The Interplay of Green Subsidy Policies and Supply Chain Treatment Decisions

Yuyin Chen[1,a*], Bohan Dai[2,b]

{jyxylhl@163.com[a], 223030157@link.cuhk.edu.cn[b]}

International College Beijing, China Agricultural University, Beijing, 100091, China[1]
Chinese University of Hong Kong, Shen Zhen (CUHKSZ), Humanities and Social Science College, Master in Urban Studies, 518100, China [2]

Abstract. The independent research and development of emission-reducing technologies by a manufacturer in a green supply chain is frequently incentivized through green subsidies based on either the total technology investment cost or the degree of greenness in each produced unit. There are two types of emission-reducing technologies: cleaner process and end-of-pipe treatment. This paper investigates which technology would be the most profitable option for a manufacturer under one of the two subsidy policies, and which subsidy would be the optimal choice for the government to facilitate emission reduction after the adoption of a particular green technology. Four Stackelberg game models are constructed and analyzed in a green supply chain composed of one manufacturer and one retailer. Subsequently, numerical simulation is performed for further exploration. The results illustrate that the manufacturer should prefer the cleaner process as the optimal choice under either subsidy policy, and that subsidy for the greenness degree per product would be more effective for emission reduction than those for the overall R&D cost of a green technology after the implementation of either technology. The results may provide strategic references for decision-making of the government and manufacturers.

Keywords: Subsidy policies; green technologies; supply chain; emission reduction; Stackelberg game.

1 Introduction

Environmental pollution produced by industrial emissions has generated widespread publicity [1]. On one hand, with growing public awareness of environmental protection, green products now gain in popularity. On the other hand, policies to facilitate emission reduction in manufacturing processes prevail. Therefore, a mode of green supply chain management gain traction among manufacturers [2]. In a green supply chain, the manufacturer generally cuts down the release of contaminants through investment in independent research and development (R&D) of one of two emission-reducing technologies: cleaner process and end-of-pipe treatment. The former technology lessens industrial waste by advancing production processes, whilst the latter operates through pollutant collecting and recycling at the final stage of production [1,3,4]. However, investment in these technologies may involve ruinously high R&D expenditure for manufacturers, for which governments usually impose emissions taxes or provide green subsidies to incentivize manufacturers to engage in a green supply chain [3]. There are two major relevant subsidy policies: subsidizing investment in R&D cost or

ICEMBDA 2023, October 27-29, Tianjin, People's Republic of China

DOI 10.4108/eai.27-10-2023.2341946

subsidizing a manufacturer based on emission reduction level per unit of product [2,5,6,7,8,9]. It remains popular and significant for researchers to explore which emission-reducing technology a manufacturer should employ and, equally importantly, which subsidy policy the government should adopt [3,5].

Previous studies have widely discussed decision-making behaviors or optimal strategies of various stakeholders, including manufacturers, suppliers, and retailers in idealized green supply chains under a range of government policies. Most examinations have been conducted through the development of game models. However, there remains a gap in the literature concerning two aspects: the specific choice of emission-reducing technologies that a manufacturer would adopt for the maximum profit under one of the two predominant subsidies, and the determination of which subsidy the government should apply when the manufacturer has developed a particular technology. In this light, the study aims to probe into the optimum strategies for the government and the manufacturer in a green supply chain under a pollution tax and two major green subsidies. To achieve this objective, based on a two-stage supply chain composed of a manufacturer and a retailer, a Stackelberg game model in which the manufacturer is the leader would be established for a detailed discussion on the best decisions in different scenarios. Then data simulation will be conducted to further demonstrate the results. This research promises to provide a theoretical reference for policy-makers and stakeholders in the manufacturing industry regarding the formulation and implementation of reasonable strategies.

2 Literature review

Extensive research has been conducted on factors affecting emission reduction level or profits in green supply chains under different conditions. Ali Borumand and Morteza Rasti-Barzok introduced a Stackelberg game model in a hypothetical green supply chain, where the retailer's investment in advertising green products was examined to identify the factors influencing profit-seeking behaviors in the supply chain. They concluded that the manufacturer would be hesitant to reduce the pollutant emissions unless the sensitivity of customer demand to market prices is above a certain level [10]. Chang Su et al. assumed a supply chain consisting of a producer and a retailer and employed the Stackelberg game to compare the carbon-emission levels, wholesale prices, and retail prices in scenarios with subsidies for green consumption and for the producer, both based on emission reduction level per product sold [11]. Junsong Bian and Zhao Xuan envisaged a three-tier supply chain with a single manufacturer and multiple competitive retailers to explore whether an emission tax or subsidies for investments in emission cuts would be more conducive to profits of the supply chain and emission reduction level [12]. Cheng Che et al. compared the emission reduction levels and profits in a dual-channel supply chain between manufacturers' participation in carbon trading and green finance loans, from the perspective of the Stackelberg game [13]. Ruxia Lyu et al. discussed the effects of three optional policies: cap-and-trade, carbon emission quota, and carbon tax on emissions reduction, as well as manufacturers' decisions in R&D investment and recycling [14]. Meanwhile, Yongxi Yi et al. focused on the maximum profits of the manufacturer and the retailer when the government chooses between taxing and subsidizing, arguing that the manufacturer profits more from an emission tax instead of a green subsidy, given that the cost of green technology R&D is relatively high or the marginal damage caused by pollution is comparatively low [15]. All of the above studies started with the establishment of game models in a framework of green supply chains for further discussion, which demonstrates their methodological relevance to this paper.

However, the above research made no mention of differences in performance between two major green subsidy policies: subsidizing green technology investment and subsidizing emission reduction level per product. More closely related to this paper is one research stream that take into consideration the category of green subsidies. For instance, Bo Fan et al. investigated discrepancies in production strategies and social welfare between the effects of the two subsidies after including investment spillover and technological risks in their game model [7]. Xiyu Cao et al. probed into the optimum emission reduction level determined by duopoly manufacturers under the influence of these two subsidies, preconditioned by a contract for supply chain coordination [6]. Di Sun and Yumiao Yu constructed a two-stage game model in a supply chain comprising duopoly manufacturers and the government. They analyzed how the market demand for a green product and overall social welfare is altered by changes in the levels of the two subsidies [9]. Xingqi Wen et al. utilized the Stackelberg game to compare levels of emission reduction and profits in the supply chain, while the government selects one out of three available policies: subsidies based on production costs, investment in green technology, and the extent of emission reduction per product. The team led by Xingqi Wen demonstrated that the subsidy aiming at the technology investment cost would be optimal if the emission reduction per unit of product is the very criterion for a policy evaluation [2]. Zhiming Li et al. sought to determine which of the two subsidies delivers greater benefits to the manufacturer and the retailer, provided that the cap-and-trade system comes into effect [8]. Yong He et al. conducted an analysis of the effects of the two green subsidies on emission reduction and the profit of the manufacturer. They considered either independent R&D or outsourcing R&D of green technology in a Stackelberg game model. Their findings asserted that the subsidy based upon investment cost would translate into a healthier decline in emissions but lower profits for the producer, compared with the alternative, as long as the producer employs independent R&D [5].

However, the literature mentioned above reckoned without categorizing the emission-reducing technologies into two distinct forms: cleaner process and end-of-pipe treatment. The categorization of green technologies is underlined in another research stream closely related to this paper. For instance, Hua Zhou et al. were the first to strictly and formally divide green technologies into two modes [4]. Dongdong Li and Jingyu Yang established a three-stage dynamic game model where the government considered technology spillover and subsidized the duopoly manufacturers according to their effective technical level. The influence of tax and technology spillover on social welfare was then discussed, with both forms of green technologies considered [3]. Susu Cheng and Fan Zhang examined the impact of the penalty-sharing contract on a green supply chain containing one manufacturer and one retailer, given that the manufacturer can choose between the two green technologies. Their findings indicated that the cleaner process generates greater social welfare and total profit for the supply chain compared to end-of-pipe treatment when the efficiency of lessening the emission stays relatively high [1].

In light of the literature stated above, it can be felt that the influence of a series of factors on behaviors and optimal strategies in modelized green supply chains has been expansively discussed. However, limitations remain in previous studies, since they have yet to consider both the distinction between two major subsidy policies and the difference between two green technologies. This study, based on the professionality and precision of previous studies, seeks to enrich the research stream of green supply chain management by exploring how the combinations between two subsidies and two technologies can induce varying effects on the supply chain.

3 Model construction and analyses

3.1 problem definition

The research concentrates on a two-stage green supply chain consisting of one manufacturer and one retailer specializing in green products. To mitigate the burden of emission tax and utilize the preference of environmentally conscious consumers, the manufacturer conducts independent research and development to create a particular emission-reducing technology. The technology, selected out of two options, promises to mitigate the emission of pollutants generated in the production process. The consumers are environmentally conscious, characterized by a preference for products with a high greenness level, or in other words, a significant level of emission reduction per product unit [15]. The government plans to subsidize the R&D of green technology by choosing from two subsidy models: one based on the total R&D investment and the other based on the extent of emission reduction per product. The manufacturer's responses to different subsidy policies tend to diverge. This study aims to address two main questions: firstly, if the form of green subsidy has been decided, which technology should be considered from the perspective of the manufacturer? Secondly, if a mode of technology has been developed, which subsidy should be employed from the perspective of the government?

3.2 basic assumptions

The study assumes that the manufacturer is the leader who determines the emission reduction level and the wholesale price, and that the retailer is the follower who decides the retail price based on the manufacturer's choices in a framework of the Stackelberg game. Both sides of the game pursue the maximum profits.

The market demand for a green product is dominated by retail price and the greenness degree [2,5]. Market demand D can be explained as:

$$D = a - bp_{ij} + cx_{ij} \tag{1}$$

Where a is the original market demand, p is the retail price, b is the coefficient of customers' sensitivity to a rise in price; x is the product's greenness degree, or rather, the emission reduction level per product [15]; c is the coefficient of consumers' green preference; i equals 1 if the cleaner process is adopted, and 2 if the end-of-pipe treatment is used; j equals 1 if the government subsidizes total R&D investment, and 2 if the subsidy is directed towards emission reduction per product unit. Assume that the market demand D equals production quantity q and also the retail volume [8].

The R&D investment $C(x)$ can be exhibited by emission reduction level per product x as:

$$C(x_{1j}) = \frac{1}{2}\alpha x_{1j}^2 \text{, if adopting cleaner process} \tag{2}$$

$$C(x_{2j}) = \frac{1}{2}\beta x_{2j}^2 \text{, if adopting end-of-pipe treatment} \tag{3}$$

Where α and β are respectively the input cost coefficients of the two technologies [2,3,5,11,16].

When the government subsidizes R&D input cost, the aggregate expenditure on the green subsidy would be: ηx_{i1}^2, in which η is the R&D cost subsidy coefficient. For subsidies based on the degree of greenness per product, the subsidy expenditure per product is: μx_{i2}, in which μ is the greenness degree subsidy coefficient [2,5].

The government can impose an emissions tax and subsidize green technology simultaneously [3]. Assume an emissions tax of t per unit of pollutant and set the emission level of contaminants at e. According to Dongdong Li and Jingyu Yang [3], with the cleaner process, the total emissions tax can be denoted as follows:

$$te = t(\lambda - x)q \tag{4}$$

In the case of end-of-pipe treatment, the total tax can be signified by:

$$te = t(\lambda q - x) \tag{5}$$

where λ is the pollutant emission coefficient ($\lambda > 0$).

For the above two equations, it is noteworthy that the technology spillover is not considered due to the single manufacturer scenario in the hypothetical supply chain, in which x exactly represents the "effective R&D level per product" as it was mentioned by Dongdong Li's team [3].

3.3 Game equilibrium: subsidizing R&D investment, cleaner process

In this combination, the government chooses an R&D input cost subsidy, while the manufacturer employs the cleaner process. Based on the assumptions above, the expected profit functions for the manufacturer and the retailer are demonstrated as follows:

$$\pi_{11}^M = (w_{11} - v - t(\lambda - x_{11}))(a - bp_{11} + cx_{11}) - \frac{1}{2}\alpha x_{11}^2 + \eta x_{11}^2 \tag{6}$$

$$\pi_{11}^S = (p_{11} - w_{11})(a - bp_{11} + cx_{11}) \tag{7}$$

where w_{11} is the wholesale price per unit of product, and v is the production cost per unit. Irrespective of whether a green technology is developed or not, the production cost per unit is assumed to remain unchanged [2]. The calculated values of values of w_{11}, p_{11} and x_{11} should simultaneously guarantee the maximum values of π_{11}^M and π_{11}^S. On this account, the backward induction method is employed:

Firstly, resolve $\frac{\partial \pi_{11}^S}{\partial p_{11}} = 0$ based on equation (7), to obtain:

$$p_{11} = \frac{a+bw11+cx11}{2b} \tag{8}$$

Substitute the p_{11} from equation (8) into (6) to obtain:

$$\pi_{11}^M = -\frac{{x_{11}}^2\alpha}{2} + x_{11}^2\eta + (a + cx_{11} + \frac{1}{2}(-a - bw_{11} - cx_{11}))(-v + w_{11} - t(-x_{11} + \lambda)) \tag{9}$$

Set the first-order partial derivatives of equation (9) with respect to w and x to be zero, to obtain simultaneous equations:

$$\frac{\partial \pi_{11}^{S}}{\partial w_{11}}=0, \text{ and } \frac{\partial \pi_{11}^{S}}{\partial x_{11}}=0 \tag{10}$$

Solve these equations to obtain:

$$w_{11}=\frac{a(ct+bt^2-2\alpha+4\eta)+(c^2+bct-2b\alpha+4b\eta)(v+t\lambda)}{c^2+2bct+b(bt^2-4\alpha+8\eta)} \tag{11}$$

$$x_{11}=\frac{(c+bt)(-a+b(v+t\lambda))}{c^2+2bct+b(bt^2-4\alpha+8\eta)} \tag{12}$$

Calculate the second-order partial derivatives of equation (9) with respect to w and x to obtain its Hessian matrix H:

$$H=\begin{bmatrix} ct-\alpha+2\eta & \frac{c}{2}-\frac{bt}{2} \\ \frac{c}{2}-\frac{bt}{2} & -b \end{bmatrix} \tag{13}$$

To secure the maximum values of π_{11}^{M} and π_{11}^{S} when (11) and (12) are satisfied, it should be guaranteed in (13) that $D_1<0$ and $D_2>0$, that is:

$$ct-\alpha+2\eta<0, \text{ and } -\frac{c^2}{4}-\frac{bct}{2}-\frac{b^2t^2}{4}+b\alpha-2b\eta>0$$

Substitute the equation (11) and (12) into (8) to obtain the expression for the optimum retail price:

$$p_{11}=\frac{a(ct+bt^2-3\alpha+6\eta)+(c^2+bct-b\alpha+2b\eta)(v+t\lambda)}{c^2+2bct+b(bt^2-4\alpha+8\eta)} \tag{14}$$

Finally, by plugging (11), (12) and (14) into (6) and (7), it is evaluated that:

$$\pi_{11}^{M}-\frac{(\alpha-2\eta)(a-b(v+t\lambda))^2}{2(c^2+2bct+b(bt^2-4\alpha+8\eta))} \tag{15}$$

$$\pi_{11}^{S}=\frac{b(\alpha-2\eta)^2(a-b(v+t\lambda))^2}{(c^2+2bct+b(bt^2-4\alpha+8\eta))^2} \tag{16}$$

To maintain economically sensible values, the parameter values should satisfy the condition: $\pi^{M}, \pi^{S}, p, w, x>0$

Corollary 1.

An increase in the input cost coefficient of cleaner process technology translates into a higher greenness degree per product unit, and a decline in the maximum profits of both the manufacturer and the retailer. By contrast, a rise in customers' green preferences leads to a lower emission level per product, an increase in the maximum profit of the manufacturer, and a downward trend in that of the retailer.

Proof: $\frac{\partial x_{11}}{\partial \alpha}>0, \frac{\partial \pi_{11}^{M}}{\partial \alpha}<0, \frac{\partial \pi_{11}^{S}}{\partial \alpha}<0, \frac{\partial x_{11}}{\partial c}<0, \frac{\partial \pi_{11}^{M}}{\partial c}>0, \frac{\partial \pi_{11}^{S}}{\partial c}<0$

3.4 Game equilibrium: subsidizing greenness degree per product, cleaner process

In this combination, the government provides the subsidy on the basis of emission reduction per unit of product, while the manufacturer adopts cleaner process. The expected profits in the green supply chain are as follows:

$$\pi_{12}^{M} = (w_{12} - v + \mu x_{12} - t(\lambda - x_{12}))(a - bp_{12} + cx_{12}) - \frac{1}{2}\alpha x_{12}^{2} \quad (17)$$

$$\pi_{12}^{S} = (p_{12} - w_{12})(a - bp_{12} + cx_{12}) \quad (18)$$

Under the conditions $-\alpha + c(t + \mu) < 0$, $-\frac{c^2}{4} - \frac{bct}{2} - \frac{b^2t^2}{4} + b\alpha - \frac{bc\mu}{2} - \frac{1}{2}b^2t\mu - \frac{b^2\mu^2}{4} > 0$, the application of the identical calculation as outlined in section 3.3 yields the following optimum values:

$$p_{12} = \frac{(v+t\lambda)(c^2-b\alpha+bc(t+\mu))+a(-3\alpha+c(t+\mu)+b(t+\mu)^2)}{c^2+2bc(t+\mu)+b(-4\alpha+b(t+\mu)^2)} \quad (19)$$

$$w_{12} = \frac{(v+t\lambda)(c^2-2b\alpha+bc(t+\mu))+a(-2\alpha+c(t+\mu)+b(t+\mu)^2)}{c^2+2bc(t+\mu)+b(-4\alpha+b(t+\mu)^2)} \quad (20)$$

$$x_{12} = -\frac{(a-b(v+t\lambda))(c+b(t+\mu))}{c^2+2bc(t+\mu)+b(-4\alpha+b(t+\mu)^2)} \quad (21)$$

The maximum profits of the manufacturer and the retailer are as follows:

$$\pi_{12}^{M} = -\frac{\alpha(a-b(v+t\lambda))^2}{2(c^2+2bc(t+\mu)+b(-4\alpha+b(t+\mu)^2))} \quad (22)$$

$$\pi_{12}^{S} = \frac{b\alpha^2(a-b(v+t\lambda))^2}{(c^2+2bc(t+\mu)+b(-4\alpha+b(t+\mu)^2))^2} \quad (23)$$

Corollary 2.

If the government subsidizes greenness degree per product while the manufacturer employs the cleaner process, an increase in input cost coefficient of the technology will give rise to a drop in the greenness degree per product, as well as the maximum profits of the green supply chain; the subsidy with greater effort will result in an upward trajectory of both the greenness degree per product and the maximum profits of the supply chain.

Proof: $\frac{\partial x_{12}}{\partial \alpha} < 0, \frac{\partial \pi_{12}^{M}}{\partial \alpha} < 0, \frac{\partial \pi_{12}^{S}}{\partial \alpha} < 0, \frac{\partial x_{12}}{\partial \mu} > 0, \frac{\partial M_{12}}{\partial \mu} > 0, \frac{\partial S_{12}}{\partial \mu} > 0$

3.5 Game equilibrium: subsidizing R&D investment, end-of-pipe treatment

In this combination, the strategy of the manufacturer is to research and develop the end-of-pipe treatment, against the backdrop of R&D input cost subsidy. Below are the expected profit functions of the green supply chain:

$$\pi_{21}^{M} = (w_{21} - v)(a - bp_{21} + cx_{21}) - \frac{1}{2}\beta x_{21}^{2} + \eta x_{21}^{2} - t\lambda(a - bp_{21} + cx_{21}) + tx_{21} \quad (24)$$

$$\pi_{21}^{S} = (p_{21} - w_{21})(a - bp_{21} + cx_{21}) \quad (25)$$

With the range limited by $-\beta + 2\eta < 0$ and $-\frac{c^2}{4} + b\beta - 2b\eta > 0$, a repetition of the same method as demonstrated above yields the following results.

$$p_{21} = \frac{-3ct+c^2(v+t\lambda)-(\beta-2\eta)(3a+b(v+t\lambda))}{c^2-4b\beta+8b\eta} \quad (26)$$

$$w_{21} = \frac{-2ct+c^2(v+t\lambda)-2(\beta-2\eta)(a+b(v+t\lambda))}{c^2-4b\beta+8b\eta} \quad (27)$$

$$x_{21} = \frac{-ac+bcv+bt(-4+c\lambda)}{c^2-4b\beta+8b\eta} \quad (28)$$

The maximum profits achievable in the supply chain are:

$$\pi_{21}^{M} = -\frac{a^2(\beta-2\eta)+2a(ct-b(\beta-2\eta)(v+t\lambda))+b(bv^2(\beta-2\eta)-2tv(c-b(\beta-2\eta)\lambda)+t^2(4-2c\lambda+b(\beta-2\eta)\lambda^2))}{2(c^2-4b\beta+8b\eta)} \quad (29)$$

$$\pi_{21}^{S} = \frac{b(ct+(\beta-2\eta)(a-b(v+t\lambda)))^2}{(c^2-4b\beta+8b\eta)^2} \quad (30)$$

Corollary 3.

An increase in the input cost coefficient of the end-of-pipe treatment can induce a downtrend of the wholesale price, retail price, greenness degree per product, and the optimum profits of the manufacturer; the retailer's maximum profit also declines if $ct > (2\eta-\beta)(a-b(v+t\lambda))$. A higher level of the subsidy coefficient leads to an uptrend of the wholesale price, retail price, greenness per product, and a lower optimum value of the manufacturer's profit; the retailer can receive a higher maximum profit level if $ct > (2\eta-\beta)(a-b(v+t\lambda))$.

Proof: $\frac{\partial w_{21}}{\partial\beta} < 0$, $\frac{\partial p_{21}}{\partial\beta} < 0$, $\frac{\partial x_{21}}{\partial\beta} < 0$, $\frac{\partial \pi_{21}^{M}}{\partial\beta} < 0$, $\frac{\partial w_{21}}{\partial\eta} > 0$, $\frac{\partial p_{21}}{\partial\eta} > 0$, $\frac{\partial x_{21}}{\partial\eta} > 0$, $\frac{\partial \pi_{21}^{M}}{\partial\eta} < 0$

for $\frac{\partial \pi_{21}^{S}}{\partial\beta} = \frac{2bc(ac-b(cv+t(-4+c\lambda)))(ct+(\beta-2\eta)(a-b(v+t\lambda)))}{(c^2-4b\beta+8b\eta)^3}$:

$c^2-4b\beta+8b\eta < 0 \rightarrow (c^2-4b\beta+8b\eta)^3 < 0$

$x_{21} = \frac{-ac+bcv+bt(-4+c\lambda)}{c^2-4b\beta+8b\eta} > 0 \rightarrow ac-b(cv+t(-4+c\lambda) > 0$

hence, if $\frac{\partial \pi_{21}^{S}}{\partial\beta} < 0$, then $ct+(\beta-2\eta)\big(a-b(v+t\lambda)\big) > 0$

in the same way, for $\frac{\partial \pi_{21}^{S}}{\partial\eta} = \frac{4bc(-ac+bcv+bt(-4+c\lambda))(ct+(\beta-2\eta)(a-b(v+t\lambda)))}{(c^2-4b\beta+8b\eta)^3}$:

if $\frac{\partial \pi_{21}^{S}}{\partial\eta} > 0$, then $ct+(\beta-2\eta)\big(a-b(v+t\lambda)\big) > 0$

3.6 Game equilibrium: subsidizing greenness degree per product, end-of-pipe treatment

In this combination, the producer prefers the end-of-pipe-treatment; the government implements a green subsidy based on the level of emission reduction per product. The expected profit functions of the green supply chain are as follows:

$$\pi_{22}^{M} = (w_{22}-v+\mu x_{22})(a-bp_{22}+cx_{22}) - \frac{1}{2}\beta x_{22}^2 - t\lambda(a-bp_{22}+cx_{22}) + tx_{22} \quad (31)$$

$$\pi_{22}^{S} = (p_{22}-w_{22})(a-bp_{22}+cx_{22}) \quad (32)$$

Within the range of $-\beta+c\mu < 0$ and $-\frac{c^2}{4}+b\beta-\frac{bc\mu}{2}-\frac{b^2\mu^2}{4} > 0$, the optimum values of p, w, x in case 3.6 are:

$$p_{22} = \frac{-3a\beta-bv\beta-bt\beta\lambda+c^2(v+t\lambda)+bt\mu+c(a+bv)\mu+ab\mu^2+ct(-3+b\lambda\mu)}{c^2+2bc\mu+b(-4\beta+b\mu^2)} \quad (33)$$

$$w_{22} = \frac{c^2(v+t\lambda)+c(a+bv)\mu-2b(v\beta+t\beta\lambda-t\mu)+ct(-2+b\lambda\mu)+a(-2\beta+b\mu^2)}{c^2+2bc\mu+b(-4\beta+b\mu^2)} \quad (34)$$

$$x_{22} = \frac{-a(c+b\mu)+bv(c+b\mu)+bt(-4+c\lambda+b\lambda\mu)}{c^2+2bc\mu+b(-4\beta+b\mu^2)} \quad (35)$$

The maximum profits of the green supply chain are:

$$\pi_{22}^{M} = \frac{2act+a^2\beta-2ab(v\beta+t\beta\lambda-t\mu)+b(bv^2\beta+t^2(4-2c\lambda+b\lambda(\beta\lambda-2\mu))-2tv(c+b(-\beta\lambda+\mu)))}{2(c^2+2bc\mu+b(-4\beta+b\mu^2))} \quad (36)$$

$$\pi_{22}^{S} = \frac{b(ct+a\beta-b(v\beta+t\beta\lambda-t\mu))^2}{(c^2+2bc\mu+b(-4\beta+b\mu^2))^2} \quad (37)$$

Corollary 4.

A higher level of R&D cost coefficient of the end-of-pipe treatment contributes to a lower degree of emission reduction per product and a higher maximum value of the manufacturer's profit; it also leads to higher maximum profit of the retailer if $ct + a\beta < b(v\beta + t\beta\lambda - t\mu)$.

Proof: $\frac{\partial x_{22}}{\partial \beta} < 0, \frac{\partial \pi_{22}^{M}}{\partial \beta} > 0$

for $\frac{\partial \pi_{22}^{S}}{\partial \beta} = -\frac{2b(c+b\mu)(ct+a\beta-b(v\beta+t\beta\lambda-t\mu))(-a(c+b\mu)+bv(c+b\mu)+bt(-4+c\lambda+b\lambda\mu))}{(c^2+2bc\mu+b(-4\beta+b\mu^2))^3}$,

$2b(c + b\mu) > 0, (c^2 + 2bc\mu + b(-4\beta + b\mu^2))^3 < 0$,

$x_{22} > 0 \rightarrow -a(c + b\mu) + bv(c + b\mu) + bt(-4 + c\lambda + b\lambda\mu) < 0$

$\rightarrow$ if $\frac{\partial \pi_{22}^{S}}{\partial \beta} > 0$, then $ct + a\beta - b(v\beta + t\beta\lambda - t\mu) < 0$

The higher the initial market demand, the lower the greenness degree per product. In addition, higher maximum profits can be achieved in the supply chain provided that $ct + a\beta < b(v\beta + t\beta\lambda - t\mu)$. These two lines of reasoning can be corroborated by the identical approach applied previously.

4 Numerical analysis

This study inclines not to engage in subtraction or simplification for comparing the values of two subsidy policies or two R&D strategies, such as $\pi_{11}^{M} - \pi_{12}^{M}$. This decision is influenced by the introduction of extra parameters λ and t, which, as opposed to some similar research [2,5], ruinously amplify complexity in any attempt at comparing the equations and disenable this mode of comparison. Instead, numerical analysis will be directly performed. The values or ranges of parameters are partly derived from Dongdong Li and Jingyu Yang [3], Xingqi Wen et al. [2], and Yong He et al. [5]. Firstly, the values of the parameters are assumed. These values are then adjusted repeatedly to ensure their adherence to the establishment conditions of game equilibriums, and also maintain economic feasibility on the graph. The adjusted parameters are: $a = 1500, b = 10, c = 10, v = 30, t = 1, \lambda = 0.5, \mu = 1, \eta = 20$. By applying Mathematica software, the simulation diagrams are exhibited as follows:

Case 1.

It is assumed that neither the manufacturer nor the government can pinpoint the exact values of R&D costs for the two technologies before one is chosen. Therefore, the government initially and tentatively determines the coefficient levels of the two major subsidies, regardless of the manufacturer's decision. Upon receiving information on the policy, the manufacturer, after sketchy evaluations, narrows down the R&D input costs into certain ranges: $\alpha \in [300,400]$, $\beta \in [200,300]$. It can be inferred from Dongdong Li's work [3] that the cleaner process may incur higher costs than the end-of-pipe treatment.

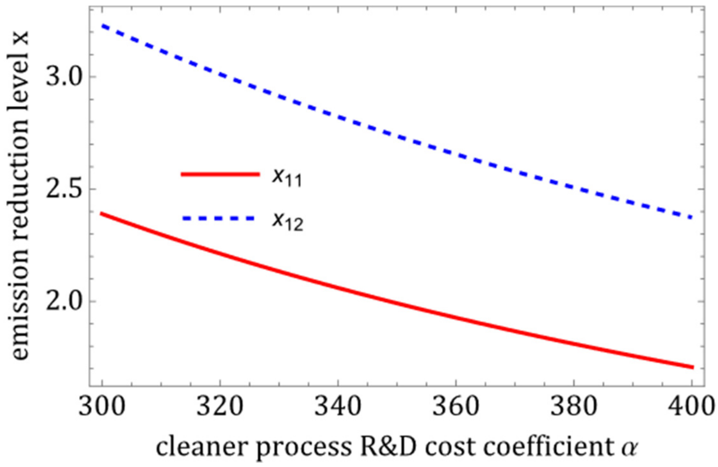

Fig. 1. The effect of the cleaner process R&D cost coefficient α on emission reduction level x, with the government deciding first.

Figure 1. illustrates the variation of greenness values per product according to an increase in the R&D cost coefficient of the cleaner process in a case where the producer decides to employ the cleaner process. Irrespective of the R&D cost rate of the cleaner process, it is pronounced from the given values of the two subsidies that the emission reduction per product, with the application of the total investment subsidy, is lower than the other option.

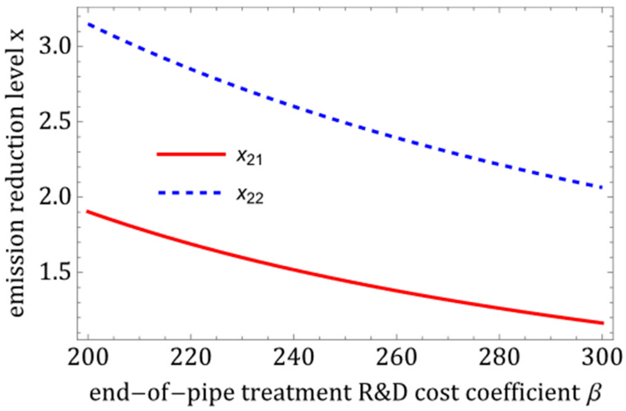

Fig. 2. The effect of the end-of-pipe treatment R&D cost coefficient β on emission reduction level x, with the government deciding first.

From Figures 1. and 2. it can be concluded that regardless of the eventual technology choice made by the producer, subsidizing the greenness degree per product beforehand always introduces a higher emission reduction level than subsidizing the total R&D cost. This finding tends to contradict one conclusion drawn by Yong He et al. [5], who argued that higher emission reduction levels are derived instead from the R&D cost subsidy. It is also noteworthy in the two figures that increases in the cost coefficient of both technologies lead to lower intensity of emission reduction.

However, the manufacturer would instead concentrate on its maximum profit available in decision-making:

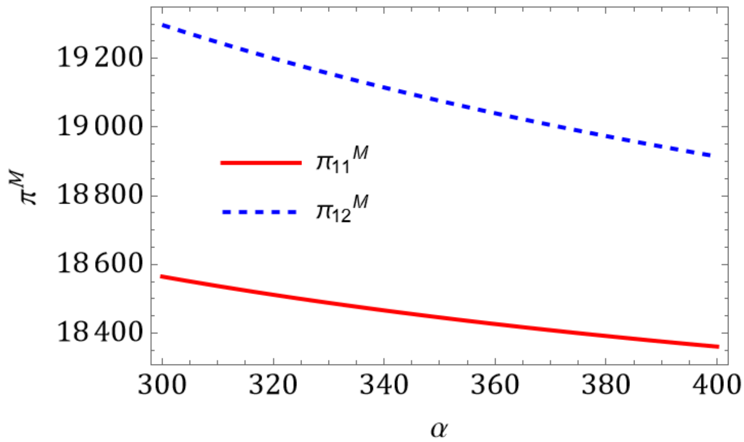

Fig. 3. The effect of the cleaner process R&D cost coefficient α on the maximum profit π^M, with the government deciding first.

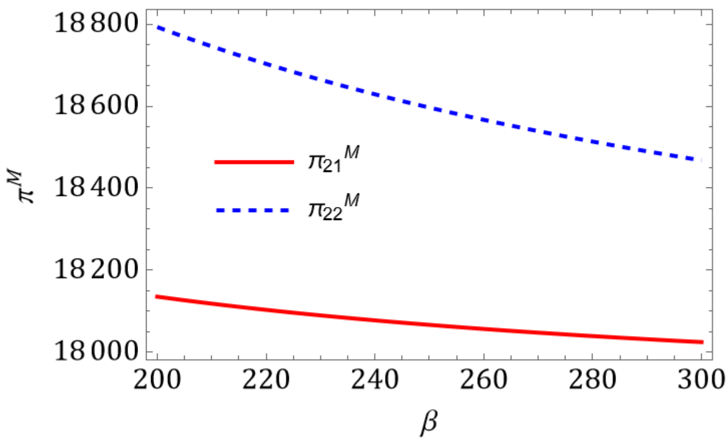

Fig. 4. The effect of the end-of-pipe treatment R&D cost coefficient β on the maximum profit π^M, with the government deciding first.

An observation of Figures 3. and 4. indicates that regardless of the technology chosen for development, subsidizing the greenness degree per unit in advance always facilitates the profit of the producer more effectively than subsidizing the total R&D cost. This finding aligns with one conclusion reached by Yong He et al. [5]. Their team asserted that subsidizing the total

R&D cost leads to a lower maximum profit than subsidizing the emission reduction level per product, especially when the producer develops innovative technology [5].

Secondly and more importantly, based on an analysis of the declining trends of these functions in Figures 3. and 4., and the significant difference between π_{11}^{M} and π_{21}^{M} where $\alpha = \beta = 300$, it can be deduced that the maximum profit, under the total R&D cost subsidy policy, when the manufacturer adopts the cleaner process, is greater than that of developing end-of-pipe treatment for the producer. This holds true as long as the R&D cost coefficients of the two technologies do not exhibit overly significant divergence. In the same way, when the government subsidizes the emission reduction level per unit, the manufacturer would employ the cleaner process to maximize profit, given that the R&D cost coefficients of the two technologies do not exhibit overly significant divergence. These two findings share similarities with the research by Dongdong Li and Jingyu Yang [3], who concluded that the cleaner process leads to a greater maximum profit than the end-of-pipe treatment if the government subsidizes the producer's effective emission reduction level.

Case 2.

In this case, the manufacturer determines the form of the green technology first, and then the government decides which subsidy policy to implement. The government puts greater emphasis on the emission reduction level than on the maximum profit of the manufacturer in this model. Hence, only the greenness degree per product will be evaluated. The government has access to the R&D cost coefficient of either the cleaner process or the end-of-pipe treatment, but not both (setting α=300 or β=200). Previous literature, when repeatedly using the μ as abscissa, tended to strictly equalize the total expenditure of the two subsidies, which entails that the coefficient μ and η were not fixed at a certain level in these works [2,5,8]. In this paper, however, η is fixed at 20, while the parameter μ remains the variable on the abscissa, because if the government were to adjust the value of η according to the changing value of μ, it would have to firstly ascertain the accurate values of both α and β. This would be a rather complex task, as in reality, the producer would not adopt both technologies at the same time [4].

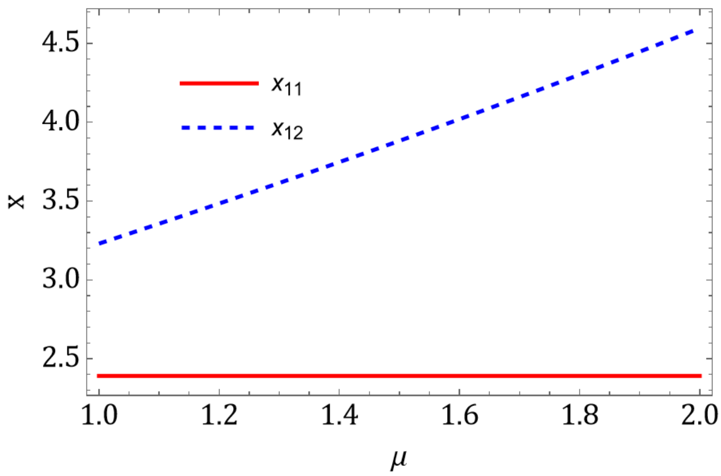

Fig. 5. The effect of per-unit greenness subsidy coefficient μ on emission reduction level x, with the manufacturer implementing the cleaner process first.

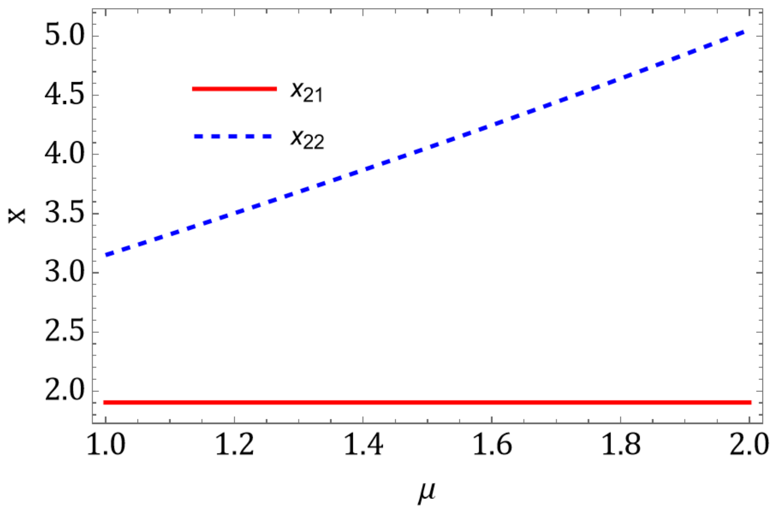

Fig. 6. The effect of per-unit greenness subsidy coefficient μ on emission reduction level x, with the manufacturer implementing the end-of-pipe treatment first.

After the confirmed development of the cleaner process, the government proceeds to observe the change in emission reduction level per product x as the greenness degree subsidy coefficient μ ranges from 1.0 to 2.0. It is observed in Figure 5. that greenness level subsidy per unit contributes to greater emission reduction when the cleaner process is employed within the projected range of μ. The trend remains the same when it comes to the selection of the end-of-pipe treatment, as can be seen in Figure 6. These two findings are similar to one conclusion shown in the literature of Zhiming Li et al., even though Zhiming Li's team presupposed that the total costs of the two subsidies are strictly identical [8]. They indicated that the total emission amount of the manufacturer is lower under the emission reduction level subsidy compared with the use of another subsidy [8].

5 Conclusions

This paper delves into the optimum choice of the manufacturer in a green supply chain between establishing the cleaner process and developing the end-of-pipe treatment in the context of government implementation of one of the two major green subsidy policies: the greenness degree subsidy per product, or the total R&D investment subsidy. The study also considers the optimum selection between the two subsidies for the government to cope with an established technology form. Two feasible subsidies and two available technologies combine into four cases, for which the backward induction method is adopted to yield the optimal values for emission reduction and greatest profits achievable in the supply chain. Furthermore, a numerical simulation is performed to further observe the behavioral inclinations of the green supply chain and the government. For all the above analyses, the major strategic references potentially conducive to a green supply chain are as follows:

Firstly, in cases where a subsidy policy is in place before the manufacturer determines which technology to choose, a rational manufacturer would prefer the cleaner process to maximize profit. This preference holds regardless of which subsidy the government provides.

Secondly, from the perspective of the government, subsidizing the greenness degree per product proves preferable to subsidizing the overall R&D cost of a green technology in terms of the aim of emission reduction, independent of which technology the producer chooses to develop, whether the manufacturer or the government initiates the decision-making process, and whether the rate of each R&D cost coefficient is high or low.

However, the study has several limitations. Firstly, it overlooks the situations that involve multiple competing or cooperating manufacturers and retailers. Secondly, it does not take into account the effects of the emissions tax on maximum profits and emission reduction level. Thirdly, it fails to address the maximum profit and pricing strategies of the retailer. These questions remain to be resolved in future literature.

Acknowledgments. Yuyin Chen: modelling, numerical analyses, writing the original draft.

Bohan Dai: topic selection, gleaning previous literature, paper revision.

References

[1] SuSu, C., Fan, Z. (2022). Optimal Emission — Reducing Technology Selection for Green Supply Chain Under Penalty — Sharing Contract. Soft Science. 36(10): 131-137

[2] Xingqi, W., Haifang, C., Jianhu, C., Chao L. (2018). Government Subsidy Policies and Effect Analysis in Green Supply Chain. Chinese Journal of Management. 15(4): 625-632

[3] Dongdong, L., Jingyu, Y. (2019). Choice of Optimal Environmental Technology Based on Government Subsidy. Chinese Journal of Management Science. 27(7): 177-185

[4] Hua, Z., Xuejiao, Z., Qiuyong, Z. (2012). The Design of Environmental Policy Instrument Based on the Incentives to Environmental Technology Innovation of Small and Medium-Sized Enterprises. 33(5): 8-18

[5] Yong, H., Zhihao, C., Nuo, L. The Impact Mechanism of Government Subsidy Approach on Manufacturer's Decision-making in Green Supply Chain. Chinese Journal of Management Science. 30(6): 87-98

[6] Xiyu, C., Yanhua, Q., Jiefang, Z. (2017). Carbon Reduction Strategy and Coordination of Supply Chain under Different Government Subsidy Modes. 51(1): 93-99

[7] . Bo, F., Weidong, M., Guowang, M. (2010). Research on Government Subsidy Policy of R&D Alliance Based on Investment Spillover. Science & Technology Progress and Policy. 27(16): 89-92

[8] Zhiming, L. Yanchun, P., Wen, Y., Jianhua, M., Ming, Z. (2021). Effects of Government Subsidies on Green Technology Investment and Green Marketing Coordination of Supply Chain under the Cap-and-trade Mechanism. Energy Economics. 101, 105426

[9] Di, S., Yumiao, Y. (2018). Determination of Optimal Government Subsidy Policy in Green Product Market. Chinese Journal of Management. 15(1): 118-126

[10] Borumand, A., Rasti-Barzoki, M. (2019). Game-Theoretic Approach to Greening, Pricing, and Advertising Policies in a Green Supply Chain. International Journal of Industrial Engineering & Production Research. 30: 273-286

[11] Su, C., Xiaojing, L., Wenyi, D. (2020). Green Supply Chain Decisions Considering Consumers' Low-Carbon Awareness under Different Government Subsidies. Sustainability. 12(6): 2281
[12] Junsong, B., Xuan, Z. (2020). Tax or Subsidy? An Analysis of Environmental Policies in Supply Chains with Retail Competition. European Journal of Operational Research. 283:901-914
[13] Cheng, C., Yi, C., Xiaoguang., Z., Liangyan, Z., Peng, G., Jingwen, Y. (2021). Study on Emission Reduction Strategies of Dual-Channel Supply Chain Considering Green Finance. Frontiers in Environmental Science. 9, 687468
[14] Ruxia, L., Cuihua, Z., Zhitang, L., Yanting, L. (2022). Manufacturers' Integrated Strategies for Emission Reduction and Recycling: The Role of Government Regulations. Computers & Industrial Engineering. 163, 107769
[15] Yongxi, Y., Yangyang, W., Chunyan, F., Yuqiong L. (2022). Taxes or Subsidies to Promote Investment in Green Technologies for A Supply Chain Considering Consumer Preferences for Green Products. Computers & Industrial Engineering. 171, 108371
[16] D'Aspremont, C., Jacquemin, A. (1988). Cooperative and Noncooperative R&D in Duopoly with Spillovers.The American Economic Review, 78(5), 1133-1137