Energy Economics 101 (2021) 105426

Contents lists available at ScienceDirect

Energy Economics

journal homepage: www.elsevier.com/locate/eneeco

Effects of government subsidies on green technology investment and green marketing coordination of supply chain under the cap-and-trade mechanism

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ARTICLE INFO

Keywords:
Cap-and-trade mechanism
Government subsidy
Green technology investment
Green marketing
Supply chain coordination

ABSTRACT

In order to promote green technology investment and emission reduction, the government usually provides subsidies to enterprises under the cap-and-trade (C&T) mechanism. Two types of subsidy policies are widely used: one is based on fixed green technology investment cost (FC subsidy) and the other is based on the amount of emission reduction (ER subsidy). This paper investigates the effects of these two government subsidies on the green decisions of a two-echelon supply chain under C&T scheme. Three Stackelberg game models are formulated and analyzed. The analytical results indicate that both manufacturer and retailer tend to collaborate on green marketing when green technology is invested and subsidized. However, the government's subsidy policy cannot guarantee green technology investment and total carbon emission reduction which also depend on the range of green investment cost, emission reduction rate of green technology and the carbon emission intensity of manufacturers. Indeed, higher subsidy will result in the implementation of more expensive but cleaner green technology. With the same subsidy budget, the manufacturer can earn more and emit less under FC subsidy, but ER subsidy can bring more profit to retailer and induce more green production and greater green marketing efforts. Therefore, the government can use FC subsidy on developed and high emission industries to control total emission and adopt ER subsidy on emerging or developing industries to promote their development.

1. Introduction

Carbon emission reduction has become common concerns in many countries. Cap-and-trade (C&T) mechanism is one of the effective carbon emission reduction regulations (Li et al., 2019; Lin and Jia, 2019). This market-oriented instrument gives each enterprise limited carbon emission quotas, i.e., the "cap" (Jiang et al., 2018; Yang et al., 2020). The enterprises need to buy carbon emission quotas in the carbon trading market for exceeding emission, otherwise they would be fined. They can also sell the surplus quotas to earn profit (Du et al., 2013). This flexible mechanism makes a comprehensive use of regulatory and market way to achieve emission reduction goal (Du et al., 2016; Zhu et al., 2018). But the efficiency of C&T can be further improved by using subsidies (Zhao et al., 2015). Government subsidy is another indispensable incentive method for carbon emission reduction (Hong and Guo, 2018; Yang et al., 2021). There are two widely used subsidy policies. One is based on fixed green technology investment cost (FC subsidy) and the other is based on the amount of emission reduction (ER subsidy). For example, the Innovation Fund, a European support program, was awarded based on several criteria, including the lowest cost per ton of CO_2 savings and the cost of innovative technologies (Carbon Trust, 2017). Besides, Shenzhen government of China subsidizes 40% of investment cost of the water-based coating equipment which can reduce volatile organic compounds emission. As for manufacturers which switch to electric forklifts, the government subsidizes 800 RMB per kWh of battery capacity (Shenzhen Habitat Environment Committee, 2018). In some regions or cities (e.g. Europe, Shenzhen and Beijing), both C&T system and subsidies are applied by the government to achieve carbon emission reduction target.

On the other hand, a global survey conducted by Accenture demonstrates that over 80% of consumers consider the greenness of products when purchasing them (Hong and Guo, 2018). The increasing consumers' green awareness becomes a market-driven factor that stimulates enterprises to make green improvement (Sueyoshi and Wang, 2014).

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https://doi.org/10.1016/j.eneco.2021.105426
Received 24 February 2021; Received in revised form 30 May 2021; Accepted 30 June 2021
Available online 8 July 2021
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Facing the government environmental regulations and consumers' green awareness, enterprises resort to green technology to reduce emission and improve their products' greenness (Wu and Pagell, 2011). In most studies related to green technology, technology investment is regarded as a continuous decision variable, where green investment cost is a continuous increasing quadratic function of emission reduction rate of green technology (Zhang et al., 2019; Zhang et al., 2018; Qiao et al., 2021). However, our survey of industry practice shows that enterprises' investment in green technology is to choose one or several green technologies associated with a fixed cost to implement (Su et al., 2012; Krass et al., 2013; Yang et al., 2018). Therefore, it's more realistic that green technology investment decision is a discrete decision variable rather than a continuous one (Yang et al., 2020; Drake et al., 2016).

Besides green technology investment, supply chain coordination on green products marketing can effectively enhance the sustainability and competitiveness of supply chain (Seuring and Müller, 2008; Subramanian et al., 2009; Zhang et al., 2013). Retailers' green marketing efforts plays an important role on turning environmental consciousness into actual purchasing behavior (Rahbar and Wahid, 2011). However, in reality, many retailers are reluctant to spend efforts and costs on green marketing as they are usually not under emission control (Hong and Guo, 2018). Therefore, green marketing cost-sharing coordination is required. In the coordination, manufacturer invests in green technology and retailer carries out green marketing on green products. And the manufacturer needs to share a proportion of marketing cost with retailer to enhance retailer's willingness of green marketing (Hong and Guo, 2018). Marketing cost-sharing contract is widely adopted on normal products in practice. For instance, Intel invited its retailers to advertise Intel products and shared 60% of the marketing cost, which is about $1.5 billion (Elkin, 2001). Walmart received about $100 million of advertising funds from its suppliers (Neff, 2009). However, without knowing the impact of government environmental policies on supply chain (i.e., C&T, subsidies), the green marketing cost-sharing coordination and contract is scarce in practice and, thus, worth exploring.

Consequently, this research investigates the impacts of government subsidies on the behaviors of manufacturer and retailer, and the efficiency of supply chain with different government subsidy policies under C&T mechanism, considering discrete characteristic of green technology investment decision and retailers' green marketing efforts. The manufacturer's operational decisions (e.g. wholesale price, green technology investment) and the retailer's operational decisions (e.g. retail price), as well as their green marketing coordination (e.g. the retailer's green marketing efforts and the manufacturer's green marketing cost-sharing ratio) are studied and compared under different subsidy policies. The following research questions will be addressed in this paper: (1) What is the impact of the government subsidy on green technology investment, emission reduction, and green marketing coordination of supply chain? (2) With the same amount of subsidy, which subsidy policy performs better on emission reduction and economic growth? (3) How do the government set forth the subsidy rate and the requirements for subsidy? To our best knowledge, this is the first paper studying the effects of different government subsidy policies on green technology investment and green marketing coordination from the perspective of supply chain under C&T mechanism. We provide a scientific basis for the government to set emission reduction policies and supply chain members to make green improvement.

To answer these important questions, in the remainder of this paper, the relevant literature is reviewed in Section 2. The problem is described and the corresponding models are mathematically formulated in Section 3. Theoretical analysis results are presented in Section 4. Section 5 provides a numerical example and verifies the analysis results. Finally, Section 6 gives the conclusions and implications.

2. Literature review

C&T policy and subsidy policy are two effective ways to curb carbon emissions. There is extensive research focusing on the comparison of government carbon emission reduction policies (Yang et al., 2018; Zhang et al., 2015; Chen et al., 2019; Cao et al., 2017; Zhang et al., 2021). In some regions or countries, these two types of policies are adopted simultaneously. Nevertheless, only a few researches considered the combined effects of C&T and subsidy policies. Caurla et al. (2018) simulated the impact of direct subsidies for biomass consumption with alternative carbon prices to reach the French biomass energy consumption target. Hussain et al. (2020) and Cao et al. (2019a) treated government subsidy as a financial incentive for enterprises under C&T system to reduce carbon emission. Zhang et al. (2020) proposed that C&T system was helpful in advancing renewable energy investments and reducing required subsidy level. Fang and Ma (2020) suggested that the government could subsidize the more burdened emission trading systems to ensure the achievement of carbon emission reduction targets. Lin and Jia (2020) highlighted that giving more subsidies to renewable energy enterprises could enhance the effectiveness of C&T mechanism on renewable energy development. Yu et al. (2021) indicated that government financial subsidies could be used to support research, development, and deployment of green technologies. However, their research only focused on one company instead of a supply chain. But analyzing from the perspective of supply chain can bring better emission reduction effect (Plambeck, 2012; Zhang and Yousaf, 2020).

Without subsidy, supply chain members are lack of capital to adopt green technology or green product promotion (Huo et al., 2018). Therefore, in recent years considerable attention has been paid to supply chain coordination with government financial subsidies (Ding et al., 2016). Wang et al. (2014) compared and explained the characteristics of four subsidy schemes, including initial subsidy, research and development subsidy, production subsidy, and recycling subsidy. Shi and Min (2015) revealed that a production subsidy was effective to encourage a longer operation period of a remanufacturing system. Ma et al. (2013) discussed that consumption subsidy could benefit both manufacturers and retailers. By comparing green product replacement subsidy and consumption subsidy, Li et al. (2018) found that the latter was more effective to enhance social welfare. Safarzadeh and Rasti-Barzoki (2019) demonstrated that subsidizing manufacturer was a better tool for supply chain energy consumption management than energy tax and subsidizing consumers. However, these researches did not explicitly mention green technology investment. Zhang and Yousaf (2020) showed that in a high green investment cost scenario, the government subsidy with a two-part tariff supply chain contract was an efficient government intervention. Nevertheless, the characteristic of discrete decision of green technology and C&T mechanism which is an effective tool to promote green investment were ignored in the above studies.

Some other studies investigated supply chain cooperation issues under C&T policy. Malladi and Sowlati (2020) analyzed the effect of C&T mechanism on a case-independent biomass supply chain. Haji Esmaeili et al. (2020) indicated that C&T performed the best by comparing the impacts of four carbon policies on bioethanol supply chains, including carbon tax, carbon cap, and carbon offset policy besides C&T mechanism. Considering manufacturers' emission reduction and retailers' green promotion, Xia et al. (2018) explored a supply chain coordination issue under the C&T mechanism. To give contract suggestions, Xu et al. (2017) presented optimal wholesale price and cost sharing contracts of supply chain under C&T mechanism. Huo et al. (2018) designed a joint-financing pattern under C&T policy that besides the retailer's carbon reduction cost sharing with the manufacturer, the bank financed the supply chain. Wang and Choi (2019) highlighted that compared with cost sharing contract, revenue sharing and two-part tariff contracts are more effective in improving overall profit and greenness under C&T mechanism. Instead of contract, Zhang et al. (2019) focused on decisions of green technology and carbon quotas trading under three supply chain power structures: Manufacturer Stackelberg, Retail Stackelberg and Vertical Nash. Although C&T mechanism does successfully reduce carbon emission under the correct decision (Zhu et al., 2019; Waltho et al., 2019), government subsidy is another effective tool and should not be ignored.

The above papers on supply chain coordination concerned about retailers' assistance to manufacturers. However, they neglected the retailers' fairness concern and green marketing efforts. Zhang et al. (2018) revealed that manufacturer could obtain much more profit than retailer if retailer made efforts on green marketing. They indicated government subsidy could not only encourage manufacturer to reduce carbon emission but also alleviate retailer's unfairness concern. Hong and Guo (2018) proposed a more realistic green marketing cost-sharing scheme where manufacturer would share the green marketing cost to increase retailer's green marketing efforts and consequently enhance consumer demand for green product. But they didn't discuss it under the C&T mechanism.

All in all, previous literatures didn't study the carbon emission reduction of supply chain under the combination of government subsidy and C&T mechanism. As far as we know, only Raghu Nandan et al. (2019) considered government intervention on a two-echelon supply chain under C&T mechanism by subsidizing/imposing fine to manufacturers. But they also ignored retailer's fairness issues and green marketing effort. What's more, the green technology investment decision was not explicitly explored. In the models related to green technology, most of the above papers only considered a linear relationship between green technology investment cost and emission reduction rate. However, as presented in the previous section, 0–1 decision of selecting green technologies associated with a fixed investment cost was more in line with the reality (Yang et al., 2020; Krass et al., 2013; Drake et al., 2016).

Papers most related to our research are summarized in Table 1, which shows all the important issues addressed by our paper. This research attempts to enrich the literature by considering the combination of government subsidy and C&T policy in a two-echelon supply chain with a green marketing cost-sharing coordination and taking the green technology investment decision as a discrete decision variable. The effects of different subsidy policies on emission reduction and supply chain coordination are also compared in this research.

3. Problem definition and model formulation

This paper considers a two-echelon supply chain which is composed of a leading manufacturer and a retailer as a follower under the C&T policy. With a limited carbon emission quota (A), the manufacturer can sell surplus/buy additional quotas in the carbon market. Besides, to decrease emission, the manufacturer can invest in green technology which is associated with a fixed investment cost (F) and carbon emission reduction rate (r). The retailer purchases products provided by the manufacturer and sells them to the consumers who have a preference for green products. Besides, the government provides subsidy to the manufacturer who invests in green technology. It's a strategy for the retailer to cooperate with the manufacturer to enhance the green product's competitiveness. In the coordination, the retailer promotes the green product and the manufacturer shares a certain proportion of the green marketing cost (Hong and Guo, 2018).

Without loss of generality, the supply chain members have positive demand and non-negative profit to ensure their survival (Wang and Choi, 2019). The product demand equals to the retailer's purchasing quantity and the manufacturer's production quantity. Its function is defined as $q(p,x,y) = a - p + bxr + y$ (Hong and Guo, 2018; Zhang et al., 2013; Raghu Nandan et al., 2019). The demand of product is associated with initial market potential (a), retail price (p), consumer green awareness level (b), manufacturer's decision on green technology (x), carbon emission reduction rate (r), and retailer's green marketing effort (y). A Stackelberg game is proposed to model the process. The sequence of decision-making is as follows. First, the manufacturer decides the wholesale price (w), green technology investment (x), and green marketing cost-sharing ratio (t) according to government subsidy. Then, the retailer determines the retail price (p), the efforts on green marketing (y) and the purchasing quantity (q) according to the manufacturer's decisions. Carbon trust survey shows that although consumers have a high level of environmental awareness, the proportion of consumers who buy green products is only around 20% (Carbon Trust, 2011). This means that marketing green products is still a costly affair for the retailer at the present stage. Therefore, like literature Zhang et al. (2013), Cao et al. (2019b), Jørgensen et al. (2001) and Chang et al. (2019), the green marketing cost is assumed as ky^2 where k is the green marketing cost

Table 1
Papers that are related to the present research.

Author	Green technology investment	Retailer's green marketing	Consumer environmental awareness	Supply chain coordination	C&T policy	Government subsidy	Comparison of subsidy policies
Hong and Guo (2018)	√	√	√	√			
Drake et al. (2016)	√				√	√	√
Hussain et al. (2020)	√				√	√	
Ding et al. (2016)	√		√	√		√	
Wang et al. (2014)						√	√
Shi and Min (2015)	√					√	√
Ma et al. (2013)				√		√	
Li et al. (2018)	√		√	√		√	√
Safarzadeh and Rasti-Barzoki (2019)	√		√	√		√	
Zhang and Yousaf (2020)	√		√	√		√	
Malladi and Sowlati (2020)				√	√		
Haji Esmaeili et al. (2020)				√	√		
Xia et al. (2018)	√	√	√	√	√		
Xu et al. (2017)	√		√	√	√		
Huo et al. (2018)				√	√		
Wang and Choi (2019)	√			√	√		
Zhang et al. (2019)	√		√		√		
Zhang et al. (2018)	√		√			√	√
Hong and Guo (2018)	√		√	√	√	√	
Raghu Nandan et al. (2019)	√	√	√	√		√	
This paper	√	√	√	√	√	√	√

coefficient and $k \geq 1/2$. The related decision variables and parameters are summarized in Table 2.

In order to analyze the impacts of government subsidies on the decisions of the manufacturer and the retailer (i.e., product prices, production quantity, green technology investment, green marketing effort and cost-sharing ratio), as well as the amount of emission reductions, the following three models are formulated under different conditions.

(1) Model 0 (M0): without green technology investment and government subsidy.

This is a basic model. The manufacturer does not invest in green technology ($x = 0$), which results in no subsidy from the government($s = 0$) and no supply chain coordination ($y = t = 0$). So, the product demand is $q = a - p$. Under the C&T mechanism, the manufacturer obtains a fixed carbon emission quota and can trade quota of $e(a - p) - A$ in the carbon market. A positive value indicates the manufacturer needs to buy carbon emission permit for exceeding emission and a negative value indicates the manufacturer can sell the surplus allowance to earn profit. The net profit of the manufacturer (π_0^M) equals the revenue minus production cost and carbon emission permit trading cost (or revenue). The retailer's net profit (π_0^R) is the revenue minus cost of purchasing products.

$$\pi_0^M(w) = (w - c)(a - p) - z(e(a - p) - A) \tag{1}$$

$$\pi_0^R(p) = (p - w)(a - p) \tag{2}$$

Subject to $a - p \geq 0, p > w \geq 0$.

(2) Model 1 (M1): FC subsidy with green technology investment

In this scenario, the manufacturer chooses to invest in green technology ($x = 1$), and the government subsidizes the manufacturer for green improvement according to the fixed green technology investment cost (FC subsidy). The amount of subsidy can be expressed as sF. The green marketing cost of retailer and manufacturer are $(1 - t)ky^2$ and tky^2 respectively. The net profit of manufacturer (π_1^M) is its revenue plus the government subsidy and minus production cost, the green technology investment cost, carbon emission permit trading cost (or revenue), as well as shared green marketing cost. The retailer's net profit (π_1^R) is the revenue minus product purchasing cost and the remaining green marketing cost.

$$\pi_1^M(w,t) = (w-c)(a-p+br+y) - (1-s)F - z((1-r)e(a-p+br+y) - A) - tky^2 \tag{3}$$

$$\pi_1^R(p, y) = (p - w)(a - p + br + y) - (1 - t)ky^2 \tag{4}$$

Subject to $a - p + br + y \geq 0, p > w \geq 0, 0 \leq t < 1, y \geq 0$

(3) Model 2 (M2): ER subsidy with green technology investment

The manufacturer invests in green technology ($x = 1$) and the government subsidizes the manufacturer according to the amount of its emission reduction (ER subsidy). The amount of subsidy can be expressed as $srez(a - p + br + y)$. The net profit equations of the manufacturer (π_2^M) and the retailer (π_2^R) are the same as M1 except the amount of government subsidy.

$$\pi_2^M(w,t) = (w-c)(a-p+br+y) - F - z((1-(1+s)r)e(a-p+br+y) - A) - tky^2 \tag{5}$$

$$\pi_2^R(p, y) = (p - w)(a - p + br + y) - (1 - t)ky^2 \tag{6}$$

Subject to $a - p + br + y \geq 0, p > w \geq 0, 0 \leq t < 1, y \geq 0$

4. Analytical results and discussion

This section analyzes the above models to obtain the optimal operational decisions of the manufacturer and the retailer, and their coordination. Then, based on these values, we can compare the impacts of two types of government subsidy policies on green technology investment, the total carbon emission and the profits of the supply chain and its members.

4.1. Optimal values

By using Stackelberg game theory to solve the above three models, we can obtain the optimal wholesale price (w^*), retail price (p^*), the manufacturer's sharing ratio of green marketing cost (t^*), and the retailer's green marketing efforts (y^*) of the three models, as well as corresponding optimal production quantity (q^*), optimal profits of the manufacturer (π^{M*}) and the retailer (π^{R*}) and total carbon emission (E^*) (as shown in Table 3).

To distinguish the three models, use subscripts of 0, 1, 2 to denote the values of Model 0, Model 1 and Model 2, respectively. It can be seen

Table 2
Model parameters and decision variables.

Decision variables	Description
x	The manufacturer's decision on green technology investment, $x \in \{0,1\}$; $x = 1$ indicates it invests in green technology, otherwise $x = 0$;
w	The unit wholesale price of the product, $w > 0$;
t	The sharing ratio of green marketing cost from the manufacturer, $0 \leq t < 1$; $t = 0$ indicates no coordination;
p	The unit retail price of the product, $p > 0$;
y	The retailer's green marketing efforts, $y \geq 0$; $y = 0$ indicates no coordination;
q	The product demand, $q \geq 0$;
Parameters	Description
s	Government subsidy to the manufacturer who makes green investment, $0 < s < 1$;
a	Initial market potential, $a > 0$;
c	The unit production cost, $c > 0$;
b	The green awareness of consumers, $0 < b < 1$;
r	The carbon emission reduction rate of green technology, $0 < r < 1$;
e	Initial carbon emission intensity from the manufacturer, $e > 0$;
z	Carbon price, $z > 0$;
k	Coefficient of retailer's green marketing cost, $k \geq 1/2$;
A	Carbon allowance allocated by the government, $A > 0$;
F	Fixed cost of green technology investment, $F > 0$;
π^u	Object's profit, $u = M, R, SC$ denotes the manufacturer, retailer and the supply chain, respectively;
E	Total carbon emissions of the manufacturer;
$\Delta\pi_{ij}^u = \pi_i^u - \pi_j^u$	Profit difference between models, $i, j = 0, 1, 2$ denotes three different models, i.e., Model 0, Model 1 and Model 2;
$\Delta E_{ij} = E_i - E_j$	Total carbon emissions difference between models, $i, j = 0, 1, 2$ denotes three different models, i.e., Model 0, Model 1 and Model 2.

Table 3
Optimal values in three scenarios.

	M0	M1	M2
w^*	$\frac{c+ez+a}{2}$	$\frac{2(8k-3)ez(1-r)+(16k-3)br+2(8k-3)c+(16k-3)a}{32k-9}$	$\frac{2(8k-3)ez(1-(s+1)r)+(16k-3)br+2(8k-3)c+(16k-3)a}{32k-9}$
p^*	$\frac{c+ez+3a}{4}$	$\frac{2(4k-3)ez(1-r)+(24k-3)br+2(4k-3)c+(24k-3)a}{32k-9}$	$\frac{2(4k-3)ez(1-(s+1)r)+(24k-3)br+2(4k-3)c+(24k-3)a}{32k-9}$
q^*	$\frac{a-c-ez}{4}$	$\frac{8k(ez(r-1)+br-c+a)}{32k-9}$	$\frac{8k(ez(r(s+1)-1)+br-c+a)}{32k-9}$
t^*	/	$\frac{1}{3}$	$\frac{1}{3}$
y^*	/	$\frac{6(ez(r-1)+br-c+a)}{32k-9}$	$\frac{6(ez(r(s+1)-1)+br-c+a)}{32k-9}$
$\pi^{M}*$	$\frac{(ez+c-a)^2}{8}+Az$	$\frac{4k(br+ez(r-1)-c+a)^2}{32k-9}+Az+(s-1)F$	$\frac{4k(br+ez(r(s+1)-1)-c+a)^2}{32k-9}+Az-F$
$\pi^{R}*$	$\frac{(ez+c-a)^2}{16}$	$\frac{8k(8k-3)(ez(r-1)+br-c+a)^2}{(32k-9)^2}$	$\frac{8k(8k-3)(ez(r(s+1)-1)+br-c+a)^2}{(32k-9)^2}$
E^*	$\frac{e(a-c-ez)}{4}$	$\frac{e(1-r)8k(ez(r-1)+br-c+a)}{32k-9}$	$\frac{e(1-r)8k(ez(r(s+1)-1)+br-c+a)}{32k-9}$

from the Table 3 that the manufacturer is willing to collaborate with the retailer and share 1/3 of the green marketing cost ($t_1^* = t_2^* = 1/3$). This result is consistent with that of Cao et al. (2019b) and Hong and Guo (2018). Meanwhile, $y_2^* > y_1^* > 0$ means that retailer is also willing to collaborate with manufacturer to raise their profits. While with ER subsidy, the retailer tends to invest more on green marketing.

4.2. Green technology investment decision

In addition to optimal values, the manufacturer's green technology investment decision under different subsidy policies is also analyzed by comparing the manufacturer's profits of subsidies models (M1, M2) and the basic model (M0), which is illustrated in the following theorem.

Theorem 1. From the perspective of the manufacturer, there exists the following relations between government subsidy (s), carbon emission intensity (e), carbon emission reduction rate (r) and green investment decision (x), as shown in Table 4. (See proof in the Appendix)

According to the constraints of the model (i.e., $p_i^* > w_i^*$, $i = 0, 1, 2$), there is a limit on the manufacturer's emission intensity, that is $e < \frac{a-c}{z}$ (See proof in the Appendix). This is reasonable because manufacturers with infinite carbon emissions would be expelled from the market under the C&T system. Besides, this maximum limit of carbon emission intensity is also applicable to Theorem 2, 3 and 5. Theorem 1 shows that under the FC subsidy, the low government subsidy ($0 < s < s_I$) cannot support the manufacturer to invest in green technology ($x = 0$). When subsidy is raised to a certain range ($s_I \le s < 1 - \frac{9(ez+c-a)^2}{8(32k-9)F}$), the manufacturer will invest in the green technology ($x = 1$) with emission reduction rate higher than a certain threshold ($r_I < r < 1$). When the subsidy is higher than a threshold ($1 - \frac{9(ez+c-a)^2}{8(32k-9)F} \le s < 1$), the manufacturer will invest in green technology ($x = 1$) no matter how low the emission reduction rate is. This indicates that under the FC subsidy, the subsidy rate can effectively affect the manufacturer's investment decision.

Like FC subsidy, when the subsidy rate is lower than a threshold ($0 < s < s_{II}$), the manufacturer also may not implement green technology under ER subsidy ($x = 0$). However, compared to FC subsidy, the green technology investment decision under the ER subsidy is more affected by the manufacturer's carbon emission intensity (e). If the carbon emission intensity is lower than a threshold ($e \le e_I$), the manufacturer will invest in green technologies ($x = 1$) regardless of the government subsidy rate and emission reduction rate. This is because ER subsidy is based on the amount of manufacturer's emission reduction. If the carbon emission intensity is small, the surplus carbon quota will be more, and thus manufacturers can get more benefits in the carbon trading market. Coupled with the amount of ER subsidies, manufacturer is willing to invest in green technologies. Therefore, the ER subsidy policy is better

Table 4
Green technology investment decisions (x) of the manufacturer over different levels of the government subsidy (s), carbon emission intensity (e), and carbon emission reduction rate (r) under FC and ER subsidies.

s	e	r	x
FC Subsidy			
$1 - \frac{9(ez+c-a)^2}{8(32k-9)F} \le s < 1$	$e < \frac{a-c}{z}$	$\forall r$	$x = 1$
$s_I \le s < 1 - \frac{9(ez+c-a)^2}{8(32k-9)F}$		$0 < r \le r_I$	$x = 0$
		$r_I < r < 1$	$x = 1$
$0 < s < s_I$		$\forall r$	$x = 0$
ER Subsidy			
$s_{II} \le s < 1$	$e \le e_I$	$\forall r$	$x = 1$
	$e_I < e < \frac{a-c}{z}$	$0 < r \le r_{II}$	$x = 0$
		$r_{II} < r < 1$	$x = 1$
$0 < s < s_{II}$	$e \le e_I$	$\forall r$	$x = 1$
	$e_I < e < \frac{a-c}{z}$		$x = 0$

where $s_I = 1 - \frac{4k(b+a-c)^2}{(32k-9)F} + \frac{(ez+c-a)^2}{8F}$, $r_I = \frac{\sqrt{\frac{32k-9}{4k}\left(F(1-s)+\frac{(c+ez-a)^2}{8}\right)} - a + c + ez}{ez+b}$, $s_{II} = \frac{\sqrt{\frac{32k-9}{4k}\left(F+\frac{(c+ez-a)^2}{8}\right)} - a + c - b}{ez}$, $e_I = \frac{3a-3c-\sqrt{8(32k-9)F}}{3z}$, $r_{II} = \frac{\sqrt{\frac{32k-9}{4k}\left(F+\frac{(c+ez-a)^2}{8}\right)} + c - a + e*z}{b+ez(1+s)}$

Table 5
Comparison of profits of the supply chain between two subsidy policies and non-investment non-subsidy scenario.

F	s	$\Delta\pi^{SC}$
FC subsidy		
$0 < F \le F_I$	$\forall s$	$\Delta\pi_{10}^{SC} \ge 0$
$F > F_I$	$0 < s < s_{III}$	$\Delta\pi_{10}^{SC} < 0$
	$s_{III} \le s < 1$	$\Delta\pi_{10}^{SC} \ge 0$
ER subsidy		
$0 < F \le F_{II}$	$\forall s$	$\Delta\pi_{20}^{SC} \ge 0$
$F > F_{II}$		$\Delta\pi_{20}^{SC} < 0$

where $F_I = \dfrac{(768k-243)(a-c-ez)^2+\left(3072k^2-960k\right)\left((b+ez)^2r^2+2(a-c-ez)(b+ez)r\right)}{16(32k-9)^2}$;

$F_{II} = \dfrac{(768k-243)(a-c-ez)^2+\left(3072k^2-960k\right)\left((b+ez(s+1))^2r^2+2(a-c-ez)(b+ez(s+1))r\right)}{16(32k-9)^2}$;

$s_{III} = 1-\dfrac{(768k-243)(a-c-ez)^2+\left(3072k^2-960k\right)\left((b+ez)^2r^2+2(a-c-ez)(b+ez)r\right)}{16(32k-9)^2F}$.

for relatively low emission intensity manufacturers, because the C&T system is effective enough to promote green technology improvement. On the other hand, if the carbon emission intensity is higher than a threshold ($e_I < e < \frac{a-c}{z}$), only when the subsidy rate and the emission reduction rate are both high ($s_{II} \le s < 1$, $r_{II} < r < 1$), the manufacturer will invest in technology ($x = 1$).

However, the above thresholds are affected by the investment cost of green technology (F) and the carbon price (z). The increase of F will narrow the range where the green technology will be invested. On the contrary, the increase of z will broaden the range. This implies that the smaller the investment cost or the higher the carbon price, the more likely the manufacturer tends to invest in green technology. As for the government, it needs to increase subsidy rate for costly green technology and can decrease subsidy rate when carbon price is high.

Theorem 2. Both FC subsidy and ER subsidy can increase the retailer's profit and the ER subsidy brings the highest ($\pi_2^R* > \pi_1^R* > \pi_0^R*$). (See proof in the Appendix)

This result can be obtained from Table 3. Theorem 2 indicates the retailer is in favor of green technology investment and ER subsidy. This is because the production demand increases due to the subsidies and the green technology investment ($q_2* > q_1* > q_0*$) and the resulting increase of revenue is higher than the retailer's green marketing cost.

In order to investigate the preference of the whole supply chain on green technology investment, the following theorem is obtained and the results are shown in Table 5. $\Delta\pi_{10}^{SC} \ge 0$ or $\Delta\pi_{20}^{SC} \ge 0$ means the profit of supply chain under FC subsidy or ER subsidy is higher than that of the basic supply chain respectively.

Theorem 3. As shown in Table 5, under FC subsidy, if $F \le F_I$, the supply chain can gain more profits than the basic supply chain no matter how low the subsidy rate is. If $F > F_I$, green investment can increase the supply chain revenue only when subsidy rate is higher than the threshold of s_{III}. Under ER subsidy, when $F \le F_{II}$, the whole supply chain can gain more profits than the basic supply chain by implementing green technology. (See proof in Appendix)

Theorem 3 provides the conditions of the green technology investment cost (F) and the subsidy rate (s) when investing in green technology can improve the overall supply chain revenue. It is found that when F is relatively low ($F \le F_I$), the supply chain can gain more profits under FC subsidy than the scenario without green investment and subsidy. On the other hand, when F is at a high level ($F > F_I$), unless the FC subsidy rate is high ($s_{III} \le s < 1$), green technology investment may not increase the whole supply chain profits. Because the high investment cost will make the supply chain unprofitable. But the threshold of s_{III} increases with the rise of green technology investment cost (F). This means that the higher investment cost, the higher subsidy rate the government needs to provide to let the supply chain make green improvement under FC subsidy.

Similarly, ER subsidy is more profitable for supply chain than non-investment and non-subsidy scenario when F is relatively low ($F \le F_{II}$). Differently, when F is relatively high ($F > F_{II}$), no matter what the subsidy rate is, the supply chain may not profit more from green investment. In addition, the threshold of F_{II} increases with the rise of ER subsidy rate, which implies high subsidy rate can induce implementation of green technology with high cost.

On the other hand, by comparing Theorem 1 and Theorem 3, it can be found that the conditions of the inducement of green technology investment are wider when considering the profit of the whole supply chain instead of just the manufacturer's profit. This means there are cases when green technology investment may not improve the manufacturers' revenue, but can improve the overall revenue of the supply chain. This is because the retailer's profit is always higher with green investment and government subsidy, as shown in Theorem 2. Therefore, the above theorems can help the government to formulate subsidy policies and corresponding subsidy rate, and the requirements of subsidy application if it expects some specific green technology to be implemented.

4.3. Impacts of subsidies on total carbon emission

By comparing the optimal values of total carbon emissions under two subsidy policies (E_2*, E_1*) in Table 3, the effects of two subsidy policies on emission reduction can be derived, as shown in the following theorems.

Theorem 4. The total carbon emission under FC subsidy is always lower than that under ER subsidy ($E_2* > E_1*$). In addition, ER subsidy will induce more green marketing efforts ($y_2* > y_1*$), greater production quantity ($q_2* > q_1*$) and higher the amount of emission reduction.

Like Theorem 1, according to the constraints of the model (i.e., $p_i* > w_i*$, $i = 1, 2$), there is a limit on the manufacturer's emission intensity, that is $e < \frac{a-c+br}{z(1-r)}$. Besides, this maximum limit of carbon emission intensity is also applicable to Theorem 6 and 7. Theorem 4 indicates that FC subsidy performs better on total carbon emission control than ER subsidy, no matter what the amount of the government subsidy is. This is because compared with FC subsidy the wholesale price and retail price under ER subsidy are lower ($w_2* < w_1*$, $p_2* < p_1*$), and the retailer makes greater efforts in green marketing ($y_2* > y_1* > 0$), which results in higher green product demand ($q_2* > q_1*$). Therefore, under the same emission reduction rate, the amount of emission reduction, which is equal to req, is greater under ER subsidy, but the total carbon emission, which is equal to $(1-r)eq$, is also greater ($E_2^* > E_1^*$).

On the other hand, the total carbon emission is not affected by subsidy rate (s) under FC subsidy. However, the production quantity increases with the rise of ER subsidy rate ($\partial q_2^*/\partial s > 0$), and thus leads to the increasing total carbon emission ($\partial E_2^*/\partial s > 0$). Therefore, ER subsidy policy is more suitable for emerging or developing industries to promote their development. FC subsidy policy is more suitable for developed and high emission industries to control total emission.

In addition, can the government subsidy guarantee the reduction of total carbon emission for sure? According to Theorem 4, we can obtain the answer by comparing the total carbon emission of Model 1 with FC subsidy (E_1^*) and the basic Model 0 (E_0^*), as shown in Theorem 5.

Theorem 5. Under different levels of carbon emission reduction rate (r), there are five types of relations between emission intensity (e) and the total carbon emission difference between M0 and M1 (ΔE_{10}), as shown in Table 6. (See proof in the Appendix)

In Table 6, $\Delta E_{10} < 0$ means the government subsidy can induce lower total carbon emission. Theorem 5 shows that the government subsidy cannot guarantee the reduction of total carbon emission for sure. There are two scenarios when the subsidy is effective.

Firstly, when the emission reduction rate of the green technology (r) is less than a small threshold ($1-\sqrt{\frac{32k-9}{32k}}$) and the manufacturer's carbon emission intensity exceeds the threshold of e_{II}, the government subsidy is effective on reducing total carbon emission. This is because investment in green technology can reduce the amount of carbon emission, and thus the manufacturer can increase its production quantity to gain more profits without exceeding the fixed carbon emission allowance under C&T system. Besides, for manufacturers with higher carbon emission intensity, the increase of carbon emission brought by the increase of output is less than the amount of emission reduction. Therefore, the total carbon emission under FC subsidy is less than that without green technology and subsidy.

Secondly, when the emission reduction rate (r) is higher than a large threshold (r_{III}), subsidizing manufacturers whose carbon emission intensity is lower than the threshold (e_{II}) would achieve the total emission reduction goal. The explanation is similar with the above scenario.

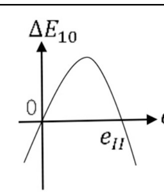
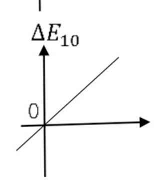
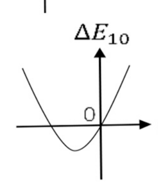
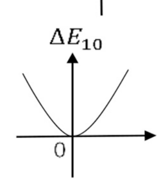
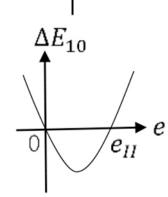
According to the results, the government can set forth the requirements for subsidy to reduce emission, such as the range of emission reduction rate of green technology and the carbon emission intensity of manufacturers.

4.4. Comparison of profits under two subsidy policies with the same budget

Theorem 6. With the same subsidy budget, the manufacturer's profit under FC subsidy is always greater than that under ER subsidy. (See proof in the Appendix)

Theorem 6 shows that FC subsidy is more profitable for the

Table 6
Comparison of total carbon emission under different scenarios.

r	e	ΔE_{10}	Relations between ΔE_{10} and e
$0<r<1-\sqrt{\frac{32k-9}{32k}}$	$0<e<\min\left\{e_{II},\frac{a-c}{z}\right\}$ $\min\left\{e_{II},\frac{a-c}{z}\right\}\le e<\frac{a-c}{z}$	$\Delta E_{10}>0$ $\Delta E_{10}<0$	
$r=1-\sqrt{\frac{32k-9}{32k}}$	$e<\frac{a-c}{z}$	$\Delta E_{10}>0$	
$1-\sqrt{\frac{32k-9}{32k}}<r<r_{III}$			
$r=r_{III}$			
$r_{III}<r<1$	$0<e<\min\left\{e_{II},\frac{a-c}{z}\right\}$ $\min\left\{e_{II},\frac{a-c}{z}\right\}\le e<\frac{a-c}{z}$	$\Delta E_{10}<0$ $\Delta E_{10}>0$	

where $r_{III}=\frac{-32k(b+c-a)-\sqrt{(32k(b+c-a))^2-4(-32kb)*9(a-c)}}{2(-32kb)}$, $e_{II}=\frac{-32k(1-r)(br-c+a)+(32k-9)(a-c)}{\left(32k-9-32k(1-r)^2\right)z}$.

manufacturer under the same subsidy amounts. The reason is that according to Theorem 4, the total carbon emission under ER subsidy is larger than that under FC subsidy ($E_2^* > E_1^*$). Therefore, it makes the purchasing cost/selling profit of emission quota in trading market under ER subsidy greater/less. On the other hand, retailer makes more green marketing effort under ER subsidy ($y_2^* > y_1^* > 0$), which means the green marketing cost shared by manufacturer is higher under ER subsidy. Consequently, in general, FC subsidy can bring more profits to the manufacturer than ER subsidy under the same subsidy budget.

According to Theorem 4 and 6, with the same subsidy budget, FC subsidy brings more profits to the manufacturer and lower total carbon emissions as well comparing to ER subsidy. However, ER subsidy gets more profits to the retailer according to Theorem 2. In order to demonstrate the beneficial conditions for the supply chain with the same subsidy budget, the following theorem is derived.

Theorem 7. With the same subsidy budget, when $0 < e \le \frac{(32k-12)(a-c+br)}{z(32k-12-r(16k-9))}$, ER subsidy can bring more profits to the supply chain than FC subsidy. When $\frac{(32k-12)(a-c+br)}{z(32k-12-r(16k-9))} < e < \frac{a-c+br}{z(1-r)}$, if ER subsidy rate $0 < s_2 \le \frac{(32k-12)(a-c+br+ez(r-1))}{(16k-3)ezr}$, then ER subsidy is more profitable to the supply chain, otherwise, FC subsidy is better. (See proof in the Appendix)

Theorem 7 indicates that with the same subsidy budget, if the manufacturer's carbon emission intensity is lower than a threshold, the ER subsidy is more conductive to the supply chain efficiency than FC subsidy. As analyzed in Theorem 1, ER subsidy policy is better for relatively low emission manufacturers. Meanwhile, the manufacturer's profit under FC subsidy is larger (but not too much larger) than that under ER subsidy. Combined with Theorem 2 that ER subsidy is more beneficial to the retailer, ER subsidy is more conductive to the supply chain with the manufacturer with low emission intensity than FC subsidy.

If the manufacturer's carbon emission intensity is higher than the threshold, which subsidy policy is better depends on the ER subsidy rate (s_2). The higher the ER subsidy rate, the greater the total carbon emission ($\partial E_2^*/\partial s_2 > 0$) and the green marketing effort ($\partial y_2^*/\partial s_2 > 0$) under ER subsidy. Therefore, it makes the purchasing cost/selling profit of emission quota in trading market under ER subsidy greater/less, and green marketing cost higher under ER subsidy. While the production quantity and green marketing effort under FC subsidy are not affected by ER subsidy rate or FC subsidy rate. Consequently, when the ER subsidy rate is higher than a threshold, FC subsidy is more profitable for the whole supply chain. Otherwise, ER subsidy is better.

The above theorems reveal that with limited budget if the government concentrates more on carbon emission reduction, FC subsidy as an effective policy should be adopted on all kinds of manufacturers. However, if the government concerns more about the development of the whole supply chain, ER subsidy is more effective if the manufacturer's emission intensity is low. For manufacturer with high emission, the government could reduce the ER subsidy rate.

5. Numerical example

To illustrate the above theoretical results, this section provides a set of numerical analysis. The values of basic parameters are selected according to the related data of Xu et al. (2017) where $a = 5$(unit/year), $c = 0.1$($\times$10\$/unit), $e = 2$(tCO_2e/unit), $A = 100$(ton/year), k=1, $F = 1.5$ ($\times$10\$). The carbon price in Beijing carbon emission trading market is 1.3($\times$10\$/tCO_2e). Based on the carbon trust surveys, about 20% of consumers prefer to buy green products (Carbon Trust, 2011). It's set that $b = 0.2$. According to the regulations in Beijing (Administrative Committee of Beijing Economic and Technological Development Zone, 2019), the subsidy rate for enterprises that carry out green improvement is 50%, thus it's set that $s = 0.5$.

5.1. Green technology investment under two subsidy policies

The first part of numerical examples illustrates the impact of two subsidy policies on green technology investment. Fig. 1 illustrates the relation between the profit differences of the manufacturer with and without subsidies ($\Delta\pi_{10}^M$ and $\Delta\pi_{20}^M$) and carbon emission reduction rate (r) and government subsidy (s). It shows that when both s and r are relatively low ($s \le 0.4$, $r \le 0.2$), the manufacturer is unwilling to invest in green technology under two subsidy policies ($\Delta\pi_{10}^M < 0$, $\Delta\pi_{20}^M < 0$). However, under two subsidy policies, the increase of r can make the manufacturer change the investment decision from non-investment to investment even when subsidy is low. In addition, when carbon emission reduction rate is at a low level ($r \le 0.2$), the increase of s under FC subsidy makes the manufacturer change the green technology investment decision from non-investment to investment, which does not happen under ER subsidy. It means FC subsidy is more effective than ER subsidy when green technology results in low emission reduction. However, when carbon emission reduction rate is at a high level ($r > 0.5$), ER subsidy is much more effective. In this situation, green technology investment under ER subsidy can brings more profits to the manufacturer than that under FC subsidy ($\pi_2^{M*} > \pi_1^{M*} > \pi_0^{M*}$). This is because the manufacturer can obtain more subsidy due to high emission reduction.

Table 7 as a supplement of Fig. 1 illustrates the results when changing the green technology investment cost F. It shows that the lower cost ($F = 0.5$) enables the manufacturer to afford green technology investment. Therefore, the government could mainly subsidize the manufacturer which invests on costly green technology, and adopt FC

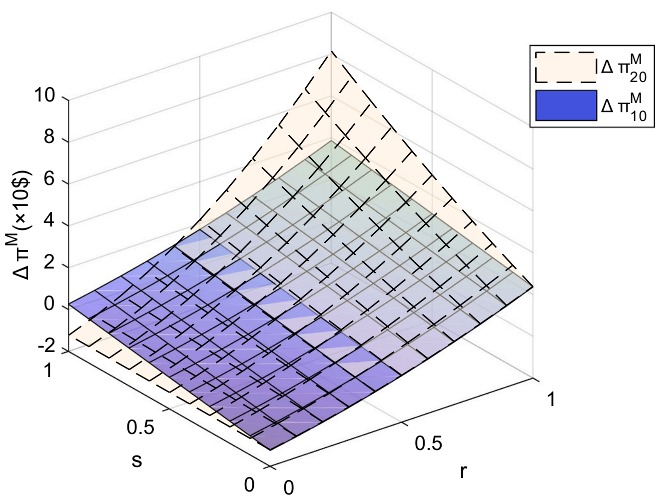


Fig. 1. Relation between $\Delta\pi_{10}^M$, $\Delta\pi_{20}^M$ and r, s.

Table 7
Green technology investment decisions (x) over all levels of parameters F, s and r under FC and ER subsidies.

F(×10 \$)	s	r	$\Delta\pi_{10}^M$(×10 \$)	x(FC subsidy)	$\Delta\pi_{20}^M$(×10 \$)	x(ER subsidy)
0.5	0.25	0.25	0.5290	1	0.5781	1
		0.75	2.3307	1	2.9931	1
	0.75	0.25	0.7790	1	0.9540	1
		0.75	2.5807	1	4.8160	1
1.5	0.25	0.25	**−0.2210**	**0**	**−0.4219**	**0**
		0.75	1.5807	1	1.9931	1
	0.75	0.25	0.5290	1	**−0.0460**	**0**
		0.75	2.3307	1	3.8160	1
2.5	0.25	0.25	**−0.9710**	**0**	**−1.4219**	**0**
		0.75	0.8307	1	0.9931	1
	0.75	0.25	0.2790	1	**−1.0460**	**0**
		0.75	2.0807	1	2.8160	1

subsidy and ER subsidy on green technology with low and high emission reduction rate respectively.

Fig. 2 illustrates the relation between the profit differences of the manufacturer with and without subsidies ($\Delta\pi_{10}^{M}$ and $\Delta\pi_{20}^{M}$) and the green awareness of consumers (b) and carbon emission reduction rate (r). Note that $\Delta\pi_{10}^{M} > 0$ or $\Delta\pi_{20}^{M} > 0$ means the subsidy can promote green technology investment. Fig. 2 shows that the increase of consumers' green awareness can enhance the manufacturer's profit and change the manufacturer's decision on green technology with emission reduction rate of 0.18 under FC subsidy and emission reduction rate of 0.28 under ER subsidy. Therefore, enhancing customers' green awareness is crucial for the manufacturer's profit and green technology investment. It is suggested that besides subsidizing the manufacturer, the government should make efforts on publicity of green consumption.

5.2. Total carbon emission reduction

The second part shows the difference of total carbon emission with and without subsidies (ΔE_{10}) under different emission reduction rate (r) and carbon emission intensity (e), as illustrated in Fig. 3. As analyzed in Section 4, since the total carbon emission under ER subsidy is always greater than that under FC subsidy ($E_1{}^* < E_2{}^*$), we can just compare the total carbon emission of FC subsidy model (M1) and the basic model (M0). $\Delta E_{10} < 0$ means subsidy can effectively achieve the purpose of total carbon emission reduction. Fig. 3 shows that the government subsidy is effective in two scenarios, that is: 1) when r is low ($r \leq 0.2$) and carbon emission intensity is relatively high ($e \geq 0.9$); 2) r is high ($r \geq 0.7$) and carbon emission intensity is low ($e \leq 0.7$). This result is consistent with the Theorem 5.

5.3. Comparison of two subsidy policies under the same subsidy budget

This part compares the total carbon emissions, the green technology investment decision and the profits of manufacturer and the supply chain between two subsidy policies with the same subsidy budget. Fig. 4 (a) is associated with a dirtier green technology but low investment cost (both r and F are low), while Fig. 4 (b) with cleaner but more expensive green technology (both r and F are high). The total subsidy budget, the subsidy rate under FC subsidy and ER subsidy are expressed as TS, s_1 and s_2 respectively. When the total subsidy budget under two subsidy policies is the same, there is $TS = s_1F = s_2erzq_2$.

Fig. 4 (a) and (b) demonstrate that the total carbon emissions under ER subsidy is greater than those under FC subsidy ($\Delta E_{20} > \Delta E_{10}$), and the total carbon emissions under FC subsidy is not affected by the subsidy budget. In addition, Fig. 4 (a) and (b) also illustrate that the manufacturer's profit under FC subsidy is greater than that under ER subsidy with the same subsidy budget ($\Delta\pi_{10}^{M} > \Delta\pi_{20}^{M}$). Moreover, Fig. 4 shows that with the increase of the subsidy budget, the manufacturer will change its decision on green technology investment ($\Delta\pi_{10}^{M} > \Delta\pi_{20}^{M} > 0$ means investment). And the profit of the supply chain is higher with subsidy policies, because the retailer's profit is higher with subsidy policies, and the supply chain efficiency is higher under ER subsidy ($\Delta\pi_{20}^{SC} > \Delta\pi_{10}^{SC} > 0$).

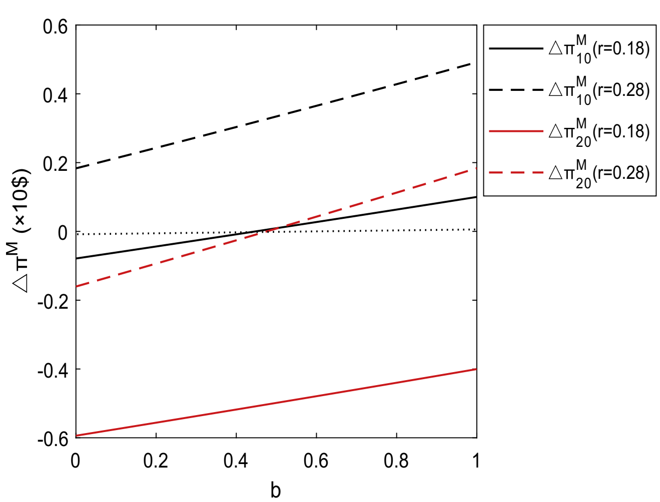


Fig. 2. Relation between $\Delta\pi_{10}^{M}$, $\Delta\pi_{20}^{M}$ and b, r.

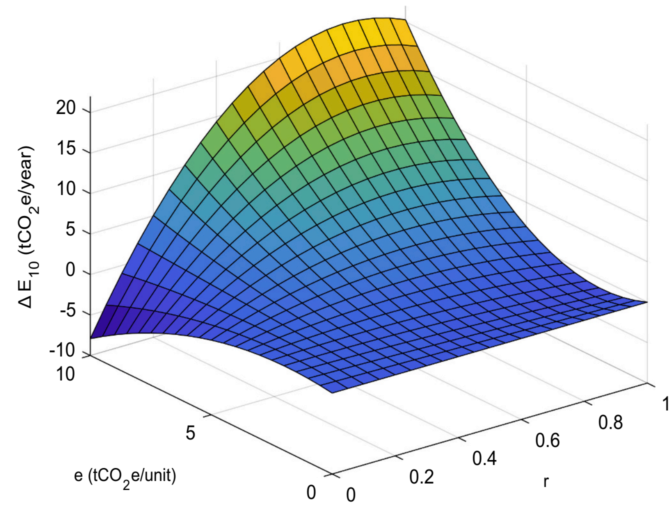


Fig. 3. Relation between ΔE_{10}, r and e.

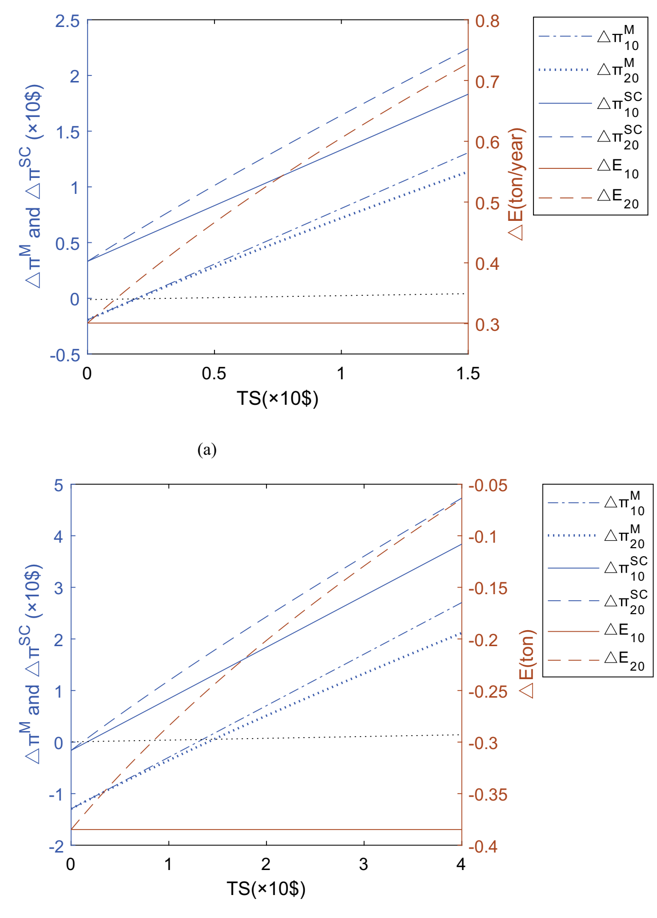


Fig. 4. Relations between $\Delta\pi_{10}^{M}$, $\Delta\pi_{20}^{M}$,$\Delta\pi_{10}^{SC}$, $\Delta\pi_{20}^{SC}$ ΔE_{10}, ΔE_{20}, and TS, r, F.

By comparing Fig. 4 (a) and (b), it is seen that with a small subsidy budget, e.g., $TS = 1$, the dirtier not the cleaner green technology will be selected but the total emission increases. However, if the government increases the subsidy budget, the cleaner one will be chosen by the manufacturer which can increase much more profits of the manufacturer as well as the efficiency of the supply chain. What's more, greater total emission will be cut down.

6. Conclusions and implications

6.1. Conclusions

To promote emission reduction, the governments of some countries or cities subsidize green technology investment under the C&T system. This research considers a supply chain under the government's environmental regulations of C&T mechanism and FC/ER subsidy. The green supply chain consists of a manufacturer who faces discrete green technology investment decision, a retailer who can make green marketing effort, and customers with green awareness. The optimal operational decisions of the manufacturer and the retailer (i.e., wholesale and retail price, production quantity) and green decisions (i.e., green technology investment, green marketing efforts) are obtained. Besides, the impacts of FC and ER subsidies on their green marketing cost-sharing coordination, total carbon emission reduction and the efficiency of the supply chain are compared. Based on the analysis, the decision-making references for the supply chain members are provided as follows:

Under the FC subsidy, the manufacturer can mainly refer to the subsidy rate and the emission reduction rate to make green technology investment decision. If the subsidy rate is raised to a certain range, the manufacturer should invest in the green technology with emission reduction rate higher than a certain threshold. When the subsidy rate is high enough, it's more profitable to make green investment regardless of the emission reduction rate. However, the threshold is influenced by the investment cost. Under the ER subsidy, besides the above two factors, the manufacturer should also consider its current carbon emission intensity. When its carbon emission intensity is at a low level, it is wiser for the manufacturer to invest in green technology. But when its emission intensity is at a high level, the manufacturer should make green investment only when the subsidy rate and the emission reduction rate are both high. In addition, it is profitable for the manufacturer to share green marketing cost with its retailer under both FC and ER subsidy policies. Meanwhile, the retailer is profitable to make efforts on green marketing under subsidy policy because of the manufacturer's green marketing cost-sharing. Comparing with FC subsidy, the retailer tends to invest more on green marketing under ER subsidy.

Whether investing in green technology can improve the overall supply chain revenue is also discussed. There are cases when green technology investment may not improve the manufacturers' revenue, but can improve the overall revenue of the supply chain as the retailer can gain higher profits. This means that when considering the profit of the supply chain instead of the manufacturer only, the conditions of inducing green technology investment are wider. Therefore, it is also valuable to extend these models to incorporate a profit-sharing contract to increase supply chain efficiency in future research.

6.2. Policy implications

Based on the analytical and numerical results, references for the government to formulate and implement subsidy policy are provided as follows:

Firstly, the government subsidy policy cannot guarantee green technology investment and total carbon emission reduction. However, the FC subsidy rate can change the investment decision of the manufacturer on green technology which doesn't happen under the ER subsidy. But the ER subsidy will induce greater emission reduction and more green marketing efforts. The ER subsidy should be adopted if the carbon emission intensity of the manufacturer is relatively low since the green technology investment decision under the ER subsidy is more affected by the manufacturer's carbon emission intensity instead of the subsidy rate. This is because the C&T mechanism can induce the green technology investment in this situation. While the government should increase subsidy rate to induce costly green technology investment if necessary and can decrease subsidy rate when carbon price is high.

Secondly, the total carbon emission under the FC subsidy is less than that under the ER subsidy, but the ER subsidy can induce more green production and consumption. Therefore, the government can apply the FC subsidy on developed and high emission industries to control total emission and adopt the ER subsidy on emerging or developing industries to promote their development. Moreover, according to the analytical results, the government can set forth the requirements for subsidy to promote green technology or reduce carbon emission, such as the range of green investment cost, emission reduction rate of green technology and the carbon emission intensity of manufacturers.

Finally, with the same amount of subsidy, the manufacturer gains more profit and emits less under the FC subsidy than the ER subsidy in most conditions. Therefore, if the government concentrates more on carbon emission reduction, the FC subsidy as an effective policy should be adopted. However, the retailer earns more under the ER subsidy because of resulting higher green product demand. In addition, as the retailer can make green marketing effort to increase green product consumption under subsidy policies, it is suggested that besides subsidizing the manufacturer, the government could also make effort on publicity of green consumption to induce green technology investment.

6.3. Possible extension

The proposed models can be extended in several directions. Firstly, the green decisions and coordination in a three-echelon supply chain are worth exploring. For example, in practice, Apple company will share the cost of green technology innovation with its suppliers. A multi-period model considering variation of carbon price is another interesting direction. In addition, the models could be extended to a dual- or multi-products supply chain in a competitive market. Besides green marketing cost-sharing, the profit-sharing and the green investment cost-sharing contract could be proposed for members in the supply chain to achieve win-win situation.

Declaration of Competing Interest

None.

Acknowledgments

This work was supported by Natural Science Foundation of China (NSFC) [grant ID 71572114], Guangdong Province of China [grant ID GD20CGL08] and Natural Science Foundation of Guangdong Province of China [grant ID 2021A1515011223]. The authors would like to thank the editor for editing the manuscript and the reviewers for their detailed and helpful comments.

Appendix A. Appendix

Proof of Theorem 1. Define $\Delta\pi_{10}^{M}$ as the manufacturer's profit difference between M0 and M1, i.e., $\Delta\pi_{10}^{M} = \frac{4k(br+ez\ (r-1)-c+a)^2}{32k-9} + (s-1)F - \frac{(ez+c-a)^2}{8}$. If

$\Delta\pi_{10}^{M} > 0$, manufacturer will invest in green technology with FC subsidy because there is an increase in profits, that is x = 1, otherwise it will not invest in green technology, that is x = 0.

According to the definition that the retail price is greater than the wholesale price in M1, i.e., $p_0{*} > w_0{*}$, the value limit of carbon emission intensity (e) can be obtained, that is $e < \frac{a-c}{z}$. Similarly, according to $p_1{*} > w_1{*}$, there is $e < \frac{a-c+br}{z(1-r)}$.According to $p_2{*} > w_2{*}$, if $z(1-r(1+s)) > 0$, then $e < \frac{a-c+br}{z(1-r(1+s))}$. If $z(1-r(1+s)) \le 0$, then $\forall e$ meet the constraints. Because M1 and M2 models are compared with M0 model respectively, and there is $\frac{a-c}{z} < \frac{a-c+br}{z(1-r)} < \frac{a-c+br}{z(1-r(1+s))}$, the value limits of e can be obtained, that is $e < \frac{a-c}{z}$.

Under the FC subsidy policy, if $e < \frac{a-c}{z}$and $k \ge 1/2$, it can be proved that $\Delta\pi_{10}^{M}$ is a convex function of carbon emission reduction rate (r). Fig. A1 shows the relations between $\Delta\pi_{10}^{M}$ and r under different government subsidy (s). It can be seen that if $1 - \frac{9(ez+c-a)^2}{8(32k-9)F} \le s \le 1$, $\Delta\pi_{10}^{M}$ has two negative intersections with the horizontal axis (r), i.e., ($r_I{'}$, 0) and (r_I, 0), where $r_I^{'} = \frac{-\sqrt{\frac{32k-9}{4k}\left(F(1-s)+\frac{(c+ez-a)^2}{8}\right)}-a+c+ez}{ez+b}$,$r_I = \frac{\sqrt{\frac{32k-9}{4k}\left(F(1-s)+\frac{(c+ez-a)^2}{8}\right)}-a+c+ez}{ez+b}$.Therefore, when $r \in (0,1)$, there is $\Delta\pi_{10}^{M} > 0$ and the optimal decision for manufacturer is to invest in green technology. If $s_I = 1 - \frac{4k(b+a-c)^2}{(32k-9)F} + \frac{(ez+c-a)^2}{8F} \le s < 1 - \frac{9(ez+c-a)^2}{8(32k-9)F}$, $\Delta\pi_{10}^{M}$ has two intersections with the horizontal axis (r), one positive (r_I, 0) and one negative ($r_I{'}$, 0). It means when $r \le r_I$, then $\Delta\pi_{10}^{M} < 0$, that is the green technology will not be selected for investment, when $r_I < r < 1$, $\Delta\pi_{10}^{M} > 0$, that is the green technology will be implemented. If $0 < s < s_I$, then $\Delta\pi_{10}^{M}$ has two intersections with the horizontal axis (r), one positive (r_I, 0) and one negative ($r_I{'}$, 0). It means when $r \in (0,1)$, $\Delta\pi_{10}^{M} < 0$ and manufacturer will not invest in green technology. The theorem is proved.

The proof of this result under the ER subsidy policy is similar and omitted.

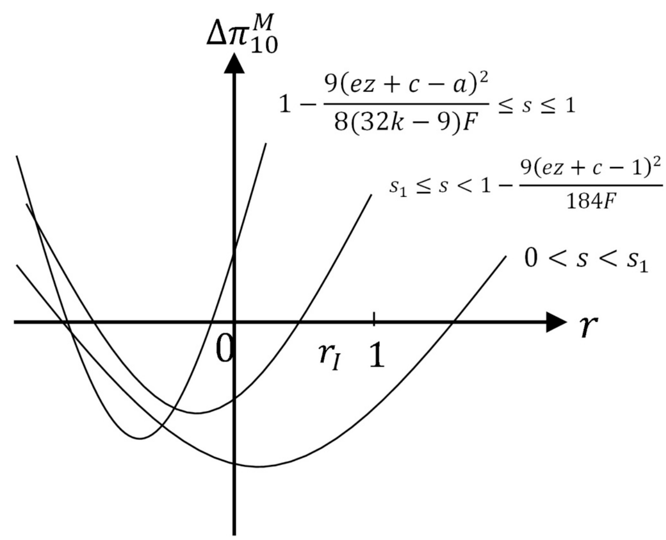


Fig. A1. Relations between $\Delta\pi_{10}^{M}$ and r under different government subsidy (s) in FC subsidy.

Proof of Theorem 2. Define $\Delta\pi_{21}^{R}$ as the difference of the profits of retailer between two subsidy policies respectively, i.e., $\Delta\pi_{21}^{R} = \pi_2^{R}{*} - \pi_1^{R}{*}$. It's found that $\Delta\pi_{21}^{R} = \left(16ekrsz(8k-3)\left(a-c+br-ez+erz+\frac{1}{2}ersz\right)\right)\Big/(32k-9)\hat{}2$. As analyzed in the Proof of Theorem 1 above, the value limits of e can be obtained, that is $e < \frac{a-c+br}{z(1-r)}$. Thus, there is $\left(a-c+br-ez+erz+\frac{1}{2}ersz\right) > 0$. When $k \ge 1/2$, then $8k-3 > 0$. Therefore, $\Delta\pi_{21}^{R} = \pi_2^{R}{*} - \pi_1^{R}{*} > 0$. The proof of $\Delta\pi_{10}^{R} = \pi_1^{R}{*} - \pi_0^{R}{*} > 0$ is similar and omitted. The theorem is proved.

Proof of Theorem 3. Define $\Delta\pi_{10}^{sc}$ as the difference of the profits of supply chain between M0 and M1, i.e., $\Delta\pi_{10}^{sc}=(s-1)F - \frac{3(ez+c-a)^2}{16} + \frac{(192k^2-60k)(ez(r-1)+br-c+a)^2}{(32k-9)^2}$. When $k \ge 1/2$, then $\frac{(768k-243)(a-c-ez)^2+(3072k^2-960k)\left((b+ez)^2r^2+2(a-c-ez)(b+ez)\,r\right)}{16(32k-9)^2} > 0$.When $F \le F_I = \frac{(768k-243)(a-c-ez)^2+(3072k^2-960k)\left((b+ez)^2r^2+2(a-c-ez)(b+ez)\,r\right)}{16(32k-9)^2}$, there is $\Delta\pi_{10}^{sc} \ge 0$ under $\forall s$. When $F > F_I$, if $s \ge s_{III} = 1 - \frac{(768k-243)(a-c-ez)^2+(3072k^2-960k)\left((b+ez)^2r^2+2(a-c-ez)(b+ez)r\right)}{16(32k-9)^2F}$, there is $\Delta\pi_{10}^{sc} \ge 0$. If $s < s_{III}$, there is $\Delta\pi_{10}^{sc} < 0$. The proof of $\Delta\pi_{20}^{SC}$ is similar and omitted. The theorem is proved.

Proof of Theorem 5. Define ΔE_{10} as the manufacturer's carbon emission difference between M0 and M1, i.e., $\Delta E_{10} = \frac{32k-9-32k(1-r)^2}{4(32k-9)}ze^2 + \frac{32k(1-r)(br-c+a)-(32k-9)(a-c)}{4(32k-9)}e$. $\Delta E_{10} < 0$ means M1 is the minimum carbon emission model and manufacturer's carbon emission of FC subsidy is less than non-investment non-subsidy scenario. At this time, government subsidy can effectively promote carbon emission reduction. Otherwise M0 is the minimum carbon emission model and government subsidy doesn't contribute to carbon emission reduction. As analyzed by the proof of Theorem 1 above, the value limits of e can be obtained, that is $e < \frac{a-c}{z}$. When ΔE_{10} is equal to 0, there are two values of e, that is $\frac{-\frac{32k(1-r)(br-c+a)-(32k-9)(a-c)}{4(32k-9)}\pm\sqrt{\left(\frac{32k(1-r)(br-c+a)-(32k-9)(a-c)}{4(32k-9)}\right)^2}}{2*\frac{32k-9-32k(1-r)^2}{4(32k-9)}z}$. Let e_{II} be the positive one of the two values.

We set $f(r) = 32k(1-r)(br-c+a) - (32k-9)(a-c)$. Fig. A2 shows the relation between $f(r)$ and r. It can be seen that $f(r)$ has two intersections with the horizontal axis (r), one positive and one negative, i.e., $\left(\frac{-32k(b+c-a)\pm\sqrt{(32k(b+c-a))^2-4(-32kb)*9(a-c)}}{2(-32kb)}, 0\right)$.let $r_{III} = \frac{-32k(b+c-a)-\sqrt{(32k(b+c-a))^2-4(-32kb)*9(a-c)}}{2(-32kb)} > 0$. According to $e < \frac{a-c}{z}$ and $k \geq 1/2$, it can be proved that $r_{III} - \left(1-\sqrt{\frac{32k-9}{32k}}\right) = \left(8+\sqrt{\frac{32k-9}{32k}}\right)(a-c) + b\sqrt{32k-9}\left(\sqrt{32k}-\sqrt{32k-9}\right) > 0$ and $1 - r_{III} = (32k-9)(a-c) > 0$, that is $0 < 1-\sqrt{\frac{32k-9}{32k}} < r_{III} < 1$.

When $32k - 9 - 32k(1-r)^2 > 0$, i.e., $r > 1-\sqrt{\frac{32k-9}{32k}}$, the relation between ΔE_{10} and e can be shown in the Fig.A3(a). Fig.A3(a) shows that if $f(r) \geq 0$, then $1-\sqrt{\frac{32k-9}{32k}} < r \leq r_{III}$. At this time, for $\forall e \in \left(0, \frac{a-c}{z}\right)$, there is $\Delta E_{10} > 0$. If $f(r) < 0$, then $r_{III} < r < 1$. For $0 < e < min\left\{e_{II}, \frac{a-c}{z}\right\}$, there is $\Delta E_{10} < 0$. For $min\left\{e_{II}, \frac{a-c}{z}\right\} < e < \frac{a-c}{z}$, there is $\Delta E_{10} > 0$.

When $32k - 9 - 32k(1-r)^2 \leq 0$, i.e., $r \leq 1-\sqrt{\frac{32k-9}{32k}}$, there is $f(r) > 0$. The relation between ΔE_{10} and e can be shown in the Fig.A3(b). Fig.A3(b) illustrates that if $r < 1-\sqrt{\frac{32k-9}{32k}}$, for $0 < e < min\left\{e_{II}, \frac{a-c}{z}\right\}$, there is $\Delta E_{10} > 0$. For $min\left\{e_{II}, \frac{a-c}{z}\right\} < e < \frac{a-c}{z}$, there is $\Delta E_{10} < 0$. If $r = 1-\sqrt{\frac{32k-9}{32k}}$, there is a positive correlation between ΔE_{10} and e. For $\forall e \in \left(0, \frac{a-c}{z}\right)$, there is $\Delta E_{10} > 0$. The theorem is proved.

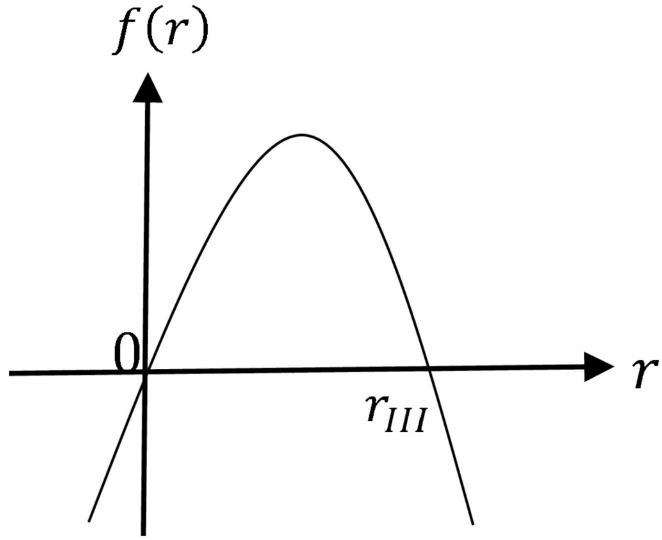
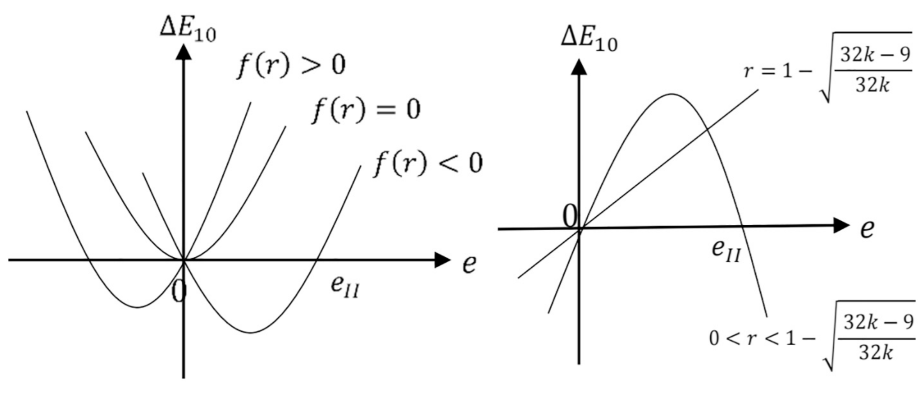


Fig. A2. Relations between $f(r)$ and r.



(a) $1-\sqrt{\frac{32k-9}{32k}} < r < 1$ (b) $0 < r \leq 1-\sqrt{\frac{32k-9}{32k}}$

Fig. A3. Relations between ΔE_{10} and e under different r.

Proof of theorem 6. Define $\Delta\pi_{12}^{M}$ as the manufacturer's profit difference between M1and M2, i.e., $\Delta\pi_{12}^{M} = \left(\frac{4k(br+ez(r-1)-c+a)^2}{32k-9} + (s-1)F + Az\right) - \left(\frac{4k(br+ez(r(s+1)-1)-c+a)^2}{32k-9} + Az - F\right)$. When the amounts of subsidies under two subsidy policies are the same, there is $s_1F = s_2erzq_2$, where s_1 and s_2 are the subsidy levels under FC subsidy and ER subsidy respectively. Thus, after simplifying $\Delta\pi_{12}^{M}$, we can find that $\Delta\pi_{12}^{M} = (4ke^2r^2z^2e^2s_2^2)/(32k-9)$. When

$k \geq 1/2$, then $32k - 9 > 0$ and $\Delta\pi_{12}^{M} > 0$. The theorem is proved.

Proof of Theorem 7. When the amounts of subsidies under two subsidy policies are the same, there is $s_1F = s_2erzq_2$, where s_1 and s_2 are the subsidy levels under FC subsidy and ER subsidy respectively. Define $\Delta\pi_{12}^{SC}$ as the supply chain's profit difference between M1and M2, i.e., $\Delta\pi_{12}^{SC} = (4ekrs_2z((12 - 32k)(a - c + br + ez(r - 1)) + (16k - 3)ezrs_2))/(32k - 9)^2$. When $k \geq 1/2$, there are $12 - 32k < 0$ and $16k - 3 > 0$. We set $f(s_2) = (12 - 32k)(a - c + br + ez(r - 1)) + (16k - 3)ezrs_2$. It can be proved that $r(16k - 9) + 12 - 32k < 0$. When $0 < e < \frac{(12-32k)(a-c+br)}{z(r(16k-9)+12-32k)}$, there are $s_2 < 1 < \frac{-(12-32k)(a-c+br+ez(r-1))}{(16k-3)ezr}$ and $f(s_2) < 0$. It means $\Delta\pi_{12}^{SC} < 0$ under $\forall s_2$. When $e > \frac{(12-32k)(a-c+br)}{z(r(16k-9)+12-32k)} > 0$, if $0 < s_2 < \frac{-(12-32k)(a-c+br+ez(r-1))}{(16k-3)ezr} < 1$, there are $f(s_2) < 0$ and $\Delta\pi_{12}^{SC} < 0$. If $1 > s_2 > \frac{-(12-32k)(a-c+br+ez(r-1))}{(16k-3)ezr}$, there are $f(s_2) > 0$ and $\Delta\pi_{12}^{SC} > 0$. The theorem is proved.

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