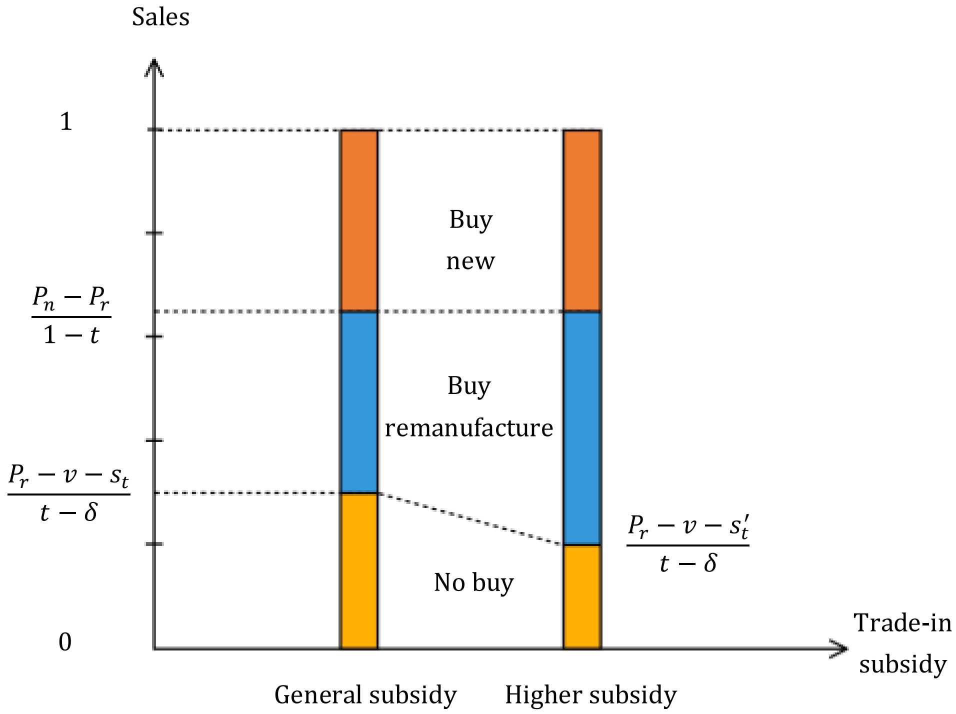

Fig.2. The influence of higher trade-in subsidy on the sales.

Regular customers who have relatively high evaluations of new product utility between $\frac{P_n-P_r}{1-t}$ and 1 tend to buy new products. Regular customers who have relatively low evaluations of new product utility between $\frac{P_r-v-s_t}{t-\delta}$ and $\frac{P_n-P_r}{1-t}$ tend to buy remanufactured products. The remaining regular customers choose to buy neither. When the trade-in subsidy is increased to s_t', regular customers whose evaluations of new product utility between $\frac{P_r-v-s_t'}{t-\delta}$ and $\frac{P_r-v-s_t}{t-\delta}$ tend to buy remanufactured products rather than nothing.

For the same commodity, consumers evaluate its value: those giving higher evaluation tend to buy new products, those giving lower evaluation prefer remanufactured products, and those giving the lowest evaluation are unlikely to make the purchase. When the government subsidy increases, the cost of obtaining remanufactured products decreases, and the consumers with the lowest evaluation may choose remanufactured products.

c) The salvage of used products b is only positively correlated with the volume of remanufactured products purchased by regular customers, $q_r^{(1-\alpha)B*}$. The higher the salvage, the higher the recycling price, and the stronger incentives for manufacturers and consumers to participate in recycling.

d) The parameter, t, represents the degree of consumer acceptance of remanufactured products. With the increase of t, the gap between the utility obtained from the remanufactured product and the new product narrows, and remanufactured products get more preference.

e) δ is positively correlated with the recycling price. The higher the utility evaluation of the used product, the higher the expected recycling price, and the less likely the consumer is to participate in the recycling.

3.2 Carbon tax

3.2.1 Descriptions

In model-N, the cost of carbon emission for the manufacturer is no longer 0. The government levies a carbon tax at the rate of c, and each manufacturer needs to pay tax for the emission from production. Fig.3 shows the closed-loop supply chain in model-N.

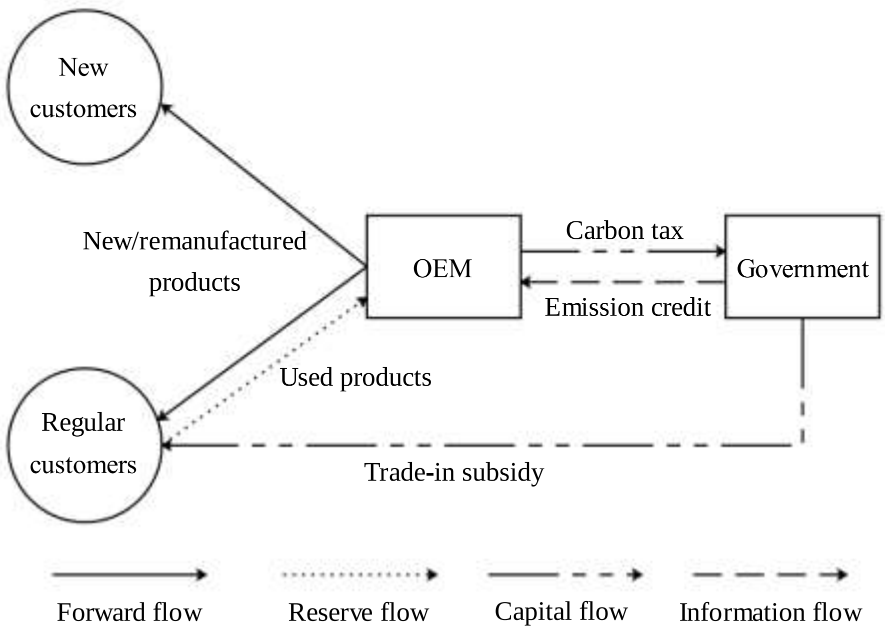

Fig.3. Closed-loop supply chain in model-N.

3.2.2 Optimal enterprise decisions

Taking carbon tax into account, the manufacturer profit in the model-N can be reformulated as:

$$\pi_M^N = (P_n - C_n - ce_n)(q_n^{\alpha} + q_n^{1-\alpha}) + (P_r - C_r - ce_r)(q_r^{\alpha} + q_r^{1-\alpha}) - (v - b)(q_n^{1-\alpha} + q_r^{1-\alpha}) \quad (2)$$

The profit of the manufacturer consists of new product revenue, remanufacturing product revenue, and recovery cost. Solving the first-order conditions for the profit-maximizing manufacturer yields the equilibrium prices as summarized by *Lemma 3*.

Lemma 3. In model-N, when $C_r + ce_r \leq t(C_n + ce_n)$ and $(t-\delta)(C_n + ce_n) - (1-\delta)(C_r + ce_r) + (1-t)(b + S_t) \geq 0$, the equilibrium price for new products is $P_n^{N*} = \frac{1+C_n+ce_n}{2}$, the equilibrium price for remanufactured products is $P_r^{N*} = \frac{t+C_r+ce_r}{2}$ and the equilibrium recycling price is $v^{N*} = \frac{b+\delta-s_t}{2}$.

On the basis of *Lemma 3*, the equilibrium sales can be determined, and the sensitivity analysis is done to make sense of the main parameters, as summarized in table 3.

Table 3. Sensitivity analysis of main parameters in model-N.

	$q_n^{\alpha N*}$	$q_r^{\alpha N*}$	$q_n^{(1-\alpha)N*}$	$q_r^{(1-\alpha)N*}$
$C_n \nearrow / C_r \nearrow$	$\searrow/\nearrow$	$\nearrow/\searrow$	$\searrow/\nearrow$	$\nearrow/\searrow$
$s_t \nearrow$	$\longrightarrow$	$\longrightarrow$	$\longrightarrow$	$\nearrow$
$t \nearrow$	$\searrow$	$\nearrow$	$\searrow$	$\nearrow$
$\alpha \nearrow$	$\nearrow$	$\nearrow$	$\searrow$	$\searrow$
$\delta \nearrow$	$\longrightarrow$	$\longrightarrow$	$\longrightarrow$	$\searrow$
$b \nearrow$	$\longrightarrow$	$\longrightarrow$	$\longrightarrow$	$\nearrow$
$c \nearrow$	$\searrow$	$\nearrow$	$\searrow$	$\nearrow$
$e_n \nearrow / e_r \nearrow$	$\searrow/\nearrow$	$\nearrow/\searrow$	$\searrow/\nearrow$	$\nearrow/\searrow$

As shown in Table 3, the sensitivity of most parameters is the same as the basic model, and the newly appeared parameter c is interpreted here. The increase of parameter c will lead to a decrease in the sales of new products and an increase in the sales of remanufactured products. The imposition of carbon tax forces enterprises to join the remanufacturing industry for lower carbon emissions.

3.3 Cap-and-trade

3.3.1 Descriptions

In model-T, an emission trading system (ETS) regulated by the government is established. At the beginning of each year, manufacturers get free allocations. If a manufacturer's emission exceeds its allocation, it needs to purchase more from others through the ETS. If a manufacturer's emission is less than its allocation, it can sell the remaining on the ETS. Fig.4 shows the closed-loop supply chain in model-T.

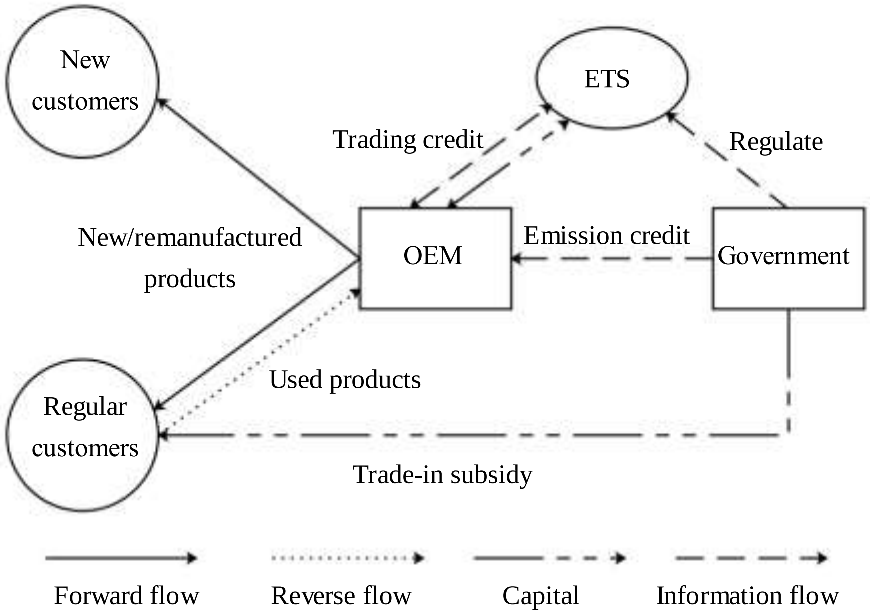

Fig.4. Closed-loop supply chain in model-T.

3.3.2 Optimal enterprise decisions

In the model-T, the manufacturer purchases or sells allocation at price c. The manufacturer profit can be reformulated as:

$$\pi_M^T = (P_n - C_n - ce_n + ce_t)(q_n^{\alpha} + q_n^{1-\alpha}) + (P_r - C_r - ce_r + ce_t)(q_r^{\alpha} + q_r^{1-\alpha}) \\ -(v-b)(q_n^{1-\alpha} + q_r^{1-\alpha}) \quad (3)$$

The profit of the manufacturer consists of new product revenue, remanufacturing product revenue, and recovery cost. Solving the first-order conditions for the profit-maximizing manufacturer yields the equilibrium prices as summarized by *Lemma 4*.

Lemma 4. When $C_r + c(e_r - e_t) \leq t(C_n + c(e_n - e_t)$ and $(t-\delta)(C_n + ce_n) - (1-\delta)(C_r + ce_r) + (1-t)(b + S_t + ce_t) \geq 0$, the equilibrium price for new products is $P_n^{T*} = \frac{1+C_n+c(e_n-e_t)}{2}$, the equilibrium price for remanufactured products is $P_r^{T*} = \frac{t+C_r+c(e_r-e_t)}{2}$ and the recycling price is $v^{T*} = \frac{b+\delta-s_t}{2}$.

On the basis of *Lemma 4*, the equilibrium sales can be determined. As shown in Table 4, the sensitivity of all the parameters remains the same as the basic model, except for the newly appeared parameter e_t. When e_t increases, the sales of new products are not likely to change, but the sales of remanufactured products will increase.

Table 4. Sensitivity analysis of main parameters in model-T.

	$q_n^{\alpha T*}$	$q_r^{\alpha T*}$	$q_n^{(1-\alpha)T*}$	$q_r^{(1-\alpha)T*}$
$C_n \nearrow / C_r \nearrow$	$\searrow/\nearrow$	$\nearrow/\searrow$	$\searrow/\nearrow$	$\nearrow/\searrow$
$s_t \nearrow$	$\longrightarrow$	$\longrightarrow$	$\longrightarrow$	$\nearrow$
$t \nearrow$	$\searrow$	$\nearrow$	$\searrow$	$\nearrow$
$\alpha \nearrow$	$\nearrow$	$\nearrow$	$\searrow$	$\searrow$
$\delta \nearrow$	$\longrightarrow$	$\longrightarrow$	$\longrightarrow$	$\searrow$
$b \nearrow$	$\longrightarrow$	$\longrightarrow$	$\longrightarrow$	$\nearrow$
$c \nearrow$	$\searrow$	$\nearrow$	$\searrow$	$\nearrow$
$e_n \nearrow / e_r \nearrow$	$\searrow/\nearrow$	$\nearrow/\searrow$	$\searrow/\nearrow$	$\nearrow/\searrow$
$e_t \nearrow$	$\longrightarrow$	$\nearrow$	$\longrightarrow$	$\nearrow$

4. Equilibrium analysis

4.1 Carbon tax versus cap-and-trade

Carbon tax and cap-and-trade are compared from manufacturer, consumer, social welfare, and environment performance aspects. Examined in four observations, key indicators include equilibrium price for new/remanufactured products, sales of new/remanufactured products, manufacturer' profit, carbon emissions, consumer surplus and social welfare.

Observation 1. Manufacturers prefer cap-and-trade to carbon tax for higher remanufactured product sales and profits.

$q_n^{\alpha T*} = q_n^{\alpha N*}$, $q_n^{(1-\alpha)T*} = q_n^{(1-\alpha)N*}$. Sales of the new product are the same in model-T and model-N. $q_r^{\alpha T*} > q_r^{\alpha N*}$, $q_r^{(1-\alpha)T*} > q_r^{(1-\alpha)N*}$. Remanufactured product sales increase in model-T but new product sales stay put, indicating that cap-and-trade motivates remanufacturing at a higher degree. To the same extent, the prices of new and remanufactured products decrease and the utilities that consumers derive from all buying options increase. Existing consumers who have purchased new or remanufactured products will stick to the same choice, but new consumers will choose the remanufactured.

Observation 2. Cap-and-trade typically outperforms carbon tax in emission reduction.

The carbon emissions can be formulated as:

$$CE = e_n(q_n^{\alpha} + q_n^{1-\alpha}) + e_r(q_r^{\alpha} + q_r^{1-\alpha}) \tag{4}$$

More remanufactured products are sold in model-T, leading to a larger amount of carbon emission in total ($CE^N - CE^T < 0$). Compared with new products, of course, remanufactured ones have much lower emission per product. Nevertheless, the overall carbon emission in model-T has a cap, over which the extra allowance can be bought from other enterprises. Thus, it makes sense to measure the carbon emission in model-T by quota:

$$CE^T = e_t q_v^T \tag{5}$$

When $e_t < \frac{-b-\sqrt{b^2-4ac}}{2a}$, the carbon emission of a manufacturer in model-T is lower; when $e_t > \frac{-b-\sqrt{b^2-4ac}}{2a}$, it is higher. As long as the allocation of free quota is kept within a reasonable range, cap-and-trade largely guarantees lower carbon emission.

Observation 3. Consumers prefer cap-and-trade as they pay less for both new and remanufactured products.

$P_n^{T*} < P_n^{N*}$, $P_r^{T*} < P_r^{N*}$ and $v^{T*} = v^{N*}$. In model-T, new and remanufactured products can be sold at lower prices, which means companies will attract more consumers.

Consumer surplus is the difference between the maximum price consumers are willing to pay and the actual price they pay. In this study, consumers' willingness to pay is evenly distributed between 0 and 1, and the consumer surplus can be determined by means of integral. As $CS^T > CS^N$, consumer surplus is larger in model-T.

$$CS = \sum_{\substack{i=n,r \\ j=\alpha,1-\alpha}} \left(\int_0^{q_i^j} \theta \, d\theta - P_i q_i^j \right) \tag{6}$$

Observation 4. Social welfare increased when cap-and-trade is adopted.

Social welfare is the sum of consumer surplus and enterprise profit:

$$SW = CS + \pi_M \tag{7}$$

In model-T, both manufacturer profit and consumer surplus increase from more remanufactured products made and sold, leading to higher social welfare. Thus, cap-and-trade promotes remanufacturing in terms of emission reduction, consumer surplus, and manufacturer profit more than carbon tax.

4.2 Government-to-enterprise-subsidy (G-to-E-S)

In addition to consumer-side subsidization, governments may offer subsidies to enterprises for remanufacturing in form of G-to-E-S. On the basis of model-N, two G-to-E-S strategies are introduced: remanufacturing preferential carbon tax and direct remanufacturing subsidies, calling them N1 and N2 separately. In N1, remanufactured products enjoy preferential carbon tax rate ρc, where $0 < \rho < 1$. In N2, the unit remanufactured product gets a subsidy s_r. The solutions of N1 and N2 is the same as model-N. On the basis of model-T, two G-to-E-S strategies are introduced: remanufacturing preferential quotas and direct remanufacturing subsidies, calling them T1 and T2 separately. In T1, remanufactured products enjoy preferential quotas βe_t, where $\beta > 1$. In T2, the unit remanufactured product gets a subsidy s_r. The solutions of T1 and T2 are the same as model-T. Table 5 observes the performance of N1, N2, T1, and T2.

Table 5. Comparison between two G-to-E-S strategies.

Comparing conditions	Model-T versus T1, T2		Model-N versus N1, N2	
	$(\beta - 1)ce_r \geq s_r$	$(\beta - 1)ce_r \leq s_r$	$(1 - \rho)ce_r \geq s_r$	$(1 - \rho)ce_r \leq s_r$
P_n/v	T = T1 = T2		N = N1 = N2	
$P_r/q_n^{\alpha}/q_n^{1-\alpha}$	T ≥ T2 ≥ T1	T ≥ T1 ≥ T2	N ≥ N2 ≥ N1	N ≥ N1 ≥ N2
CE	T ≥ T1 ≥ T2	T ≥ T2 ≥ T1	N ≥ N1 ≥ N2	N ≥ N2 ≥ N1
$q_r^{\alpha}/q_r^{1-\alpha}/\pi_M/CS/SW$	T1 ≥ T2 ≥ T	T2 ≥ T1 ≥ T	N1 ≥ N2 ≥ N	N2 ≥ N1 ≥ N

Note: N represents model-N and T represents model-T.

The comparison is based on the same subsidy intensity. The effects of the two subsidy strategies are very similar, as detailed below.

a) Both G-to-E-S strategies drive down the price of remanufactured products and enhance their competitiveness.

b) Both G-to-E-S strategies restrain the new product business but promote the remanufacturing business.

c) Both G-to-E-S strategies reduce carbon emissions and increase corporate profit, consumer surplus, and social welfare.

d) The more subsidies, the lower the prices of remanufactured products, the larger the sales volume, the greater the carbon emission, enterprise profit, consumer surplus, and social welfare.

5. Numerical study

A numerical study is conducted to explore the policy options for reducing carbon emissions of the remanufacturing industry, as it is hard to obtain real data from enterprises. To avoid the meaningless sales volume of 0, the constraints, $P_r \leq tP_n$ and $(t-\delta)P_n-(1-\delta)P_r+(1-t)(v+S_t)>0$, are established in *Lemma 1*. Under the condition that the constraints are met, the effect of carbon emission quotas rate e_t and carbon tax rate c on the manufacturer profit, carbon emission, consumer surplus, and social welfare are examined in model-T. The numerical setting is as follows: $C_n=0.4, C_r=0.25, t=0.7, \alpha=0.4, s_t=0.2, e_n=0.4, e_r=0.2, \rho=0.5, b=0.1, \delta=0.3, s_r=0.05$. In order to simulate the real situation where the carbon tax rate is fixed and the carbon price can be changed, parameter c in model-N is fixed to 0.5 but variable in model-T. Fig.5 indicates that model-T exhibits better economic performance, especially when e_t is bigger.

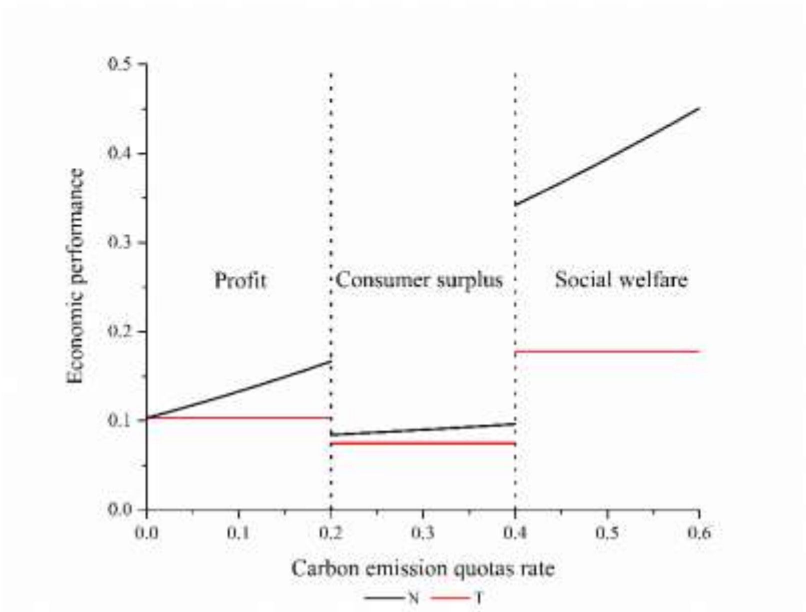

Fig.5. The influence of carbon emission quotas rate on economic performance.

Fig.6 reveals that the carbon emission in model-T typically lower when e_t is under a reasonable level. Only when e_t exceeds a relatively high level (around 0.4), the carbon emission in model-N becomes lower. At a reasonable carbon quota level in the real world, it is rare to see the lower carbon footprint of model-N.

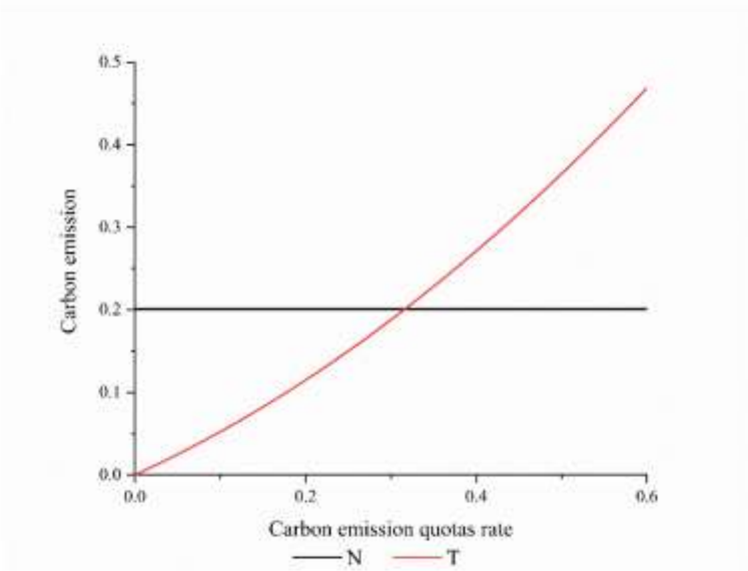

Fig.6. The influence of carbon emission quotas rate on carbon emission.

Basically, Fig.5 and Fig.6 illustrate the analyses in Section 4. In addition, this study explores the influence of carbon price on model-T. Sets $e_t = 0.3$, Fig.7 and Fig.8 simulate the influence of c on the economic performance and carbon emission of model-T respectively. Fig.7 suggests that higher carbon prices lead to lower economic performance, making the economic performance of model-T better when the carbon price is relatively low. From the perspective of carbon emissions, both manufacturers and consumers bear the responsibility. As the increase in carbon price leads to higher production cost, manufacturer profit as well as consumer surplus will decline. Not always a bad thing, however, a higher carbon price stimulates manufacturers and consumers to choose greener options.

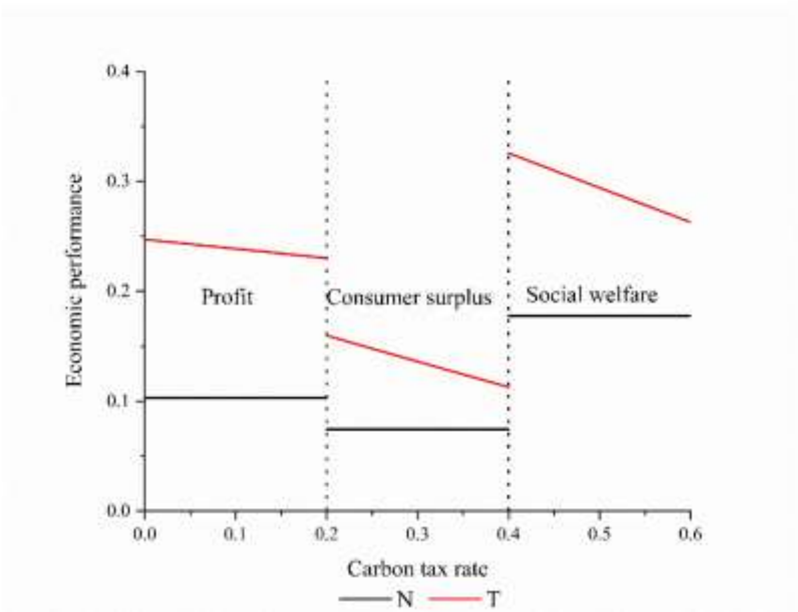

Fig.7. The influence of carbon tax rate on the economic performance ($e_t = 0.3$).

Fig.8 reveals that the higher the carbon price, the greater the carbon emission in a big enough e_t; but completely opposite when e is small, and the carbon emission in model-T is always lower in the low carbon price. In particular, when $e_t = 0.2$, the carbon price loses the ability to regulate carbon emission. If e_t is higher than e_r, the quota obtained for remanufactured products exceeds their production needs, resulting in quota surplus. The increase of carbon price will increase the value of quota, which urges manufacturers to gain more benefits by increasing the output of remanufactured products. Only when $e_t > 0.2$ and the carbon price is high, the carbon emission in model-T is higher.

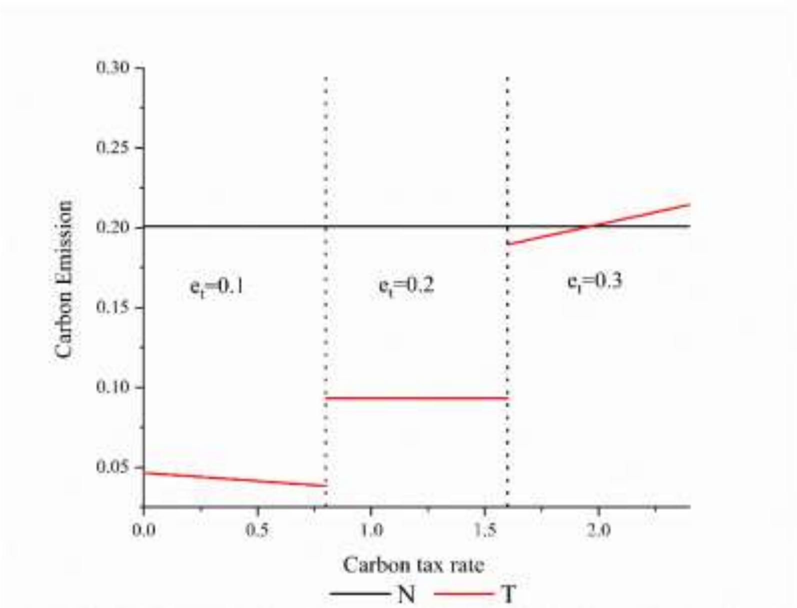

Fig.8. The influence of carbon tax rate on carbon emission.

The results of the numerical study are consistent with the analyses in Section 4. When carbon tax is equal to the carbon price, model-T can bring better economic performance (enterprise profit, consumer surplus, and social welfare), but carbon emission is not always the lowest. When the quota coefficient exceeds the threshold, the carbon emission of model-T will exceed that of model-N. In addition, the carbon price has a negative effect on economic performance, and the impact of the carbon price on carbon emission varies when the quota coefficient takes different values.

According to the base setting, we conduct another 2^k factory experiment with $k = 3$, where three levels for the carbon tax rate is 0.2, 0,4 and 0,6, and three levels for the carbon emission quotas rate is 0.1, 0,2 and 0.3. Presented in Tables A1 and A2 in the Appendix, the numerical results generated from the nine cases are consistent with the managerial findings in this section.

6. Lessons learned elsewhere

The mathematical analyses are based on the situation of one country in which neither ETS nor carbon tax has been implemented for the remanufacturing industry, as in the case of China and most other developing countries. For a more comprehensive understanding of emission control designs, this study examines the existing systems all over the world. Table 6 and Table 7 compare 12 representative carbon tax systems and 10 representative cap-and-trade systems, respectively.

The proportion of emissions covered by each jurisdiction ranges from 11 percent to 85 percent. The carbon tax and ETS systems in most industrialized countries still have a large space for further development. For instance, Switzerland implements both cap-and-trade and carbon tax but achieves merely 46 percent. Similar to China that targets the thermal power industry in building its national ETS, the carbon tax and ETS systems of most jurisdictions cover energy-intensive sectors, mainly power generation, aviation, manufacturing, transportation, and heating. Though the remanufacturing industry is yet to be covered, it is closely related to the traditional manufacturing sector.

One issue facing the remanufacturing industry is how to handle the situation in which an enterprise may be required to pay a carbon tax and purchase emission quotas at the same time if both are implemented in a country. In the EU, its ETS overlaps with many members' carbon tax in various sectors, and these countries exempt carbon tax from relevant enterprises. Norway, for example, grants tax exemptions for operations covered by EU's ETS. For emerging economies like China to establish emission-control mechanisms for the remanufacturing industry and the related manufacturing sector, it is important to avoid double levies.

In the ETS pilots of China, fewer than 10 percent allocations are auctioned through the systems but more than 90 percent are allocated free to enterprises by the government. Countries launching similar pilot projects take the same approach, such as in the case of South Korea. Some jurisdictions that implemented ETSs earlier are doing the opposite. In Alberta, for instance, 100 percent of allocations are auctioned. The electric sector of the EU also takes the full auction approach. Meanwhile, other countries are exploring more flexible carbon policies. Swiss and Mexico allow large industrial emitters to opt out of carbon tax and switch to cap-and-trade. This kind of flexibility allows enterprises to choose an optimal carbon emission reduction system, as *Observation 1* shows in this study. If similar flexible carbon policies are launched for remanufacturing, enterprises may make a choice between carbon tax and cap-and-trade following the findings of this study.

Table 6. 12 representative carbon tax systems.

Jurisdiction	Year launched	Price August 2017 US$/$tCO_2$	Proportion of emission sources covered (%)	Emissions covered by the instrument $MtCO_2e$	Coverage	Opt out of carbon tax
Finland	1990	69-73	36	21	Fossil fuels (electricity and commercial aviation excluded)	
Norway	1991	4-56	60	32	Oil, gasoline and natural gas	
Sweden	1991	140	42	23	Fossil fuels (only heating and transport)	
Denmark	1992	27	45	22	Oil, natural gas, coal, and waste incineration	
British Columbia	2008	24	70	43	70-75% of the provincial anthropogenic emissions, almost every sector	
Switzerland	2008	87	35	5	Fossil fuels (only heating and power generation)	Allowed (for large emitters only)
Ireland	2010	24	33	20	Natural gas, oil, and solid fuels	
Iceland	2010	12	55	3	Diesel, gasoline, oil and liquid petroleum gas	
Japan	2012	3	70	926	Fossil fuels (agriculture, fishing, domestic aviation, and railways excluded)	
United Kingdom	2013	24	25	127	Fossil fuels (only power generation on Great Britain)	
France	2014	36	40	185	Natural gas, oil, and coal (only transport and heating)	
Mexico	2014	1-3	46	332	Fossil fuels that exceed the carbon intensity of natural gas	Allowed (for large emitters only)

Note: ETSs in Switzerland and Mexico allow large emitters to opt out of carbon tax for carbon quota.

Sources: Haites (2018) and Carl and Fedor (2016)

Table 7. 10 representative cap-and-trade systems.

Jurisdiction	Year launched	Price August 2017 US$/$tCO_2$	Proportion of emission sources covered (%)	Emissions covered by the instrument $MtCO_2e$	Coverage	Allocation
European Union	2005	6	45	1,939	Electric power sector, energy-intensive industrial sectors, and aviation	Electric sector (all through auctions), industrial sectors (30% free), aviation (85% free)
Alberta	2007	24	45	123	Emitters exceeding 100,000 tons annually	All through auctions
New Zealand	2008	13	51	41	Economic sectors	Free allocation and government window sales
Switzerland	2008	7	11	17	Large, energy-intensive industrial emitters	30% free (2020), power sector (all through auctions)
RGGI(USA)	2009	4	21	86	Power plants greater than 25MW in capacity	9% free
Japan	2010	14	19	17	Lager energy users	Nearly 100% free
California	2013	15	85	375	Manufacturers and power plants exceeding 25,000 tons annually	Industrial (90% free), electricity, natural gas, and motor fuel distributors (all through auctions)
Quebec	2013	15	85	68	Emitters exceeding 25,000 tons annually	Industrial (90% free), natural gas and motor fuel distributors (all through auctions)
China	2013	1-8	35-60	1,144	Emitters exceeding 25,000 tons annually	More than 90% Free
South Korea	2015	18	68	470	Power generation and airlines; manufacturers exceeding 100,000 tons annually	100% free

Note: Japan's ETS includes Tokyo and Saitama; Chin's ETS includes Beijing, Guangdong, Shanghai, Shenzhen, Tianjin, Chongqing, and Hubei.

Sources: Haites (2018) and Carl and Fedor (2016)

7. Conclusion

This study establishes a single-cycle closed-loop supply chain and analyzes the optimal decisions of a remanufacturer under carbon tax and cap-and-trade policies. It compares their economic performance and environmental performance in the context of trade-in and consumer subsidy with different models. In addition, the modeling takes two government-to-enterprise-subsidy (G-to-E-S) policies, direct subsidy, and policy bias, into account. The findings yield helpful insights for the government to formulate carbon policies for the remanufacturing industry and useful guidance for enterprises to cope with government carbon regulations.

Researchers posit that cap-and-trade benefits remanufacturing (Chai, Xiao, Lai et al., 2018). This study further shows that carbon tax is also helpful, but typically not as much as cap-and-trade, especially when the sector is still at the development stage. The major findings include:

(a) Generally, cap-and-trade has a better fit with remanufacturing than carbon tax. In most cases, cap-and-trade wins in economic performance whereas carbon tax is not considered very economy-friendly. As for the overall environmental performance, cap-and-trade outperforms carbon tax in terms of emission reduction as long as the cap is kept under a reasonable level by the government. Thus, cap-and-trade is in a better position to help the remanufacturing industry become more environment-friendly and promote the transformation of enterprises to cleaner production.

(b) When remanufacturing enterprises undertake efforts to reduce carbon emissions through either cap-and-trade or carbon tax, G-to-E-S helps them further optimize business processes and increase the production of remanufactured products, which means less pollution and cleaner production. The models developed to compare direct subsidy and policy bias provide insights on how the government should implement G-to-E-S under different carbon policies.

(c) When an emission trading system (ETS) already exists, it is better off to implement cap-and-trade for the remanufacturing industry with a relatively low carbon quota price. Otherwise, carbon tax is a viable option.

The findings provide helpful insights for China and comparable countries to design carbon emission reduction policies for the remanufacturing industry and similar sectors with great cleaner production potential. Other countries with similar economic development, Brazil and India for example, can refer to the findings in this study in their implementation of carbon emission reduction systems. Countries that recently established ETSs similar to that in China, such as South Korea and New Zealand, may also find the insights from the comparison between carbon tax and cap-and-trade helpful for promoting cleaner production.

At the enterprise level, this study examines whether it is worthwhile for an organization to opt out of carbon tax for carbon quota when it has a choice. The results suggest that it is a viable option for large emitters in countries that implement both carbon tax and cap-and-trade systems, like Mexico and Switzerland. Although this study focuses on remanufacturing, one cleaner production sector, the general findings are also applicable to other industries where traditional and sustainable operations coexist. Establishing ETSs for those sectors and subsiding green products are conductive to the reduction of carbon emissions.

This study has limitations that point to future research directions. First of all, the mathematical models are based on a single cycle, and multiple-cycle models are worth further explorations. In addition, the quota setup in carbon trading is specified in accordance with the existing method of China's carbon trading system, and the industrial baseline method may be used to make the findings more generalizable. Finally, there is a new trade-in-old-for-remanufactured strategy, which can be compared with the trade-in-old-for-new strategy in this study.

Appendix

Proof of Lemma 1.

For new customers：

When $U_r^{\alpha} > U_n^{\alpha}$ and $U_r^{\alpha} > 0$, new customers will choose to buy remanufactured products to maximize the utility. The sales are $q_n^{\alpha} = \alpha\left(1 - \frac{P_n - P_r}{1-t}\right)$ and $q_r^{\alpha} = \alpha\left(\frac{P_n - P_r}{1-t} - \frac{P_r}{t}\right)$.When $U_n^{\alpha} > U_r^{\alpha}$ and $U_n^{\alpha} > 0$, New customers will choose to buy new products to maximize the utility. The sales are $q_n^{\alpha} = \alpha(1 - P_n)$ and $q_r^{\alpha} = 0$.

For regular customers:

When $U_r^{1-\alpha} > U_n^{1-\alpha}$ and $U_r^{1-\alpha} > 0$, regular customers will choose to buy remanufactured products to maximize the utility. The sales are $q_n^{1-\alpha} = (1-\alpha)\left(1 - \frac{P_n - P_r}{1-t}\right)$ and $q_r^{1-\alpha} = (1-\alpha)\left(\frac{P_n - P_r}{1-t} - \frac{P_r - v - s_t}{t-\delta}\right)$.When $U_n^{1-\alpha} > U_r^{1-\alpha}$ and $U_n^{1-\alpha} > 0$, regular customers will choose to buy new products to maximize the utility. The sales are $q_n^{1-\alpha} = (1-\alpha)\left(1 - \frac{P_r - v - s_t}{t-\delta}\right)$ and $q_r^{1-\alpha} = 0$.

This study explores the policy options for reducing carbon emissions of the remanufacturing industry. Other than the remanufacturing sales volume of 0, the sales can then be determined.

Proof of Lemma 2. Taking $\boldsymbol{P_n}$, $\boldsymbol{P_r}$ and $\boldsymbol{v}$ as decision variables, take the derivative of equation (1) and get the Hessian matrix:

$$\begin{bmatrix} \frac{2}{t-1} & \frac{2}{1-t} & 0 \\ \frac{2}{1-t} & \frac{2}{t-1} - \frac{2(t-\alpha\delta)}{t(t-\delta)} & \frac{1-\alpha}{t-\delta} \\ 0 & \frac{1-\alpha}{t-\delta} & \frac{2(\alpha-1)}{t-\delta} \end{bmatrix} \tag{8}$$

The Hessian matrix is negative, and there is an optimal solution for equation (1)

$$\begin{cases} \frac{\partial \pi_M^B}{\partial P_n} = 0 \\ \frac{\partial \pi_M^B}{\partial P_r} = 0 \\ \frac{\partial \pi_M^B}{\partial v} = 0 \end{cases} \tag{9}$$

The optimal solution is $P_n^{B*} = \frac{1+C_n}{2}$, $P_r^{B*} = \frac{t+C_r}{2}$ and $v^{B*} = \frac{b+\delta+s_t}{2}$.

Proof of Lemma 3. Taking $\boldsymbol{P_n}$, $\boldsymbol{P_r}$ and $\boldsymbol{v}$ as decision variables, take the derivative of equation (2) and get the Hessian matrix:

$$\begin{bmatrix} \frac{2}{t-1} & \frac{2}{1-t} & 0 \\ \frac{2}{1-t} & \frac{2}{t-1} - \frac{2(t-\alpha\delta)}{t(t-\delta)} & \frac{1-\alpha}{t-\delta} \\ 0 & \frac{1-\alpha}{t-\delta} & \frac{2(\alpha-1)}{t-\delta} \end{bmatrix} \tag{10}$$

The Hessian matrix is negative, and there is an optimal solution for equation (2)

$$\begin{cases} \dfrac{\partial \pi_M^N}{\partial P_n} = 0 \\ \dfrac{\partial \pi_M^N}{\partial P_r} = 0 \\ \dfrac{\partial \pi_M^N}{\partial v} = 0 \end{cases} \tag{11}$$

The optimal solution is $P_n^{N*} = \frac{1+C_n+ce_n}{2}$, $P_r^{N*} = \frac{t+C_r+ce_r}{2}$ and $v^{N*} = \frac{b+\delta+s_t}{2}$.

Proof of Lemma 4. Taking $\boldsymbol{P_n}$, $\boldsymbol{P_r}$ and $\boldsymbol{v}$ as decision variables, take the derivative of equation (3) and get the Hessian matrix:

$$\begin{bmatrix} \dfrac{2}{t-1} & \dfrac{2}{1-t} & 0 \\ \dfrac{2}{1-t} & \dfrac{2}{t-1} - \dfrac{2(t-\alpha\delta)}{t(t-\delta)} & \dfrac{1-\alpha}{t-\delta} \\ 0 & \dfrac{1-\alpha}{t-\delta} & \dfrac{2(\alpha-1)}{t-\delta} \end{bmatrix} \tag{12}$$

The Hessian matrix is negative, and there is an optimal solution for equation (3)

$$\begin{cases} \dfrac{\partial \pi_M^T}{\partial P_n} = 0 \\ \dfrac{\partial \pi_M^T}{\partial P_r} = 0 \\ \dfrac{\partial \pi_M^T}{\partial v} = 0 \end{cases} \tag{13}$$

The optimal solution is $P_n^{T*} = \frac{1+C_n+ce_n-ce_t}{2}$, $P_r^{T*} = \frac{t+C_r+ce_r-ce_t}{2}$ and $v^{T*} = \frac{b+\delta+s_t}{2}$.

Proof of Table 2. Substituting the optimal pricing into the equation of demand, the optimal demand can be derived, as shown below:$q_n^{\alpha B*} = \alpha\left(\frac{1}{2} - \frac{C_n-C_r}{2(1-t)}\right)$, $q_r^{\alpha B*} = \alpha\frac{tC_n-C_r}{2t(1-t)}$, $q_n^{(1-\alpha)B*} = (1-\alpha)\left(\frac{1}{2} - \frac{C_n-C_r}{2(1-t)}\right)$ and$q_r^{(1-\alpha)B*} = (1-\alpha)\frac{(t-\delta)C_n-(1-\delta)C_r+(1-t)(b+s_t)}{2(1-t)(t-\delta)}$.

Derivatives of different variables can be solved by the demand function.

$\frac{\partial q_n^{\alpha B*}}{\partial C_n} = -\frac{\alpha}{2(1-t)} < 0$, $\frac{\partial q_r^{\alpha B*}}{\partial C_n} = \frac{\alpha}{2(1-t)} > 0$, $\frac{\partial q_n^{(1-\alpha)B*}}{\partial C_n} = -\frac{1-\alpha}{2(1-t)} < 0$, $\frac{\partial q_r^{(1-\alpha)B*}}{\partial C_n} = \frac{1-\alpha}{2(1-t)} > 0$; $\frac{\partial q_n^{\alpha B*}}{\partial C_r} = \frac{\alpha}{2(1-t)} > 0$, $\frac{\partial q_r^{\alpha B*}}{\partial C_r} = -\frac{\alpha}{2t(1-t)} < 0$, $\frac{\partial q_n^{(1-\alpha)B*}}{\partial C_r} = \frac{1-\alpha}{2(1-t)} > 0$, $\frac{\partial q_r^{(1-\alpha)B*}}{\partial C_r} = -\frac{(1-\alpha)(1-\delta)}{2(1-t)(t-\delta)} < 0$; $\frac{\partial q_n^{\alpha B*}}{\partial s_t} = 0$, $\frac{\partial q_r^{\alpha B*}}{\partial s_t} = 0$, $\frac{\partial q_n^{(1-\alpha)B*}}{\partial s_t} = 0$, $\frac{\partial q_r^{(1-\alpha)B*}}{\partial s_t} = \frac{1-\alpha}{2(t-\delta)} > 0$; $\frac{\partial q_n^{\alpha B*}}{\partial t} = -\frac{\alpha(C_n-C_r)}{2(1-t)^2} < 0$, $\frac{\partial q_r^{\alpha B*}}{\partial t} = \frac{\alpha(t^2C_n+(1-2t)C_r)}{2t^2(1-t)^2} > \frac{\alpha(t^2C_r+(1-2t)C_r)}{2t^2(1-t)^2} > 0$, $\frac{\partial q_n^{(1-\alpha)B*}}{\partial t} = -\frac{(1-\alpha)(C_n-C_r)}{2(1-t)^2} < 0$, $\frac{\partial q_r^{(1-\alpha)B*}}{\partial t} = \frac{(t-\delta)[(t-\delta)C_n-(1-\delta)C_r+(1-t)(b+S_t)]}{2(t-\delta)^2(1-t)^2} + \frac{(1-t)(1-\delta)[C_r-b-S_t]}{2(t-\delta)^2(1-t)^2} > 0$; $\frac{\partial q_n^{\alpha B*}}{\partial \alpha} = \frac{1}{2} - \frac{C_n-C_r}{2(1-t)} > 0$, $\frac{\partial q_r^{\alpha B*}}{\partial \alpha} = \frac{tC_n-C_r}{2t(1-t)} > 0$, $\frac{\partial q_n^{(1-\alpha)B*}}{\partial \alpha} = -\frac{1}{2} + \frac{C_n-C_r}{2(1-t)} < 0$, $\frac{\partial q_r^{(1-\alpha)B*}}{\partial \alpha} = -\frac{(t-\delta)C_n-(1-\delta)C_r+(1-t)(b+s_t)}{2(1-t)(t-\delta)} < 0$; $\frac{\partial q_n^{\alpha B*}}{\partial \delta} = 0$, $\frac{\partial q_r^{\alpha B*}}{\partial \delta} = 0$, $\frac{\partial q_n^{(1-\alpha)B*}}{\partial \delta} = 0$, $\frac{\partial q_r^{(1-\alpha)B*}}{\partial \delta} = \frac{(1-\alpha)(b+s_t-C_r)}{2(t-\delta)^2} < 0$; $\frac{\partial q_n^{\alpha B*}}{\partial b} = 0$, $\frac{\partial q_r^{\alpha B*}}{\partial b} = 0$, $\frac{\partial q_n^{(1-\alpha)B*}}{\partial b} = 0$, $\frac{\partial q_r^{(1-\alpha)B*}}{\partial b} = \frac{1-\alpha}{2(t-\delta)} > 0$. Where $(t-\delta)C_n - (1-\delta)C_r + (1-t)(b+S_t) \geq 0$ and $b + s_t - C_r < 0$.

Proof of Table 3. Substituting the optimal pricing into the equation of demand, the optimal demand can be derived, as shown below: $q_n^{\alpha N*} = \alpha\left(\frac{1}{2} - \frac{C_n+ce_n-C_r-ce_r}{2(1-t)}\right)$, $q_r^{\alpha N*} = \alpha\frac{tC_n+tce_n-C_r-ce_r}{2t(1-t)}$, $q_n^{(1-\alpha)N*} = (1-\alpha)\left(\frac{1}{2} - \frac{C_n+ce_n-C_r-ce_r}{2(1-t)}\right)$ and $q_r^{(1-\alpha)N*} = (1-\alpha)\frac{(t-\delta)(C_n+ce_n)-(1-\delta)(C_r+ce_r)+(1-t)(b+s_t)}{2(1-t)(t-\delta)}$.

Derivatives of different variables can be solved by the demand function.

$\frac{\partial q_n^{\alpha N*}}{\partial C_n} = -\frac{\alpha}{2(1-t)} < 0$, $\frac{\partial q_r^{\alpha N*}}{\partial C_n} = \frac{\alpha}{2(1-t)} > 0$, $\frac{\partial q_n^{(1-\alpha)N*}}{\partial C_n} = -\frac{1-\alpha}{2(1-t)} < 0$, $\frac{\partial q_r^{(1-\alpha)N*}}{\partial C_n} = \frac{1-\alpha}{2(1-t)} > 0$; $\frac{\partial q_n^{\alpha N*}}{\partial C_r} = \frac{\alpha}{2(1-t)} > 0$, $\frac{\partial q_r^{\alpha N*}}{\partial C_r} = -\frac{\alpha}{2t(1-t)} < 0$, $\frac{\partial q_n^{(1-\alpha)N*}}{\partial C_r} = \frac{1-\alpha}{2(1-t)} > 0$, $\frac{\partial q_r^{(1-\alpha)N*}}{\partial C_r} = -\frac{(1-\alpha)(1-\delta)}{2(1-t)(t-\delta)} < 0$; $\frac{\partial q_n^{\alpha N*}}{\partial s_t} = 0$, $\frac{\partial q_r^{\alpha N*}}{\partial s_t} = 0$, $\frac{\partial q_n^{(1-\alpha)N*}}{\partial s_t} = 0$, $\frac{\partial q_r^{(1-\alpha)N*}}{\partial s_t} = \frac{1-\alpha}{2(t-\delta)} > 0$; $\frac{\partial q_n^{\alpha N*}}{\partial t} = -\frac{\alpha(C_n+ce_n-C_r-ce_r)}{2(1-t)^2} < 0$, $\frac{\partial q_r^{\alpha N*}}{\partial t} = \frac{\alpha\left(t^2(C_n+ce_n)+(1-2t)(C_r+ce_r)\right)}{2t^2(1-t)^2} > \frac{\alpha\left(t^2(C_r+ce_r)+(1-2t)(C_r+ce_r)\right)}{2t^2(1-t)^2} > 0$, $\frac{\partial q_n^{(1-\alpha)N*}}{\partial t} = -\frac{(1-\alpha)(C_n+ce_n-C_r-ce_r)}{2(1-t)^2} < 0$, $\frac{\partial q_r^{(1-\alpha)N*}}{\partial t} = \frac{(t-\delta)[(t-\delta)(C_n+ce_n)-(1-\delta)(C_r+ce_r)+(1-t)(b+S_t)]}{2(t-\delta)^2(1-t)^2} + \frac{(1-t)(1-\delta)[C_r+ce_r-b-S_t]}{2(t-\delta)^2(1-t)^2} > 0$; $\frac{\partial q_n^{\alpha N*}}{\partial \alpha} = \frac{1}{2} - \frac{C_n+ce_n-C_r-ce_r}{2(1-t)} > 0$, $\frac{\partial q_r^{\alpha N*}}{\partial \alpha} = \frac{tC_n+tce_n-C_r-ce_r}{2t(1-t)} > 0$, $\frac{\partial q_n^{(1-\alpha)N*}}{\partial \alpha} = -\frac{1}{2} + \frac{C_n+ce_n-C_r-ce_r}{2(1-t)} < 0$, $\frac{\partial q_r^{(1-\alpha)N*}}{\partial \alpha} = -\frac{(t-\delta)(C_n+ce_n)-(1-\delta)(C_r+ce_r)+(1-t)(b+s_t)}{2(1-t)(t-\delta)} < 0$; $\frac{\partial q_n^{\alpha N*}}{\partial \delta} = 0$, $\frac{\partial q_r^{\alpha N*}}{\partial \delta} = 0$, $\frac{\partial q_n^{(1-\alpha)N*}}{\partial \delta} = 0$, $\frac{\partial q_r^{(1-\alpha)N*}}{\partial \delta} = \frac{(1-\alpha)(b+s_t-C_r-ce_r)}{2(t-\delta)^2} < 0$; $\frac{\partial q_n^{\alpha N*}}{\partial b} = 0$, $\frac{\partial q_r^{\alpha N*}}{\partial b} = 0$, $\frac{\partial q_n^{(1-\alpha)N*}}{\partial b} = 0$, $\frac{\partial q_r^{(1-\alpha)N*}}{\partial b} = \frac{1-\alpha}{2(t-\delta)} > 0$; $\frac{\partial q_n^{\alpha N*}}{\partial c} = -\frac{\alpha(e_n-e_r)}{2(1-t)} < 0$, $\frac{\partial q_r^{\alpha N*}}{\partial c} = \frac{\alpha(te_n-e_r)}{2t(1-t)} > 0$, $\frac{\partial q_n^{(1-\alpha)N*}}{\partial c} = -\frac{(1-\alpha)(e_n-e_r)}{2(1-t)} < 0$, $\frac{\partial q_r^{(1-\alpha)N*}}{\partial c} = \frac{(1-\alpha)[(t-\delta)e_n-(1-\delta)e_r]}{2(t-\delta)(1-t)} > 0$; $\frac{\partial q_n^{\alpha N*}}{\partial e_n} = -\frac{\alpha c}{2(1-t)} < 0$, $\frac{\partial q_r^{\alpha N*}}{\partial e_n} = \frac{\alpha c}{2(1-t)} > 0$, $\frac{\partial q_n^{(1-\alpha)N*}}{\partial e_n} = -\frac{(1-\alpha)c}{2(1-t)} < 0$, $\frac{\partial q_r^{(1-\alpha)N*}}{\partial e_n} = \frac{(1-\alpha)c}{2(1-t)} > 0$; $\frac{\partial q_n^{\alpha N*}}{\partial e_r} = \frac{\alpha c}{2(1-t)} > 0$, $\frac{\partial q_r^{\alpha N*}}{\partial e_r} = -\frac{\alpha c}{2(1-t)} < 0$, $\frac{\partial q_n^{(1-\alpha)N*}}{\partial e_r} = \frac{(1-\alpha)c}{2(1-t)} > 0$, $\frac{\partial q_r^{(1-\alpha)N*}}{\partial e_r} = -\frac{(1-\alpha)(1-\delta)c}{2(t-\delta)(1-t)} < 0$. Where $(t-\delta)(C_n+ce_n)-(1-\delta)(C_r+ce_r)+(1-t)(b+S_t) \geq 0$ and $b+s_t-C_r-ce_r < 0$.

Proof of Table 4. Substituting the optimal pricing into the equation of demand, the optimal demand can be derived, as shown below:

$q_n^{\alpha T*} = \alpha\left(\frac{1}{2} - \frac{C_n+ce_n-C_r-ce_r}{2(1-t)}\right)$, $q_r^{\alpha T*} = \alpha\frac{tC_n+tce_n-C_r-ce_r+(1-t)ce_t}{2t(1-t)}$, $q_n^{(1-\alpha)T*} = (1-\alpha)\left(\frac{1}{2} - \frac{C_n+ce_n-C_r-ce_r}{2(1-t)}\right)$ and $q_r^{(1-\alpha)T*} = (1-\alpha)\frac{(t-\delta)(C_n+ce_n)-(1-\delta)(C_r+ce_r)+(1-t)(b+s_t+ce_t)}{2(1-t)(t-\delta)}$.

Derivatives of different variables can be solved by the demand function.

$\frac{\partial q_n^{\alpha T*}}{\partial C_n} = -\frac{\alpha}{2(1-t)} < 0$, $\frac{\partial q_r^{\alpha T*}}{\partial C_n} = \frac{\alpha}{2(1-t)} > 0$, $\frac{\partial q_n^{(1-\alpha)T*}}{\partial C_n} = -\frac{1-\alpha}{2(1-t)} < 0$, $\frac{\partial q_r^{(1-\alpha)T*}}{\partial C_n} = \frac{1-\alpha}{2(1-t)} > 0$; $\frac{\partial q_n^{\alpha T*}}{\partial C_r} = \frac{\alpha}{2(1-t)} > 0$, $\frac{\partial q_r^{\alpha T*}}{\partial C_r} = -\frac{\alpha}{2t(1-t)} < 0$, $\frac{\partial q_n^{(1-\alpha)T*}}{\partial C_r} = \frac{1-\alpha}{2(1-t)} > 0$, $\frac{\partial q_r^{(1-\alpha)T*}}{\partial C_r} = -\frac{(1-\alpha)(1-\delta)}{2(1-t)(t-\delta)} < 0$; $\frac{\partial q_n^{\alpha T*}}{\partial s_t} = 0$, $\frac{\partial q_r^{\alpha T*}}{\partial s_t} = 0$, $\frac{\partial q_n^{(1-\alpha)T*}}{\partial s_t} = 0$, $\frac{\partial q_r^{(1-\alpha)T*}}{\partial s_t} = \frac{1-\alpha}{2(t-\delta)} > 0$; $\frac{\partial q_n^{\alpha T*}}{\partial t} = -\frac{\alpha(C_n+ce_n-C_r-ce_r)}{2(1-t)^2} < 0$, $\frac{\partial q_r^{\alpha T*}}{\partial t} = \frac{\alpha(t^2(C_n+ce_n-ce_t)+(1-2t)(C_r+ce_r-ce_t)+(t+3t^2)ce_t)}{2t^2(1-t)^2} > \frac{\alpha(t^2(C_r+ce_r-ce_t)+(1-2t)(C_r+ce_r-ce_t)+(t+3t^2)ce_t)}{2t^2(1-t)^2} > 0$, $\frac{\partial q_n^{(1-\alpha)T*}}{\partial t} = -\frac{(1-\alpha)(C_n+ce_n-C_r-ce_r)}{2(1-t)^2} < 0$, $\frac{\partial q_r^{(1-\alpha)T*}}{\partial t} = \frac{(t-\delta)[\,(t-\delta)(C_n+ce_n)-(1-\delta)(C_r+ce_r)+(1-t)(b+S_t+ce_t)]}{2(t-\delta)^2(1-t)^2} + \frac{(1-t)(1-\delta)[C_r+ce_r-b-S_t-ce_t]}{2(t-\delta)^2(1-t)^2} > 0$; $\frac{\partial q_n^{\alpha T*}}{\partial \alpha} = \frac{1}{2} - \frac{C_n+ce_n-C_r-ce_r}{2(1-t)} > 0$, $\frac{\partial q_r^{\alpha T*}}{\partial \alpha} = \frac{tC_n+tce_n-C_r-ce_r+(1-t)ce_t}{2t(1-t)} > 0$, $\frac{\partial q_n^{(1-\alpha)T*}}{\partial \alpha} = -\frac{1}{2} + \frac{C_n+ce_n-C_r-ce_r}{2(1-t)} < 0$, $\frac{\partial q_r^{(1-\alpha)T*}}{\partial \alpha} =$

$-\frac{(t-\delta)(C_n+ce_n)-(1-\delta)(C_r+ce_r)+(1-t)(b+s_t+ce_t)}{2(1-t)(t-\delta)} < 0$; $\frac{\partial q_n^{\alpha T*}}{\partial \delta} = 0$, $\frac{\partial q_r^{\alpha T*}}{\partial \delta} = 0$, $\frac{\partial q_n^{(1-\alpha)T*}}{\partial \delta} = 0$, $\frac{\partial q_r^{(1-\alpha)T*}}{\partial C_n} = \frac{(1-\alpha)(b+s_t+ce_t-C_r-ce_r)}{2(t-\delta)^2} < 0$; $\frac{\partial q_n^{\alpha T*}}{\partial b} = 0$, $\frac{\partial q_r^{\alpha T*}}{\partial b} = 0$, $\frac{\partial q_n^{(1-\alpha)T*}}{\partial b} = 0$, $\frac{\partial q_r^{(1-\alpha)T*}}{\partial b} = \frac{1-\alpha}{2(t-\delta)} > 0$; $\frac{\partial q_n^{\alpha T*}}{\partial c} = -\frac{\alpha(e_n-e_r)}{2(1-t)} < 0$, $\frac{\partial q_r^{\alpha T*}}{\partial c} = \frac{\alpha(te_n-e_r+(1-t)e_t)}{2t(1-t)} > 0$, $\frac{\partial q_n^{(1-\alpha)T*}}{\partial c} = -\frac{(1-\alpha)(e_n-e_r)}{2(1-t)} < 0$, $\frac{\partial q_r^{(1-\alpha)T*}}{\partial c} = \frac{(1-\alpha)[(t-\delta)e_n-(1-\delta)e_r+(1-t)e_t]}{2(t-\delta)(1-t)} > 0$; $\frac{\partial q_n^{\alpha T*}}{\partial e_n} = -\frac{\alpha c}{2(1-t)} < 0$, $\frac{\partial q_r^{\alpha T*}}{\partial e_n} = \frac{\alpha c}{2(1-t)} > 0$, $\frac{\partial q_n^{(1-\alpha)T*}}{\partial e_n} = -\frac{(1-\alpha)c}{2(1-t)} < 0$, $\frac{\partial q_r^{(1-\alpha)T*}}{\partial e_n} = \frac{(1-\alpha)c}{2(1-t)} > 0$; $\frac{\partial q_n^{\alpha T*}}{\partial e_r} = \frac{\alpha c}{2(1-t)} > 0$, $\frac{\partial q_r^{\alpha T*}}{\partial e_r} = -\frac{\alpha c}{2(1-t)} < 0$, $\frac{\partial q_n^{(1-\alpha)T*}}{\partial e_r} = \frac{(1-\alpha)c}{2(1-t)} > 0$, $\frac{\partial q_r^{(1-\alpha)T*}}{\partial e_r} = -\frac{(1-\alpha)(1-\delta)c}{2(t-\delta)(1-t)} < 0$;Where $(t-\delta)(C_n+ce_n)-(1-\delta)(C_r+ce_r)+(1-t)(b+S_t+ce_t) \geq 0$ and $b+s_t+ce_t-C_r-ce_r < 0$.

Proof of Observation 1.

The profits of the manufacturers can be formulated as:

$$\pi_M^N = (P_n - C_n - ce_n)(q_n^{\alpha} + q_n^{1-\alpha}) + (P_r - C_r - ce_r)(q_r^{\alpha} + q_r^{1-\alpha}) - (v-b)(q_n^{1-\alpha} + q_r^{1-\alpha}) \tag{14}$$

$$\begin{aligned}\pi_M^T = (P_n - C_n - ce_n)(q_n^{\alpha} + q_n^{1-\alpha}) + (P_r - C_r - ce_r)(q_r^{\alpha} + q_r^{1-\alpha}) - (v-b)(q_n^{1-\alpha} + q_r^{1-\alpha}) \\ +ce_t(q_n^{\alpha} + q_n^{1-\alpha} + q_r^{\alpha} + q_r^{1-\alpha})\end{aligned} \tag{15}$$

And the difference between the two profits is:

$$\begin{aligned}\pi_M^T - \pi_M^N = \frac{ce_t}{2}\left(q_n^{\alpha N*} + q_r^{\alpha N*} + q_n^{(1-\alpha)N*} + q_r^{(1-\alpha)N*}\right) + \frac{t - C_r - ce_r + ce_t}{2}\left(\frac{(1-\alpha)ce_t}{2(t-\delta)} + \frac{\alpha ce_t}{2t}\right) \\ -(v-b)\frac{(1-\alpha)ce_t}{2(t-\delta)}\end{aligned} \tag{16}$$

Under model-T, the precondition for remanufacturing is that the comprehensive profit of remanufacturing is positive，that is: $\frac{t-C_r-ce_r+ce_t}{2} - (v-b) > 0$, it can then be determined that $\pi_M^T - \pi_M^N > 0$.

Proof of Observation 2.

The difference of the carbon emissions in model-T and model-N can be formulated as:

$$\begin{aligned}CE^N - CE^T &= CE^N - e_t\left(q_n^{\alpha N*} + q_n^{(1-\alpha)N*} + q_r^{\alpha N*} + q_r^{(1-\alpha)N*}\right) - e_t\left(\frac{(1-\alpha)ce_t}{2(t-\delta)} + \frac{\alpha ce_t}{2t}\right) \\ &= CE^N - e_t\left(q_n^{\alpha N*} + q_n^{(1-\alpha)N*} + q_r^{\alpha N*} + q_r^{(1-\alpha)N*}\right) - c{e_t}^2\frac{t-\alpha\delta}{2t(t-\delta)}\end{aligned} \tag{17}$$

Reformulate it as a function of e_t: $F(e_t) = ae_t + b{e_t}^2 + c$. Where $a = -\left(q_n^{\alpha N*} + q_n^{(1-\alpha)N*} + q_r^{\alpha N*} + q_r^{(1-\alpha)N*}\right)$, $b = -c\frac{t-\alpha\delta}{2t(t-\delta)}$ and $c = CE^N$. Obviously, $a < 0, b < 0, c > 0$, it can then be determined that when $0 < e_t < \frac{-b-\sqrt{b^2-4ac}}{2a}$, $CE^N - CE^T > 0$, when $e_t > \frac{-b-\sqrt{b^2-4ac}}{2a}$, $CE^N - CE^T < 0$.

Proof of Observation 3.

The difference of the consumers' surplus in model-T and model-N can be formulated as:

$$CS^T - CS^N = e_t{}^2 c^2\left(\frac{1}{8t} + \frac{(1-\alpha)\delta}{4t(t-\delta)}\right) + e_t c \left\{ \begin{array}{c} \dfrac{q_n^{\alpha N*} + q_n^{(1-\alpha)N*} + \left(1 - \dfrac{t}{2(t-\delta)}\right) q_r^{(1-\alpha)N*}}{2} \\ + \dfrac{q_r^{\alpha N*}}{4} + \alpha \dfrac{P_r^{N*} + t\dfrac{P_n^{N*} - P_r^{N*}}{1-t} - 2P_r^{N*}}{4t} \\ + \dfrac{1-\alpha}{(t-\delta)}\left[\dfrac{t}{2}\left(\dfrac{P_n^{N*} - P_r^{N*}}{1-t} + \dfrac{P_r^{N*} - V^{N*} - s_t}{t-\delta}\right) - P_r^{N*}\right] \end{array} \right\} \tag{18}$$

See it as a function of e_t, it can then be determined that when $e_t > 0$, $CS^T - CS^N > 0$.

Table A1. Results on price and quantity generated by model-N (carbon tax) and model-T (cap-and-trade).

Parameter		Price						Quantity							
c	e_t	P_n^{T*}	P_n^{N*}	P_r^{T*}	P_r^{N*}	v^{T*}	v^{N*}	$q_n^{\alpha T*}$	$q_n^{\alpha N*}$	$q_r^{\alpha T*}$	$q_r^{\alpha N*}$	$q_n^{(1-\alpha)T*}$	$q_n^{(1-\alpha)N*}$	$q_r^{(1-\alpha)T*}$	$q_r^{(1-\alpha)N*}$
0.2	0.1	0.730	0.740	0.485	0.495	0.100	0.100	0.073	0.073	0.050	0.044	0.110	0.110	0.213	0.198
	0.2	0.720	0.740	0.475	0.495	0.100	0.100	0.073	0.073	0.055	0.044	0.110	0.110	0.218	0.198
	0.3	0.710	0.740	0.465	0.495	0.100	0.100	0.073	0.073	0.061	0.044	0.110	0.110	0.233	0.198
0.4	0.1	0.760	0.780	0.495	0.515	0.100	0.100	0.047	0.047	0.070	0.059	0.070	0.070	0.238	0.208
	0.2	0.740	0.780	0.475	0.515	0.100	0.100	0.047	0.047	0.082	0.059	0.070	0.070	0.268	0.208
	0.3	0.720	0.780	0.455	0.515	0.100	0.100	0.047	0.047	0.093	0.059	0.070	0.070	0.298	0.208
0.6	0.1	0.790	0.820	0.505	0.535	0.100	0.100	0.020	0.020	0.091	0.074	0.030	0.030	0.263	0.218
	0.2	0.760	0.820	0.475	0.535	0.100	0.100	0.020	0.020	0.109	0.074	0.030	0.030	0.308	0.218
	0.3	0.730	0.820	0.445	0.535	0.100	0.100	0.020	0.020	0.126	0.074	0.030	0.030	0.353	0.218

Note: $C_n = 0.4, C_r = 0.25, t = 0.7, \alpha = 0.4, s_t = 0.2, e_n = 0.4, e_r = 0.2, \rho = 0.5, b = 0.1, \delta = 0.3, s_r = 0.05$.

Table A2. Results on economic and environmental performances generated by model-N (carbon tax) and model-T (cap-and-trade).

Parameter		Economic performance						Environmental performance	
c	e_t	π_M^T	π_M^N	CS^T	CS^N	SW^T	SW^N	CE^T	CE^N
0.2	0.1	0.199	0.103	0.156	0.075	0.355	0.178	0.045	0.201
	0.2	0.214	0.103	0.158	0.075	0.372	0.178	0.093	0.201
	0.3	0.230	0.103	0.160	0.075	0.390	0.178	0.146	0.201
0.4	0.1	0.154	0.103	0.104	0.075	0.258	0.178	0.042	0.201
	0.2	0.182	0.103	0.108	0.075	0.291	0.178	0.093	0.201
	0.3	0.213	0.103	0.113	0.075	0.326	0.178	0.152	0.201
0.6	0.1	0.112	0.103	0.054	0.075	0.167	0.178	0.040	0.201
	0.2	0.151	0.103	0.060	0.075	0.211	0.178	0.093	0.201
	0.3	0.195	0.103	0.067	0.075	0.263	0.178	0.158	0.201

Note: $C_n = 0.4, C_r = 0.25, t = 0.7, \alpha = 0.4, s_t = 0.2, e_n = 0.4, e_r = 0.2, \rho = 0.5, b = 0.1, \delta = 0.3, s_r = 0.05$.

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