Improving sustainability and social responsibility of a two-tier supply chain investing in emission reduction technology

Qingguo Bai[a,*], Mingyuan Chen[b], Yiannis Nikolaidis[c], Jianteng Xu[a,d]

[a]*Institute of Operations Research, School of Management, Qufu Normal University, Rizhao, 276826, China*
[b]*Department of Mechanical and Industrial Engineering, Concordia University, Montreal, H3G 1M8, Canada*
[c]*Department of Applied Informatics, University of Macedonia, 54636 Thessaloniki, Greece*
[d]*Department of Supply Chain and Business Technology Management, John Molson School of Business, Concordia University, Montreal, H3G 1M8, Canada*

Abstract

This paper studies a retailer-dominated supply chain including a single upstream manufacturer that produces two substitutable products and a single downstream retailer that undertakes corporate social responsibility activities. The manufacturer is also regulated by a cap-and-trade policy. We first compare two optimization models for a decentralized system, one that does and one that does not incorporate emission reduction technology, to show that profit of each system member in the former is higher than that in the latter, while the opposite is true for carbon emissions when the technology level invested by the manufacturer is higher than a threshold. To test the performance of the decentralized model that incorporates emission reduction technology, we model a centralized system and reveal that the system profit in the decentralized model is increased and the corresponding carbon emissions generated during production can be reduced. These findings motivate us to propose a revenue and cost-sharing contract to coordinate the decentralized system. The result shows that the economic and environmental sustainability of the decentralized system can be improved. Finally, several managerial implications are derived by conducting a numerical study.

Keywords: Retailer-dominated supply chain, CSR, emission reduction technology, sustainability, coordination

1. Introduction

As global market competition has increased and economic sustainability has become more important, corporate social responsibility (CSR) has become a key aspect of modern business operations management. Generally, CSR is a form of corporate self-regulation and is defined as the obligations of the firm to a broad set of stakeholders beyond firm shareholders [1]. An increasing number of companies have invested in CSR activities to improve their sustainability, and the Governance & Accountability (G&A) Institute research team reports that in 2017, 85% of the S&P (Standard & Poor's) 500 companies published CSR reports, compared with just under 20% reporting in 2011. For instance, Walmart, the largest retailer in the world, has invested in many CSR activities to enhance its economic, environmental and social sustainability, including committing to a zero waste goal, helping workers to advance their careers in retail, reducing packaging, improving the energy efficiency of its stores and trucking fleet, and taking measures to make its supply chain greener. The company's latest CSR report shows that as of the end of the previous fiscal year, Walmart had successfully diverted 78% of its global waste from landfills. On the other hand, as concerns about environmental sustainability continue to grow, the need to reduce carbon emissions has received considerable attention because they represent one of the main contributors to global warming. To curb carbon emissions, an increasing number of countries and regional organizations have implemented emissions trading schemes (or cap-and-trade policy), with the European Union Emission Trading Scheme (EU ETS) being the world's first international emissions trading system.

*Corresponding author.
Email addresses: hustbaiqg@alumni.hust.edu.cn (Qingguo Bai), mychen@encs.concordia.ca (Mingyuan Chen), nikolai@uom.edu.gr(Yiannis Nikolaidis), jiantengxu@163.com(Jianteng Xu)

Under a cap-and-trade system, the company receives a cap from a government agency, and surplus or extra carbon emission permits can be sold or bought through a carbon market when a firm generates less or higher than the cap. China has just launched its much-anticipated national ETS, overtaking the EU as the world's largest carbon market [2]. In addition, considerable empirical evidence and numerous studies reveal that customers prefer environmentally friendly products with CSR attributes [3–5].

Efforts to reduce carbon emissions have produced many challenges for the management of retailer-dominated supply chains because the product production stage in these supply chains is the major contributor to carbon emissions. For example, the recent environmental report for Apple's iPhone X revealed that 79 kilograms of carbon dioxide emissions are emitted during the life of a single phone, while approximately 89% of these emissions are generated in the production stage [6]. In particular, with the trend toward globalization, most manufacturers and suppliers of multinational companies are located in low-cost countries, such as developing nations, which are far away from these multinational companies' home countries. These manufacturers and suppliers are termed offshore suppliers [7]. Under the pressures of government regulation and the need to secure market share, retailers that undertake CSR require their suppliers to control greenhouse gas emissions generated in the manufacturing stage to improve the environmental sustainability of their systems. As mentioned above, Walmart is the first store to set science-based targets for carbon emissions reduction and its goal is to curb supply chain emissions by 1 billion tons by 2030. To attain such goal, Walmart launches Project Gigaton and requires its suppliers to provide carbon emission label for their products. In 2017, Walmart's suppliers reduced their collective greenhouse gas emissions by over 20 million tons. However, geographical distance and cultural and many other differences often make it difficult for the retailer to supervise offshore suppliers' production activities. In addition, with the increasing customer demands for product diversification, many manufacturers have to produce multiple products to satisfy customers' various demands [8]. For example, in May 2019, Apple launched new 13-inch MacBook Pro, in which two configuration models, 1.4GHz Quad-Core Processor with 128GB and 256 GB storages, are sold at unit prices $1,699 and $1, 949, respectively. These two configuration models of 13-inch MacBook Pro can be considered as substituting products in consumer electronics market. This also creates further difficulties in managing retailer-dominated CSR supply chains due to the price competition of the substitutable products.

Many coordination models for different types of the CSR supply chains have been developed and analyzed in the recent literature, e.g., Letizia and Hendrikse [1], Hsueh [9], Panda and Modak [10] and Panda et al. [11]. However, the impacts of government behavior or emission reduction on system coordination are not considered in the CSR supply chains mentioned earlier. On the other hand, there is growing literature that studies the supply chain management under the constraint of carbon emission reduction [12–16]. Recently, Yang et al. [17] and Bai et al. [18] consider cap-and-trade policy in a make-to-order(MTO) supplier-retailer supply chain with two products, respectively. The main research characteristic of the two literature is that the supplier-dominated system is assumed and the investment in the CSR activities is not considered. As mentioned earlier, those companies such as Walmart usually have the channel power in their supply chains. Hence, for the retailer-dominated CSR supply chain under a cap-and-trade policy, the following key questions arise. First, how will the manufacturer respond when the retailer requires the manufacturer to control greenhouse gas emissions generated during production ? Second, what are the influences of controlling greenhouse gas emissions on the operational strategies of system members when two substitutable products are considered in a retailer-dominated CSR supply chain ? Third, can a retailer-dominated CSR supply chain improve economic and environmental sustainability through a proper contract if the technology is invested to control carbon emissions?

Driven by the practical challenges discussed above, this paper considers a single-manufacturer and single-retailer system under the cap-and-trade policy in the context of retailer-dominated scenario. The manufacturer manufactures two substitutable products and the retailer undertakes CSR activities with the investment in consumer environmental education and improving the energy efficiency of its stores. In this system, the production is the main contributor to carbon emissions. We first formulate two decentralized models, one with and one without emission reduction technology, and compare these two models. We then formulate a centralized system with emission reduction technology and compare it with the corresponding decentralized model. A revenue-and cost-sharing (RC) contract is further proposed for coordination of the decentralized model with the emission reduction technology. Finally, we conduct a numerical study to gain several managerial insights.

We summarize the major contributions of this work as follows: First, different from previous studies that usually ignore the channel power of the downstream firm in the supply chain and only consider the investment in CSR

activities to improve the system sustainability, we consider both emission reduction technology and carbon policy in a retailer-dominated CSR supply chain with two substitutable products. We study the influences of the system follower's investment in technology on the sustainability of the supply chain when the leader of the system undertakes CSR activities. Second, in the decentralized model with the emission reduction technology, we quantitatively derive an upper limit on the loss of profit for non-cooperation between the follower and the leader of the system, and obtain the conditions under which carbon emissions are reduced. Third, we design an effective contract to guarantee a win-win situation when the emission reduction technology is invested in the decentralized supply chain under a cap-and-trade policy. We also prove that the economic and environmental sustainability of the decentralized system can be improved by the new coordination mechanism designed in this paper. This result also enriches the supply chain coordination studies related to CSR or low-carbon goals.

The rest of the work is organized as follows. Relevant literature is reviewed in Section 2. Section 3 describes the problem and introduces notations. In Section 4, we provide four models for the supply chain problem discussed in this paper. Section 5 conducts a numerical study to gain several managerial implications. The final section summarizes the main conclusions of this work.

2. Literature review

The following two streams of research are related to this work and they are: the impacts of CSR on operational strategies in supply chain models and the impacts of carbon-cutting on operational strategies in supply chain models.

2.1. Impacts of CSR on operational strategies in supply chain models

As supply chains face increasing competition in a global market, the incorporation of CSR into the supply chain has gained increasing attention, and many researchers have conducted significant studies investigating the influences of CSR on the supply chain. Ni and Li [19] incorporate CSR behavior into a single-supplier-single-dealer system. When the two system members play two types of CSR games, the authors solve for the corresponding equilibriums to consider the influences of CSR behavior on the operational strategies of the system. Arya and Mittendorf [20] analyze several consequences for supply chains when the government provides subsidies for CSR activities. The authors further summarize the impacts of the CSR subsidies on supply chain behavior. Govindan and Shankar [21] propose a hybrid multi-criteria decision making method to analyze the supplier selection problem based on CSR practices. Lee et al. [22] consider a vertical system with two competing firms and analyze the impacts of market competitiveness on firms implementing CSR practices. Liu et al. [23] incorporate CSR and government behavior into a single-retailer and multi-supplier system. The authors use a three-period Stackelberg game to investigate the impacts of the CSR effort and government subsidies on system operational strategies.

In developing the models discussed above, the researchers consider a decentralized system and study the influences of CSR on the operational strategies of the system's individual members. Several other researchers focus on analyzing coordination in CSR supply chains. Recently, Ni et al. [24] consider a wholesale contract to study the allocation of social responsibility and coordination in a single-supplier-single-firm system. Panda et al. [25] study a system with a single-manufacturer, single-distributor and single-retailer, where the manufacturer has the channel power and invests in CSR activities. The authors propose a contract bargaining process to provide certain implications. Wu et al. [26] propose a CSR supply chain including an original equipment manufacturer (OEM) and an upstream supplier as market disruptions may affect CSR activities. Ma et al. [27] consider a single-manufacturer-single-retailer system under information asymmetry, where the retailer has the channel power. The authors adopt a two-part contract to coordinate it when the manufacturer invests in CSR activities. Raza [28] consider a single-manufacturer-single-retailer system, where the manufacturer invests in CSR activities. For three different demand scenarios, the author studies the coordination decision to gain certain managerial insights. Ebrahimi and Hosseini-Motlagh [29] consider the competition of the CSR investment in a single-manufacturer and two-competing-retailer system. The authors assume that the demand depends on the green quality and CSR investment and propose an environmental and social cost sharing contract to coordinate the supply chain.

All models discussed above study the coordination of a CSR supply chain from the perspective of the firm's internal economic behavior and do not consider the impacts of government behavior or emission reduction on supply chain coordination. However, government regulation on carbon emissions plays an important role in determining and

enhancing a system's level of CSR. This paper focuses on analyzing whether the follower of the system invests in the technology for emission reduction when a CSR supply chain is subject to cap-and-trade policy. An effective contract will also be designed to coordinate the CSR system proposed in this work.

2.2. Impacts of carbon-cutting on operational strategies in supply chain models

Managing a supply chain while reducing carbon emissions has become the key topic in operations management because of increasing concerns for environmental protection and sustainability [30–33]. Many researchers have recently studied the operational decisions and coordination of supply chains under different types of government regulations. Ding et al. [34] propose a two-stage system with both environmental constraints and carbon cap regulation. By modeling and comparing non-cooperative and collaborative supply chains, the authors focus on studying the influences of government policy on improving the system's environmental performance. Toptal and Çetinkaya [35] consider the coordination of a single-buyer-single-vendor system under the cap-and-trade and carbon tax policies. For decentralized and centralized cases under each form of carbon regulation, the authors also solve the operational strategies of the supply chains. Xu et al. [8] analyze the influences of the emission trading price on the optimal production and pricing strategies when the manufacturer is subject to cap-and-trade policy. Bazan et al. [36] assume that an emission tax is paid for exceeding the emissions cap and consider two coordination models for a closed-loop supply chain. Xu et al. [37] use price discount contracts to analyze a dual-channel system coordination when the system is subject to carbon emission capacity regulation. Chen and Benjaafar [38] provide a buyer-supplier supply chain model with carbon footprints in the framework of the classical economic order quantity model. When each member is subject to a carbon tax, the authors prove that penalizing each firm for its emissions may yield higher overall supply chain emissions.

All models discussed above assume that different government regulations are imposed on the supply chain to control the carbon emissions emitted by its activities and focus on analyzing the influences of these government policies on the operational strategies or coordination of the supply chain. In several industries such as cement and steel, many firms have also invested in certain alternative pollution-abatement technologies to curb carbon emissions [39, 40]. Currently, more and more researchers have investigated the operational decisions of investing in emission reduction technology in operational management. Luo et al. [41] study the optimal joint pricing and emission reduction decisions of two competing manufacturers under the cap-and-trade policy. Xu et al. [42] coordinate a make-to-order (MTO) manufacturer-retailer system that the manufacturer is subject to cap-and-trade policy and invests in green technology to control the emissions generated during manufacturing. Ji et al. [43] consider an O2O retailer supply chain that a manufacturer is regulated by the cap-and-trade policy and the retailer sells low-carbon products by dual-channel. The authors provide three optimization models for the supply chain and study the optimal joint pricing and emission reduction decisions. Xia et al. [44] consider reciprocal preferences and consumers' low-carbon awareness into a single-manufacturer-one-buyer system. Yang and Chen [45] coordinate a retailer-dominated manufacturer-buyer system under the carbon tax policy. Hong and Guo [46] develop a green manufacturer-buyer system, where the manufacturer and the buyer produce and promote the green product, respectively. The authors propose and compare three types of contracts for coordination. Bai et al. [47] analyze the emission reduction strategy and coordination of a single-manufacturer and two-retailer system for vendor-managed deteriorating item inventory under the cap-and-trade policy. Cao and Yu [48] consider a two-stage supply chain under the cap-and-trade policy including a single supplier and a single capital-constrained manufacturer. Under the stochastic demand, the authors focus on studying the impacts of carbon policy on the financing and performance of the supply chain.

In developing the models mentioned above, the researchers focus on studying the emission reduction strategies and coordination of a single product system. Recently, several researchers study the impacts of emission reduction on the supply chain with two products. Yang et al. [17] consider two products in a single-manufacturer-single-buyer under the cap-and-trade policy. By assuming that the two products have the competition on emission reduction rate instead of price, the authors solve the product greenness decisions and coordination of the horizontal and vertical supply chains. Bai et al. [18] develop a supplier-dominated system under the cap-and-trade policy that the supplier sells two kinds of fresh materials to the manufacturer and then the manufacturer uses them to produce two types of finished products for selling to customers. The authors study carbon emission reduction strategy and coordination of the supply chain.

Table 1 summarizes the main results derived in the aforementioned literature and shows the differences between the models studied in the literature and that studied in the present work. Contrary to the literature that considers a

single product, we develop a manufacture-retailer CSR system with two substitutable products under the constrain of emission reduction and study how the CSR supply chain achieves a win-win outcome when the system is coordinated by the RC contract. Contrary to the literature that considers two products, in this paper, we model the supply chain with two substitutable products as a retailer-dominated system. We focus on analyzing how the CSR decision of the downstream retailer affects the carbon-cutting strategies of the upstream manufacturer under the cap-and-trade policy. We further design a new contract mechanism for coordination.

3. Problem description and model analysis

3.1. Problem description and notations

Consider a single-manufacturer and single-retailer system that the retailer has the channel power. The manufacturer adopts an MTO policy to produce and provide two substitutable products to the retailer, where the unit production cost and wholesale price of product i ($i = 1, 2$) are c_i and w_i, respectively. The unit carbon emission of product i in the manufacturing stage is e_i. A carbon cap-and-trade policy(one of the government's regulatory policies) is imposed on the manufacturer with carbon emissions cap E and unit price of carbon emission permits c_p. The downstream retailer sells these two products with price competition at selling price p_i for product i. To enhance firm reputation and social responsibility, the retailer undertakes CSR activities with the investment in consumer environmental education and improving the energy efficiency of its stores. Following Ma et al. [27], Bai et al. [49], and Modak et al. [50], we assume that the retailer's level of CSR and investment are θ and $\frac{1}{2}\eta_1\theta^2$, respectively, where η_1 is the coefficient of the retailer's CSR investment.

As the channel leader, the retailer also requires the upstream manufacturer to control the carbon emissions of these two products and to label the actual emission quantities on their packages. Responding to it, the emission reduction technology with the level e is invested by the manufacturer for carbon-cutting, and the unit carbon emission of product i in the manufacturing stage is $e_i - e$, and the technology investment cost is $\frac{1}{2}\eta_2 e^2$, where η_2 is the parameter of the technology cost. Without loss of generality, $0 \le e < min\{e_1, e_2\}$ is assumed to guarantee the feasibility of the model, where $e = 0$ implies that the carbon emissions of the each product cannot be reduced, i.e., the emission reduction technology is not invested by the manufacturer, and the latter inequality holds because carbon emissions cannot be completely eliminated in reality by investing in emission reduction technology. The retailer maximizes her profit by deciding the optimal CSR level and the sale prices of the two products, and the manufacturer maximizes his profit by deciding the optimal technology level and the wholesale prices of the two products.

It has been verified by Auger et al. [3], Bolton and Mattila [4], and Liu et al. [5] that both enhancing a firm's CSR and reducing the carbon emissions of its product play a positive role in increasing market demand. Hence, for the problem considered above, we express the demand functions for the two substitutable products as

$$d_i = a_i - p_i + \alpha p_{3-i} + \beta\theta + \gamma e, \; for\ i = 1\ and\ 2 \tag{1}$$

where a_i (> 0) is the base capacity of the market for product i, α ($0 < \alpha < 1$) is the cross-price-sensitivity parameter, and β (> 0) and γ (> 0) measure the effects of the CSR level and the emission technology level on the demands of two products, respectively. Note that the additive demand form is widely adopted in the marketing and economics literature because it facilitates deriving several intuitive managerial insights [17, 42, 51].

The profits of the retailer and the manufacturer, $\Pi_r(p_1, p_2, \theta)$ and $\Pi_m(w_1, w_2, e)$, and the carbon emissions $J(e)$ are expressed as

$$\Pi_r(p_1, p_2, \theta) = \sum_{i=1}^{2}(p_i - w_i)d_i - \frac{1}{2}\eta_1\theta^2, \tag{2}$$

$$\Pi_m(w_1, w_2, e) = \sum_{i=1}^{2}(w_i - c_i)d_i - \frac{1}{2}\eta_2 e^2 + c_p[E - \sum_{i=1}^{2}(e_i - e)d_i], \tag{3}$$

respectively.

Table 1. Comparative study of relevant literature with present work

Article	Supply chain structure	Product characteristic	Demand influence factor	Game approach	Reason of investment in emission reduction technology	Coordination mechanism	Win-win
Yang et al. [17]	Manufacturer-retailer	Two	Price and product greening level	Manufacturer-led		RS	√
Bai et al. [18]	Supplier-manufacturer	Two	Price and emission reduction technology	Supplier-led		RIS	√
Ebrahimi and Hosseini-Motlagh [29]	Single-manufacturer and two-competing-retailer	Single	Green quality and CSR dependent	Manufacturer-led		ESS	
Luo et al. [41]	Two competing firms	Single	Price and green technology level	Nash game			
Xu et al. [42]	Manufacturer-retailer	Single	Price and CEA level	Manufacturer-led game		CS, WP, and TT	
Ji et al. [43]	O2O retailer supply chain	Single	Price, emission reduction level, and promotional level	Retailer-led			
Xia et al. [44]	Manufacturer-retailer	Single	Price and emission reduction level	Manufacturer-led			
Yang and Chen [45]	Manufacturer-retailer	Single	Price and CEA level	Manufacturer-led		CS, RS	
Hong and Guo [46]	Manufacturer-retailer	Single	Price and product greening level	Manufacturer-led		Po, GCS, and TT	
Bai et al. [47]	Single-supplier and two-competing-retailer	Single	Price and green technology level	Supplier-led		RS	√
Cao and Yu [48]	Single-supplier and single-capital-constrained-manufacturer	Single	Stochastic	Supplier-led		Guarantee contract	
Present work	Manufacturer-retailer	Two	Price, CSR level and emission reduction technology level	Retailer-led	√	RC	√

Note: √=covered, CEA=Consumer environmental awareness, CS=Cost-sharing, ESS=Environmental and social-sharing, GCS=Green-marketing cost-sharing, PO=Price-only, RC=Revenue- and cost-sharing, RS=Revenue-sharing, RIS=revenue- and investment-sharing, TT=Two-part tariff, VMI=vendor-managed inventory, WP=Wholesale price.

Table 2. Model parameters, decision variables and objective functions

Parameters	
a_i	Base market size of product i, $i = 1, 2$
c_i	Unit production cost of product i, $i = 1, 2$
d_i	Demand function of product i, $i = 1, 2$
e_i	Carbon emissions per unit product i, in the production stage when the emission reduction level is zero, $i = 1, 2$
w_i	Unit wholesale price of product i, $i = 1, 2$
c_p	Unit price of trading carbon emission permit
E	Carbon emission cap
α	Cross-price-sensitivity parameter of the demand function, $0 < \alpha < 1$
β	CSR elasticity parameter of the demand, $\beta > 0$
γ	Emission reduction technology elasticity parameter of the demand function, $\gamma > 0$
η_1	Coefficient of the retailer's CSR investment, $\eta_1 > 0$
η_2	Coefficient of the manufacturer's emission technology investment, $\eta_2 > 0$
Decision variables	
p_i	Unit selling price of the product i, $i = 1, 2$
w_i	Unit wholesale price of the product i sold from the manufacturer to the retailer, $i = 1, 2$
θ	CSR level of the retailer
e	Emission reduction technology level of the manufacturer
ρ	Contract parameter in the RC contract, $0 < \rho < 1$
Objective functions	
$\Pi_r(p_1, p_2, \theta)$	Total profit of the retailer in the decentralized supply chain
$\Pi_{r/rc}(p_1, p_2, \theta)$	Total profit of the retailer in the RC contract
$\Pi_m(w_1, w_2)$	Total profit of the manufacturer in the decentralized supply chain without the emission reduction technology
$\Pi_m(w_1, w_2, e)$	Total profit of the manufacturer in the decentralized supply chain with the emission reduction technology
$\Pi_{m/rc}(w_1, w_2, e)$	Total profit of the manufacturer in the RC contract with the emission reduction technology
$\Pi_c(p_1, p_2, \theta, e)$	Total profit of the supply chain in the centralized supply chain with the emission reduction technology
$J(e)$	Total carbon emissions generated from the production process

In Eq.(3), $\sum_i (e_i - e)d_i$ represents the carbon emissions emitted during the production stage. For simplification, we denote emissions by $J(e)$, i.e.,

$$J(e) = \sum_{i=1}^{2} (e_i - e)d_i, \tag{4}$$

Table 2 describes the major notations and parameters used in developing the corresponding mathematical models. For the feasibility of the analytic model proposed throughout the work, we assume that $\eta_2[(1-\alpha)\eta_1 - \beta^2] > \eta_1[\gamma + c_p(1-\alpha)]^2$, which is consistent with the practical reality that the level of CSR or technology is improved by a large investment. Similar assumptions have been studied in the recent studies, e.g., Ni et al. [24], Yang and Chen [45], and Modak et al. [50]. We have added the superscripts "C", "HT", and "RC" to the respective variables to represent their corresponding optimal values in the centralized system, decentralized system with the emission reduction technology and that under the RC contract, respectively. Similarly, we have added the superscript "NT" to the respective variables of the decentralized system without the emission reduction technology for representing their corresponding optimal values. We have also provided all proofs of analytic results in Appendices.

3.2. Two decentralized models with and without the emission reduction technology

Considering that the retailer has the channel power in the supply chain mentioned above, we use a retailer-Stackelberg game to model the relationship between the two members of the system, and obtain a decentralized model with the emission reduction technology. The sequence of events is described as follows: First, the retailer decides the sale prices of the two substitutable products and the level of CSR to maximize her profit. Second, observing the decisions of the system leader, the manufacturer choose the wholesale prices and the level of the emission reduction technology to optimize his profit. In addition, if the manufacturer does not invest in the emission reduction technology, using above retailer-Stackelberg game method, we further obtain a decentralized supply chain model without the emission reduction technology.

We first solve the optimal operational strategies for two decentralized models, one with and one without emission reduction technology. By comparing these two decentralized models, we investigate the reasons that the supply chain invests in the technology to achieve carbon-cutting. For the model that the emission reduction technology is invested by the manufacturer, we solve Eqs.(1) and (2) to obtain several results.

Theorem 3.1. *In the decentralized model with the emission reduction technology, the following holds:*

(i) There exist optimal vales of w_1^{HT}, w_2^{HT}, and e^{HT} to maximize $\Pi_m(w_1, w_2, e)$, and they are

$$w_1^{HT} = \frac{[\gamma + c_p(1-\alpha)]\eta_1[a_1 + \alpha a_2 + 3(1-\alpha^2)(c_1 + c_p e_1)] + (1+\alpha)\{\beta^2\eta_2 + 2\eta_1[\gamma^2 - c_p^2(1-\alpha)^2]\}e^{HT}}{4(1-\alpha^2)\eta_1[\gamma + c_p(1-\alpha)]}, \tag{5}$$

$$w_2^{HT} = \frac{[\gamma + c_p(1-\alpha)]\eta_1[\alpha a_1 + a_2 + 3(1-\alpha^2)(c_2 + c_p e_2)] + (1+\alpha)\{\beta^2\eta_1 + 2\eta_1[\gamma^2 - c_p^2(1-\alpha)^2]\}e^{HT}}{4(1-\alpha^2)\eta_1[\gamma + c_p(1-\alpha)]} \tag{6}$$

and

$$e^{HT} = \frac{[\gamma + c_p(1-\alpha)]\eta_1\{a_1 + a_2 - (1-\alpha)[c_1 + c_2 + c_p(e_1 + e_2)]\}}{4\eta_1\{(1-\alpha)\eta_2 - [\gamma + c_p(1-\alpha)]^2\} - 2\beta^2\eta_2}. \tag{7}$$

(ii) There exist optimal values of p_1^{HT}, p_2^{HT}, and θ^{HT} to maximize $\Pi_r(p_1, p_2, \theta)$, and they are

$$p_1^{HT} = \frac{\beta\eta_2[3a_1 + 3\alpha a_2 + (1-\alpha^2)(c_1 + c_p e_1)] + (1+\alpha)\{3\beta^2\eta_2 + 2\eta_1[\gamma^2 - c_p^2(1-\alpha)^2]\}\theta^{HT}}{4\beta\eta_2(1-\alpha^2)}, \tag{8}$$

$$p_2^{HT} = \frac{\beta\eta_2[3\alpha a_1 + 3a_2 + (1-\alpha^2)(c_2 + c_p e_2)] + (1+\alpha)\{3\beta^2\eta_2 + 2\eta_1[\gamma^2 - c_p^2(1-\alpha)^2]\}\theta^{HT}}{4\beta\eta_2(1-\alpha^2)} \tag{9}$$

and

$$\theta^{HT} = \frac{\beta\eta_2\{a_1 + a_2 - (1-\alpha)[c_1 + c_2 + c_p(e_1 + e_2)]\}}{4\eta_1\{(1-\alpha)\eta_2 - [\gamma + c_p(1-\alpha)]^2\} - 2\beta^2\eta_2}. \tag{10}$$

From Theorem 3.1, we have that the uniqueness of the system's optimal equilibrium decision is proved to be existed for optimizing the profits of the two members of the system when they make strategies separately. The closed-form expressions of these optimal solutions also show that the technology level is directly proportional to the CSR level, implying that increasing the CSR level initially leads the retailer to invest more in the technology for carbon-cutting.

We use Theorem 3.1 to have several observations.

Theorem 3.2. *In the decentralized model with the emission reduction technology, the following holds:*

(i) The optimal values of the system members' profits are

$$\Pi_m(e^{HT}, w_1^{HT}, w_2^{HT}) = \frac{\sum_{i=1}^{2}[a_i + \alpha a_{3-i} - (1-\alpha^2)(c_i + c_p e_i)][a_i - (c_i + c_p e_i) + \alpha(c_{3-i} + c_p e_{3-i})]}{16(1-\alpha^2)} + \frac{\{4(1-\alpha)\eta_1\eta_2\{\beta^2\eta_2 + \eta_1[\gamma + c_p(1-\alpha)]^2\} - \{\beta^2\eta_2 + 2\eta_1[\gamma + c_p(1-\alpha)]^2\}^2\}(e^{HT})^2}{8(1-\alpha)\eta_1^2[\gamma + c_p(1-\alpha)]^2} + c_p E \tag{11}$$

and

$$\Pi_r(p_1^{HT}, p_2^{HT}, \theta^{HT}) = \frac{\sum_{i=1}^{2}[a_i + \alpha(c_{3-i} + c_p e_{3-i}) - (c_i + c_p e_i)][a_i + \alpha a_{3-i} - (1-\alpha^2)(c_i + c_p e_i)]}{8(1-\alpha^2)} + \frac{\{[2(1-\alpha)\eta_1 - \beta^2]\eta_2 - 2\eta_1[\gamma + c_p(1-\alpha)]^2\}\{\beta^2\eta_2 + 2\eta_1[\gamma + c_p(1-\alpha)]^2\}(\theta^{HT})^2}{4(1-\alpha)\beta^2\eta_2^2}, \tag{12}$$

Table 3. The main results for the decentralized model without the emission reduction technology

Decision variables and objective functions	Values
θ^{NT}	$\frac{\beta\,[a_1+a_2-(1-\alpha)(c_1+c_pe_1)-(1-\alpha)(c_2+c_pe_2)]}{2[2(1-\alpha)\eta_1-\beta^2]}$
p_1^{NT}	$\frac{3a_1+3\alpha a_2+(1-\alpha^2)(c_1+c_pe_1)+3(1+\alpha)\beta\theta^{NT}}{4(1-\alpha^2)}$
p_2^{NT}	$\frac{3\alpha a_1+3a_2+(1-\alpha^2)(c_2+c_pe_2)+3(1+\alpha)\beta\theta^{NT}}{4(1-\alpha^2)}$
w_1^{NT}	$\frac{a_1+\alpha a_2+3(1-\alpha^2)(c_1+c_pe_1)+(1+\alpha)\beta\theta^{NT}}{4(1-\alpha^2)}$
w_2^{NT}	$\frac{\alpha a_1+a_2+3(1-\alpha^2)(c_2+c_pe_2)+(1+\alpha)\beta\theta^{NT}}{4(1-\alpha^2)}$
$\Pi_m(w_1^{NT},w_2^{NT})$	$\frac{\sum_{i=1}^{2}[a_i+\alpha a_{3-i}-(1-\alpha^2)(c_i+c_pe_i)][a_i-(c_i+c_pe_i)+\alpha(c_{3-i}+c_pe_{3-i})]}{16(1-\alpha^2)}+\frac{[4(1-\alpha)\eta_1-\beta^2](\theta^{NT})^2}{8(1-\alpha)}+c_pe_iF$
$\Pi_r(p_1^{NT},p_2^{NT},\theta^{NT})$	$\frac{\sum_{i=1}^{2}[a_i+\alpha a_{3-i}-(1-\alpha^2)(c_i+c_pe_i)][a_i-(c_i+c_pe_i)+\alpha(c_{3-i}+c_pe_{3-i})]}{8(1-\alpha^2)}+\frac{[2(1-\alpha)\eta_1-\beta^2](\theta^{NT})^2}{4(1-\alpha)}$
$J(e^{NT})$	$\frac{\sum_{i=1}^{2}e_i[a_i-(c_i+c_pe_i)+\alpha(c_{3-i}+c_pe_{3-i})]}{4}+\frac{\beta(e_1+e_2)\theta^{NT}}{4}$

respectively.

(ii) The corresponding carbon emissions are

$$J(e^{HT}) = \frac{1}{4}\sum_{i=1}^{2} e_i\,[a_i + \alpha(c_{3-i} + c_pe_{3-i}) - (c_i + c_pe_i)] + \frac{(e_1 + e_2)\{\beta^2\eta_2 + 2\eta_1[\gamma + c_p(1-\alpha)]\}e^{HT}}{4\eta_1[\gamma + c_p(1-\alpha)]} - \frac{(1-\alpha)\eta_2(e^{HT})^2}{\gamma + c_p(1-\alpha)}. \tag{13}$$

Theorem 3.2 identifies the optimal profits and carbon emissions of the supply chain members. From Theorem 3.2(i), we observe that when the cap-and-trade policy is imposed on the manufacturer, the cap has a linear effect on his optimal profit, while it has no influence on the retailer's profit. From Theorem 3.2(ii), we also find that there is no correlation between the carbon cap and the carbon emissions, implying that as a market-based approach, the cap-and-trade policy is implemented to provide several economic incentives to the supply chain.

To analyze the influences of the emissions reduction on the performance of the decentralized model, we further consider the decentralized case that the manufacturer does not invest in the technology to achieve carbon-cutting. Similar to the proofs of Theorem 3.1 and 3.2, we solve the decentralized model without the emission reduction technology and summarize the corresponding results in Table 3. The detailed calculations are shown in Appendix C.

From Theorems 3.1 and 3.2 and Table 3, we have several observations.

Theorem 3.3. *In the decentralized model without the emission reduction technology, the following holds:*

(i) $\theta^{HT} > \theta^{NT}$.

(ii) When $\gamma \geq c_p(1-\alpha)$ *or when* $\gamma < c_p(1-\alpha)$ *and* $\eta_1 < \frac{\beta^2[\gamma+2c_p(1-\alpha)]}{(1-\alpha)[c_p(1-\alpha)-\gamma]}$, $p_i^{HT} > p_i^{NT}$, $i = 1, 2$. *Otherwise,* $p_i^{HT} \leq p_i^{NT}$.

(iii) When $\gamma \geq c_p(1-\alpha)$ *or when* $\gamma < c_p(1-\alpha)$ *and* $\eta_1 < \frac{\beta^2[\gamma+c_p(1-\alpha)]}{2(1-\alpha)[c_p(1-\alpha)-\gamma]}$, $w_i^{HT} > w_i^{NT}$, $i = 1, 2$. *Otherwise,* $w_i^{HT} \leq w_i^{NT}$.

(iv) $\Pi_m(e^{HT}, w_1^{HT}, w_2^{HT}) > \Pi_m(w_1^{NT}, w_2^{NT})$, $\Pi_r(p_1^{HT}, p_2^{HT}, \theta^{HT}) > \Pi_r(p_1^{NT}, p_2^{NT}, \theta^{NT})$.

(v) There exists a threshold e_t *such that if* $e^{HT} > e_t$, $J(e^{HT}) < J(e^{NT})$, *otherwise,* $J(e^{HT}) \geq J(e^{NT})$, *where* $e_t = \frac{(e_1+e_2)[\gamma+c_p(1-\alpha)]^2\eta_1}{[2(1-\alpha)\eta_2-\beta^2]\eta_2}$.

Theorem 3.3 compares the decentralized models with and without the emission reduction technology. Theorem 3.3(i) shows that the CSR level in the decentralized model with the emission reduction technology is bigger than that in the decentralized model without the emission reduction technology. This also implies that the retailer with a higher CSR level is more willing to require its follower to invest in the technology for carbon-cutting and increasing its social reputation. Theorem 3.3 (ii) and (iii) provide certain conditions that compare the differences in the sale and

wholesale prices of these two products in these two decentralized supply chains. Theorem 3.3 (iv) shows that when the technology is invested by the manufacturer to control carbon emissions, the profit of each member is more than that in the supply chain without the emission reduction technology, respectively. This also explains the common real-world observation that the investments in CSR and emission reduction technology increase the social reputation of the system and that each member of the system can benefit from this improvement. From Theorem 3.3(v), we have that when the level of the emission reduction technology is higher than the threshold, the manufacturer will have lower carbon emissions than in the case without emission reduction technology. In summary, compared with the decentralized supply chain without the emission reduction technology, the system that invests in the emission reduction technology will obtain higher profits and a higher CSR level, while it may also generate more carbon emissions. This leads us to further investigate the coordination of the decentralized model in the presence of emission reduction technology.

3.3. Coordination of the decentralized model with the emission reduction technology

We first model a centralized system with the emission reduction technology to test the performance of the decentralized case. As for the centralized model, the two members of the system are vertically integrated in the same one, and they maximize the system's profit by jointly determining the optimal operational strategies. In this case, the system's profit is

$$\Pi_c(p_1, p_2, \theta, e) = \sum_{i=1}^{2}(p_i - c_i)d_i - \frac{1}{2}\eta_1\theta^2 - \frac{1}{2}\eta_2 e^2 + c_p[E - \sum_{i=1}^{2}(e_i - e)d_i] \tag{14}$$

We solve Eq.(14) to have several results.

Theorem 3.4. *In the centralized model with the emission reduction technology, the following holds:*
(i) There exist optimal values of p_1^C, p_2^C, θ^C, and e^C, to maximize $\Pi_c(p_1, p_2, \theta, e)$, and they are

$$p_1^C = \frac{\beta\eta_2[a_1 + \alpha a_2 + (1-\alpha^2)(c_1 + c_p e_1)] + (1+\alpha)\{\beta^2\eta_2 + \eta_1[\gamma^2 - c^2(1-\alpha)^2]\}\theta^C}{2\beta\eta_2(1-\alpha^2)}, \tag{15}$$

$$p_2^C = \frac{\beta\eta_2[\alpha a_1 + a_2 + (1-\alpha^2)(c_2 + c_p e_2)] + (1+\alpha)\{\beta^2\eta_2 + \eta_1[\gamma^2 - c^2(1-\alpha)^2]\}\theta^C}{2\beta\eta_2(1-\alpha^2)}, \tag{16}$$

$$e^C = \frac{\eta_1[\gamma + c_p(1-\alpha)]\theta^C}{\beta\eta_2} \tag{17}$$

and

$$\theta^C = \frac{\beta\eta_2\{a_1 + a_2 - (1-\alpha)[c_1 + c_2 + c_p(e_1 + e_2)]\}}{2\eta_1\{(1-\alpha)\eta_2 - [\gamma + c_p(1-\alpha)]^2\} - 2\beta^2\eta_2}. \tag{18}$$

(ii) The optimal values of the system's profit and carbon emissions are

$$\Pi_c(p_1^C, p_2^C, \theta^C, e^C) = \frac{\sum_{i=1}^{2}[a_i + \alpha a_{3-i} - (1-\alpha^2)(c_i + c_p e_i)][a_i + \alpha(c_{3-i} + c_p e_{3-i}) - (c_i + c_p e_i)]}{4(1-\alpha^2)} + \frac{\{\beta^2\eta_2 + \eta_1[\gamma + c_p(1-\alpha)]^2\}\{[(1-\alpha)\eta_1 - \beta^2]\eta_2 - \eta_1[\gamma + c_p(1-\alpha)]^2\}(\theta^C)^2}{2(1-\alpha)(\beta\eta_2)^2} + c_p E \tag{19}$$

and

$$J(e^C) = \frac{1}{2}\sum_{i=1}^{2} e_i[a_i + \alpha(c_{3-i} + c_p e_{3-i}) - (c_i + c_p e_i)] + \frac{(e_1 + e_2)\{\beta^2\eta_2 + \eta_1[\gamma + c_p(1-\alpha)]^2\}e^C}{2\eta_1[\gamma + c_p(1-\alpha)]} - \frac{(1-\alpha)\eta_2(e^C)^2}{\gamma + c_p(1-\alpha)}, \tag{20}$$

respectively.

Theorem 3.4 shows the closed-form expressions for the optimal operational strategies in the centralized model and the corresponding profit and carbon emissions. Theorem (3.4)(i) demonstrates the existence and uniqueness of the optimal joint pricing and levels of CSR and emission reduction technology for the centralized model. Theorem (3.4)(ii) shows the expressions for the optimal system profit and the corresponding amount of the carbon emissions.

Let $\Omega = \frac{2\eta_1\{(1-\alpha)\eta_2-[\gamma+c_p(1-\alpha)]^2\}-\beta^2\eta_2}{\eta_1\{(1-\alpha)\eta_2-[\gamma+c_p(1-\alpha)]^2\}-\beta^2\eta_2}$. We compare Theorems 3.1, 3.2 with 3.4 and come to the following conclusions.

Theorem 3.5. *For the centralized and decentralized models with the emission reduction technology, the following holds:*

(i) $\theta_1^C = \Omega\theta^{HT}$, $e_2^C = \Omega e^{HT}$, *where* $\Omega > 2$.

(ii) There exists a threshold Ω_{t_i} *such that if* $p_i^{HT} > \Omega_{t_i}$, *then* $p_i^C > p_i^{HT}$; *otherwise,* $p_i^C \le p_i^{HT}$, *where* $\Omega_{t_i} = \frac{a_1+\theta_1 a_{3-i}}{a_{3-i}} - \frac{\{(\Omega-3)\beta^2\eta_2+(\Omega-2)\eta_1[\gamma^2-c_p^2(1-\alpha)^2]\}\theta^{HT}}{2(1-\alpha)\beta\eta_2}$ *and* $i = 1, 2$.

(iii) $1 < \frac{\Pi_c(p^C,p^C,\theta^C,e^C)}{\Pi_m(e_2,w_1^{HT},w_2^{HT})+\Pi_r(p_1,p_2,\theta_1^{HT},\theta_2^{HT})} < \Omega_u$, *where*

$$\Omega_u = \frac{4\Omega^2\{\beta^2\eta_2+\eta_1[\gamma+c_p(1-\alpha)]^2\}\{[(1-\alpha)\eta_1-\beta^2]\eta_2-\eta_1[\gamma+c_p(1-\alpha)]^2\}}{4(1-\alpha)\eta_1\eta_2\{3\eta_1[\gamma+c_p(1-\alpha)]^2+2\beta^2\eta_2\}-3\{2\eta_1[\gamma+c_p(1-\alpha)]^2+\beta^2\eta_2\}^2}. \tag{21}$$

(iv) When $e_1 = e_2 = e_0$, *there exists a threshold* e_t *such that if* $e^{HT} < e_t$, *then* $J(e^C) > J(e^{HT})$; *otherwise,* $J(e^C) \le J(e^{HT})$, *where* $e_t = \frac{e_0}{\Omega+1}$

Theorem 3.5 compares the decentralized model with the centralized model when the technology is invested by the manufacturer to achieve carbon-cutting. From Theorem 3.5(i), we derive that the levels of the retailer's CSR and manufacturer's emission reduction technology in the centralized model are at least twice as high as those in the decentralized case. Theorem 3.5 (ii) provides certain conditions to compare the selling prices of the two products between these two models. From Theorem 3.5 (iii), we find that the system profit in the centralized model is higher than that in the decentralized model, while the profit in the former case is at most $\Omega_u(> \frac{4}{3})$ times that in the latter case. This implies that the system profit will increase when these two members are willing to cooperate with one another; moreover, under the cap-and-trade policy, the cap yields an upper limit on the potential improvement in the system profit. Theorem 3.5 (iv) shows that when investments are made in the technology to achieve carbon-cutting, less carbon emissions may be emitted in the centralized system than in the decentralized system.

In summary, the profit of the decentralized system may be increased and the amount of carbon emissions may be reduced when the two members of the system cooperate and jointly make the operational decisions consistent with those in the centralized case. Therefore, we will design an RC contract to coordinate the decentralized system in the presence of emission reduction technology. The RC contract proposed in this paper is given by: To motivate the manufacturer to make the technology level consistent with that of the centralized case, the retailer, as a leader, first implements the same selling decisions for the two products as in the centralized system and then absorbs a fraction $1 - \rho$ of the manufacturer's technology investment. In exchange, the follower of the system would like to share ρ of the retailer's CSR investment cost and to return $1 - \rho$ of the total revenue gained from trading emission permits and sale the two products. Under the RC contract, the profits of supply chain members are expressed as

$$\Pi_{m/rc}(w_1, w_2, e) = \sum_{i=1}^{2}(\rho w_i - c_i)d_i - \frac{1}{2}\rho\eta_2 e^2 - \frac{1}{2}\rho\eta_1\theta^2 + \rho c_p[E - \sum_{i=1}^{2}(e_i - e)d_i], \tag{22}$$

and

$$\Pi_{r/rc}(p_1, p_2, \theta) = \sum_{i=1}^{2}(p_i - \rho w_i)d_i - \frac{1}{2}(1-\rho)\eta_1\theta^2 - \frac{1}{2}(1-\rho)\eta_2 e^2 + (1-\rho)c_p[E - \sum_{i=1}^{2}(e_i - e)d_i], \tag{23}$$

respectively.

Solving Eq.(22) and using the coordination of the RC contract yields the following observation.

Theorem 3.6. *Under the RC contract, the following holds:*

(i) The RC contract yields coordination of the decentralized system in the presence of emission reduction technology when $e^{RC} = e^C$ *and* $p_i^{RC} = p_i^C$, $i = 1, 2$. *Furthermore, the corresponding CSR level and the wholesale prices of the two products are*

$$\theta^{RC} = \frac{\beta\eta_2\{a_1 + a_2 - (1-\alpha)[c_1 + c_2 + c_p(e_1 + e_2)]\}}{2\eta_1\{(1-\alpha)\eta_2 - [\gamma + c_p(1-\alpha)]^2\} - 2\beta^2\eta_2} \tag{24}$$

and

$$w_i^{RC} = \frac{\rho p_i^C + (1-\rho)c_i}{\rho}, \; i = 1, 2, \tag{25}$$

respectively.

(ii) The RC contract is accepted by each member of the system if and only if the fraction ρ *satisfies* $\frac{\Pi_m(e^{HT}, w_1^{HT}, w_2^{HT})}{\Pi_c(p_1^C, p_2^C, \theta^C, e^C)} \le \rho \le 1 - \frac{\Pi_r(p_1^{HT}, p_2^{HT}, \theta^{HT})}{\Pi_c(p_1^C, p_2^C, \theta^C, e^C)}$;

(iii) $\Pi_{m/rc}(w_1^{RC}, w_2^{RC}, e^{RC}) + \Pi_{r/rc}(p_1^{RC}, p_2^{RC}, \theta^{RC}) = \Pi_c(p_1^C, p_2^C, \theta^C, e^C)$ *and* $J(e^{RC}) = J(e^C)$.

Theorem 3.6 shows the optimal operational decisions, profits and corresponding emissions for the decentralized system under the RC contract. Theorem 3.6(i) shows that the RC contract plays an effective role in coordinating the decentralized system when $e^{RC} = e^C$ and $p_i^{RC} = p_i^C$, $i = 1, 2$. These coordination conditions also imply that the CSR level under the RC contract is the same as that in the centralized model. This implies that the optimal operational decision is consistent with that of the centralized system when the follower of the system is willing to select the same operational decision as in the centralized case to achieve coordination. From Theorem 3.6(i), we also observe that the wholesale prices are more than the corresponding selling prices when the RC contract plays an effective role in the coordination of the supply chain. The main reason for this result is that investment in a higher technology level to achieve coordination encourages its follower to enhance the wholesale prices of the two products. Theorem 3.6(ii) shows the feasible range of the contract fraction ρ for which each member of the system accepts the RC contract. The existence of this feasible range means that the RC contract can yield a win-win outcome. Theorem 3.6(iii) demonstrates that the optimal system profit and carbon emissions in the centralized system are the same as those in the decentralized model with the RC contract. These findings proposed in Theorem 3.6 confirm that the decentralized system with the emission reduction technology is coordinated perfectly by the RC contract.

We further use Theorem 3.6 to come to the following observation.

Corollary 3.7. *When the two members accept the RC contract, the following holds:*

(i) $\Pi_m(w_1^{HT}, w_2^{HT}, e^{HT}) \le \Pi_{m/rc}(w_1^{RC}, w_2^{RC}, e^{RC}) \le \Pi_c(p_1^C, p_2^C, \theta^C, e^C) - \Pi_r(p_1^{HT}, p_2^{HT}, \theta^{HT})$

(ii) $\Pi_r(p_1^{HT}, p_2^{HT}, \theta^{HT}) \le \Pi_{r/rc}(p_1^{RC}, p_2^{RC}, \theta^{RC}) \le \Pi_c(p_1^C, p_2^C, \theta^C, e^C)$.

Corollary 3.7 is intuitive. From Corollary 3.7, we observe that the lower and upper bounds of the profits for both members of the system are provided when the system achieves a win-win outcome under the RC contract. It also shows that the interval length between the upper bound and the lower bound of the retailer's profit is larger than that of the manufacturer. This also explains why the retailer, as the leader, is willing to provide certain incentives to the manufacturer to achieve cooperation.

In the context of the RC contract, we propose a new RC(NRC) contract to coordinate the decentralized system without the emission reduction technology. The NRC contract is given by: The retailer, as a leader, first implements the same sale prices of the two products and the level of CSR as in the centralized system. In exchange, the follower of the system would like to share ρ of the retailer's CSR investment cost and to return of the total revenue gained from trading emission permits and sale the two products. By an analysis similar to Theorem 3.6, we have the following observation.

Corollary 3.8. *For the decentralized supply chain without the emission reduction technology, the NRC contract leads to perfect coordination.*

Corollary 3.8 shows that when the manufacture does not invest in the emission reduction technology, the supply chain can be coordinated perfectly by the NRC contract. Under the NRC contract, there exist feasible values of the coordination parameter such that each member of the system accepts the contract. This finding is in line with that of the coordinated system with the emission reduction technology.

4. Numerical study

This section provides several numerical examples with sensitivity analysis to gain several managerial insights with illustrating the above theoretical results.

4.1. Numerical example

All parameter values are $a_1 = 1000, a_2 = 800, \alpha = 0.6, \beta = 1.5, \gamma = 1.2, \eta_1 = 65, \eta_2 = 80, c_1 = 10, c_2 = 8, e_1 = 150$, $e_2 = 140$ and $c_p = 5$. The value of E is 43, 000, 44, 000, 45, 000, 46, 000, or 47, 000, with the above-given parameter values to solve the decentralized models with and without emission reduction technology, and we obtain the corresponding computational results, which are presented in Table 4.

Table 4. The optimal solutions for the decentralized models with and without emission reduction technology

Model	(p_1; p_2; θ)	(w_1; w_2; e)	Retailer's profit	Manufacturer's profit	Total profit	Carbon emissions
Model with the emission reduction technology						
E = 43, 000	(1954;1847.3;27.47)	(1126.3; 1056; 47.62)	361,480	408,000	769,480	46,517
E = 44, 000	(1954; 1847.3; 27.47)	(1126.3; 1056; 47.62)	361,480	413,000	774,480	46,517
E = 45, 000	(1954; 1847.3; 27.47)	(1126.3; 1056; 47.62)	361,480	418,000	779,480	46,517
E = 46, 000	(1954; 1847.3; 27.47)	(1126.3; 1056; 47.62)	361,480	423,000	784,480	46,517
E = 47, 000	(1954; 1847.3; 27.47)	(1126.3; 1056; 47.62)	361,480	428,000	789,480	46,517
Model without the emission reduction technology						
E = 43, 000	(1975.8; 1869; 18.28)	(1165.3; 1095; -)	240,750	340,810	581,560	46,098
E = 44, 000	(1975.8; 1869; 18.28)	(1165.3; 1095; -)	240,750	345,810	586,560	46,098
E = 45, 000	(1975.8; 1869; 18.28)	(1165.3; 1095; -)	240,750	350,810	591,560	46,098
E = 46, 000	(1975.8; 1869; 18.28)	(1165.3; 1095; -)	240,750	355,810	596,560	46,098
E = 47, 000	(1975.8; 1869; 18.28)	(1165.3; 1095; -)	240,750	360,810	601,560	46,098

The following observations are summarized from Table 4.

(1) For the decentralized model with the emission reduction technology, when E increases, the optimal selling and wholesale prices of the two products, the CSR level, the emission reduction technology level, the retailer's profit and the corresponding carbon emissions keep unchanged while the manufacturer's profit increases. Similar results are obtained for the system without the emission reduction technology. This means that the optimal operational decisions for any members of the system are not affected by varying the value of E. Moreover, in each model, increasing the value of E yields an improvement in the manufacturer's profit and no changes in emissions. This also demonstrates that cap-and-trade is implemented in reality to provide several economic incentives to the primary emitter of greenhouse gas emissions.

(2) The selling and wholesale prices of the two products in the system with the emission reduction technology are less than those in the supply chain without the emission reduction technology. The opposite is the case for the CSR level, the system members' profits, and the carbon emissions. A higher level of CSR encourages the retailer to require her follower to invest more in the technology to control greenhouse gas emissions and increase the system's reputation. The retailer also lowers the sale prices to enhance the demands of two products, which leads to decreases in the wholesale price of each product. Decreasing sale prices of the two products and increasing levels of CSR and the technology yield improvements in the demands for the two products. Eventually, the system members' profits increase, respectively. In particular, investing in the emission reduction technology produces more profits for the retailer than her follower. For example, When E = 45000, compared with the system without the emission reduction technology, the system members' profits in the model with the emission reduction technology increase by 50.15%

and 19.15%, respectively. On the other hand, in this example, the carbon emissions emitted by the system with the emission reduction technology are more than those in the system without the emission reduction technology. The main reason for this result is that the technology level for controlling carbon emissions is less than the threshold e_t = 48.50.

Selecting E = 45, 000 and using the parameter values given in the above example, in the following, we focus on solving the supply chain coordination model when investments are made in the emission reduction technology. Table 5 shows that computational results for the centralized case, the decentralized case and the latter under the RC contract.

Table 5. Comparisons of three models for the supply chain with the emission reduction technology

Model	(p_1; p_2; θ)	(w_1; w_2; e)	Retailer's profit	Manufacturer's profit	Total profit	Carbon emissions
Centralized model	(1544.6; 1456.1; 58.95)	(-; -; 102.18)	-	-	1,000,600	44,045
Decentralized model	(1954; 1847.3; 27.47)	(1126.3; 1056; 47.62)	361,480	418,000	779,480	46,517
Coordination model						
ρ = 0.4	(1544.6; 1456.1; 58.95)	(1559.6; 1468.1; 102.18)	600,360	400,240	1,000,600	44,045
ρ = 0.45	(1544.6; 1456.1; 58.95)	(1556.8; 1456.9; 102.18)	550,330	450,270	1,000,600	44,045
ρ = 0.5	(1544.6; 1456.1; 58.95)	(1554.6; 1464.1; 102.18)	500,300	500,300	1,000,600	44,045
ρ = 0.6	(1544.6; 1456.1; 58.95)	(1551.3; 1461.4; 102.18)	400,240	600,360	1,000,600	44,045
ρ = 0.65	(1544.6; 1456.1; 58.95)	(1550.0; 1460.4; 102.18)	350,210	650,390	1,000,600	44,045

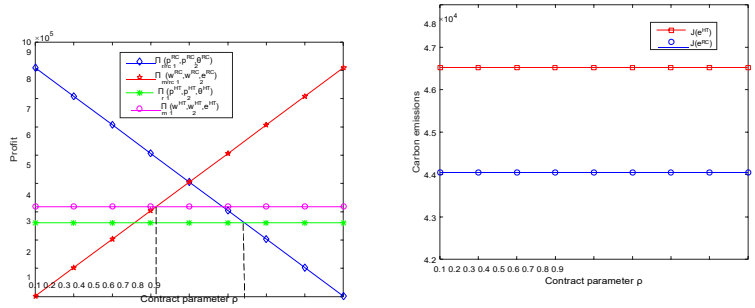
From Table 5, we come to the following conclusions:

(1) The optimal CSR level, the emission reduction technology level and the system profit are all higher in the centralized model than in the decentralized model, while the opposite is the case for the sale prices of the two products and carbon emissions. Compared with the decentralized model, cooperation between both members of the system in the centralized model encourages the retailer to lower the sale prices to improve the market demand of each product and to improve the CSR level for enhancing the system's social reputation. The manufacturer also invests more in the technology to control greenhouse gas emissions. Decreasing sale prices of the two products and increasing levels of CSR and emission reduction technology yield an improvement in the demands for the two products, which eventually yields an improvement in the system profit. In summary, the numerical results in this example reveal that the profits and carbon emissions are higher and lower, respectively, in the centralized system than those in the decentralized supply chain. For example, compared with the decentralized model, the system profit in the centralized model is 28.37% higher, while the corresponding carbon emissions are decreased by 5.31%. This observation means that the centralized system has higher profit and lower carbon emissions than the decentralized system.

(2) The sale prices of the two products, the levels of CSR and emission reduction technology, the system profit and the corresponding carbon emissions do not differ between the coordinated and centralized systems. Moreover, the manufacturer sets a higher value of the wholesale price of each product in the coordinated system than in the decentralized system. When the RC plays an effective role in the system coordination, the retailer provides several incentives such as improving the wholesale price of each product to make the operational decisions of the system consistent with those in the centralized model. In this scenario, the system profit and carbon emissions in the coordination model are the same as those in the centralized model. In particular, when the coordination parameter ρ is higher than 0.4178, the manufacturer gains higher profit in the coordinated model than in the decentralized model. When ρ is close to 0.6387, the retailer gains lower profit in the coordinated model than in the decentralized model. A graphical representation of the trend in the coordination parameter ρ is provided in Figure 1. From Figure 1, we observe that when ρ is in the range of [0.4178, 0.6387], each system member gains higher profit in the coordinated model than in the decentralized model, meaning that the RC contract is accepted by the two supply chain members. Figure 1 also draws that carbon-cutting is achieved when the RC contract coordinates the decentralized system.

4.2. Sensitivity analysis

In this section, using the numerical example above, we perform a static sensitivity analysis to study the impacts of several key parameters, a_i, c_i, e_i, (i = 1, 2), c_p, and E, on the coordination of the supply chain in the presence of the emission reduction technology. When performing the static sensitivity analysis, we change each of the parameters by



(a) Comparison of the profit.

(b) Comparison of carbon emissions .

Figure 1: Comparisons of the decentralized supply chain and the coordination supply chain .

+20%, +10%, −10% and −20% with holding others unchanged. Table 6 summarizes the corresponding computational results.

From Table 6, we have the following observations:

(1) Under the RC contract, when the base market size for each product $a_i (i = 1, 2)$ increases, the selling and wholesale prices of the two products, the levels of CSR and emission reduction technology, and the profits of the retailer and the manufacturer increase, while carbon emissions decrease. Moreover, the profits of the retailer and the manufacturer and the corresponding carbon emissions are more sensitive to changes in a_1 than to changes in a_2. For example, when a_1 is changes from −10% to +10%, the profits of the retailer and the manufacturer increase by 29.54% and 29.54%, while carbon emissions decrease by 19.76%. On the other hand, when a_2 changes from −10% to +10%, the profits of the retailer and the manufacturer increase by 22.29% and 22.29%, while carbon emissions decrease by 17.58%. In reality, a higher value of the base market size for the product means that the firm gains more market share and has important market power. When a_i increases, the retailer increases its level of the CSR and requires his follower to invest in a higher level of emission reduction technology such that more social responsibilities are taken and the social reputation of the supply chain is increased. An increase in the investment in CSR encourages the retailer to increase the selling prices of the two products. The RC contract also encourages the retailer to provide the manufacturer with economic incentives for coordination by allowing the manufacturer to increase the wholesale prices of the two products. Increases in the levels of CSR and the emission reduction technology and the selling price of product $3 - i$ eventually lead to an increase in the demand for product $i (i = 1, 2)$. Hence, the profits of the retailer and the manufacturer increase because of increases in the selling and wholesale prices of the two products and the market demands. Moreover, an increase in the level of the emission reduction technology is sufficient to reduce carbon emissions, despite that the demands for the two products increase.

(2) Under the RC contract, when the unit production price of each product $c_i (i = 1, 2)$ increases, the selling and wholesale prices of product i and carbon emissions increase, the levels of CSR and the emission reduction technology and the profits of the retailer and the manufacturer decrease, while the selling and wholesale prices of product $3 - i$ remain unchanged. These observations mean that although there is price competition between these two products, the selling and wholesale prices of product i are not sensitive to changes in the unit production price of product $3 - i$. Increasing the value of c_i encourages the manufacturer to increase the wholesale price of product i and invest in a lower level of the emission reduction technology such that the production cost can be reduced. The retailer, as the leader, accepts the manufacturer's operational decisions to achieve coordination. In this scenario, the retailer has to increase the selling price of product i and reduce the investment in CSR activities. The demand for product i decreases and the demand for product $3 - i$ increases with an increase in the selling price of product i and decreases in the levels of CSR and the emission reduction technology, while the selling price of product $3 - i$ remains unchanged. In particular, a decrease in the demand for product i eventually leads to decreases in the profits of the retailer and the manufacturer. When c_i increases, investing in a lower level of the emission reduction technology and an increase in the demand for product $3 - i$ also lead to increased carbon emissions.

(3) Under the RC contract, when the carbon emission per unit of product e_i increase, the selling and wholesale

Table 6. Sensitivity analysis for several key parameters in the RC contract with ρ = 0.55 in the Example

Parameter	Value(Percentage)	$(p_1^{RC}; p_2^{RC}; \theta^{RC})$	$(w_1^{RC}; w_2^{RC}; e^{RC})$	$\Pi_{r/rc}$	$\Pi_{m/rc}$	$J(e^{RC})$
a_1	1200(+20%)	(1702.2; 1551.2; 68.67)	(1710.38; 1557.75; 119.03)	577,755	706,145	31,704
	1100(+10%)	(1623.4; 1503.7; 63.81)	(1631.59; 1510.25; 110.61)	511,290	624,910	38,584
	900(-10%)	(1465.8;1408.5;54.09)	(1473.98; 1415.05; 93.76)	394,690.5	482,399.5	48,087
	800(-20%)	(1387.0; 1361.0; 49.23)	(1395.18; 1367.55; 85.33)	344,556	421,124	50,708
a_2	960(+20%)	(1620.7; 1582.2; 66.73)	(1628.89; 1588.75; 115.66)	547,875	669,625	33,826
	880(+10%)	(1582.7; 1519.2; 62.84)	(1590.88; 1525.75; 108.92)	497,340	607,860	39,390
	720(-10%)	(1506.6; 1393.1; 55.06)	(1514.78; 1399.65; 95.44)	406683	497,057	47,792
	640(-20%)	(1468.5; 1330; 51.17)	(1476.68; 1336.55; 88.70)	366,583.5	448,046.5	50,630
c_1	12(+20%)	(1545.6; 1456.1; 58.91)	(1553.78; 1462.65; 102.11)	449,779.5	549,730.5	44,077
	11(+10%)	(1545.1; 1456.1; 58.93)	(1553.28; 1462.65; 102.15)	450,045	550,055	44,061
	9(-10%)	(1544.1; 1456.1; 58.97)	(1552.28; 1462.65; 102.21)	450,495	550,605	44,029
	8(-20%)	(1543.6; 1456.1; 58.99)	(1551.78; 1462.65; 102.25)	450,765	550,935	44,013
c_2	9.6(+20%)	(1544.6; 1456.9; 58.92)	(1552.78; 1463.45; 102.13)	449,919	549,901	44,084
	8.8(+10%)	(1544.6; 1456.5; 58.94)	(1552.78; 1463.05; 102.15)	450,090	550,110	44,065
	7.2(-10%)	(1544.6; 1455.7; 58.97)	(1552.78; 1462.25; 102.21)	450,450	550,550	44,026
	6.4(-20%)	(1544.6; 1455.3; 58.98)	(1552.78; 1461.85; 102.23)	450,630	550,770	44,007
e_1	180(+20%)	(1619.2; 1455.7; 56.03)	(1627.38; 1462.25; 97.13)	416,686.5	509,283.5	59,835
	165(+10%)	(1581.9; 1455.9; 57.50)	(1590.08; 1462.45; 99.65)	432,756	528,924	52,644
	135(-10%)	(1507.3; 1456.3; 60.41)	(1515.48; 1462.85; 104.71)	469,215	573,485	34,040
	120(-20%)	(1470.0; 1456.5; 61.87)	(1478.18; 1463.05; 107.24)	489,600	598,400	22,628
e_2	168(+20%)	(1544.2; 1525.7; 56.23)	(1552.38; 1532.25; 97.46)	422,424	516,296	58,443
	154(+10%)	(1544.4; 1490.9; 57.59)	(1552.58; 1497.45; 99.82)	435,721.5	532,548.5	51,857
	126(-10%)	(1544.8; 1421.3; 60.31)	(1552.98; 1427.85; 104.54)	466,065	569,635	35,008
	112(-20%)	(1545.0; 1386.5; 61.67)	(1553.18; 1393.05; 106.90)	483,120	590,480	24,746
c_p	6(+20%)	(1545.9; 1452.4; 62.23)	(1554.08; 1458.95; 121.34)	454,545	555,555	25,774
	5.5(+10%)	(1548.0; 1457.0; 60.33)	(1556.18; 1463.55; 111.10)	451,395	551,705	35,722
	4.5(-10%)	(1536.8; 1450.8; 57.98)	(1544.98; 1457.35; 94.23)	450,900	551,100	51,345
	4(-20%)	(1525.3; 1441.8; 57.34)	(1533.48; 1448.35; 86.97)	453,060	553,740	58,011
E	54000(+20%)	(1544.6; 1456.1; 58.95)	(1552.78; 1462.65; 102.18)	470,520	575,080	44,045
	49500(+10%)	(1544.6; 1456.1; 58.95)	(1552.78; 1462.65; 102.18)	460,395	562,705	44,045
	40500(-10%)	(1544.6; 1456.1; 58.95)	(1552.78; 1462.65; 102.18)	440,140.5	537,949.5	44,045
	36000(-20%)	(1544.6; 1456.1; 58.95)	(1552.78; 1462.65; 102.18)	430,015.5	525,574.5	44,045

prices of product i and carbon emissions increase while the selling and wholesale prices of product $3-i$, the levels of CSR and the emission reduction technology and the profits of the retailer and the manufacturer decrease. When the manufacturer produces product i with higher carbon emissions per unit, the retailer (as the leader) increases the selling price of product i and decreases the selling price of product $3-i$ and reduces investment in CSR activities such that the order quantity of product 1 is decreased. The RC contract encourages the manufacturer to increase the wholesale price of product i and decrease the wholesale price of product $3-i$. The manufacturer, as the follower, also invests in a lower level of the emission reduction technology to decrease the demand for product i in response to the actions of the retailer. An increase in the selling price of product i and decreases in the selling price of product $3-i$ and the levels of CSR and the emission reduction technology lead to an increase in the demand for product $3-i$. On the one hand, decreases in the selling and wholesale prices of product $3-i$ and the demand for product i are sufficient to decrease the profits of the retailer and manufacturer. On the other hand, increases in the carbon emissions per unit of product i and the demand for product $3-i$, and investment in a lower level of the emission reduction technology lead to increased carbon emissions.

(4) Under the RC contract, when the unit price of carbon emissions permits c_p increases, the levels of CSR and the emission reduction technology increase, the profits of the retailer and the manufacturer first decrease and then increase,

and carbon emissions decrease, while the selling and wholesale prices of the two products first increase and then decrease. When the carbon emissions exceed the carbon cap, increasing the value of c_p encourages the manufacturer, as the emitter, to invest in a higher level of the emission reduction technology such that cost of buying the emission permits can be decreased by reducing the carbon emissions. The manufacturer also increases the wholesale prices of the two products to generate more revenue. An increase in the investment in the emission reduction technology encourages the retailer to increase investment in CSR activities to enhance the social reputation of the supply chain. The retailer also increases the selling prices of the two products to defray the cost of CSR activities. Increases in the levels of CSR and the emission reduction technology and the selling price of product 3 _ i eventually lead to an increase in the demand for product i. In this scenario, the profits of the retailer and the manufacturer decrease due to increases in the wholesale prices of the two products and investment of CSR and the technology. On the other hand, when the carbon emissions are below the carbon cap, a higher value of c_p urges the manufacturer to invest in a higher level of the emission reduction technology such that more revenue can be generated by selling the excess emission permits. This also allows the manufacturer to decrease the wholesale prices of the two products. The RC contract encourages the retailer to decrease the selling prices of the two products and enhance its CSR activities to achieve cooperation and increase the demands for two products. In this scenario, the increases in the demands for two products are sufficient to increase the profits of the retailer and the manufacturer. Moreover, the carbon emissions decrease with an increase in the value of c_p because the investment in the emission reduction technology is higher.

(5) Under the RC contract, when the carbon emission cap E increases, the selling and wholesale prices, the levels of CSR and the emission reduction technology and carbon emissions remain unchanged, while the profits of the retailer and the manufacturer increase. The RC contract encourages the retailer and the manufacturer to reach an agreement for determining the optimal operational decisions to maximize their profits. When the carbon cap increases, the retailer and the manufacturer maintain their operational decisions to avoid breaking this agreement because the value of the carbon cap is determined and allocated by the government. In this scenario, keeping the operational decisions of the manufacturer unchanged means that the manufacturer generates the same amount of carbon emissions. Moreover, the manufacturer will buy the emission permits at a lower cost or sell them to gain more revenue. This means that an increase in the carbon cap leads to an increase in the manufacturer's profit, which eventually leads to an increase in the retailer's profit under the RC contract.

5. Conclusions

Sustainability has become an integral component of supply chain management, and an increasing number of large firms undertake CSR activities and sell low-carbon products to improve the sustainability of both themselves and their entire systems, which also give rise to many new challenges for their suppliers. These challenges include operational decisions on investing in emission reduction technology. This motivates us to propose a retailer-dominated system with a single-retailer and single-manufacturer under the cap-and-trade policy, where the retailer undertakes CSR activities with the investment of improving the energy efficiency of its stores. In this system, the manufacturer manufactures two substitutable products and sells to the retailer, and the production process is the main source of carbon emissions. By formulating and comparing two optimization models for decentralized systems with and without the emission reduction technology, we analyze the main reason that the emission reduction technology is invested. We then model the centralized supply chain with the emission reduction technology and design an RC contract for coordinating the decentralized system. The theoretical results derived in this paper are further illustrated by a numerical study, and we have several managerial insights. Firstly, when both supply chain members make decisions separately to optimize their respective profits, if the manufacturer invests in the emission reduction technology under the cap-and-trade policy, his profit can be increased and the corresponding carbon emission can be controlled. In this scenario, the leader of the system engages in more CSR activities. Secondly, comparing with the decentralized supply chain, the centralized supply can achieve great improvement in both the environmental and economic sustainability, and the centralized system engages in more CSR activities and invests more in the technology for achieving carbon-cutting. Finally, when the retailer proposes the RC contract for cooperation, the contract fraction parameter can be determined to guarantee that each member of the system accepts the RC contract.

While this study yields several constructive managerial insights shown above, some of the main implications are provided in several aspects. Firstly, for the retailer that has the channel power, this study provides theoretical support to integrate CSR practices into supply chain management. The decision makers of the retailer can use the RC contract

to motivate the system partners to invest in the emission reduction technology and accept the cooperation for achieving the improvement of the system sustainability. Secondly, for the manufacturer that is regulated by the cap-and-trade policy, this study provides theoretical evidence that the emission reduction technology is invested to improve the sustainability of the supply chain and helps the decision makers to determine the optimal technology level when the system leader engages in CSR practices. Finally, for the government agency, this study provides certain reference to implement the carbon policy on the carbon permit allocation.

The main limitations of the present work are summarized as follows: First, we assume the deterministic demand to model the CSR supply chain, however, in reality, it is a common phenomenon that the demand is uncertainty due to the fire market competition [52, 53]. In this scenario, considering demand uncertainty in the CSR supply chain would be more challenging and may provide other insights. Second, referring to the existing literature that includes Toptal and Çetinkaya [35], Bazan et al. [36], and Modak et al. [50], etc., we conduct numerical study based on artificial data to illustrate the theoretical results and gain several insights. However, the significance and representative of the present work would be much stronger if the models developed in the present work are evaluated using a real data set that is collected from the real world.

There are several extensions deserving further discussion. We would analyze the impact of government subsidies or product recovery on coordinating a sustainable supply chain from a social welfare perspective. In addition, we would extend the system developed in this work to the case that two different types of the emission reduction technologies are adopted to control greenhouse gas emissions generated from manufacturing two substitutable products.

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Appendices

Appendix A. Proof of Theorem 3.1

Using the Stackelberg game, we first solve the optimal strategies of the manufacture before obtaining the equilibrium strategies of the retailer. For $i = 1$ and 2, let $p_i = w_i + \delta_i$, where $\delta_i \geq 0$. Substituting Eq.(1) into Eq.(3) and using $p_i = w_i + \delta_i$ to simplify it, we have

$$\Pi_m(w_1, w_2, e) = \sum_{i=1}^{2} [w_i - c_i - c_p(e_i - e)][a_i - (w_i + \delta_i) + \alpha(w_{3-i} + \delta_{3-i}) + \beta\theta + \gamma e] - \frac{1}{2}\eta_2 e^2 + c_p E. \tag{A.1}$$

For any values of θ and δ_i, $i = 1, 2$, we simplify $\frac{\partial \Pi_m(w_1,w_2,e)}{\partial w_i}$ and $\frac{\partial \Pi_m(w_1,w_2,e)}{\partial e}$ as

$$\frac{\partial \Pi_m(w_1, w_2, e)}{\partial w_i} = a_i - (w_i + \delta_i) + \alpha(w_{3-i} + \delta_{3-i}) + \beta\theta + \gamma e - [w_i - c_i - c_p(e_i - e)] + \alpha[w_{3-i} - c_{3-i} - c_p(e_{3-i} - e)],\ i = 1, 2, \tag{A.2}$$

and

$$\frac{\partial \Pi_m(w_1, w_2, e)}{\partial e} = \sum_{i=1}^{2} \gamma[w_i - c_i - c_p(e_i - e)] + \sum_{i+1} c_p[a_i - (w_i + \delta_i) + \alpha(w_{3-i} + \delta_{3-i}) + \beta\theta + \gamma e] - \eta_2 e. \tag{A.3}$$

Taking the second partial derivatives of $\Pi_m(w_1, w_2, e)$ with respect to w_i and e yields $\frac{\partial^2\Pi_m(w_1,w_2,e)}{\partial w_i^2} = \frac{\partial^2\Pi_m(w_1,w_2,e)}{\partial w_{3-i}^2} = -2$, $\frac{\partial^2\Pi_m(w_1,w_2,e)}{\partial w_i\partial w_{3-i}} = 2\alpha$, $\frac{\partial^2\Pi_m(w_1,w_2,e)}{\partial w_i\partial e} = \frac{\partial^2\Pi_m(w_1,w_2,e)}{\partial w_{3-i}\partial e} = \gamma - c_p(1-\alpha)$, and $\frac{\partial^2\Pi_m(w_1,w_2,e)}{\partial e^2} = 4\gamma c_p - \eta_2$. Using $\eta_2 > \frac{\gamma + c_p(1-\alpha)]^2}{1-\alpha}$, we have $\frac{\partial^2\Pi_m(w_1,w_2,e)}{\partial e^2} < 0$, $\frac{\partial^2\Pi_m(w_1,w_2,e)}{\partial e^2} \cdot \frac{\partial^2\Pi_m(w_1,w_2,e)}{\partial w_1^2} - \left(\frac{\partial^2\Pi_m(w_1,w_2,e)}{\partial e\partial w_1}\right)^2 = 2\eta_2 - 8\gamma c_p - [\gamma - c_p(1-\alpha)]^2 > 0$ and $|\nabla^2\Pi_m| = 4(1+\alpha)\{[\gamma + c_p(1-\alpha)]^2 - (1-\alpha)\eta_2\} < 0$, where $\nabla^2\Pi_m$ is the Hessian matrix of $\Pi_m(w_1, w_2, e)$ and

$$|\nabla^2\Pi_m| = \begin{vmatrix} \frac{\partial^2\Pi_m(w_1,w_2,e)}{\partial e^2} & \frac{\partial^2\Pi_m(w_1,w_2,e)}{\partial e\partial w_1} & \frac{\partial^2\Pi_m(w_1,w_2,e)}{\partial e\partial w_2} \\ \frac{\partial^2\Pi_m(w_1,w_2,e)}{\partial w_1\partial e} & \frac{\partial^2\Pi_m(w_1,w_2,e)}{\partial w_1^2} & \frac{\partial^2\Pi_m(w_1,w_2,e)}{\partial w_1\partial w_2} \\ \frac{\partial^2\Pi_m(w_1,w_2,e)}{\partial w_2\partial e} & \frac{\partial^2\Pi_m(w_1,w_2,e)}{\partial w_2\partial w_1} & \frac{\partial^2\Pi_m(w_1,w_2,e)}{\partial w_2^2} \end{vmatrix}_{3\times 3} \tag{A.4}$$

Hence, we have that the Hessian matrix $\nabla^2\Pi_m$ of $\Pi_m(w_1, w_2, e)$ is a negative definite matrix which shows that $\Pi_m(w_1, w_2, e)$ is jointly concave in $w_i (i = 1, 2)$ and e.

Using $p_i = w_i + \delta_i$ and solving Eq.(A.2) yield

$$w_i^{HT} = c_i + c_p(e_i - e) + \frac{a_i + \alpha a_{3-i} - (1-\alpha^2)p_i + (1+\alpha)(\beta\theta + \gamma e)}{1-\alpha^2}, \; i = 1, 2. \tag{A.5}$$

We substitute Eq.(A.5) into Eq.(A.3) and have

$$e^{HT} = \frac{[\gamma + c_p(1-\alpha)][a_1 + a_2 - (1-\alpha)(p_1 + p_2) + 2\beta\theta]}{(1-\alpha)\eta_2 - 2\gamma[\gamma + c_p(1-\alpha)]}. \tag{A.6}$$

Let $A_1 = \frac{2(1-\alpha)\eta_2 - [\gamma + c_p(1-\alpha)][3\gamma + c_p(1-\alpha)]}{(1-\alpha)\eta_2 - 2\gamma[\gamma + c_p(1-\alpha)]}$, $A_2 = \frac{[\gamma^2 - c_p^2(1-\alpha)^2]}{(1-\alpha)\eta_2 - 2\gamma[\gamma + c_p(1-\alpha)]}$, $B_1 = -\frac{\{(1-\alpha)\eta_2 - (1-\alpha)\gamma[\gamma + c_p(1-\alpha)]\}}{(1-\alpha)\eta_2 - 2\gamma[\gamma + c_p(1-\alpha)]}$, $B_2 = \frac{\alpha(1-\alpha)\eta_2 - (1+\alpha)\gamma[\gamma + c_p(1-\alpha)]}{(1-\alpha)\eta_2 - 2\gamma[\gamma + c_p(1-\alpha)]}$, $C_1 = \frac{\beta\{-\eta_2 + 2c_p[\gamma + c_p(1-\alpha)]\}}{(1-\alpha)\eta_2 - 2\gamma[\gamma + c_p(1-\alpha)]}$, and $C_2 = \frac{(1-\alpha)\beta\eta_2}{(1-\alpha)\eta_2 - 2\gamma[\gamma + c_p(1-\alpha)]}$. Using Eqs.(A.5), (A.6), and Eq.(2), and taking the first partial derivative of $\Pi_r(p_1, p_2, \theta)$ with respect to p_1, p_2 and θ, we have

$$\frac{\partial\Pi_r(p_1, p_2, \theta)}{\partial p_1} = \sum_{i=1}^{2} A_i(a_i - p_i + \alpha p_{3-i} + \beta\theta + \gamma e^{HT}) + \sum_{i=1}^{2} B_i(p_i - w_i^{HT}), \tag{A.7}$$

$$\frac{\partial\Pi_r(p_1, p_2, \theta)}{\partial p_2} = \sum_{i=1}^{2} A_{3-i}(a_i - p_i + \alpha p_{3-i} + \beta\theta + \gamma e^{HT}) + \sum_{i=1}^{2} B_{3-i}(p_i - w_i^{HT}), \tag{A.8}$$

and

$$\frac{\partial\Pi_r(p_1, p_2, \theta)}{\partial\theta} = C_1\sum_{i=1}^{2}(a_i - p_i + \alpha p_{3-i} + \beta\theta + \gamma e^{HT}) + C_2\sum_{i=1}^{2}(p_i - w^{HT}_i) - \eta_1\theta \tag{A.9}$$

We further take the second partial derivatives of $\Pi_r(p_1, p_2, \theta)$ with respect to p_1, p_2 and θ. From Eqs.(A.7), (A.8) and (A.9), we have $\frac{\partial^2\Pi_r(p_1,p_2,\theta)}{\partial p_1^2} = \frac{\partial^2\Pi_r(p_1,p_2,\theta)}{\partial p_2^2} = 2B_1(A_1 + A_2)$, $\frac{\partial^2\Pi_r(p_1,p_2,\theta)}{\partial\theta^2} = 4C_1C_2 - \eta_1$, $\frac{\partial^2\Pi_r(p_1,p_2,\theta)}{\partial p_1\partial p_2} = A_1B_2 + A_2B_1$, $\frac{\partial^2\Pi_r(p_1,p_2,\theta)}{\partial p_1\partial\theta} = \frac{\partial^2\Pi_r(p_1,p_2,\theta)}{\partial p_2\partial\theta} = (A_1 + A_2)C_2 + (B_1 + B_2)C_1$. Let $\nabla^2\Pi_r$ be the Hessian matrix of $\Pi_r(p_1, p_2, \theta)$, where

$$\nabla^2\Pi_r = \begin{vmatrix} \frac{\partial^2\Pi_r(p_1,p_2,\theta)}{\partial p_1^2} & \frac{\partial^2\Pi_r(p_1,p_2,\theta)}{\partial p_1\partial p_2} & \frac{\partial^2\Pi_r(p_1,p_2,\theta)}{\partial p_1\partial\theta} \\ \frac{\partial^2\Pi_r(p_1,p_2,\theta)}{\partial p_2\partial p_1} & \frac{\partial^2\Pi_r(p_1,p_2,\theta)}{\partial p_2^2} & \frac{\partial^2\Pi_r(p_1,p_2,\theta)}{\partial p_2\partial\theta} \\ \frac{\partial^2\Pi_r(p_1,p_2,\theta)}{\partial\theta\partial p_1} & \frac{\partial^2\Pi_r(p_1,p_2,\theta)}{\partial\theta\partial p_2} & \frac{\partial^2\Pi_r(p_1,p_2,\theta)}{\partial\theta^2} \end{vmatrix}_{3\times 3} \tag{A.10}$$

In the following, we will show that $\nabla^2\Pi$ is a negative definite matrix by proving (i) $\partial\ \Pi^r(p_1,p_2,\theta) < 0$, (ii) $\partial\ \Pi^r(p_1,p_2,\theta)$.

∂p^2

r

2 2

∂p^2

$\frac{\partial \Pi_r(p_1,p_2,\theta)}{} > \left(\frac{\partial \Pi_r(p_1,p_2,\theta)}{}\right)^2$ and (iii) $|\nabla^2\Pi_r| < 0$.

$c_p(1-\alpha)]^2$ and we simplify $2B_1(A_1+A_2)$ as $\frac{-2f(\eta_2)}{\{(1-\alpha)\eta_2-2\gamma[\gamma+c_p(1-\alpha)]^2\}^2}$, i.e., $\frac{\partial^2\Pi_r(p_1,p_2,\theta)}{\partial p_1^2}=\frac{-2f(\eta_2)}{\{(1-\alpha)\eta_2-2\gamma[\gamma+c_p(1-\alpha)]^2\}^2}$. If $0<\gamma\le\frac{c_p(1-\alpha)[5+3\alpha+\sqrt{2(1+\alpha)}]}{9\alpha+7}$, from $\frac{\partial f(\eta_2)}{\partial\eta_2}=4(1-\alpha)^2\eta_2-(1-\alpha)[\gamma+c_p(1-\alpha)][(5+3\alpha)\gamma+c_p(1-\alpha)^2]$, we derive that $f(\eta_2)$ is an increasing function of η_2 when $\eta_2\ge\frac{[\gamma+c_p(1-\alpha)][(5+3\alpha)\gamma+c_p(1-\alpha)^2]}{4(1-\alpha)}$. In this scenario, there exists a root η_2^0 such that $f(\eta_2^0)=0$, where $\eta_2^0=\frac{[\gamma+c_p(1-\alpha)]\{(5+3\alpha)\gamma+c_p(1-\alpha)^2+\sqrt{(1-\alpha)[-(9\alpha+7)\gamma^2+2(5+3\alpha)c_p(1-\alpha)\gamma+c_p^2(1-\alpha)^3]}\}}{4(1-\alpha)}$. Using $0<\gamma\le\frac{c_p(1-\alpha)[5+3\alpha+\sqrt{2(1+\alpha)}]}{9\alpha+7}$, we can prove $\frac{[\gamma+c_p(1-\alpha)][(5+3\alpha)\gamma+c_p(1-\alpha)^2]}{4(1-\alpha)}<\eta_2^0<\frac{[\gamma+c_p(1-\alpha)]^2}{1-\alpha}$. This means that $f(\eta_2)>0$ when $\eta_2>\frac{[\gamma+c_p(1-\alpha)]^2}{1-\alpha}$. On the other hand, if $\gamma>\frac{c_p(1-\alpha)[5+3\alpha+\sqrt{2(1+\alpha)}]}{9\alpha+7}$, calculating the discriminant of the equation $f(\eta_2)=0$ yields that the root of this equation does not exist. This means that for any value of η_2, we have $f(\eta_2)>0$. Hence, we have $\frac{\partial^2\Pi_r(p_1,p_2,\theta)}{\partial p_1^2}<0$ when $\gamma>\frac{[\gamma+c_p(1-\alpha)^2]^2}{1-\alpha}$.

For case (ii), from $\frac{\partial^2\Pi_r(p_1,p_2,\theta)}{\partial p_1^2}\cdot\frac{\partial^2\Pi_r(p_1,p_2,\theta)}{\partial p_2^2}-(\frac{\partial^2\Pi_r(p_1,p_2,\theta)}{\partial p_1\partial p_2})^2=4A_1(B_1-B_2)[(B_1+B_2)A_1+2A_2B_1]$, we have $\frac{\partial^2\Pi_r(p_1,p_2,\theta)}{\partial p_1^2}\cdot\frac{\partial^2\Pi_r(p_1,p_2,\theta)}{\partial p_2^2}-(\frac{\partial^2\Pi_r(p_1,p_2,\theta)}{\partial p_1\partial p_2})^2=\frac{16(1-\alpha)^2(1+\alpha)\eta_2^2\{(1-\alpha)\eta_2-[\gamma+c_p(1-\alpha)]^2\}}{\{(1-\alpha)\eta_2-2\gamma[\gamma+c_p(1-\alpha)]\}^2}>0$.

For case (iii), using $2B_1(A_1+A_2)-(A_1B_2+A_2B_1)=-4(1+\alpha)$ and $(4C_1C_2-\eta_1)[2B_1(A_1+A_2)+(A_1B_2+A_2B_1]-2[(A_1+A_2)C_2+(B_1+B_2)C_1]^2=\frac{2(1-\alpha)^2\eta_2\{[2\eta_1(1-\alpha)-\beta^2]\eta_2-2\eta_1[\gamma+c_p(1-\alpha)]^2\}}{\{(1-\alpha)\eta_2-2\gamma[\gamma+c_p(1-\alpha)]\}^2}$, we have

$$
\begin{aligned}
|\nabla^2\Pi_r| &= \left[\frac{\partial^2\Pi_r(p_1,p_2,\theta)}{\partial p_1^2}-\frac{\partial^2\Pi_r(p_1,p_2,\theta)}{\partial p_1\partial p_2}\right]\left\{\frac{\partial^2\Pi_r(p_1,p_2,\theta)}{\partial\theta^2}\left[\frac{\partial^2\Pi_r(p_1,p_2,\theta)}{\partial p_1^2}+\frac{\partial^2\Pi_r(p_1,p_2,\theta)}{\partial p_1\partial p_2}\right]\right. \quad \text{(A.11)}\\
&\quad \left.-2\left[\frac{\partial^2\Pi_r(p_1,p_2,\theta)}{\partial p_1\partial\theta}\right]^2\right\}\\
&= [2B_1(A_1+A_2)-(A_1B_2+A_2B_1)]\{(4C_1C_2-\eta_1)[2B_1(A_1+A_2)+(A_1B_2+A_2B_1]\\
&\quad -2[(A_1+A_2)C_2+(B_1+B_2)C_1]^2\}\\
&= \frac{-8(1+\alpha)(1-\alpha)^2\eta_2\{[2\eta_1(1-\alpha)-\beta^2]\eta_2-2\eta_1[\gamma+c_p(1-\alpha)]^2\}}{\{(1-\alpha)\eta_2-2\gamma[\gamma+c_p(1-\alpha)]\}^2}<0
\end{aligned}
$$

The last equation hold because of $0<\alpha<1$ and $\eta_2[(1-\alpha)\eta_1-\beta^2]>\eta_1[\gamma+c_p(1-\alpha)]^2$.

Using $\frac{\partial\Pi_r(p_1,p_2,\theta)}{\partial p_i}=0$, $i=1,2$, and $\frac{\partial\Pi_r(p_1,p_2,\theta)}{\partial\theta}=0$, from Eqs.(A.7), (A.8) and (A.9), we have

$$\sum_{i=1}^{2}(A_i+A_{3-i})[a_i+a_{3-i}-(1-\alpha)(p_i+p_{3-i})+2\beta\theta+2\gamma e^{HT}]=-\sum_{i=1}^{2}(B_i+B_{3-i})[p_i-w_i^{HT}+(p_{3-i}-w_{3-i}^{HT})] \quad \text{(A.12)}$$

and

$$C_1\sum_{i=1}^{2}(a_i-p_i+\alpha p_{3-i}+\beta\theta+\gamma e)+C_2\sum_{i=1}^{2}(p_i-w_i^{HT})=\eta_1\theta \quad \text{(A.13)}$$

Solving Eqs.(A.12) and (A.13) yields

$$\sum_{i=1}^{2}(a_i-p_i+\alpha p_{3-i}+\beta\theta+\gamma e^{HT})=\frac{(B_1+B_2)\eta_1\theta}{(B_1+B_2)C_1-(A_1+A_2)C_2}=\frac{(1-\alpha)\eta_1\theta}{\beta} \quad \text{(A.14)}$$

and

$$\sum_{i=1}^{2}(p_i-w_i^{HT})=\frac{(A_1+A_2)\eta_1\theta}{(A_1+A_2)C_2-(B_1+B_2)C_1}=\frac{2\eta_1\theta\{(1-\alpha)\eta_2-[\gamma+c_p(1-\alpha)]^2\}}{(1-\alpha)\beta\eta_2}. \quad \text{(A.15)}$$

Using Eqs.(A.5) and (A.6), we rearrange Eqs.(A.14) and (A.15) as

$$e^{HT} = \frac{[\gamma + c_p(1 - \alpha)]\eta_1\theta^{HT}}{\beta\eta_2} = \frac{[\gamma + c_p(1-\alpha)]\eta_1\{a_1 + a_2 - (1-\alpha)[c_1 + c_2 + c_p(e_1 + e_2)]\}}{4\eta_1\{(1-\alpha)\eta_2 - [\gamma + c_p(1-\alpha)]^2\} - 2\beta^2\eta_2} \tag{A.16}$$

and

$$\theta^{HT} = \frac{\beta\eta_2\{a_1 + a_2 - (1-\alpha)[c_1 + c_2 + c_p(e_1 + e_2)]\}}{4\eta_1\{(1-\alpha)\eta_2 - [\gamma + c_p(1-\alpha)]^2\} - 2\beta^2\eta_2} \tag{A.17}$$

We note that $\min\{a_1, a_2\} \geq \max\{(1-\alpha)(c_1 + c_p e_1), (1-\alpha)(c_2 + c_p e_2)$ is assumed for the feasibility of models considered throughout the work. Using it and from Eqs.(A.16) and A.17), we have $e^{HT} \geq 0$ and $\theta^{HT} \geq 0$. Using Eqs.(A.14) and (A.15), we rearrange Eqs.(A.7) and (A.8) as

$$4p_1 - 4\alpha p_2 = 3a_1 + 3\beta\theta^{HT} + 2[\gamma - c_p(1-\alpha)]e^{HT} - \alpha(c_2 + c_p e_2) + c_1 + c_p e_1 \tag{A.18}$$

and

$$4p_2 - 4\alpha p_1 = 3a_2 + 3\beta\theta^{HT} + 2[\gamma - c_p(1-\alpha)]e^{HT} - \alpha(c_1 + c_p e_1) + c_2 + c_p e_2. \tag{A.19}$$

Solving Eqs.(A.18) and (A.19) yields

$$p_1^{HT} = \frac{\beta\eta_2[3a_1 + 3\alpha a_2 + (1-\alpha^2)(c_1 + c_p e_1)] + (1+\alpha)\{3\beta^2\eta_2 + 2\eta_1[\gamma^2 - c_p^2(1-\alpha)^2]\}\theta^{HT}}{4\beta\eta_2(1-\alpha^2)}, \tag{A.20}$$

and

$$p_2^{HT} = \frac{\beta\eta_2[3\alpha a_1 + 3a_2 + (1-\alpha^2)(c_2 + c_p e_2)] + (1+\alpha)\{3\beta^2\eta_2 + 2\eta_1[\gamma^2 - c_p^2(1-\alpha)^2]\}\theta^{HT}}{4\beta\eta_2(1-\alpha^2)}. \tag{A.21}$$

This completes the proof of Theorem 3.1(ii). Using Eqs.(A.16), (A.20) and (A.21) to simplify Eq.(A.5)and (6), we prove Theorem 3.1(i).

Appendix B. Proof of Theorem 3.2

(i) We use Eqs.(8) and (9) to simplify Eq.(1), and have

$$d_1^{HT} = \frac{\beta\eta_2[a_1 + \alpha(c_2 + c_p e_2) - (c_1 + c_p e_1)] + \{\beta^2\eta_2 + 2\eta_1[\gamma + c_p(1-\alpha)]^2\}\theta^{HT}}{4\beta\eta_2} \tag{B.1}$$

and

$$d_2^{HT} = \frac{\beta\eta_2[a_2 + \alpha(c_1 + c_p e_1) - (c_2 + c_p e_2)] + \{\beta^2\eta_2 + 2\eta_1[\gamma + c_p(1-\alpha)]^2\}\theta^{HT}}{4\beta\eta_2}. \tag{B.2}$$

From Eqs.(5) and (6), we have

$$w_1^{HT} - c_1 - c_p(e_1 - e^{HT}) = \frac{\beta\eta_2[a_1 + \alpha a_2 - (1-\alpha^2)(c_1 + c_p e_1] + (1+\alpha)\{\beta^2\eta_2 + 2\eta_1[\gamma + c_p(1-\alpha)]^2\}\theta^{HT}}{4(1-\alpha^2)\beta\eta_2} \tag{B.3}$$

and

$$w_2^{HT} - c_2 - c_p(e_2 - e^{HT}) = \frac{\beta\eta_2[a_2 + \alpha a_1 - (1-\alpha^2)(c_2 + c_p e_2] + (1+\alpha)\{\beta^2\eta_2 + 2\eta_1[\gamma + c_p(1-\alpha)]^2\}\theta^{HT}}{4(1-\alpha^2)\beta\eta_2}. \tag{B.4}$$

Substituting Eqs.(B.1),(B.2), (B.3), and (B.4) into Eq.(3), we rearrange the optimal value of the retailer's profit as

$$\Pi_m(e^{HT}, w_1^{HT}, w_2^{HT}) = \frac{\sum_{i=1}^{2}[a_i + \alpha a_{3-i} - (1-\alpha^2)(c_i + c_p e_i)][a_i - (c_i + c_p e_i) + \alpha(c_{3-i} + c_p e_{3-i})]}{16(1-\alpha^2)} + \frac{\{4(1-\alpha)\eta_1\eta_2\{\beta^2\eta_2 + \eta_1[\gamma + c_p(1-\alpha)]^2\} - \{\beta^2\eta_2 + 2\eta_1[\gamma + c_p(1-\alpha)]^2\}^2\}(\theta^{HT})^2}{8(1-\alpha)(\beta\eta_2)^2} + c_p E \tag{B.5}$$

$$= \frac{\sum_{i=1}^{2}[a_i + \alpha a_{3-i} - (1-\alpha^2)(c_i + c_p e_i)][a_i - (c_i + c_p e_i) + \alpha(c_{3-i} + c_p e_{3-i})]}{16(1-\alpha^2)} + \frac{\{4(1-\alpha)\eta_1\eta_2\{\beta^2\eta_2 + \eta_1[\gamma + c_p(1-\alpha)]^2\} - \{\beta^2\eta_2 + 2\eta_1[\gamma + c_p(1-\alpha)]^2\}^2\}(e^{HT})^2}{8(1-\alpha)\eta_1^2[\gamma + c_p(1-\alpha)]^2} + c_p E$$

Similarly, using Eqs.(5), (6), (8) and (9), we have

$$p_i^{HT} - w_i^{HT} = \frac{a_i + \alpha a_{3-i} - (1-\alpha^2)(c_i + c_p e_i) + \beta(1+\alpha)\theta^{HT}}{2(1-\alpha^2)} \tag{B.6}$$

Substituting Eqs.(B.1), (B.2) and (B.6) into Eq.(2), we rearrange the optimal value of the manufacturer's profit as

$$\Pi_r(p_1^{HT}, p_2^{HT}, \theta^{HT}) = \frac{\sum_{i=1}[a_i + \alpha(c_{3-i} + c_p e_{3-i}) - (c_i + c_p e_i)][a_i + \alpha a_{3-i} - (1-\alpha^2)(c_i + c_p e_i)]}{8(1-\alpha^2)} \cdot \frac{\{[2(1-\alpha)\eta_1 - \beta^2]\eta_2 - 2\eta_1[\gamma + c_p(1-\alpha)]^2\}\{\beta^2\eta_2 + 2\eta_1[\gamma + c_p(1-\alpha)]^2\}(\theta^{HT})^2}{4(1-\alpha)\beta^2\eta_2^2}. \tag{B.7}$$

(ii) Using Eqs.(B.1) and (B.2), we obtain

$$d_1^{HT} + d_2^{HT} = \frac{(1-\alpha)\eta_1\theta^{HT}}{\beta} = \frac{(1-\alpha)\eta_2 e^{HT}}{\gamma + c_p(1-\alpha)} \tag{B.8}$$

Using Eqs.(B.1), (B.2) and (B.7) to simplify Eq.(4), we have

$$J(e^{HT}) = \frac{1}{4}\sum_{i=1}^{2} e_i[a_i + \alpha(c_{3-i} + c_p e_{3-i}) - (c_i + c_p e_i)] + \frac{(e_1 + e_2)\{\beta^2\eta_2 + 2\eta_1[\gamma + c_p(1-\alpha)]^2\}e^{HT}}{4\eta_1[\gamma + c_p(1-\alpha)]} - \frac{(1-\alpha)\eta_2(e^{HT})^2}{\gamma + c_p(1-\alpha)}. \tag{B.9}$$

Appendix C. Calculations for the results summarized in Table 3

For the decentralized model without the emission reduction technology, we have $d_i = a_i - p_i + \alpha p_{3-i} + \beta\theta, i = 1, 2$. From Eqs.(2) and (3), we further simplify the profits of the system members as

$$\Pi_r(p_1, p_2, \theta) = \sum_{i=1}^{2}(p_i - w_i)(a_i - p_i + \alpha p_{3-i} + \beta\theta) - \frac{1}{2}\eta_1\theta^2 \tag{C.1}$$

and

$$\Pi_m(w_1, w_2) = \sum_{i=1}^{2}(w_i - c_i)(a_i - p_i + \alpha p_{3-i} + \beta\theta) + c_p[E - \sum_{i=1}^{2} e_i(a_i - p_i + \alpha p_{3-i} + \beta\theta)], \tag{C.2}$$

respectively.

Similar analysis for Theorem 3.1, we let $p_i = w_i + \delta_i$, where $\delta_i \geq 0$, $i = 1, 2$ and substitute them into Eqs.(C.2). After simplification, we rearrange Eq.(C.2) as

$$\Pi_m(w_1, w_2) = \sum_{i=1}^{2} (w_i - c_i - c_p e_i)[a_i - (w_i + \delta_i) + \alpha(w_{3-i} + \delta_{3-i}) + \beta\theta] + c_p E \tag{C.3}$$

We further tak the second partial derivatives of $\Pi_m(w_1, w_2)$ with respect to w_i and from Eq.(C.3), and have $\frac{\partial^2 \Pi_m(w_1,w_2)}{\partial w_1^2} = \frac{\partial^2 \Pi_m(w_1,w_2)}{\partial w_2^2} = -2$ and $\frac{\partial^2 \Pi_m(w_1,w_2)}{\partial w_1 \partial w_2} = 2\alpha$. Using $0 < \alpha < 1$, we have $\frac{\partial^2 \Pi_m(w_1,w_2)}{\partial w_1^2} \cdot \frac{\partial^2 \Pi_m(w_1,w_2)}{\partial w_2^2} - \left(\frac{\partial^2 \Pi_m(w_1,w_2)}{\partial w_1 \partial w_2}\right)^2 = 4(1 - \alpha^2) > 0$, which implies that $\Pi_m(w_1, w_2)$ is jointly concave in w_1 and w_2.

From Eq.(C.3), we solve $\frac{\partial \Pi_m(w_1,w_2)}{\partial w_i} =$ and obtain the optimal wholesale prices of the two products as

$$w_i^{NT} = \frac{a_i + \alpha a_{3-i} + (1 - \alpha^2)(c_i + c_p e_i) - (1 - \alpha^2)p_i + (1 + \alpha)\beta\theta}{1 - \alpha^2}, \; i = 1, 2. \tag{C.4}$$

Using Eq.(C.4), we rearrange Eq.(C.1) as

$$\Pi_r(p_1, p_2, \theta) = \sum_{i=1}^{2} \frac{[(1 - \alpha^2)(2p_i - c_i - c_p e_i) - (a_i + \alpha a_{3-i}) - (1 + \alpha)\beta\theta](a_i - p_i + \alpha p_{3-i} + \beta\theta)}{1 - \alpha^2} - \frac{1}{2}\eta_2\theta^2. \tag{C.5}$$

Taking the second partial derivatives of $\Pi_r(p_1, p_2, \theta)$ with respect to p_i and θ, from Eq.(C.5), we have $\frac{\partial^2 \Pi_r(p_1,p_2,\theta)}{\partial p_1^2} = \frac{\partial^2 \Pi_r(p_1,p_2,\theta)}{\partial p_2^2} = -4$, $\frac{\partial^2 \Pi_r(p_1,p_2,\theta)}{\partial p_1 \partial p_2} = 4\alpha$, $\frac{\partial^2 \Pi_r(p_1,p_2,\theta)}{\partial p_1 \partial \theta} = \frac{\partial^2 \Pi_r(p_1,p_2,\theta)}{\partial p_2 \partial \theta} = 3\beta$, and $\frac{\partial^2 \Pi_r(p_1,p_2,\theta)}{\partial \theta^2} = -\eta_1 - \frac{4\beta^2}{1-\alpha}$. Recalling $\eta_2[(1-\alpha)\eta_1 - \beta^2] > \eta_1[\gamma + c_p(1 - \alpha)]^2$, we have $\eta_1 > \frac{\beta^2}{1-\alpha}$, and further have $\frac{\partial^2 \Pi_r(p_1,p_2,\theta)}{\partial p_1^2} \cdot \frac{\partial^2 \Pi_r(p_1,p_2,\theta)}{\partial p_2^2} - \left(\frac{\partial^2 \Pi_r(p_1,p_2,\theta)}{\partial p_1 \partial p_2}\right)^2 = 16(1 - \alpha^2) > 0$ This result implies that $\nabla^2 \Pi_r$ is a negative definite matrix.

and $|\nabla^2 \Pi_r| = 8(1 + \alpha)[\beta^2 - 2(1 - \alpha)\eta_1] < 0$, where $\nabla^2 \Pi_r$ be the Hessian matrix of $\Pi_r(p_1, p_2, \theta)$.

Solvin $\frac{\partial \Pi_r(p_1,p_2,\theta)}{\partial p_1} = 0$, $\frac{\partial \Pi_r(p_1,p_2,\theta)}{\partial p_2} = 0$, and $\frac{\partial \Pi_r(p_1,p_2,\theta)}{\partial \theta} = 0$, and from Eq.(C.5), w have

$$p_i^{NT} = \frac{3a_i + 3\alpha a_{3-i} + (1 - \alpha^2)(c_i + c_p e_i) + 3(1 + \alpha)\beta\theta^{NT}}{4(1 - \alpha^2)}, \; i = 1, 2, \tag{C.6}$$

and

$$\theta^{NT} = \frac{\beta[a_1 + a_2 - (1 - \alpha)(c_1 + c_p e_1) - (1 - \alpha)(c_2 + c_p e_2)]}{2[2(1 - \alpha)\eta_1 - \beta^2]} \tag{C.7}$$

Using Eq.(C.6), we rearrange Eq.(C.4) as

$$w_i^{NT} = \frac{a_i + \alpha a_{3-i} + 3(1 - \alpha^2)(c_i + c_p e_i) + (1 + \alpha)\beta\theta^{NT}}{4(1 - \alpha^2)} \tag{C.8}$$

Similarly, using Eqs.(C.6), (C.7), and (C.8), we have

$$\Pi_r(p_1^{NT}, p_2^{NT}, \theta^{NT}) = \frac{\sum_{i=1}^{2}[a_i + \alpha a_{3-i} - (1 - \alpha^2)(c_i + c_p e_i)][a_i - (c_i + c_p e_i) + \alpha(c_{3-i} + c_p e_{3-i})]}{8(1 - \alpha^2)} + \frac{[2(1 - \alpha)\eta_1 - \beta^2](\theta^{NT})^2}{4(1 - \alpha)}, \tag{C.9}$$

$$\Pi_m(w_1^{NT}, w_2^{NT}) = \frac{\sum_{i=1}^{2}[a_i + \alpha a_{3-i} - (1 - \alpha^2)(c_i + c_p e_i][a_i - (c_i + c_p e_i) + \alpha(c_{3-i} + c_p e_{3-i})]}{16(1 - \alpha^2)} \tag{C.10}$$

$$+\frac{[4(1-\alpha)\eta_1-\beta^2](\theta^{NT})^2}{8(1-\alpha)}+c_p E,$$

and

$$J(e^{NT})=\frac{\sum_{i=1}^{2} e_i[a_i-(c_i+c_p e_i)+\alpha(c_{3-i}+c_p e_{3-i})]}{4}+\frac{\beta(e_1+e_2)\theta^{NT}}{4}. \tag{C.11}$$

Appendix D. Proof of Theorem 3.3

(i) Using Eq.(8) and Table 2, we have

$$\frac{\theta^{HT}}{\theta^{NT}}=\frac{\eta_2[2(1-\alpha)\eta_1-\beta^2]}{2\eta_1\{(1-\alpha)\eta_2-[\gamma+c_p(1-\alpha)]^2\}-\beta^2\eta_2}>1, \tag{D.1}$$

(ii) From Eqs.(9) and (10), and Table 2, and using Eq.(D.1), we have

$$p_1^{HT}-p_1^{NT}=p_2^{HT}-p_2^{NT}=\frac{\{3\beta^2\eta_2+2\eta_1[\gamma^2-c_p^2(1-\alpha)^2]\}\theta^{HT}}{4(1-\alpha)\beta\eta_2}-\frac{3\beta\theta^{NT}}{4(1-\alpha)} \tag{D.2}$$

$$=\frac{\eta_1[\gamma+c_p(1-\alpha)]\{[2(1-\alpha)\eta_1-\beta^2][\gamma-c_p(1-\alpha)]+3\beta^2[\gamma+c_p(1-\alpha)]\}\theta^{HT}}{2(1-\alpha)\beta\eta_2[2(1-\alpha)\eta_1-\beta^2]}$$

When $\gamma \geq c_p(1-\alpha)$, we have $p_i^{HT} > p_i^{NT}$, $i = 1, 2$. When $\gamma < c_p(1-\alpha)$, if $\eta_1 < \frac{\beta^2[\gamma+2c_p(1-\alpha)]}{(1-\alpha)[c_p(1-\alpha)-\gamma]}$, then $p_i^{HT} > p_i^{NT}$, otherwise, $p_i^{HT} \leq p_i^{NT}$.

(iii) From Eqs.(5) and (6), and Table 2, and using Eq.(D.1), we have

$$w_1^{HT}-w_1^{NT}=w_2^{HT}-w_2^{NT}=\frac{\{\beta^2\eta_2+2\eta_1[\gamma^2-c_p^2(1-\alpha)^2]\}\theta^{HT}}{4(1-\alpha)\beta\eta_2}-\frac{\beta\theta^{NT}}{4(1-\alpha)} \tag{D.3}$$

$$=\frac{\eta_1[\gamma+c_p(1-\alpha)]\{[2(1-\alpha)\eta_1-\beta^2][\gamma-c_p(1-\alpha)]+\beta^2[\gamma+c_p(1-\alpha)]\}\theta^{HT}}{2(1-\alpha)\beta\eta_2[2(1-\alpha)\eta_1-\beta^2]}$$

From Eq.(D.3), we have that when $\gamma \geq c_p(1-\alpha)$, $w_i^{HT} > w_i^{NT}$, $i = 1, 2$. When $\gamma < c_p(1-\alpha)$, if $\eta_1 < \frac{\beta^2[\gamma+c_p(1-\alpha)]}{2(1-\alpha)[c_p(1-\alpha)-\gamma]}$, then $w_i^{HT} > w_i^{NT}$, otherwise, $w_i^{HT} \leq w_i^{NT}$.

(iv) From Eqs.(11) and (D.1 and Table 2, after simplification and we have

$$\Pi_m(e^{HT},w_1^{HT},w_2^{HT})-\Pi_m(w_1^{NT},w_2^{NT}) \tag{D.4}$$

$$=\frac{\{4(1-\alpha)\eta_1\eta_2\{\beta^2\eta_2+\eta_1[\gamma+c_p(1-\alpha)]^2\}(\theta^{HT})^2}{8(1-\alpha)(\beta\eta_2)^2}-\frac{\{\beta^2\eta_2+2\eta_1[\gamma+c_p(1-\alpha)]^2\}^2(\theta^{HT})^2}{8(1-\alpha)(\beta\eta_2)^2}$$

$$-\frac{[4(1-\alpha)\eta_1-\beta^2](\theta^{NT})^2}{8(1-\alpha)}$$

$$=\frac{(\theta^{NT})^2\eta_1 F}{[2(1-\alpha)\eta_1-\beta^2]^2(\beta\eta_2)^2},$$

where $F=\eta_2[2(1-\alpha)\eta_1-\beta^2]^2\{(1-\alpha)\eta_2-[\gamma+c_p(1-\alpha)]^2\}-(1-\alpha)\{[2(1-\alpha)\eta_1-\beta^2]\eta_2-2\eta_1[\gamma+c_p(1-\alpha)]^2\}^2$.

Rearranging the expression of F, we have

$$F=\frac{[\gamma+c_p(1-\alpha)]^2[2(1-\alpha)\eta_1+\beta^2]}{[2(1-\alpha)\eta_1-\beta^2]^3}\left\{\eta_2-\frac{4(1-\alpha)\eta_1^2[\gamma+c_p(1-\alpha)]^2}{[2(1-\alpha)\eta_1+\beta^2][2(1-\alpha)\eta_1-\beta^2]}\right\}. \tag{D.5}$$

Using $\eta_2 > \frac{2\eta_1[\gamma+c_p(1-\alpha)]^2}{2(1-\alpha)\eta_1-\beta^2}$ and $0 < \frac{2(1-\alpha)\eta_1}{2(1-\alpha)\eta_1+\beta^2} < 1$, we have $F > 0$ and $\Pi_m(e^{HT}, w_1^{HT}, w_2^{HT}) - \Pi_m(w_1^{NT}, w_2^{NT}) > 0$, i.e., $\Pi_m(e^{HT}, w_1^{HT}, w_2^{HT}) > \Pi_m(w_1^{NT}, w_2^{NT})$

Similarly, from Eqs.(12) and (D.1 and Table 2,

$$\begin{aligned}
&\Pi_r(p_1^{HT}, p_2^{HT}, \theta^{HT}) - \Pi_r(p_1^{NT}, p_2^{NT}, \theta^{NT}) \qquad \text{(D.6)}\\
&= \frac{\{[2(1-\alpha)\eta_1-\beta^2]\eta_2 - 2\eta_1[\gamma+c_p(1-\alpha)]^2\}\{\beta^2\eta_2+2\eta_1[\gamma+c_p(1-\alpha)]^2\}(\theta^{HT})^2}{4(1-\alpha)(\beta\eta_2)^2}\\
&\quad - \frac{[2(1-\alpha)\eta_1-\beta^2](\theta^{NT})^2}{4(1-\alpha)}\\
&= \frac{\eta^2[\gamma+c_p(1-\alpha)]^2\{[2(1-\alpha)\eta_1-\beta^2]\eta_2 - 2\eta_1[\gamma+c_p(1-\alpha)]^2\}(\theta^{HT})^2}{(\beta\eta_2)^2[2(1-\alpha)\eta_1-\beta^2]} > 0.
\end{aligned}$$

Eq.(D.6) yields $\Pi_r(p_1^{HT}, p_2^{HT}, \theta^{HT}) > \Pi_r(p_1^{NT}, p_2^{NT}, \theta^{NT})$.

(v) From Eqs.(13) and (D.1) and Table 2, after simplification and we have

$$\begin{aligned}
J(e^{HT}) - J(e^{NT}) &= \frac{(e_1+e_2)\{\beta^2\eta_2+2\eta_1[\gamma+c_p(1-\alpha)]\}\theta^{HT}}{4\beta\eta_2} - \frac{(1-\alpha)[\gamma+c_p(1-\alpha)]\eta_1^2(\theta^{HT})^2}{(\beta\eta_2)^2} \qquad \text{(D.7)}\\
&\quad - \frac{\beta(e_1+e_2)\theta^{NT}}{4}\\
&= \frac{(1-\alpha)\eta_1\theta^{HT}}{\beta^2}\left\{\frac{(e_1+e_2)\eta_1[\gamma+c_p(1-\alpha)]^2}{[2(1-\alpha)\eta_1-\beta^2]\eta_2} - e^{HT}\right\}
\end{aligned}$$

From Eq.(D.7), we have that if $e^{HT} < \frac{(e_1+e_2)[\gamma+c_p(1-\alpha)]^2\eta_1}{[2(1-\alpha)\eta_2-\beta^2]\eta_2}$, then $J(e^{HT}) > J(e^{NT})$, otherwise, $J(e^{HT}) \leq J(e^{NT})$.

Appendix E. Proof of Theorem 3.4

(i) From Eq.(14), we take the first partial derivative of $\Pi_c(p_1, p_2, \theta, e)$ with respect to p_1, p_2, θ, and e, and have

$$\frac{\partial \Pi_c(p_1, p_2, \theta, e)}{\partial p_1} = a_1 - p_1 + \alpha p_2 + \beta\theta + \gamma e - [p_1 - c_1 - c_p(e_1 - e)] + \alpha[p_2 - c_2 - c_p(e_2 - e)], \qquad \text{(E.1)}$$

$$\frac{\partial \Pi_c(p_1, p_2, \theta, e)}{\partial p_2} = \alpha[p_1 - c_1 - c_p(e_1 - e)] + a_2 - p_2 + \alpha p_1 + \beta\theta + \gamma e - [p_2 - c_2 - c_p(e_2 - e)], \qquad \text{(E.2)}$$

$$\frac{\partial \Pi_c(p_1, p_2, \theta, e)}{\partial \theta} = \beta[p_1 - c_1 - c_p(e_1 - e)] + \beta[p_2 - c_2 - c_p(e_2 - e)] - \eta_1\theta, \qquad \text{(E.3)}$$

and

$$\begin{aligned}
\frac{\partial \Pi_c(p_1, p_2, \theta, e)}{\partial e} &= c_p[a_1 + a_2 - (1-\alpha)(p_1+p_2) + 2\beta\theta + 2\gamma e] + \gamma[p_1 + p_2 - (c_1+c_2) \qquad \text{(E.4)}\\
&\quad - c_p(e_1 + e_2 - 2e)] - \eta_2 e
\end{aligned}$$

Taking the second partial derivatives of $\Pi_c(p_1, p_2, \theta, e)$ with respect to p_1, p_2, θ, and e, we further have $\frac{\partial^2\Pi_c(p_1,p_2,\theta,e)}{\partial p_1^2} = \frac{\partial^2\Pi_c(p_1,p_2,\theta,e)}{\partial p_2^2} = -2$, $\frac{\partial^2\Pi_c(p_1,p_2,\theta,e)}{\partial p_1\partial p_2} = 2\alpha$, $\frac{\partial^2\Pi_c(p_1,p_2,\theta,e)}{\partial p_1\partial\theta} = \frac{\partial^2\Pi_c(p_1,p_2,\theta,e)}{\partial p_2\partial\theta} = \beta$, $\frac{\partial^2\Pi_c(p_1,p_2,\theta,e)}{\partial p_1\partial e} = \frac{\partial^2\Pi_c(p_1,p_2,\theta,e)}{\partial p_2\partial e} = \gamma - c_p(1-\alpha)$, $\frac{\partial^2\Pi_c(p_1,p_2,\theta,e)}{\partial e\partial\theta} = 2\beta c_p$, $\frac{\partial^2\Pi_c(p_1,p_2,\theta,e)}{\partial\theta^2} = -\eta_1$, and $\frac{\partial^2\Pi_c(p_1,p_2,\theta,e)}{\partial e^2} = 4c_p\gamma - \eta_2$. Let $\nabla^2\Pi_c$ be the Hessian matrix of

$\Pi_c(p_1, p_2, \theta, e)$, where

$$\nabla^2\Pi_c = \begin{bmatrix} \frac{\partial^2\Pi_c(p_1,p_2,\theta,e)}{\partial p_1^2} & \frac{\partial^2\Pi_c(p_1,p_2,\theta,e)}{\partial p_1\partial p_2} & \frac{\partial^2\Pi_c(p_1,p_2,\theta,e)}{\partial p_1\partial\theta} & \frac{\partial^2\Pi_c(p_1,p_2,\theta,e)}{\partial p_1\partial e} \\ \frac{\partial^2\Pi_c(p_1,p_2,\theta,e)}{\partial p_2\partial p_1} & \frac{\partial^2\Pi_c(p_1,p_2,\theta,e)}{\partial p_2^2} & \frac{\partial^2\Pi_c(p_1,p_2,\theta,e)}{\partial p_2\partial\theta} & \frac{\partial^2\Pi_c(p_1,p_2,\theta,e)}{\partial p_2\partial e} \\ \frac{\partial^2\Pi_c(p_1,p_2,\theta,e)}{\partial\theta\partial p_1} & \frac{\partial^2\Pi_c(p_1,p_2,\theta,e)}{\partial\theta\partial p_2} & \frac{\partial^2\Pi_c(p_1,p_2,\theta,e)}{\partial\theta^2} & \frac{\partial^2\Pi_c(p_1,p_2,\theta,e)}{\partial\theta\partial e} \\ \frac{\partial^2\Pi_c(p_1,p_2,\theta,e)}{\partial e\partial p_1} & \frac{\partial^2\Pi_c(p_1,p_2,\theta,e)}{\partial e\partial p_2} & \frac{\partial^2\Pi_c(p_1,p_2,\theta,e)}{\partial e\partial\theta} & \frac{\partial^2\Pi_c(p_1,p_2,\theta,e)}{\partial e^2} \end{bmatrix}_{4\times 4} \tag{E.5}$$

Using $0 < \alpha < 1$ and $(1-\alpha)\eta_1 - \beta^2 > 0$, we have that the values of the first, second and third order leading principal minors of $\nabla^2\Pi_c$ are $-2(<0)$, $4(1-\alpha^2)(>0)$ and $4(1+\alpha)[\beta^2 - (1-\alpha)\eta_1](<0)$, respectively. Using $\eta_2[(1-\alpha)\eta_1 - \beta^2] > \eta_1[\gamma + c_p(1-\alpha)]^2$, we further have $|\nabla^2\Pi_c| = 4(1+\alpha)\{\eta_2[(1-\alpha)\eta_1 - \beta^2] - \eta_1[\gamma + c_p(1-\alpha)]^2\} > 0$. This means that $\nabla^2\Pi_c$ a negative definite matrix and $\Pi_c(p_1, p_2, \theta, e)$ is jointly concave in p_1, p_2, θ and e.

From Eqs.(E.1)-(E.5) and solving $\frac{\partial\Pi_c(p_1,p_2,\theta,e)}{\partial p_1} = 0$, $\frac{\partial\Pi_c(p_1,p_2,\theta,e)}{\partial p_2} = 0$, $\frac{\partial\Pi_c(p_1,p_2,\theta,e)}{\partial\theta} = 0$ and $\frac{\partial\Pi_c(p_1,p_2,\theta,e)}{\partial e} = 0$, we have

$$p_1^C = \frac{\beta\eta_2[a_1 + \alpha a_2 + (1-\alpha^2)(c_1 + c_p e_1)] + (1+\alpha)\{\beta^2\eta_2 + \eta_1[\gamma^2 - c^2(1_p - \alpha)^2]\}\theta^C}{2\beta\eta_2(1-\alpha^2)}, \tag{E.6}$$

$$p_2^C = \frac{\beta\eta_2[\alpha a_1 + a_2 + (1-\alpha^2)(c_2 + c_p e_2)] + (1+\alpha)\{\beta^2\eta_2 + \eta_1[\gamma^2 - c^2(1_p - \alpha)^2]\}\theta^C}{2\beta\eta_2(1-\alpha^2)}, \tag{E.7}$$

$$e^C = \frac{\eta_1[\gamma + c_p(1-\alpha)]\theta^C}{\beta\eta_2} \tag{E.8}$$

and

$$\theta^C = \frac{\beta\eta_2\{a_1 + a_2 - (1-\alpha)[c_1 + c_2 + c_p(e_1 + e_2)]\}}{2\eta_1\{(1-\alpha)\eta_2 - [\gamma + c_p(1-\alpha)]^2\} - 2\beta^2\eta_2}. \tag{E.9}$$

(ii) From Eqs.(E.6)-(E.9), we have

$$p_i^C - c_i - c_p(e_i - e^C) = \frac{a_i + \alpha a_{3-i} - (1-\alpha^2)(c_i + c_p e_i) + (1+\alpha)\{\beta\theta^C + [\gamma + c_p(1-\alpha)]e^C\}}{2(1-\alpha^2)}, \; i = 1, 2, \tag{E.10}$$

$$a_i - p_i^C + \alpha\, p_{3-i}^C + \beta\theta^C + \gamma\, e^C = \frac{a_i + \alpha(c_{3-i} + c_p e_{3-i}) - (c_i + c_p e_i) + \beta\theta^C + [\gamma + c_p(1-\alpha)]e^C}{2}, \; i = 1, 2 \tag{E.11}$$

and

$$\beta\theta^C + [\gamma + c_p(1-\alpha)]e^C = \frac{\{\beta^2\eta_2 + \eta_1[\gamma + c_p(1-\alpha)]^2\}\theta^C}{\beta\eta_2}. \tag{E.12}$$

Substituting Eqs.(E.10), (E.11), and (E.12) into Eqs.(14) and (4), and after simplification, we have

$$\Pi_c(p_1^C, p_2^C, \theta^C, e^C) = \frac{\sum_{i=1}^{2}[a_i + \alpha a_{3-i} - (1-\alpha^2)(c_i + c_p e_i)][a_i + \alpha(c_{3-i} + c_p e_{3-i}) - (c_i + c_p e_i)]}{4(1-\alpha^2)} + \frac{\{\beta^2\eta_2 + \eta_1[\gamma + c_p(1-\alpha)]^2\}\{[(1-\alpha)\eta_1 - \beta^2]\eta_2 - \eta_1[\gamma + c_p(1-\alpha)]^2\}(\theta^C)^2}{2(1-\alpha)(\beta\eta_2)^2} + c_p E \tag{E.13}$$

and

$$J(e^C) = \frac{1}{2}\sum_{i=1}^{2} e_i[a_i + \alpha(c_{3-i} + c_p e_{3-i}) - (c_i + c_p e_i)] + \frac{(e_1 + e_2)\{\beta^2\eta_2 + \eta_1[\gamma + c_p(1-\alpha)]^2\}e^C}{2\eta_1[\gamma + c_p(1-\alpha)]} \tag{E.14}$$

$$-\frac{(1-\alpha)\eta_2(e^C)^2}{\gamma + c_p(1-\alpha)}.$$

Appendix F. Proof of Theorem 3.5

(i) Comparing Eqs.(7) and (10) with Eqs.(17) and (18), we have $\theta_1^C = \Omega\theta^{HT}$ and $e_2^C = \Omega e^{HT}$.

(ii) Comparing Eq.(8) with Eq.(15) yields

$$\begin{aligned} 2p_1^{HT} - p_1^C &= \frac{a_1 + \alpha a_2}{1-\alpha^2} + \frac{\beta^2\eta_2(2\theta^{HT} - \theta^C) + \eta_1[\gamma^2 - c_p^2(1-\alpha)^2](2\theta^{HT} - \theta^C)}{2(1-\alpha)\beta\eta_2} \\ &= \frac{a_1 + \alpha a_2}{1-\alpha^2} - \frac{\{(\Omega-3)\beta^2\eta_2 + (\Omega-2)\eta_1[\gamma^2 - c_p^2(1-\alpha)^2]\}\theta^{HT}}{2(1-\alpha)\beta\eta_2} \\ &= \Omega_{t_1}. \end{aligned} \tag{F.1}$$

Rearranging Eq.(F.1), we have

$$p_1^C - p_1^{HT} = p_1^{HT} - \Omega_{t_1}. \tag{F.2}$$

From Eq.(F.2), we have that if $p_1^{HT} > \Omega_{t_1}$, then $p_1^C > p_1^{HT}$, otherwise, $p_1^C \le p_1^{HT}$. Similarly, we prove it for the product 2.

(iii) Using $\eta_2[(1-\alpha)\eta_1 - \beta^2] > \eta_1[\gamma + c_p(1-\alpha)]^2$, we have

$$\frac{(1-\alpha)\eta_1\eta_2\{2(1-\alpha)\eta_1\eta_2 - 2\eta_1[\gamma + c_p(1-\alpha)]^2 + \beta^2\eta_2\}}{(1-\alpha)\eta_1\eta_2 - \{\beta^2\eta_2 + \eta_1[\gamma + c_p(1-\alpha)]^2\}} > \frac{4(1-\alpha)\eta_1\eta_2\{(1-\alpha)\eta_1\eta_2 - \eta_1[\gamma + c_p(1-\alpha)]^2\}}{2(1-\alpha)\eta_1\eta_2 - 2\eta_1[\gamma + c_p(1-\alpha)]^2 - \beta^2\eta_2} \tag{F.3}$$

and

$$\begin{aligned} &\frac{(1-\alpha)\eta_1\eta_2\{2(1-\alpha)\eta_1\eta_2 - 2\eta_1[\gamma + c_p(1-\alpha)]^2 + \beta^2\eta_2\}}{\{(1-\alpha)\eta_1\eta_2 - \beta^2\eta_2 - \eta_1[\gamma + c_p(1-\alpha)]^2\}\{2(1-\alpha)\eta_1\eta_2 - 2\eta_1[\gamma + c_p(1-\alpha)]^2 - \beta^2\eta_2\}} - 1 \\ &> \frac{4(1-\alpha)\eta_1\eta_2\{(1-\alpha)\eta_1\eta_2 - \eta_1[\gamma + c_p(1-\alpha)]^2\}}{\{2(1-\alpha)\eta_1\eta_2 - 2\eta_1[\gamma + c_p(1-\alpha)]^2 - \beta^2\eta_2\}^2} - 1. \end{aligned} \tag{F.4}$$

Rearranging Eq.(F.4), we have

$$\begin{aligned} &\frac{3\{\beta^2\eta_2 + \eta_1[\gamma + c_p(1-\alpha)]^2\}}{(1-\alpha)\eta_1\eta_2 - \{\beta^2\eta_2 + \eta_1[\gamma + c_p(1-\alpha)]^2\}} > \frac{2\{\beta^2\eta_2 + 2\eta_1[\gamma + c_p(1-\alpha)]^2\}}{2(1-\alpha)\eta_1\eta_2 - \{\beta^2\eta_2 + 2\eta_1[\gamma + c_p(1-\alpha)]^2\}} \\ &+ \frac{4(1-\alpha)\eta_1\eta_2\{\beta^2\eta_2 + \eta_1[\gamma + c_p(1-\alpha)]^2\} - \{\beta^2\eta_2 + 2\eta_1[\gamma + c_p(1-\alpha)]^2\}^2}{\{2(1-\alpha)\eta_1\eta_2 - 2\eta_1[\gamma + c_p(1-\alpha)]^2 - \beta^2\eta_2\}^2}. \end{aligned} \tag{F.5}$$

Using Eqs.(10) and (18) to simplify Eq.(F.5), and from Eqs.(11), (12), and (19), we rearrange Eq.(F.5) as

$$\frac{\Pi_c(p_1^C, p_2^C, \theta^C, e^C) - c_pE - A_0}{4} > \frac{\Pi_r(p_1^{HT}, p_2^{HT}, \theta^{HT}) + \Pi_m(e^{HT}, w_1^{HT}, w_2^{HT}) - c_pE - B_0}{3} > 0, \tag{F.6}$$

where $A_0 = \frac{\sum_{i=1}^{3}[a_i + \alpha a_{3-i} - (1-\alpha^2)(c_i + c_pe_i)][a_i + \alpha(c_{3-i} + c_pe_{3-i}) - (c_i + c_pe_i)]}{4(1-\alpha^2)}$ and $B_0 = \frac{3}{4}A_0$.

Using $\frac{\Pi_c(p_1^C, p_2^C, \theta^C, e^C) - c_pE - B_0}{3} > \frac{\Pi_c(p_1^C, p_2^C, \theta^C, e^C) - c_pE - B_0}{4} > \frac{\Pi_c(p_1^C, p_2^C, \theta^C, e^C) - c_pE - A_0}{4}$, from Eq.(F.6), we have

$$\Pi_c(p_1^C, p_2^C, \theta^C, e^C) > \Pi_r(p_1^{HT}, p_2^{HT}, \theta^{HT}) + \Pi_m(e^{HT}, w_1^{HT}, w_2^{HT}) \tag{F.7}$$

and

$$\frac{\Pi_c(p_1^C, p_2^C, \theta^C, e^C)}{\Pi_r(p_1^{HT}, p_2^{HT}, \theta^{HT}) + \Pi_m(e^{HT}, w_1^{HT}, w_2^{HT})} < \frac{\Pi_c(p_1^C, p_2^C, \theta^C, e^C) - c_pE}{\Pi_r(p_1^{HT}, p_2^{HT}, \theta^{HT}) + \Pi_m(e^{HT}, w_1^{HT}, w_2^{HT}) - c_pE} \tag{F.8}$$

$$< \frac{\Pi_c(p^C, p^C, \theta^C, e^C) - c_pE - A_0}{\Pi_r(p_1^{HT}, p_2^{HT}, \theta^{HT}) + \Pi_m(e^{HT}, w_1^{HT}, w_2^{HT}) - c_pE - B_0}.$$

The last inequality holds because of $A_0 > B_0$. On the other hand, from Eqs.(11), (12), and (19), we also have

$$\frac{\Pi_c(p^C, p^C, \theta^C, e^C) - c_pE - A_0}{\Pi_r(p_1^{HT}, p_2^{HT}, \theta^{HT}) + \Pi_m(e^{HT}, w_1^{HT}, w_2^{HT}) - c_pE - B_0} \tag{F.9}$$

$$= \frac{4\Omega^2\{\beta^2\eta_2 + \eta_1[\gamma + c_p(1-\alpha)]^2\}\{[(1-\alpha)\eta_1 - \beta^2]\eta_2 - \eta_1[\gamma + c_p(1-\alpha)]^2\}}{4(1-\alpha)\eta_1\eta_2\{3\eta_1[\gamma + c_p(1-\alpha)]^2 + 2\beta^2\eta_2\} - 3\{2\eta_1[\gamma + c_p(1-\alpha)]^2 + \beta^2\eta_2\}^2} = \Omega_u.$$

Eqs.(F.8) and (F.9) yields

$$\frac{\Pi_c(p_1^C, p_2^C, \theta^C, e^C)}{\Pi_r(p_1^{HT}, p_2^{HT}, \theta^{HT}) + \Pi_m(e^{HT}, w_1^{HT}, w_2^{HT})} < \Omega_u. \tag{F.10}$$

(iv) When $e_1 = e_2 = e_0$, using Eqs.(7) and (17), and comparing Eq.(17) with Eq.(**??**), we have

$$J(e^C) - J(e^{HT}) = \frac{(1-\alpha)(\Omega-1)\eta_2 e^{HT}[e_0 - (\Omega+1)e^{HT}]}{\gamma + c_p(1-\alpha)}. \tag{F.11}$$

Using $\Omega > 2$ and $0 < \alpha < 1$, from Eq.(F.11), we have that if $e^{HT} < \frac{e_0}{\Omega+1}$, then $J(e^C) > J(e^{HT})$. Otherwise, $J(e^C) \le J(e^{HT})$.

Appendix G. Proof of Theorem 3.6

(i) For $i = 1, 2$, let $p_i = w_i + \delta_i$, where $\delta_i \ge 0$. Substituting Eq.(1) into Eq.(22) and using $p_i = w_i + \delta_i$ to simplify it, we have

$$\Pi_{m/rc}(w_1, w_2, e) = \sum_{i=1}^{2}[\rho w_i - c_i - \rho c_p(e_i - e)][a_i - (w_i + \delta_i) + \alpha(w_{3-i} + \delta_{3-i}) + \beta\theta + \gamma e] - \frac{1}{2}\rho\eta_1\theta^2 - \frac{1}{2}\rho\eta_2 e^2 + \rho c_p E. \tag{G.1}$$

For any values of θ and δ_i, $i = 1, 2$, we rearrange $\frac{\partial \Pi_{m/rc}(w_1, w_2, e)}{\partial w_i}$ and $\frac{\partial \Pi_{m/rc}(w_1, w_2, e)}{\partial e}$ as

$$\frac{\partial \Pi_{m/rc}(w_1, w_2, e)}{\partial w_i} = \rho[a_i - (w_i + \delta_i) + \alpha(w_{3-i} + \delta_{3-i}) + \beta\theta + \gamma e] - [\rho w_i - c_i - \rho c_p(e_i - e)] + \alpha[\rho w_{3-i} - c_{3-i} - \rho c_p(e_{3-i} - e)],\ i = 1, 2, \tag{G.2}$$

and

$$\frac{\partial \Pi_{m/rc}(w_1, w_2, e)}{\partial e} = \sum_{i=1}^{2}\gamma[\rho w_i - c_i - \rho c_p(e_i - e)] + \sum_{i=1}^{2}\rho[a_i - (w_i + \delta_i) + \alpha(w_{3-i} + \delta_{3-i}) + \beta\theta + \gamma e] - \rho\eta_2 e. \tag{G.3}$$

Solving Eqs. (G.2) and (G.3) yields

$$w_i^{RC} = \frac{c_i + \rho c_p(e_i - e^{RC})}{\rho} + \frac{a_i + \alpha a_{3-i} - (1-\alpha^2)p_i^{RC} + (1+\alpha)(\beta\theta^{RC} + \gamma e^{RC})}{1-\alpha^2},\ i = 1, 2, \tag{G.4}$$

and

$$e^{RC} = \frac{[\gamma + c_p(1-\alpha)][a_1 + a_2 - (1-\alpha)(p_1^{RC} + p_2^{RC}) + 2\beta\theta^{RC}]}{(1-\alpha)\eta_2 - 2\gamma[\gamma + c_p(1-\alpha)]}. \tag{G.5}$$

From the definition of the RC contract, we have that if solving $e^{RC} = e^C$ and $p_i^{RC} = p^C$, $i = 1, 2$, yields that there exists the feasible solutions for $(\theta^{RC}, w_1^{RC}, w_2^{RC})$ satisfying $\theta^{RC} = \theta^C$ and $w_i^{RC} > 0$, $i = 1, 2$, then the RC contract leads to the system coordination. Using the coordination conditions $e^{RC} = e^C$ and $p_i^{RC} = p_i^C$, $i = 1, 2$, and from Eqs.(15),(16), and (18), we compare Eq.(17) with Eq.(G.5) and have

$$\theta^{RC} = \theta^C = \frac{\beta\eta_2\{a_1 + a_2 - (1-\alpha)[c_1 + c_2 + c_p(e_1 + e_2)]\}}{2\eta_1\{(1-\alpha)\eta_2 - [\gamma + c_p(1-\alpha)]^2\} - 2\beta^2\eta_2}. \tag{G.6}$$

Substituting Eqs.(15),(16), (G.5), and (G.6) into Eq.(G.4), we have

$$w_i^{RC} = \frac{\rho p_i^C + (1-\rho)c_i}{\rho}, \; i = 1, 2. \tag{G.7}$$

(ii) Using Eqs.(G.5) and (G.6), we have

$$\begin{aligned} \rho w_i^{RC} - c_i - \rho(e_i - e^{RC}) &= \frac{\rho a_i + \alpha a_{3-i} - (1-\alpha^2)p_i^C + (1+\alpha)(\beta\theta^C + \gamma e^C)]}{1-\alpha^2} \\ &= \frac{a_i + \alpha a_{3-i} - (1-\alpha^2)(c_i + c_p e_i) + (1+\alpha)\{\beta\theta^C + [\gamma + c_p(1-\alpha)]e^C\}}{2(1-\alpha^2)} \\ &= p_i^C - c_i - c_p(e_i - e^C), \; i = 1, 2, \end{aligned} \tag{G.8}$$

and

$$p_i^{RC} - \rho w_i^{RC} - (1-\rho)c_p(e_i - e^{RC}) = (1-\rho)[p_i^C - c_i - c_p(e_i - e^C)], \; i = 1, 2. \tag{G.9}$$

We substitute Eqs.(G.8) and (G.9) into Eqs.(22) and (23), and have

$$\begin{aligned} \Pi_{m/rc}(w_1^{RC}, w_2^{RC}, e^{RC}) &= \rho\{\sum_{i=1}^{2}[p_i^C - c_i - c_p(e_i - e^C)](a_i - p_i^C + \alpha p_{3-i}^C + \beta\theta^C + \gamma e^C) \\ &\quad - \frac{1}{2}\eta_1(\theta^C)^2 - \frac{1}{2}(\eta_2 e^C)^2 + c_p E\} \\ &= \rho\Pi_c(p^C, p_1^C, p_2^C, \theta^C, e^C) \end{aligned} \tag{G.10}$$

and

$$\begin{aligned} \Pi_{r/rc}(p_1^{RC}, p_2^{RC}, \theta^{RC}) &= (1-\rho)\{\sum_{i=1}^{2}[p_i^C - c_i - c_p(e_i - e^C)](a_i - p_i^C + \alpha p_{3-i}^C + \beta\theta^C + \gamma e^C) \\ &\quad - \frac{1}{2}\eta_1(\theta^C)^2 - \frac{1}{2}(\eta_2 e^C)^2 + c_p E\} \\ &= (1-\rho)\Pi_c(p^C, p_1^C, p_2^C, \theta^C, e^C) \end{aligned} \tag{G.11}$$

The RC contract coordinated the supply chain perfectly if and only if the profits of the manufacturer and the retailer are not less than those in the decentralized case without the RC contract, respectively, i.e., $\Pi_{m/rc}(w_1^{RC}, w_2^{RC}, e^{RC}) \geq \Pi_m(w_1^{HT}, w_2^{HT}, e^{HT})$ and $\Pi_{r/rc}(p_1^{RC}, p_2^{RC}, \theta^{RC}) \geq \Pi_r(p_1^{HT}, p_2^{HT}, \theta^{HT})$. Using Eq.(F.7), we compare Eqs.(G.10) and

(G.11) with Eqs.(11) and (12), respectively, and have

$$\frac{\Pi_m(e^{HT}, w_1^{HT}, w_2^{HT})}{\Pi_c(p_1^C, p_2^C, \theta^C, e^C)} \le \rho \le 1 - \frac{\Pi_r(p_1^{HT}, p_2^{HT}, \theta^{HT})}{\Pi_c(p_1^C, p_2^C, \theta^C, e^C)}. \tag{G.12}$$

(iii) Using $\theta^{RC} = \theta^C$, $e^{RC} = e^C$ and $p_i^{RC} = p_i^C$, $i = 1, 2$, from Eqs.(G.10), (G.11) and (20), we easily have $\Pi_{m/rc}(w_1^{RC}, w_2^{RC}, e^{RC}) + \Pi_{r/rc}(p_1^{RC}, p_2^{RC}, \theta^{RC}) = \Pi_c(p_1^C, p_2^C, \theta^C, e^C)$ and $J(e^{RC}) = J(e^C)$.

Appendix H. Proof of Corollary 3.8

First, we consider an optimization model for a centralized supply chain without the emissions reduction technology. From Eqs.(C.1) and (C.2), we express the system's profit of the centralized case as

$$\Pi_c(p_1, p_2, \theta) = \sum_{i=1}^{2}(p_i - c_i)(a_i - p_i + \alpha p_{3-i} + \beta\theta) - \frac{1}{2}\eta_1\theta^2 + c_p[E - \sum_{i=1}^{2} e_i(a_i - p_i + \alpha p_{3-i} + \beta\theta)] \tag{H.1}$$

Using $0 < \alpha < 1$ and $(1 - \alpha)\eta_1 - \beta^2 > 0$, and solving $\frac{\partial \Pi_c(p_1, p_2, \theta)}{\partial p_1} = 0$, $\frac{\partial \Pi_c(p_1, p_2, \theta)}{\partial p_2} = 0$, and $\frac{\partial \Pi_c(p_1, p_2, \theta)}{\partial \theta} = 0$, we have the optimal sale prices of two products and the level of CSR as

$$p_i^{NC} = \frac{a_i + \alpha a_{3-i} + (1 - \alpha^2)(c_i + c_p e_i) + \beta(1 + \alpha)\theta^{NC}}{2(1 - \alpha^2)}, \; i = 1, 2, \tag{H.2}$$

and

$$\theta^{NC} = \frac{\beta\{a_1 + a_2 - (1 - \alpha)[c_1 + c_2 + c_p(e_1 + e_2)]\}}{2[(1 - \alpha)\eta_1 - \beta^2]}. \tag{H.3}$$

Second, from Eqs.(C.1) and (C.2), the profits of the retailer and the manufacturer under the NRC contract are expressed as

$$\Pi_{r/nrc}(p_1, p_2, \theta) = \sum_{i=1}^{2}(p_i - \rho w_i)(a_i - p_i + \alpha p_{3-i} + \beta\theta) - \frac{1}{2}(1 - \rho)\eta_1\theta^2 + (1 - \rho)c_p[E - \sum_{i=1}^{2} e_i(a_i - p_i + \alpha p_{3-i} + \beta\theta)] \tag{H.4}$$

and

$$\Pi_{m/nrc}(w_1, w_2) = \sum_{i=1}^{2}(\rho w_i - c_i)(a_i - p_i + \alpha p_{3-i} + \beta\theta) - \frac{1}{2}\rho\eta_1\theta^2 + \rho c_p[E - \sum_{i=1}^{2} e_i(a_i - p_i + \alpha p_{3-i} + \beta\theta)], \tag{H.5}$$

respectively.

Using $p_i = w_i + \delta_i$, $i = 1, 2$, and solving $\frac{\partial \Pi_{m/nrc}(w_1, w_2)}{\partial w_1} = 0$ and $\frac{\partial \Pi_{m/nrc}(w_1, w_2)}{\partial w_2} = 0$, we have the optimal wholesale prices of two products under the NRC contract as

$$w_i^{NRC} = \frac{c_i + \rho c_p e_i}{\rho} + \frac{a_i + \alpha a_{3-i} - (1 - \alpha^2)p_i^{NRC} + (1 + \alpha)\beta\theta^{NRC}}{1 - \alpha^2}, \; i = 1, 2. \tag{H.6}$$

From the definition of the NRC, and using the coordination conditions $p_i^{NRC} = p_i^{NC}$, $i = 1, 2$, and $\theta^{NRC} = \theta^{NC}$, we have that there exists the feasible solution for w_i satisfying $w_i > 0$. In this scenario, the NRC contract coordinates the decentralized supply chain without the emission reduction technology and the optimal wholesale prices of two

products shown in Eq.(H.6) are re-expressed as

$$w_i^{NRC} = \frac{\rho p_i^{NRC} + (1-\rho)c_i}{\rho}, i = 1, 2. \tag{H.7}$$

Finally, using the coordination conditions and Eq.(H.7), we have

$$\rho w_i^{NRC} - c_i - \rho c_p e_i = \rho(p_i^{NC} - c_i - c_p e_i), i = 1, 2, \tag{H.8}$$

and

$$p_i^{NRC} - \rho w_i^{NRC} = (1-\rho)(p_i^{NC} - c_i), i = 1, 2. \tag{H.9}$$

Using Eqs.(H.8) and (H.9), and from Eqs.(H.1), (H.4), and (H.5), we have $\Pi_{r/nrc}(p_1^{NRC}, p_2^{NRC}, \theta^{NRC}) = (1-\rho)\Pi_c(p_1^{NC}, p_2^{NC}, \theta^{NC})$ and $\Pi_{m/nrc}(w_1^{NRC}, w_2^{NRC}) = \rho\Pi_c(p_1^{NC}, p_2^{NC}, \theta^{NC})$.

The NRC contract leads to perfect coordination if and only if $\Pi_{r/nrc}(p_1^{NRC}, p_2^{NRC}, \theta^{NRC}) \geq \Pi_r(p_1^{NT}, p_2^{NT}, \theta^{NT})$ and $\Pi_{m/nrc}(w_1^{NRC}, w_2^{NRC}) \geq \Pi_{m/nrc}(w_1^{NT}, w_2^{NT})$. From Table 3, we further that there exist feasible values of ρ satisfying

$$\frac{\Pi_m(w_1^{NT}, w_2^{NT})}{\Pi_c(p_1^{NC}, p_2^{NC}, \theta^{NC})} \leq \rho \leq 1 - \frac{\Pi_r(p_1^{NT}, p_2^{NT}, \theta^{NT})}{\Pi_c(p_1^{NC}, p_2^{NC}, \theta^{NC})}. \tag{H.10}$$

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