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# Carbon Tax or Low-Carbon Subsidy? Carbon Reduction Policy Options under CCUS Investment

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**Abstract:** Great expectations are placed in carbon capture, utilization, and storage (CCUS) technology to achieve the goal of carbon neutrality. Governments adopt carbon tax policies to discourage manufacturing that is not eco-friendly, and subsidies to encourage low-carbon production methods. This research investigates which carbon reduction incentive policy is more viable for the supply chain under CCUS application. The most significant finding is that carbon tax and low-carbon subsidy policies are applicable to high-pollution and low-pollution supply chains with the goal of maximizing social welfare. Both policies play a significant role in reducing carbon emissions. However, it is very important for the government to set reasonable policy parameters. Specifically, carbon tax and low-carbon subsidy values should be set in the intermediate level rather than being too large or too small to achieve higher social welfare. We also find that the higher the value of carbon dioxide ($CO_2$) in CCUS projects, the higher the economic performance and social welfare, but the lower the environmental efficiency. Governments should properly regulate the value of $CO_2$ after weighing economic performance, environmental efficiency and social welfare. The findings yield useful insights into the industry-wise design of carbon emission reduction policies for CCUS and similar projects.

**Keywords:** CCUS; carbon tax; low-carbon subsidy; policy comparison

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## 1. Introduction

Climate change is accelerating the global ecology to dangerous levels. Greenhouse gases have been widely recognized as the critical cause of extreme climate events [1]. The issue related to carbon neutrality has received a large amount of attention and concern over the last several years [2]. Carbon capture, utilization, and storage (CCUS) has been accepted as a critical technology to reduce $CO_2$ emissions and mitigate climate change hazards [3]. CCUS technology captures, purifies, and stores the $CO_2$ emitted in the production process. Then, the captured $CO_2$ is sold to specific buyers, and utilized in enhancing oil recovery, gas recovery, and coal bed methane [4]. CCUS has been identified as an important technology for promoting carbon emission reduction [5]. According to the global status of CCUS 2021 released by the Global CCUS Institute, there are 135 CCUS projects in operation worldwide, and the number is growing rapidly. Qilu Petrochemical—Shengli Oilfield Project is a representative CCUS project in China [6]. In this project, Qilu Petrochemical first captures $CO_2$ from the tail gas of gasification equipment using liquefaction purification technology. Then, the captured $CO_2$ is sold and transported to Shengli Oil Field through land or pipeline. Ultimately, the $CO_2$ is used for oil displacement in Shengli Oil Field. Data show that the efficiency of $CO_2$ oil displacement is 40% higher than that of water. The CCUS project is expected to inject more than 1000 tons of carbon dioxide ($CO_2$) into 73 wells over 15 years. In addition, nearly 3 million tons of oil production and more than 12% of the oil extraction rate will be increased. Most importantly, the project can reduce $CO_2$ emissions by 1 million tons per year. Figure 1 clearly illustrates the CCUS supply chain system. The Quest Carbon Capture and Storage (QCCS) project, funded and operated by Royal Dutch Shell in Western Canada, is one of the world's first large-scale CCUS projects. The project captured and stored one million tons of $CO_2$ ahead of schedule in its first year of operation [7]. To date, Quest has captured and stored over 6 million tons of $CO_2$. In totally, the CCUS project plays a critical role in addressing the global greenhouse effect and climate change [8]. The International Energy Agency (IEA) predicted that CCUS will account for nearly 15% of total global emission reductions by 2070 [6].

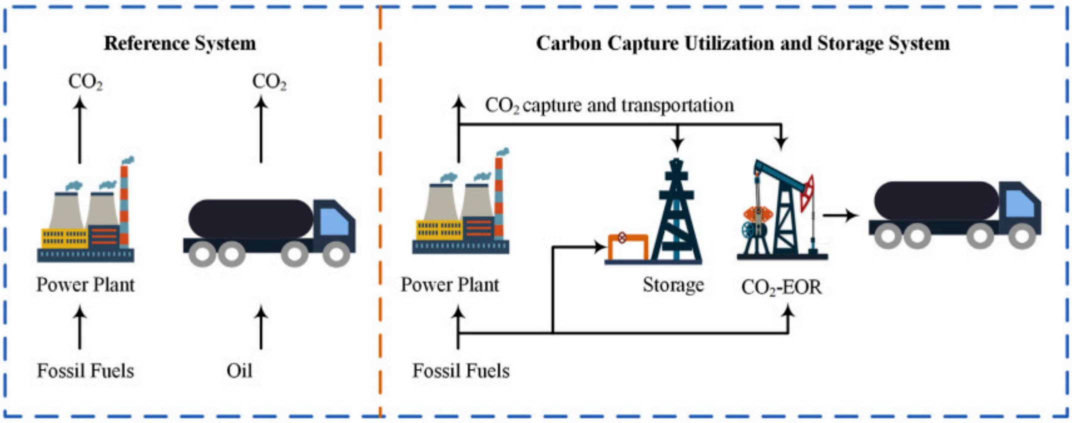


**Figure 1.** Illustration of CCUS supply chain system (source: figure is used with permission from Zhang et al. [4]).

As the role of CCUS projects in carbon emission reduction continues to be highlighted, the world is accelerating the investment in and construction of CCUS projects. The data from the International Energy Agency (IEA) predicts that total investment in CCUS projects will total USD 67.09 billion in the period 2026–2030, which could increase to USD 776.61 billion in the period 2056–2060 [9]. The carbon emission reduction incentive policy initiated by the government is an important way to promote enterprises to invest in CCUS projects and implement carbon emission reduction [10]. The incentive policies mainly include mandatory policies and voluntary policies [11]. Mandatory policy means that the government adopts a mandatory carbon control mechanism to regulate the high emission behavior of enterprises. Carbon cap and carbon tax are two common types of mandatory policies [12]. With a carbon cap policy, the government issues fixed carbon emission quotas to enterprises and prohibits them from exceeding carbon caps [13]. Cap-and-trade policy is a deformation of the carbon cap policy. It allows enterprises with insufficient and surplus allowances to buy and sell carbon emission rights in the carbon trading market [12]. With a carbon tax policy, the government imposes a carbon tax on enterprises that emit $CO_2$ [14]. To sum up, the mandatory policy is regarded as a penalty policy. In contrast, the voluntary policy is a reward policy. Typical voluntary policies include pure carbon trading policy and low-carbon subsidy policies. With a carbon trading policy, the $CO_2$ emission reductions are quantified as CERs. Enterprises can obtain a profit from selling CERs. With a pure carbon trading policy, manufacturers are not penalized for not implementing carbon reductions [11]. With the low-carbon subsidy policy, the government provides subsidies to the enterprises that implement carbon emission reduction [15].

Based the above discussion, we know that academia has achieved a lot in the research on carbon emission reduction incentive policies. However, since the CCUS project is in the early stage of industrial application, the research on the combination of CCUS and carbon emission reduction incentive policies is still in the initial stage. Very few studies have analyzed how to design a policy to facilitate carbon emission reduction in supply chains with CCUS applications. Our work aims to fill this gap by addressing the following research questions.

(i) How does the carbon tax policy and the low-carbon subsidy policy affect the optimal operation decision of the supply chain?
(ii) How does the government choose between carbon tax and low-carbon subsidy policy to simultaneously improve economic efficiency, environmental performance and social welfare?
(iii) In addition to policy options, what strategies can the government formulate to further enhance social welfare?

To answer the above questions, we first construct model A and model S to characterize the CCUS supply chain using carbon tax and low-carbon subsidy policies, respectively. Then, we conduct decision optimization and sensitivity analysis to optimize the CCUS supply chain. Most importantly, we compare the differences between model A and model S in terms of operational decision-making, supply chain profits, carbon emission reductions, and social welfare. Many significant conclusions are obtained in this research. The results provide a policy basis for the government to reasonably select and optimize carbon emission reduction incentive policies to achieve sustainable development of the supply chain with CCUS applications.

The novelty and significance of the study are summarized as follows. First, we are one of the few studies to characterize the supply chain decision models with CCUS technology and carbon control policy applications. The optimal operational decisions and environmental policies are deeply analyzed to guide decision makers in rational joint operational and environmental decisions. The economic efficiency, environmental performance, and social welfare of the CCUS supply chain and their influencing factors are also examined. Second, as far as we know, ours is one of the first studies in the field of operations management to explore the impacts of carbon reduction incentive policies such as carbon tax and low-carbon subsidy on the performance of CCUS supply chain. More importantly, we answer the question of which strategy is more feasible for the CCUS supply chain (achieving greater joint economic–environment–social performance) by quantitatively comparing carbon tax and low-carbon subsidy policies. The findings yield useful insights into the industry-wise design of carbon emission reduction policies for CCUS and similar projects.

## 2. Literature Review

We review the literature most related to our research from two aspects: (i) the carbon emission reduction incentive policies, including mandatory policy and voluntary policy; (ii) the comparison of carbon reduction incentive policies, especially the comparison of mandatory and voluntary policies. They are reviewed accordingly as follows.

### *2.1. Carbon Emission Reduction Incentive Policies*

We first review the literature on carbon emission reduction incentive policies. The policies include mandatory policies such as cap-and-trade and carbon tax, voluntary policies such as low-carbon subsidy and reduction-and-trading.

Cap-and-trade policy is a typical mandatory emission reduction policy. Zhang et al. [16] examined the impact of power structures on the governmental cap regulation and manufacturer's low carbon strategy. Tang and Yang [17] analyzed the effects of power structure and financing mode on the capital-constrained low-carbon supply chain. Liu et al. [18] compared three carbon emission reduction modes: manufacturer emission reduction, retailer emission reduction, and joint emission reduction, and found that joint emission reduction mode has the highest social welfare. Xu et al. [19] investigated the government's optimal region-cap setting strategy by comparing grandfather-based allocation and benchmark-based allocation rules.

In addition to the carbon cap policy, the carbon tax policy is another mandatory policy (carbon penalty policy). Krass et al. [20] analyzed the impacts of regulatory policies of environmental tax, cost subsidy and consumer rebate on the choice of green technology and social welfare. They found that the combined policy can incentivize firms to adopt greener technology, thereby improving social welfare. Pal and Saha [21] explored the best application conditions of privatization policy when privatization and carbon tax can be used simultaneously for environmental improvement. Zhou et al. [22] examined the impacts of carbon tax policy and consumer environmental awareness on social welfare. Yu et al. [23] investigated the impacts of carbon emissions tax on the supply chain channel structure, and provided the applicable conditions of decentralized structure and centralized structure, respectively. Chen et al. [14] analyzed the optimal carbon tax design with respect to different power structures and green technology investment efficiencies. Zhou et al. [24] provided a comprehensive review of combined research on carbon taxes and low-carbon supply chain operations. Gopalakrishnan et al. [25] designed a footprint-balanced scheme to rationally reallocate carbon emissions and carbon tax costs using cooperative game theory methodology.

Different from the mandatory policy, the voluntary policy, i.e., low-carbon subsidy policy, has proved to be another effective way to motivate enterprises to implement carbon emission reduction. In this regard, Xu et al. [15] compared four kinds of governmental subsidy strategies, and found that subsidizing to both manufacturer and retailer is more profitable for the supply chain and the government. Bao et al. [26] uncovered that the government subsidy scheme contributes to the carbon reduction of the new energy vehicle supply chain. Zhang and Huang [27] compared consumer subsidy (CS) and the R&D subsidy (RS) programs, and found that both CS and RS programs might pose negative impacts on the environment. Ma et al. [28] summarized the role of government subsidies in promoting carbon reduction and information sharing of the supply chain. Liu et al. [11] discussed the conditions under which manufacturers choose to introduce voluntary carbon emission reduction policies and the impacts of supply chain competition. Xu et al. [29] examined the effects of horizontal integration on social welfare under the interaction of carbon tax and green subsidy, and provided the optimal subsidy and carbon tax levels.

While the above-mentioned studies are rich in research on carbon emission reduction policies and policies, studies rarely involve CCUS. CCUS emerges in the supply chain operations research field until recent years. Among the few studies, Wang and Qie [30] built an analytical real options model to explore when the supply chain should invest in CCUS. Zhang et al. [4] used a multi-objective mixed integer linear programming to optimize the CCUS supply chain with economic and environmental concerns. Ostovari et al. [8] quantified the large-scale potential of $CO_2$ mineralization in Europe by designing a climate-optimal supply chain for $CO_2$ CCUS. To sum up, the research related to CCUS supply chain operations is very limited. We enrich CCUS supply chain research by pioneering the design and comparison of carbon emission reduction incentives such as a carbon tax and a low-carbon subsidy.

### *2.2. The Comparison of Carbon Reduction Incentive Policies*

More recently, a stream of research has emerged exploring the comparison of cap-and-trade and carbon tax policies in low-carbon supply chain. Miao et al. [31] showed that the implementation of carbon regulations such as carbon tax and cap-and-trade hurts the manufacturer. However, a well-designed subsidy scheme can improve the manufacturer's profit, and simultaneously reduce the carbon emissions. Anand and Giraud-Carrier [32] analyzed and compared cap-and-trade and carbon tax regulations, and proved that well-chosen regulation can simultaneously improve firms' profits, environmental performance, and social welfare. Hu et al. [33] compared carbon tax and cap-and-trade policies and answered which policy is more viable for Chinese remanufacturing industry. Sun and Yang [34] pointed out that a cap-and-trade policy is more effective than a carbon tax policy in improving social welfare. Chen et al. [35] also proved that a cap-and-trade policy is more efficient than a carbon tax in reducing carbon emissions and promoting clean innovation. Hasan et al. [12] analyzed the optimal inventory level and technology investment joint decisions under different carbon regulations such as cap-and-trade, carbon tax, and strict carbon limit. Zhou et al. [36] summarized the respective advantages of a carbon tax and cap-and-trade, for example, the former has higher cost efficiency and the latter has lower sector-level impacts. Fan et al. [1] indicated that when the correlation between the sales market and the permit trading market is moderate, the carbon tax policy shows an advantage in terms of technology investment compared with cap-and-trade. Yu et al. [37] investigated an online platform's decision between reselling and marketplace modes, and a government's selection between cap-and-trade and carbon tax regulations.

The comparison of carrot and stick (i.e., penalty and subsidy) policies has also drawn significant attention from a large body of research. Yin et al. [38] gave the optimal carbon emission policy to maximize social welfare by comparing the carbon tax and low-carbon subsidy policies. Huang et al. [39] compared border tax (BT) and output-based allocation (OB), where the former and latter adopt "stick" and "carrot" approaches. They found that BT shows higher superiority than OB. Ma et al. [40] analyzed the optimal government intervention strategy in the automotive low-carbon supply chain by comparing a carbon tax and a consumer subsidy. Zhu et al. [41] found that the hybrid model shows potential in outperforming the other two policies in terms of the optimal technology R&D by comparing cash subsidy, carbon regulation, and hybrid model. Guo et al. [42] found that the incentive-compatible combination policy composed of carbon tax and low-carbon subsidy is better than the pure carbon tax policy. He et al. [2] explored the impacts of the penalty and subsidy regulations on the straw-based bioenergy supply chain, and presented the respective applicable conditions of the two regulations. Dou and Choi [43] formulated optimal old product collection strategies, and designed a "carrot-and-stick" policy consisting of a carbon tax and a subsidy to motivate both the supply chain and consumers to accept the advocated strategies. Wang and Zhang [44] examined the interplay between subsidies and regulation under competition. The results showed that the effects of regulation and subsidies may offset or reinforce depending on the situation. Wu et al. [45] compared three carbon regulatory policies: carbon tax, low-low-carbon subsidy, and a mixed policy, and indicated that a mixed policy is a supply chain equilibrium strategy.

The above studies have carried out a significant amount of research on the comparison of carbon emission reduction incentive policies without considering specific carbon emission reduction technologies such as CCUS. However, virtually none of the current research has considered the impact of CCUS technology on the choice of carbon emission reduction policies. We are almost the first to conduct a comparative study of carbon emission reduction policies around the CCUS supply chain. We then selected some classical studies that focus on low-carbon supply chain to highlight the contributions of this research (see Table 1).

**Table 1.** Positioning of this research in the literature.

| Research | Carbon Tax Policy | Low-Carbon Subsidy Policy | CCUS | Policy Comparison |
|---|---|---|---|---|
| Yu et al. [23]; Gopalakrishnan et al. [25] | √ | × | × | × |
| Bao et al. [26]; Ma et al. [28] | × | √ | × | × |
| Zhang et al. [4]; Ostovari et al. [8] | × | × | √ | × |
| Yin et al. [38]; Wu et al. [45] | √ | √ | × | √ |
| This study | √ | √ | √ | √ |

## 3. Model Description

We consider a supply chain consisting of a manufacturer $M$ and a retailer $R$. The manufacturer (she) produces products at unit cost $c$. The products are sold to the retailer at wholesale price $w$. Then, the retailer sells the products to consumers at retail price $p$. The demand function of products is $q = a - bp$ (Zhou et al. [22]), where $a$ is the initial market potential demand, and $b$ measures the price sensitivity (Yu et al. [23]).

The manufacturing process generates a large amount of carbon emissions. We assume that the initial carbon emission per unit of product is $e_0$. Obviously, parameter $e_0$ quantifies the pollution level of the manufacturer/product (Yu et al., [23]). In order to alleviate the product pollution to the environment, the manufacturer initiates the CCUS project. In this project, the manufacturer invests in research and development (i.e., R&D) cost to achieve carbon capture and carbon storage in the production process. The R&D cost of achieving carbon capture and carbon storage is $0.5he^2$, which is a quadratic function of carbon emission reduction per unit product $e$ (Dou and Choi [43]; Deng and Liu [46]; Liu et al. [47]). In this cost function, $h$ represents the carbon emission reduction cost coefficient. It is worth noting that in the traditional cap-and-trade policy, the remaining carbon emission quota of enterprises can be sold in the carbon trading market (Liu et al. [11]). However, in the CCUS project, what can be traded is the stored $CO_2$ (Wang and Qie [30]). This is the main difference between the cap-and-trade policy and the CCUS mechanism. We assume that the $CO_2$ selling price is $u$.

The government designs two kinds of carbon reduction incentive policies, namely carbon tax policy and low-carbon subsidy policy (Wu et al. [45]). We use the symbols A and S ($j = A, S$) to identify these two policies, respectively. In model A, the government imposes a carbon tax of $t$ per unit of carbon emission. In model S, the government issues a low-carbon subsidy of $s$ per unit of carbon emission reduction. Hence, policy A and policy S can be regarded as a punishment policy and a reward policy, respectively. Figure 2 is an illustration of models A and S.

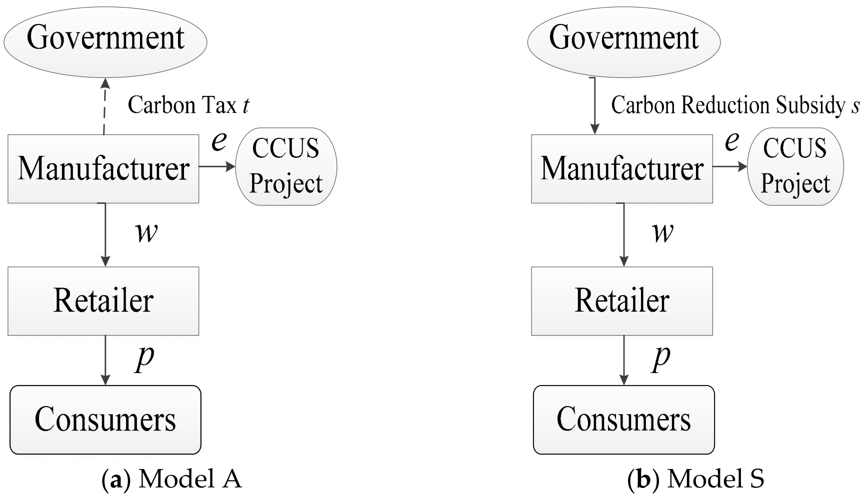


**Figure 2.** Illustration of supply chain structures and carbon policies.

We use a Stackelberg game to describe the relationship among the government, manufacturer and retailer, where the government, the manufacturer, and the retailer are the game leader, the sub-leader and the follower, respectively (Xu et al. [19]). The manufacturer and the retailer aim to maximize their profits, while the government's goal is to maximize social welfare (Zhang et al. [16]). To explore our research questions, we establish three game models as follows. In model A, the manufacturer earns wholesale revenue $(w^A - c)q^A$ and carbon sales revenue $ue^Aq^A$ while paying for carbon capture and storage R&D cost $\frac{1}{2}h(e^A)^2$ and carbon tax $t(e_0 - e^A)q^A$ (Hu et al. [33]). The retailer earns retail revenue $(p^A - w^A)q^A$. The social welfare function consists of four parts. The first is the sum of the profits of manufacturer and retailer $\pi_M^A + \pi_R^A$. The second is the total carbon tax value of the government $t(e_0 - e^A)q^A$. The third is the cost of environmental damage caused by carbon emissions $\frac{1}{2}g((e_0 - e^A)q^A)^2$ (Sun and Yang [34]). The fourth is the consumer surplus $\frac{1}{2}d(q^A)^2$ (Liu et al. [18]). In summary, the profits of the manufacturer ($\pi_M^A$) and the retailer ($\pi_R^A$), and social welfare ($SW^A$) in model A are:

$$\pi_M^A = (w^A - c)q^A - \frac{1}{2}h(e^A)^2 + ue^A q^A - t(e_0 - e^A)q^A, \tag{1}$$

$$\pi_R^A = (p^A - w^A)q^A, \tag{2}$$

$$SW^A = \pi_M^A + \pi_R^A + t(e_0 - e^A)q^A - \frac{1}{2}g((e_0 - e^A)q^A)^2 + \frac{1}{2}d(q^A)^2. \tag{3}$$

In model $S$, the government no longer levies carbon tax on the manufacturer, but issues a carbon emission reduction subsidy $se^S q^S$ to her (Xu et al. [19]). The profits of the supply chain members and the total social welfare are characterized as follows:

$$\pi_M^S = (w^S - c)q^S - \frac{1}{2}h(e^S)^2 + (u+s)e^S q^S, \tag{4}$$

$$\pi_R^S = (p^S - w^S)q^S, \tag{5}$$

$$SW^S = \pi_M^S + \pi_R^S - se^S q^S - \frac{1}{2}g((e_0 - e^S)q^S)^2 + \frac{1}{2}d(q^S)^2. \tag{6}$$

We have characterized the supply chain decision models under carbon tax and low-carbon subsidy policies. In the following sections, we first analyze the decision-making behavior of supply chain members. Then, we conduct policy comparisons to help the government make reasonable choices between carbon tax and low-carbon subsidy policies. All proofs of propositions are contained in Appendix A.

## 4. Equilibrium Analysis

The supply chain decision sequence is as follows. Given carbon tax $t$ and low-carbon subsidy $s$, the manufacturer first decides the optimal wholesale price $w^{j*}$ and carbon emission reduction per unit product $e^{j*}$. Then, the retailer charges the optimal retail price $p^{j*}$. Finally, we can obtain the total carbon emissions of the supply chain $E^{j*}$, the profits of the supply chain members $\pi_i^{j*}(i = M, R)$, and the overall social welfare $SW^{j*}$. The backward induction is used for equilibrium analysis (Zhang et al. [16]). The equilibrium results in model A are summarized as Proposition 1.

**Proposition 1.** *The optimal decisions, profits and carbon emissions of A model are following:*

$$w^{A*} = \frac{2be_0ht + 2ah + 2bch - abu^2 - 2abut - abt^2}{b(4h - bu^2 - 2but - bt^2)}, \tag{7}$$

$$e^{A*} = \frac{(u+t)(a - bc - bte_0)}{4h - bu^2 - 2but - bt^2}, \tag{8}$$

$$p^{A*} = \frac{be_0ht + 3ah + bch - abu^2 - 2abut - abt^2}{b(4h - bu^2 - 2but - bt^2)}, \tag{9}$$

$$\pi_M^{A*} = \frac{h(bc - a + bte_0)^2}{2b(4h - bu^2 - 2but - bt^2)}, \tag{10}$$

$$\pi_R^{A*} = \frac{h^2(bc - a + bte_0)^2}{b(bu^2 + 2but + bt^2 - 4h)^2}, \tag{11}$$

$$E^{A*} = \frac{h(bc - a + bte_0)(au + at - 4e_0h - bcu - bct + bu^2e_0 + bute_0)}{(bu^2 + 2but + bt^2 - 4h)^2}, \tag{12}$$

To investigate the influences of main parameters on the optimal decisions, profits, and carbon emissions, we perform a parametric sensitivity analysis below.

**Proposition 2.** *The changes of optimal decisions, profits, and carbon emissions with respect to* $e_0$ *in model A have the following features:* $w^{A*}$ *and* $p^{A*}$ *are increasing in* $e_0$. $e^{A*}$, $\pi_M^{A*}$, *and* $\pi_R^{A*}$ *are decreasing in* $e_0$. *If* $e_0 < \tilde{e}_1$, *then* $E^{A*}$ *is increasing in* $e_0$; *otherwise,* $E^{A*}$ *is decreasing in* $e_0$.

Proposition 2 illustrates the effects of initial carbon emissions (i.e., product pollution level) on the decisions, profits, and carbon emissions of the supply chain. We can understand Proposition 2 from the following aspects. The total carbon tax paid by the manufacturer increases with the level of product pollution. In order to dilute the carbon tax cost, the manufacturer chooses to raise the wholesale price and reduce R&D investment in carbon emission reduction. The manufacturer's reactions to carbon tax result in two outcomes: lower sales (i.e., lower production) and lower carbon emission reductions per unit of product. The above results imply that as product pollution level increases, the manufacturer opts to reduce production rather than reduce carbon emissions per unit of product in response to the carbon tax penalty. Then, we explore the impacts of carbon selling price on the supply chain and carbon emissions under model A. The following proposition is obtained through sensitivity analysis.

**Proposition 3.** *The changes of optimal decisions, profits, and carbon emissions with respect to* $u$ *in model A have the following features:* $w^{A*}$ *and* $p^{A*}$ *are decreasing in* $u$. $e^{A*}$, $\pi_M^{A*}$, *and* $\pi_R^{A*}$ *are increasing in* $u$. *If* $e_0 < \tilde{e}_2$, *then* $E^{A*}$ *is decreasing in* $u$; *otherwise,* $E^{A*}$ *is increasing in* $u$.

Proposition 3 shows the analysis results for parameter $u$. As $u$ increases, the operating cost of the supply chain decreases. As a result, the manufacturer lowers the wholesale price and increases the carbon emission reductions. The retailer lowers the retail price. The consumers increase the purchases. On the whole, the increase of $u$ stimulates two effects: a sales-increase effect and a unit-product-carbon-emission-reduction effect. These two effects promote and inhibit the increase in total carbon emissions, respectively. Recalling Proposition 2, that when $e_0$ is low, the unit-product-carbon-emission-reduction effect outperforms the sales-increase effect. Thus, $E^{A*}$ is decreasing in $u$. Otherwise, $E^{A*}$ is increasing in $u$. Through the above analysis, we obtain the following managerial insights. When the manufacturer produces low-polluting products, increasing the $CO_2$ selling price is an effective means to incentivize the manufacturer to reduce carbon emissions. Otherwise, when the manufacturer produces high-polluting products, raising the $CO_2$ selling price increases $CO_2$ emissions of the supply chain. Then, we explore the impacts of carbon tax on the supply chain.

**Proposition 4.** *The changes of optimal decisions, profits, and carbon emissions with respect to* $t$ *in model A have the following features: If* $e_0 < \tilde{e}_3$, *then* $w^{A*}$ *is decreasing in* $t$; *otherwise,* $w^{A*}$ *is increasing in* $t$. *If* $e_0 < \tilde{e}_4$, *then* $p^{A*}$ *is decreasing in* $t$; *otherwise,* $p^{A*}$ *is increasing in* $t$. *If* $e_0 < \tilde{e}_5$, *then* $e^{A*}$ *is increasing in* $t$; *otherwise,* $e^{A*}$ *is decreasing in* $t$. *If* $e_0 < \tilde{e}_6$, *then* $\pi_M^{A*}$ *is increasing in* $t$; *otherwise,* $\pi_M^{A*}$ *is decreasing in* $t$. *If* $e_0 < \tilde{e}_7$, *then* $\pi_R^{A*}$ *is increasing in* $t$; *otherwise,* $\pi_R^{A*}$ *is decreasing in* $t$. $E^{A*}$ *is decreasing in* $t$.

We obtain the following findings by observing Proposition 4. First, the carbon tax policy can effectively reduce the total carbon emissions of the supply chain, in which the high-polluting manufacturer chooses to reduce carbon emissions by limiting production. The low-pollution manufacturer controls total emissions by reducing carbon emissions per unit of product. The findings can be well-explained by Proposition 2. Second, and interestingly, the carbon tax policy can simultaneously increase the economic efficiency and environmental performance of the supply chain that produces low-polluting products. The reason is that the carbon tax policy motivates the manufacturer to reduce carbon emissions, thereby increasing her carbon sales revenue. Summarizing the above results, the carbon tax policy can improve the environmental performance of the supply chain, but it may reduce the economic efficiency of the supply chain, especially the supply chain that produces high-polluting products. This result is consistent with those of Wu et al. [45]. They also found that while a carbon tax is beneficial to the ecological environment, it would also increase the economic burden on supply chains.

We already fully understand the impact of carbon tax policy on the supply chain implementing CCUS project. In the following part, we analyze the low-carbon subsidy policy. We characterize the equilibrium under the low-carbon subsidy scheme in the following proposition:

**Proposition 5.** *The optimal decisions and profits of S model are following:*

$$w^{S*} = \frac{abs^2 + 2absu + abu^2 - 2ah - 2bch}{b(bs^2 + 2bsu + bu^2 - 4h)}, \tag{13}$$

$$e^{S*} = \frac{(s+u)(a-bc)}{4h - bs^2 - 2bsu - bu^2}, \tag{14}$$

$$p^{S*} = \frac{3ah + bch - abs^2 - 2absu - abu^2}{b(4h - bs^2 - 2bsu - bu^2)}, \tag{15}$$

$$\pi_M^{S*} = \frac{h(a-bc)^2}{2b(4h - bs^2 - 2bsu - bu^2)}, \tag{16}$$

$$\pi_R^{S*} = \frac{h^2(a-bc)^2}{b(bs^2 + 2bsu + bu^2 - 4h)^2}, \tag{17}$$

$$E^{S*} = \frac{h(bc-a)(as + au - 4e_0h - bcs - bcu + bs^2e_0 + bu^2e_0 + 2bsue_0)}{(bs^2 + 2bsu + bu^2 - 4h)^2}. \tag{18}$$

Based on the equilibrium results, we examine the influence of $e_0$ on the supply chain and obtain the following proposition.

**Proposition 6.** *The changes of optimal decisions, profits, and carbon emissions with respect to $e_0$ in model S have the following features: $w^{S*}$, $p^{S*}$, $e^{S*}$, $\pi_M^{S*}$, and $\pi_R^{S*}$ are unchanging in $e_0$. $E^{S*}$ is increasing in $e_0$.*

Proposition 6 shows that the optimal decisions and profits under model S are not affected by parameter $e_0$. The reason is that the government subsidizes the manufacturer based on her carbon reductions rather than the carbon emissions. However, carbon reductions are independent of $e_0$. We also find from Proposition 6 that the higher the pollution level of the product, the higher the total carbon emissions of the supply chain. This conclusion is significantly different from Proposition 2.

To investigate the effects of $CO_2$ selling price on the low-carbon subsidy policy, we conduct a sensitivity analysis as Proposition 7.

**Proposition 7.** *The changes of optimal decisions, profits, and carbon emissions with respect to $u$ in model S have the following features: The $w^{S*}$ and $p^{S*}$ are decreasing in $u$. $e^{S*}$, $\pi_M^{S*}$, and $\pi_R^{S*}$ are increasing in $u$. If $a < \tilde{a}_1$, then $E^{S*}$ is increasing in $u$; otherwise, $E^{S*}$ is decreasing in $u$.*

The conclusion of Proposition 7 is similar to that of Proposition 3; therefore, we omit its explanation. However, we obtain the following management implications from Proposition 7. Raising the $CO_2$ selling price always improves the economic performance of the supply chain; however, it may detrimental to the environmental efficiency. The above results provide management implications for the government to reasonably adjust the $CO_2$ trading price of CCUS projects.

**Proposition 8.** *The changes of optimal decisions, profits, and carbon emissions with respect to s in model S have the following features: $w^{S*}$ and $p^{S*}$ are decreasing in s. $e^{S*}$, $\pi_M^{S*}$, and $\pi_R^{S*}$ are increasing in s. If $a < \widetilde{a}_2$, then $E^{S*}$ is increasing in s; If $a > \widetilde{a}_2$, then $E^{S*}$ is decreasing in s.*

Proposition 8 indicates that the low-carbon subsidy policy always improves the economic efficiency of the supply chain; however, it may harm the environmental performance. This view is identical to that of Zhang et al. [48] and Yao et al. [49]. We can explain this result as follows. Low-carbon subsidy reduces operating cost and generates additional revenue for the manufacturer. Therefore, in order to obtain more low-carbon subsidy, the manufacturer increases production by reducing wholesale price; on the other hand, more carbon emission reductions are obtained by increasing carbon emission reductions per unit of product. However, a low-carbon subsidy motivates an increase in production that could lead to an increase in total carbon emissions. As is illustrated in Proposition 8, only when the basic market demand of the product is high can increasing low-carbon subsidy reduce the total carbon emissions of the supply chain.

## 5. Model Comparison

Different carbon policies have different impacts on economic performance, environmental efficiency and social welfare (Yu [50]). We further investigate the relationship between carbon policies and supply chain performance under CCUS applications. By comparing the optimal decisions and outcomes among different policies, we gain some managerial insights to find which policy choice is beneficial to the economy and environment. The optimal decisions are first compared as Proposition 9.

**Proposition 9.** *(i) When $s \geq t$, the wholesale price, retail price, and carbon emission reduction per unit product in different models have the following orders: $w^A > w^S$, $p^A > p^S$, and $e^A < e^S$. (ii) When $s < t$, the wholesale price, retail price, and carbon emission reduction per unit product in different models have the following orders: If $e_0 < \widetilde{e}_8$, then $w^A < w^S$; If $e_0 > \widetilde{e}_8$, then $w^A > w^S$. If $e_0 < \widetilde{e}_9$, then $p^A < p^S$; If $e_0 > \widetilde{e}_9$, then $p^A > p^S$. If $e_0 < \widetilde{e}_{10}$, then $e^A > e^S$; If $e_0 > \widetilde{e}_{10}$, then $e^A < e^S$.*

The analysis of Proposition 9 is as follows. When the low-carbon subsidy value is higher than the carbon tax value, the production volume and carbon emission reductions per unit product under low-carbon subsidy policy are higher than those under carbon tax policy. In contrast, when the low-carbon subsidy value is lower than the carbon tax value, the above comparison result is still valid only if product pollution degree is high. The comparison results are easy to understand. Model S has a significant cost advantage over model A. The cost advantage is eliminated only when $s < t$ and $e_0$ is low.

Next, we compare the optimal profits and carbon emissions of the two carbon emission reduction incentive policies to explore the impact of policy on the optimal supply chain performance and discuss which policy is the better one. Through theoretical analysis, the following proposition is derived.

**Proposition 10.** *(i) When $s \geq t$, the profits and carbon emissions in different models have the following orders: $\pi_M^A < \pi_M^S$ and $\pi_R^A < \pi_R^S$ always hold. If $e_0 < \widetilde{e}_{12}$, then $E^A > E^S$; Otherwise, $E^A < E^S$. (ii) When $s < t$, the profits and carbon emissions in different models have the following orders: If $e_0 < \widetilde{e}_{11}$, then $\pi_M^A > \pi_M^S$; If $e_0 > \widetilde{e}_{11}$, then $\pi_M^A < \pi_M^S$. If $e_0 < \widetilde{e}_{12}$, then $\pi_R^A > \pi_R^S$; If $e_0 > \widetilde{e}_{12}$, then $\pi_R^A < \pi_R^S$. $E^A < E^S$always holds.*

Proposition 10 implies the following conclusion. When $s > t$, the economic efficiency of the supply chain in model S is always better than that in model A. However, only when $e_0$ is low, the environmental performance of the supply chain in model S is better than that in model A. When $s > t$, the environmental performance of the supply chain in model A is always better than that in model S. Moreover, only when $e_0$ is low is the economic efficiency of the supply chain in model A better than that in model S. Based on the results of Proposition 9, we can make an appropriate interpretation of Proposition 10. When $s > t$, because the S model has a cost advantage over the A model, the economic efficiency of the supply chain in the S model is obviously higher than that in the A model. If $e_0 > \tilde{e}_{12}$, i.e., the pollution degree of products is high, the manufacturer is penalized with a high carbon tax under model A. Hence, the manufacturer is more aggressive in reducing carbon emissions in the A model than in the S model, i.e., $E^A < E^S$. When $s < t$, affected by the carbon tax penalty, the manufacturer has a higher incentive to reduce carbon emissions. Thus, $E^A < E^S$ always holds. If $e_0$ is low enough, the carbon selling revenue of the manufacturer under the A model is higher than that of the S model. Thus, we have $\pi_M^A > \pi_M^S$ and $\pi_R^A > \pi_R^S$. Otherwise, if $e_0$ is high enough, the carbon tax penalty effect exceeds the $CO_2$ sales effect. Hence, the economic performance of the supply chain under the A model is lower than that under the S model, i.e., $\pi_M^A < \pi_M^S$ and $\pi_R^A < \pi_R^S$. The above research conclusions are consistent with the research of Chen and Hu [51], Li and Peng [52]. They also found that a carbon tax policy and a low-carbon subsidy policy have advantages in promoting economic performance and environmental efficiency growth, respectively. As the degree of pollution and environmental damage of products increases, the government's carbon control policy should be changed from low-carbon subsidy to carbon tax (Guo and Huang [53]).

We obtain the following managerial insights: First, for low-pollution supply chain, when the low-carbon subsidy value is higher and lower than the carbon tax value, the government should adopt the low-carbon subsidy policy and the carbon tax policy respectively. Second, for high-pollution supply chain, the government that prefers economic efficiency and environmental performance should choose the low-carbon subsidy policy and the carbon tax policy, respectively. The above conclusions provide policy suggestions for the government to reasonably choose the carbon emission reduction incentive policy to improve social welfare.

## 6. Numerical Study

In this section, we verify the above theoretical conclusions utilizing numerical examples. We also gain more conclusions and managerial insights that are difficult to obtain directly from theoretical analysis. A survey of some manufacturing enterprises and CCUS projects in China is first conducted. Based on survey data processing and statistical analysis, we set the parameters as follows:

$$a = 1000, b = 0.5, c = 30, h = 30, g = 0.0005, d = 1, t = 2, s = 2, u = 2, e_0 = 200.$$

Then, we conduct the numerical study from three aspects. First, we compare the two models to answer which model has higher economic efficiency, environmental performance, and social welfare. Second, we analyze the effects of main parameters on social welfare and address the managerial insights. The results of our experiments are shown in Figures 3–12 (The * in the figures depicts the optimal results).

### *6.1. Model Comparison and Optimal Mode Selection*

In this part, we explore which model has lower carbon emissions, and higher economic efficiency and social welfare by comparing models A and S. Figures 3–6 are illustrations of the comparison results. As shown in these figures, the profits of the supply chain members and social welfare are decreasing or unchanging in the product initial unit carbon emissions. The total carbon emissions increase as the initial unit carbon emissions increase. The results verify Propositions 2 and 6.

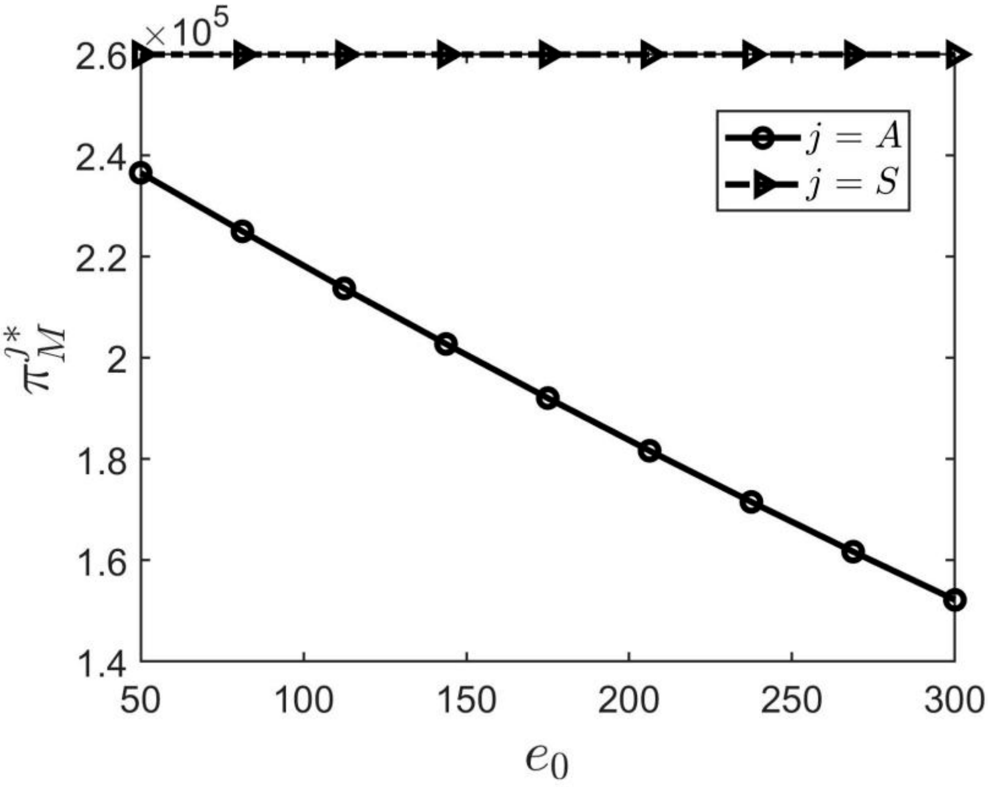


**Figure 3.** The impact of $e_0$ on manufacturers' profits under different models.

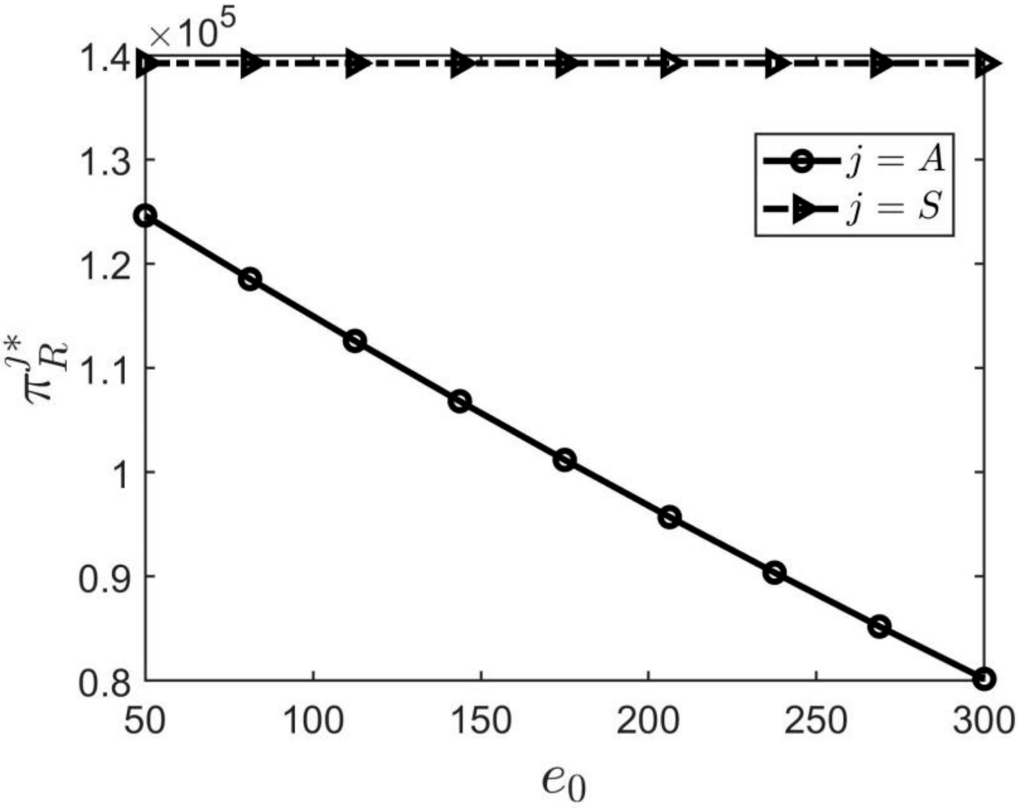


**Figure 4.** The impact of $e_0$ on retailers' profits under different models.

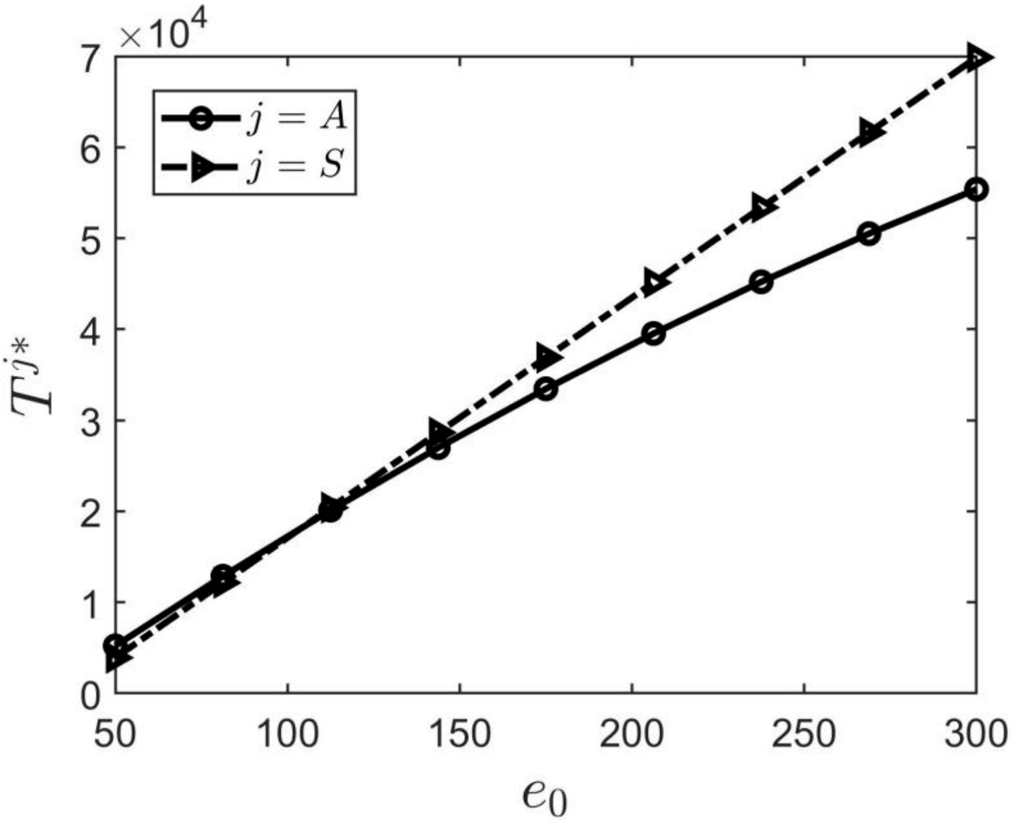


**Figure 5.** The impact of $e_0$ on carbon emissions under different models.

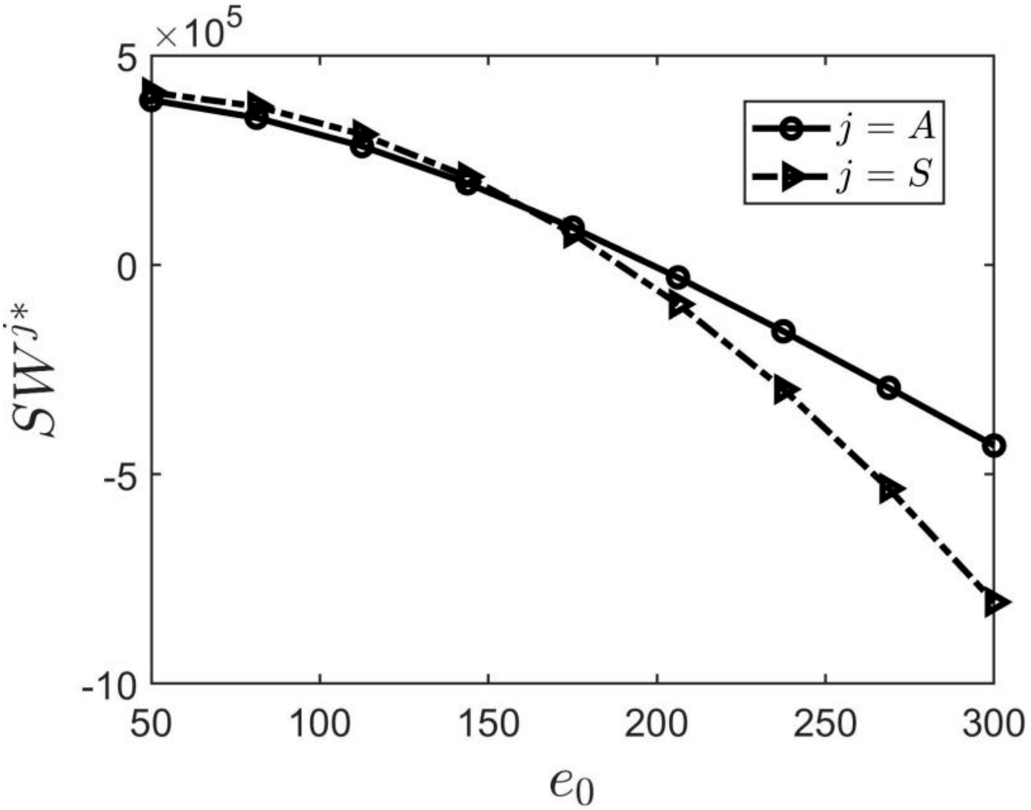


**Figure 6.** The impact of $e_0$ on social welfare under different models.

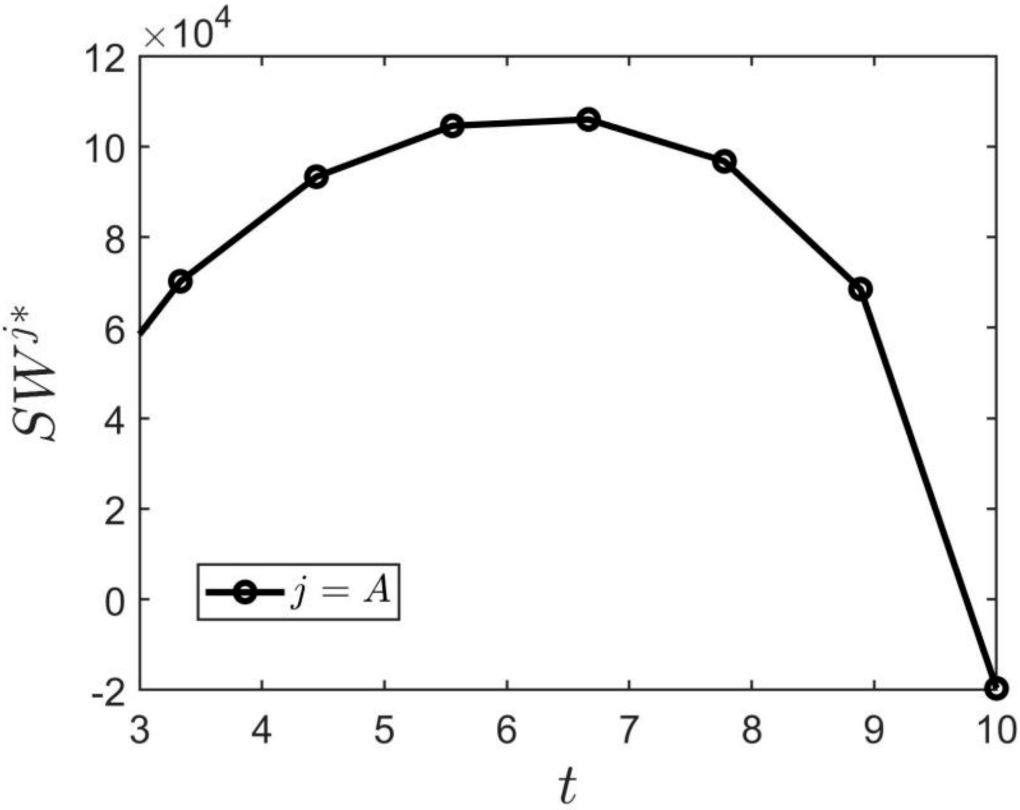


**Figure 7.** The impact of $t$ on social welfare under model A.

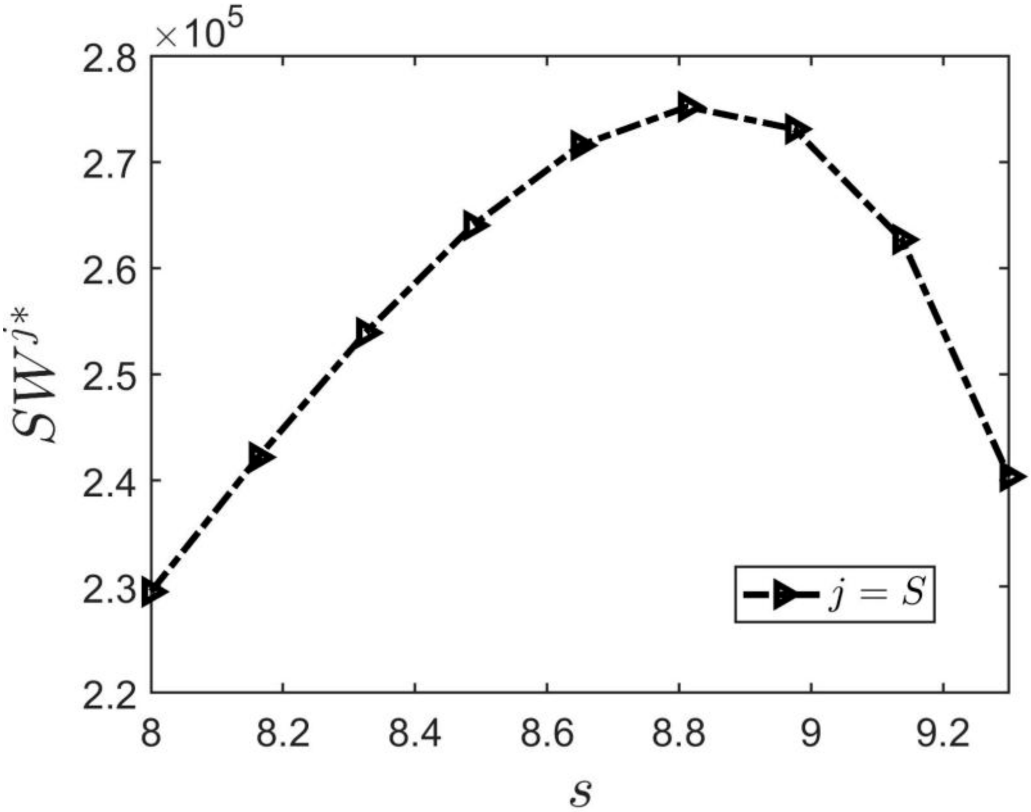


**Figure 8.** The impact of $s$ on social welfare under model S.

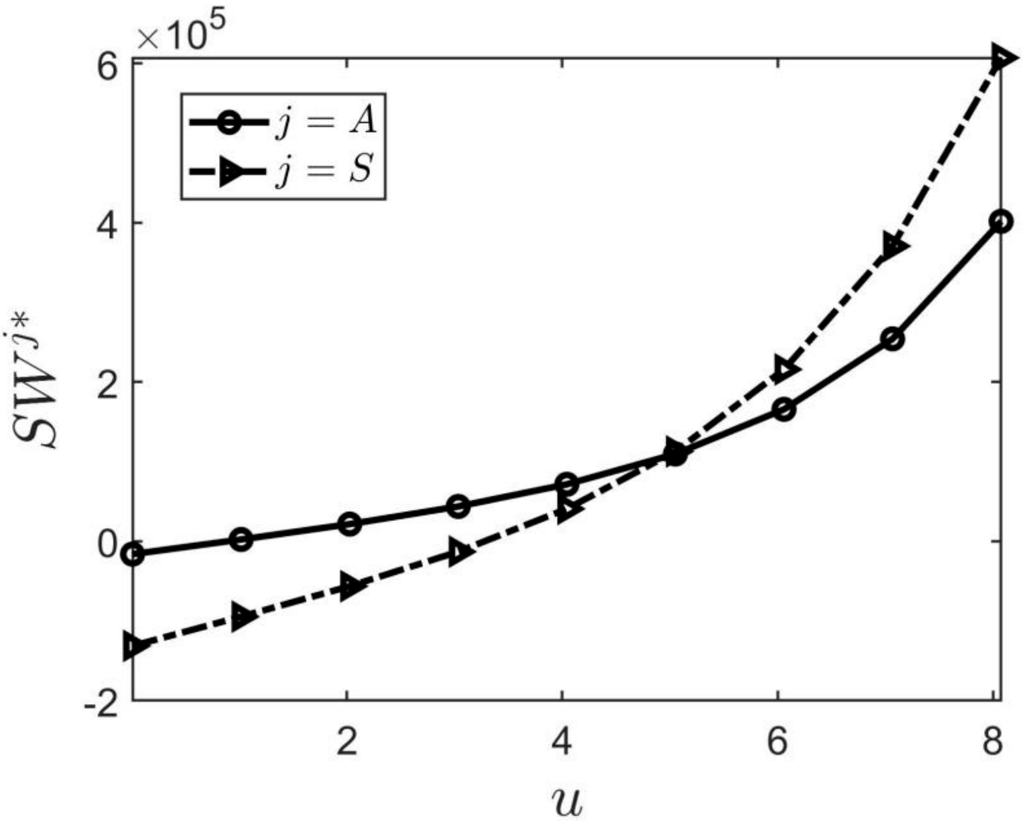


**Figure 9.** The impact of $u$ on social welfare under different models.

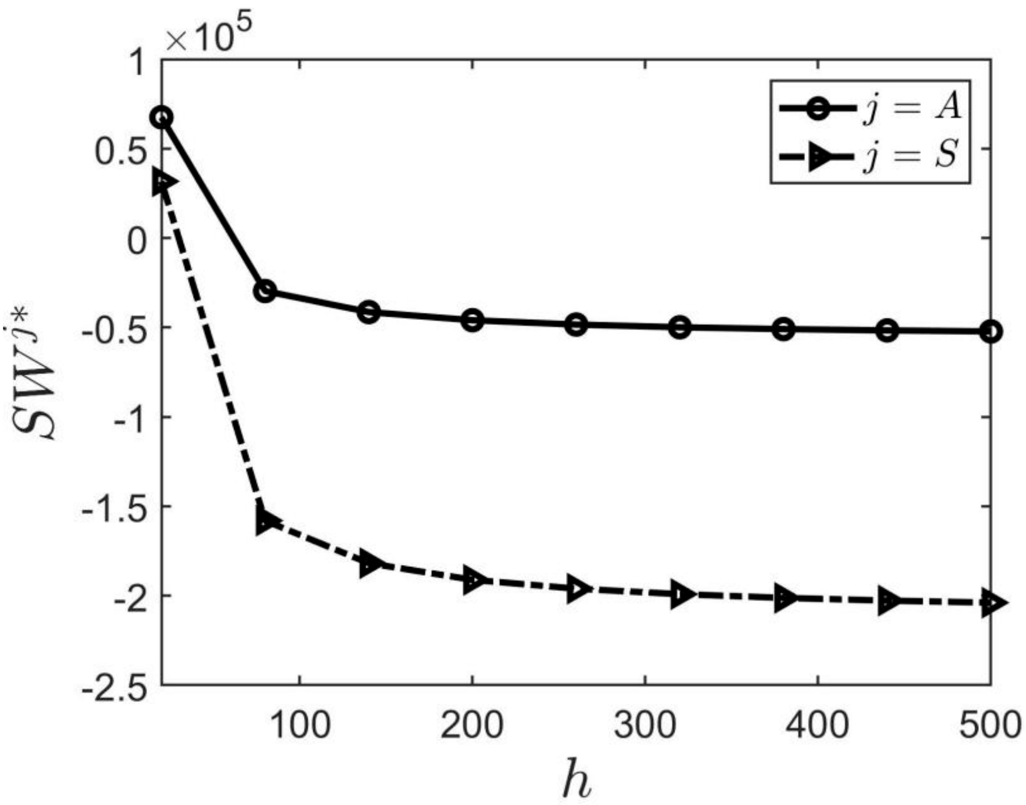


**Figure 10.** The impact of $h$ on social welfare under different models.

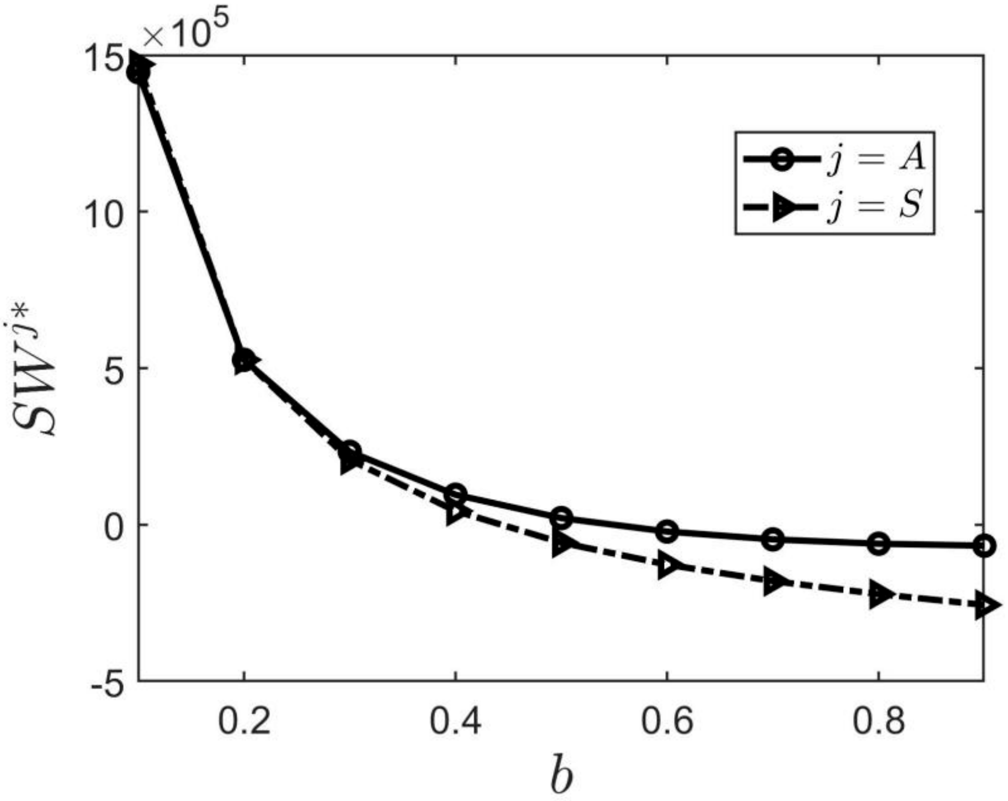


**Figure 11.** The impact of $b$ on social welfare under different models.

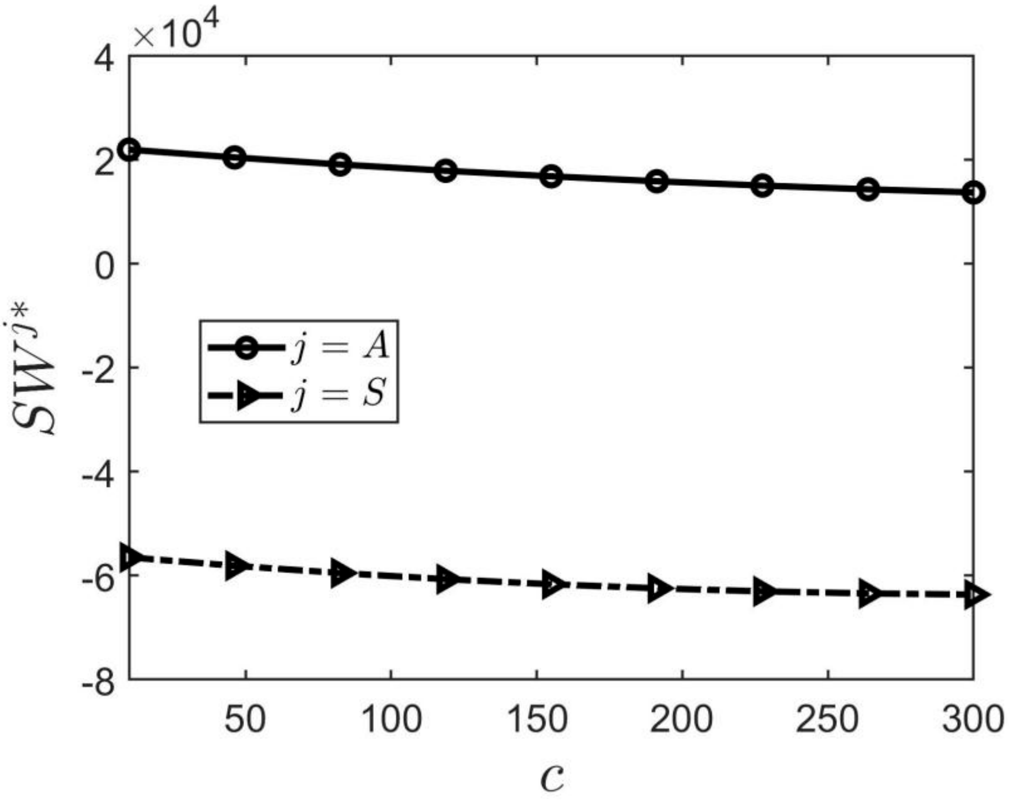


**Figure 12.** The impact of $c$ on social welfare under different models.

Through model comparison, we find the following results. First, the supply chain profit in model S is higher than that in model A, and the profit gap increases as $e_0$ increases

(See Figures 3 and 4). Second, when parameter $e_0$ is relatively low, the carbon emissions (social welfare) in the S model are (is) lower (higher) than that in the A model.

The above results can be explained as follows. In models S and A, the supply chain is subsidized and penalized, respectively. That means that the operating cost of the supply chain in the S model is lower than that of the A model. Hence, the supply chain profit in model S is higher than that in model A. Meanwhile, the carbon emission reduction per unit product and the total order quantity of the supply chain under the S model are higher than those of the A model. Therefore, the total carbon emissions in model S is higher than that in model A only when parameter $e_0$ is low enough. The above research conclusion is consistent with the study of Shu et al. [54]. They also found that although carbon tax policy is helpful to achieve carbon emission reduction target, it may lose supply chain profit. The government should introduce low-carbon subsidy policy to achieve both environmental and economic win–win situations.

Through the above analysis, we obtain the following managerial insights. From the perspective of reducing carbon emissions and increasing total social welfare, when the manufacturer implements CCUS project, the government should use the mandatory policy (i.e., carbon tax policy) and the voluntary policy (i.e., low-carbon subsidy policy) to achieve carbon reduction incentives for high-polluting and low-polluting enterprises, respectively (Guo and Huang [53]). The above research results provide policy suggestions for the government to increase social welfare through policy selection.

### *6.2. Impacts of Main Parameters on Social Welfare*

In this section, we first investigate the impacts of carbon tax and low-carbon subsidy on social welfare, in order to enlighten the government on how to optimally set the policy parameters. Second, we explore the effects of other main parameters on social welfare to obtain more managerial insights.

As shown in Figures 7 and 8, in model A, social welfare increases first and then decreases with the carbon tax. In model S, when the low-carbon subsidy rate is at the intermediate level, social welfare reaches the maximum. The reason is as follows. In model A, the operating cost of the supply chain increases with the carbon tax. Thus, the supply chain profit is decreasing in carbon tax. Meanwhile, it is clear that supply chain carbon emissions decrease with the carbon tax. Only when the carbon tax takes the middle value does social welfare reach the maximum. The impact of low-carbon subsidy on social welfare can be similarly explained.

Through the above analysis, we can obtain the following valuable policy recommendations for the government. Taking into account economic efficiency and environment should set the carbon tax and low-carbon subsidy values in the middle rather than too low or too high when implementing the carbon tax and low-carbon subsidy policies. This view is consistent with those of Wu et al. [45] and Yao et al. [49]. Wu et al. [45] found that the supply chain economic performance increases slightly as the carbon tax coefficient increases before declining rapidly. Yao et al. [49] found that property developers are less inclined to build low-carbon houses when low-carbon subsidy rate exceeds a certain critical point.

The above analysis provides strategies for the government to reasonably design the parameters of carbon emission reduction policies. Then, we further analyze the impact of other parameters on the supply chain and social welfare. Figure 9 shows that regardless of the model, social welfare increases with the carbon sales price. Figures 10–12 illustrate that, when the $CO_2$ selling price is low, social welfare under model A is higher than under model S; otherwise, the conclusion is the opposite. Therefore, the government should use a carbon tax policy and a low-carbon subsidy policy to incentivize manufacturers to reduce carbon emissions when the $CO_2$ selling price is low and high enough, respectively. Similarly, it can be seen from Figure 11 that when the consumer price sensitivity coefficient is low and high enough, policy S and policy A should be used, respectively, to control carbon emissions and increase social welfare.

## 7. Conclusions

Global climate change is affecting ecosystems, and carbon reduction has become a global consensus. CCUS is one of the key technologies to deal with global climate change, which has received worldwide attention. In order to encourage the supply chain to reduce carbon emissions by investing in CCUS, the government has introduced two kinds of policies: carbon tax and low-carbon subsidy. The former penalizes carbon emissions, while the latter rewards emissions reductions. We systematically analyze and summarize the optimal carbon emission reduction incentive policies of the government from three aspects: the choice of carbon policy, the parameter setting of carbon policy and the setting of carbon price, etc. We first compare carbon tax and low-carbon subsidy from three aspects: economic performance, environmental efficiency and social welfare. We find that under the same conditions, low-carbon subsidy policy generates higher economic performance than carbon tax policy. When the degree of product pollution is high, the environmental efficiency and social welfare under carbon tax policy are higher than those under low-carbon subsidy policy; otherwise, the conclusion is opposite. Therefore, with the aim of maximizing social welfare, the government should adopt carbon tax policy and low-carbon subsidy policy for high-polluting and low-polluting supply chains, respectively. Given the optimal carbon policy choice of the government, we further study the way to set the parameter of selected carbon policy. We find that the increase of carbon tax value always improves the environmental efficiency of supply chain, but may reduce the economic performance. In contrast, the increase of carbon subsidy value always improves the economic performance of supply chain, but may reduce the environmental efficiency. A significant and interesting finding is that social welfare level of the supply chain reaches its maximum when the carbon tax value and the carbon subsidy value are set at an intermediate level. The above results provide decision support for the government to reasonably set carbon policy parameters. Specifically, the government should set the carbon tax value and the low-carbon subsidy value at a middle level, rather than too high or too low. We also provide managerial insights for the government to reasonably regulate the $CO_2$ trading price in CCUS projects based on the following research conclusions. Regardless of which carbon policy is adopted, the economic performance and social welfare increase with the $CO_2$ trading price. Hence, in order to improve the overall social welfare, the government should formulate policies to control the $CO_2$ trading price within a higher range, for example, by setting a government-directed price for $CO_2$ similar to that for natural gas by adopting the $CO_2$ trading access system to properly increase the scarcity of $CO_2$. The above research results provide systematic decision-making suggestions for the government to reasonably formulate carbon emission reduction incentive policies for CCUS projects. In the future, we can conduct evaluative studies on the input–output of CCUS projects.

**Author Contributions:** All authors contributed to the study conception and design. Spot investigation and data collection were performed by Q.Z. The first draft of the manuscript was written by Q.Z. Methodology, formal analysis, and experimental work were mainly contributed by Y.W. with guidance from L.L. L.L. was involved in the critical revision of the article for important intellectual content. All authors commented on previous versions of the manuscript. All authors have read and agreed to the published version of the manuscript.

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## Appendix A

**Proof of Proposition 1.** Taking the second-order partial derivatives of $\pi_R^A$ with respect to $p^A$ yields that $\frac{d^2\pi_R^A}{d(p^A)^2} = -2b < 0$. Hence, $\pi_R^A(p^A)$ is a concave function with respect to $p^A$. Then solving the first-order condition $\frac{d\pi_R^A}{dp^A} = 0$, we can obtain the optimal response function $p^{A*}(w^A) = \frac{a+bw^{Ap}}{2b}$. Substituting $p^{A*}(w^A)$ into Equation (1), we obtain the Hessian matrix of (1) with respect to $w^A$ and $e^A$:

$$H_M = \begin{bmatrix} -b & -\frac{b(u+t)}{2} \\ -\frac{b(u+t)}{2} & -h \end{bmatrix}.$$

The sequential principal minors of $H_M$ are: $-b < 0$, $\frac{b(4h-bu^2-2but-bt^2)}{4} > 0$. Thus, $\pi_M^A(w^A, e^A)$ is a joint concave function of $w^A$ and $e^A$. Solving the first order conditional equations $\frac{d\pi_M^A}{dw^A} = 0$, $\frac{d\pi_M^A}{de^A} = 0$ yields

$$w^{A*} = \frac{2be_0ht + 2ah + 2bch - abu^2 - 2abut - abt^2}{b(4h - bu^2 - 2but - bt^2)},$$

$$e^{A*} = \frac{(u+t)(a - bc - bte_0)}{4h - bu^2 - 2but - bt^2}.$$

Then, it is easy to further obtain that $p^{A*}$, $\pi_M^{A*}$, $\pi_R^{A*}$, and $E^{A*}$ satisfy Equations (9)–(12), respectively.

**Proof of Proposition 2.** Differentiating the optimal decisions, profits, and carbon emissions with respect to $e_0$ yields

$$\frac{dw^{A*}}{de_0} = \frac{2th}{4h - bu^2 - 2but - bt^2} > 0,\ \frac{dp^{A*}}{de_0} = \frac{th}{4h - bu^2 - 2but - bt^2} > 0,$$

$$\frac{de^{A*}}{de_0} = -\frac{bt(u+t)}{4h - bu^2 - 2but - bt^2} < 0,\ \frac{d\pi_M^{A*}}{de_0} = -\frac{th(a - bc - bte_0)}{4h - bu^2 - 2but - bt^2} < 0,$$

$$\frac{d\pi_R^{A*}}{de_0} = -\frac{2th^2(a - bc - bte_0)}{(bu^2 + 2but + bt^2 - 4h)^2} < 0.$$

The above evidences confirm the changes of $w^{A*}$, $p^{A*}$, $e^{A*}$, $\pi_M^{A*}$, and $\pi_R^{A*}$ on $e_0$ in Proposition 1. Then, we prove the relationship between $E^{A*}$ and $e_0$. The differential of $E^{A*}$ with respect to $e_0$ is

$$\frac{dE^{A*}}{de_0} = \frac{h(2e_0b^2u^2t + cb^2u^2 + 2e_0b^2ut^2 - cb^2t^2 - abu^2 + abt^2 - 8e_0hbt - 4chb + 4ah)}{(bu^2 + 2but + bt^2 - 4h)^2}.$$

It is easy to see that $\frac{dE^{A*}}{de_0}$ is a linear monotone function with respect to $e_0$. Let $\bar{e}_0 = \frac{a-bc}{bt}$. Since $e_0 < \bar{e}_0$ is a necessary condition for $q^{A*} > 0$, we assume that $0 < e_0 < \bar{e}_0$. At the left and right endpoints of the valid interval of $e_0$, the values of $\frac{dE^{A*}}{de_0}$ are $\frac{dE^{A*}}{de_0}\Big|_{e_0=0} = \frac{h(a-bc)(4h-bu^2+bt^2)}{(bu^2+2but+bt^2-4h)^2} > 0$ and

$$\frac{dE^{A*}}{de_0}\Big|_{e_0=\bar{e}_0} = -\frac{h(a - bc)}{4h - bu^2 - 2but - bt^2} < 0.$$

That means that there exists a threshold $\widetilde{e}_1$ such that $\frac{dE^{A*}}{de_0} > 0$ when $e_0 < \widetilde{e}_1$, and $\frac{dE^{A*}}{de_0} < 0$ when $e_0 > \widetilde{e}_1$. Here, we obtain Proposition 2.

**Proof of Proposition 3.** The supply chain system is effective only when the optimal decisions and profits are greater than 0. Hence, from $\pi_M^{A*} > 0$ and $e^{A*} > 0$, we know that $4h - bu^2 - 2but - bt^2 > 0$ and $a - bc - bte_0 > 0$. Then, the following differentials are obviously true:

$$\frac{dw^{A*}}{du} = -\frac{4h(u+t)(a-bc-bte_0)}{(bu^2+2but+bt^2-4h)^2} < 0,$$

$$\frac{de^{A*}}{du} = \frac{(a-bc-bte_0)(bu^2+2but+bt^2+4h)}{(bu^2+2but+bt^2-4h)^2} > 0,$$

$$\frac{dp^{A*}}{du} = \frac{2h(u+t)(bc-a+bte_0)}{(bu^2+2but+bt^2-4h)^2} < 0,$$

$$\frac{d\pi_M^{A*}}{du} = \frac{h(u+t)(bc-a+bte_0)^2}{(bu^2+2but+bt^2-4h)^2} > 0,$$

$$\frac{d\pi_R^{A*}}{du} = \frac{4h^2(u+t)(bc-a+bte_0)^2}{(4h-bu^2-2but-bt^2)^3} > 0.$$

Part of the conclusion of Proposition 3 is proved. Then we show how $E^{A*}$ varies with $u$. The first-order condition of $E^{A*}$ on $u$ is

$$\frac{dE^{A*}}{du} = \frac{\begin{bmatrix} h(a-bc-bte_0)(-2e_0b^2u^3 - 3e_0b^2u^2t + 3cb^2u^2 + 6cb^2ut + e_0b^2t^3 + \\ 3cb^2t^2 - 3abu^2 - 6abut + 8e_0hbu - 3abt^2 + 12e_0hbt + 4chb - 4ah) \end{bmatrix}}{(4h-bu^2-2but-bt^2)^3}.$$

Let

$A_1 = -2e_0b^2u^3 - 3e_0b^2u^2t + 3cb^2u^2 + 6cb^2ut + e_0b^2t^3 + 3cb^2t^2 - 3abu^2 - 6abut + 8e_0hbu - 3abt^2 + 12e_0hbt + 4chb - 4ah.$

We have shown that $a - bc - bte_0 > 0$ and $4h - bu^2 - 2but - bt^2 > 0$. That means, the sign of $\frac{dE^{A*}}{du}$ depends on the size of $A_1$. Obviously, $A_1$ is a linear function of $e_0$. Meanwhile, we have

$$\left.\frac{dA_1}{du}\right|_{e_0=0} = -(a-bc)(3bu^2+6but+3bt^2+4h) < 0,$$

$$\left.\frac{dA_1}{du}\right|_{e_0=\bar{e}_0} = \frac{2(u+t)(a-bc)(4h-bu^2-2but-bt^2)}{t} > 0.$$

The above evidences indicate that there exists a threshold $\widetilde{e}_2$ such that $A_1 < 0$ when $e_0 < \widetilde{e}_2$, and $A_1 > 0$ when $e_0 > \widetilde{e}_2$. Summarizing the above conditions, we conclude that if $e_0 < \widetilde{e}_2$, then, $E^{A*}$ is decreasing in $u$; otherwise, $E^{A*}$ is increasing in $u$. By combining the above results, we complete the proof of Proposition 3.

**Proof of Proposition 4.** Differentiating $w^{A*}$ with respect to $t$ yields

$$\frac{dw^{A*}}{dt} = \frac{2h(4e_0h - 2at - 2au + 2bcu + 2bct - bu^2e_0 + bt^2e_0)}{(bu^2+2but+bt^2-4h)^2}.$$

It can be seen that $\frac{dw^{A*}}{dt}$ is a linear function of $e_0$. Further, we have $\left.\frac{dw^{A*}}{dt}\right|_{e_0=0} = -\frac{4h(u+t)(a-bc-bte_0)}{(bu^2+2but+bt^2-4h)^2} < 0$ and $\left.\frac{dw^{A*}}{dt}\right|_{e_0=\bar{e}_0} = \frac{2h(a-bc)}{bt(4h-bu^2-2but-bt^2)} > 0$.

The inequalities imply that there exists a threshold $\widetilde{e}_3$ such that if $e_0 < \widetilde{e}_3$, then $w^{A*}$ is decreasing in $t$; otherwise, $w^{A*}$ is increasing in $t$.

Similarly, differentiating $p^{A*}$ and $e^{A*}$ with respect to $t$ yields

$$\frac{dp^{A*}}{dt} = \frac{h(4e_0h - 2at - 2au + 2bcu + 2bct - bu^2e_0 + bt^2e_0)}{(bu^2 + 2but + bt^2 - 4h)^2},$$

$$\frac{de^{A*}}{dt} = \frac{\left[\begin{array}{c} e_0b^2u^3 + 2e_0b^2u^2t - cb^2u^2 + e_0b^2ut^2 - 2cb^2ut - cb^2t^2 + \\ abu^2 + 2abut - 4e_0hbu + abt^2 - 8e_0hbt - 4chb + 4ah \end{array}\right]}{(bu^2 + 2but + bt^2 - 4h)^2}.$$

$\frac{dp^{A*}}{dt}$ and $\frac{de^{A*}}{dt}$ are all linear functions of $e_0$. Meanwhile, we obtain the following inequalities:

$$\left.\frac{dp^{A*}}{dt}\right|_{e_0=0} = -\frac{2h(u+t)(a-bc)}{(bu^2 + 2but + bt^2 - 4h)^2} < 0,$$

$$\left.\frac{dp^{A*}}{dt}\right|_{e_0=\bar{e}_0} = \frac{h(a-bc)}{bt(4h - bu^2 - 2but - bt^2)} > 0,$$

$$\left.\frac{de^{A*}}{dt}\right|_{e_0=0} = \frac{(a-bc)(bu^2 + 2but + bt^2 + 4h)}{(bu^2 + 2but + bt^2 - 4h)^2} > 0,$$

$$\left.\frac{de^{A*}}{dt}\right|_{e_0=\bar{e}_0} = -\frac{(u+t)(a-bc)}{t(4h - bu^2 - 2but - bt^2)} < 0.$$

The above evidences confirm the relationship between $p^{A*}$, $e^{A*}$, and $t$ in Proposition 4. Further, by taking the derivation of $\pi_M^{A*}$ with respect to $t$, we know that $\frac{d\pi_M^{A*}}{dt} = \frac{h(a-bc-bte_0)(au+at-4e_0h-bcu-bct+bu^2e_0+bute_0)}{(bu^2+2but+bt^2-4h)^2}$ is a linear function with respect to $e_0$. Let $A_2 = au + at - 4e_0h - bcu - bct + bu^2e_0 + bute_0$. Since $a - bc - bte_0 > 0$ always holds, the sign of $\frac{d\pi_M^{A*}}{dt}$ depends on $A_2$. At the two endpoints of the valid interval of $e_0$, the size of $\frac{dA_2}{dt}$ satisfies the following inequalities:

$$\left.\frac{dA_2}{dt}\right|_{e_0=0} = (u+t)(a-bc) > 0\,,\ \left.\frac{dA_2}{dt}\right|_{e_0=\bar{e}_0} = -\frac{(a-bc)(4h - bu^2 - 2but - bt^2)}{bt} < 0.$$

The results indicate that $\frac{d\pi_M^{A*}}{dt} > 0$ and $\frac{d\pi_M^{A*}}{dt} < 0$ establish when $e_0$ is low and high, respectively. In a similar way, we can also prove that $\frac{d\pi_R^{A*}}{dt} > 0$ and $\frac{d\pi_R^{A*}}{dt} < 0$ when $e_0$ is less than and greater than a certain threshold. Moreover, $\frac{dE^{A*}}{dt} < 0$ always holds in the valid interval of $e_0$. Combining the above results, Proposition 4 is clearly proved.

**Proof of Proposition 5.** The proof of Proposition 5 is similar to that of Proposition 1; thus, we have omitted it.

**Proof of Proposition 6.** It is easy to see that the expressions of $w^{S*}$, $p^{S*}$, $e^{S*}$, $\pi_M^{S*}$, and $\pi_R^{S*}$ do not contain parameter $e_0$. Thus, $w^{S*}$, $p^{S*}$, $e^{S*}$, $\pi_M^{S*}$, and $\pi_R^{S*}$ are unchanging in $e_0$. Moreover, we have $\frac{dE^{S*}}{de_0} = \frac{h(a-bc)}{4h-bs^2-2bsu-bu^2} > 0$, which means that $E^{S*}$ is increasing in $e_0$. The proof is complete.

**Proof of Proposition 7.** It can be seen from $\pi_M^{S*} > 0$ and $e^{S*} > 0$ that both $a - bc$ and $4h - bs^2 - 2bsu - bu^2$ are greater than 0. Therefore, we have:

$$\frac{dw^{S*}}{du} = -\frac{4h(s+u)(a-bc)}{(bs^2+2bsu+bu^2-4h)^2} < 0,$$

$$\frac{de^{S*}}{du} = \frac{(a-bc)(bs^2+2bsu+bu^2+4h)}{(bs^2+2bsu+bu^2-4h)^2} > 0,$$

$$\frac{dp^{S*}}{du} = -\frac{2h(s+u)(a-bc)}{(bs^2+2bsu+bu^2-4h)^2} < 0,$$

$$\frac{d\pi_M^{S*}}{du} = \frac{h(s+u)(a-bc)^2}{(bs^2+2bsu+bu^2-4h)^2} > 0,$$

$$\frac{d\pi_R^{S*}}{du} = \frac{4h^2(s+u)(a-bc)^2}{(4h-bs^2-2bsu-bu^2)^3} > 0.$$

The changes of $w^{S*}$, $p^{S*}$, $e^{S*}$, $\pi_M^{S*}$, and $\pi_R^{S*}$ with respect to $u$ are vindicated. The first order derivative of the $E^{S*}$ with respect to $u$ is

$$\frac{dE^{S*}}{du} = -\frac{\left[\begin{array}{c} h(a-bc)((3bs^2+6bsu+3bu^2+4h)a+2e_0b^2s^3+6e_0b^2s^2u-3cb^2s^2+ \\ 6e_0b^2su^2-6cb^2su+2e_0b^2u^3-3cb^2u^2-8e_0hbs-8e_0hbu-4chb) \end{array}\right]}{(4h-bs^2-2bsu-bu^2)^3}.$$

Let $A_3 = (3bs^2+6bsu+3bu^2+4h)a+2e_0b^2s^3+6e_0b^2s^2u-3cb^2s^2+6e_0b^2su^2-6cb^2su+ 2e_0b^2u^3-3cb^2u^2-8e_0hbs-8e_0hbu-4chb.$

Since $a - bc > 0$ and $4h - bs^2 - 2bsu - bu^2 > 0$, the sign of $\frac{dE^{S*}}{du}$ depends on the size of $A_3$. It is obvious to see that $A_3$ is a linearly increasing function of $a$. From $q^{S*} > 0$, we know that $a > bc$. Let $\underline{a} = bc$. It is clear to see that $A_3\big|_{a=\underline{a}} = -2be_0(s+u)(4h-bs^2-2bsu-bu^2) < 0$. Recalling that $A_3$ is a continuously increasing function with respect to $a$. Meanwhile, the valid range of $a$ has no upper limit. Combing the above conditions, we conclude that $A_3 < 0$ and $A_3 > 0$ when $a$ is below and above a certain threshold, respectively. The above results imply that if $a < \tilde{a}_1$, then $E^{S*}$ is increasing in $u$; otherwise, $E^{S*}$ is decreasing in $u$. We complete the proof of Proposition 7.

**Proof of Proposition 8.** We derive the following inequalities by differentiating the variables with respect to $s$:

$$\frac{dw^{S*}}{ds} = -\frac{4h(s+u)(a-bc)}{(bs^2+2bsu+bu^2-4h)^2} < 0,$$

$$\frac{de^{S*}}{ds} = \frac{(a-bc)(bs^2+2bsu+bu^2+4h)}{(bs^2+2bsu+bu^2-4h)^2} > 0,$$

$$\frac{dp^{S*}}{ds} = -\frac{2h(s+u)(a-bc)}{(bs^2+2bsu+bu^2-4h)^2} < 0,\ \frac{d\pi_M^{S*}}{ds} = \frac{h(s+u)(a-bc)^2}{(bs^2+2bsu+bu^2-4h)^2} > 0,$$

$$\frac{d\pi_R^{S*}}{ds} = \frac{(4h^2(s+u)(a-bc)^2)}{(4h-bs^2-2bsu-bu^2)^3} > 0.$$

Moreover, similar to the proof of Proposition 7, we can prove that $E^{S*}$ is increasing and decreasing in $a$ is $a < \tilde{a}_2$ and $a > \tilde{a}_2$, respectively. Thus, we can obtain Proposition 8.

**Proof of Proposition 9.** The gap between $w^A$ and $w^S$ is

$$w^A - w^S = -\frac{\left[\begin{array}{c} 2h(at^2 - as^2 - 2asu + 2aut - 4te_0h + bcs^2 - bct^2 + bs^2te_0 + bu^2te_0 + \\ 2bcsu - 2bcut + 2bsute_0) \end{array}\right]}{(4h - bs^2 - 2bsu - bu^2)(4h - bu^2 - 2but - bt^2)}.$$

It is easy to see that $w^A - w^S$ is a linear function of $e_0$. Meanwhile, we can verify that

$$(w^A - w^S)\Big|_{e_0=0} = \frac{2h(s-t)(a-bc)(s+2u+t)}{(4h - bs^2 - 2bsu - bu^2)(4h - bu^2 - 2but - bt^2)},$$

$$(w^A - w^S)\Big|_{e_0=\bar{e}_0} = \frac{2h(a-bc)}{b(4h - bs^2 - 2bsu - bu^2)} > 0.$$

The above conditions imply that when $s > t$, $w^A > w^S$ always holds; otherwise, $w^A > w^S$ holds only when $e_0$ is greater than a certain threshold. The same method can prove the relationship between $p^A$ and $p^S$; therefore, we omit the analysis process. Further, taking the difference between $e^A$ and $e^S$ yields the following formula:

$$e^A - e^S = \frac{\left[\begin{array}{l} (e_0b^2s^2ut + cb^2s^2u + e_0b^2s^2t^2 + cb^2s^2t + 2e_0b^2su^2t + cb^2su^2 + 2e_0b^2sut^2 - cb^2st^2 + \\ e_0b^2u^3t + e_0b^2u^2t^2 - cb^2u^2t - cb^2ut^2 - abs^2u - abs^2t - absu^2 + abst^2 + 4chbs + \\ abu^2t + abut^2 - 4e_0hbut - 4e_0hbt^2 - 4chbt - 4ahs + 4aht) \end{array}\right]}{(bs^2 + 2bsu + bu^2 - 4h)(bu^2 + 2but + bt^2 - 4h)}.$$

It is obvious to see that $e^A - e^S$ is a linear function of $e_0$. When $e_0 = 0$ and $e_0 = \bar{e}_0$, the values of $e^A - e^S$ are as follows:

$$(e^A - e^S)\Big|_{e_0=0} = -\frac{(s-t)(a-bc)(4h + bu^2 + bsu + bst + but)}{(4h - bs^2 - 2bsu - bu^2)(4h - bu^2 - 2but - bt^2)},$$

$$(e^A - e^S)\Big|_{e_0=\bar{e}_0} = -\frac{(s+t)(a-bc)}{4h - bs^2 - 2bsu - bu^2} < 0.$$

The relationship between $e^A$ and $e^S$ in Proposition 9 obviously holds. In addition, the above analysis results support the conclusions in Proposition 9.

**Proof of Proposition 10.** Taking the difference between $\pi_M^A$ and $\pi_M^S$ yields the following equation:

$$\pi_M^A - \pi_M^S = \frac{\left[\begin{array}{l} h(bt^2(4h - bs^2 - 2bsu - bu^2)e_0^2 - 2t(a-bc)(4h - bs^2 - 2bsu - bu^2)e_0 - \\ (s-t)(a-bc)^2(s+2u+t)) \end{array}\right]}{2(4h - bs^2 - 2bsu - bu^2)(4h - bu^2 - 2but - bt^2)}.$$

Let $A_4(e_0) = bt^2(4h - bs^2 - 2bsu - bu^2)e_0^2 - 2t(a-bc)(4h - bs^2 - 2bsu - bu^2)e_0 - (s-t)(a-bc)^2(s+2u+t)$. It is clear to see that $A_4(e_0)$ is a quadratic function with respect to $e_0$. Since both $4h - bs^2 - 2bsu - bu^2$ and $(a-bc)(4h - bs^2 - 2bsu - bu^2)$ are greater than 0, the quadratic and first-order coefficients of $A_4(e_0)$ are greater than 0 and less than 0, respectively. The abscissa of the symmetry axis of the function $A_4(e_0)$ is $\tilde{x} = \frac{a-bc}{bt} = \bar{e}_0 > 0$. When $s > t$, the constant term of $A_4(e_0)$ is lower than 0. $A_4(e_0)$ is a continuously decreasing function of $e_0$ in the interval $(0, \bar{e}_0]$. Meanwhile, we also have

$$A_4(e_0)\Big|_{e_0=0} = -(s-t)(a-bc)^2(s+2u+t) < 0,$$

$$A_4(e_0)\Big|_{e_0=\bar{e}_0} = -\frac{(a-bc)^2(4h-bu^2-2but-bt^2)}{b} < 0.$$

That means, $A_4(e_0) < 0$ always holds when $\bar{e}_0 \in (0, \bar{e}_0]$. Since

$$\pi_M^A - \pi_M^S = \frac{hA_4(e_0)}{2(4h-bs^2-2bsu-bu^2)(4h-bu^2-2but-bt^2)},$$

$\pi_M^A - \pi_M^S < 0$ obviously holds.

When $s < t$, the constant term of $A_4(e_0)$ is greater than 0. In addition, the following inequalities establish:

$$A_4(e_0)\Big|_{e_0=0} = -(s-t)(a-bc)^2(s+2u+t) > 0,$$

$$A_4(e_0)\Big|_{e_0=\bar{e}_0} = -\frac{(a-bc)^2(4h-bu^2-2but-bt^2)}{b} < 0.$$

Therefore, $A_4(e_0) > 0$ and $A_4(e_0) < 0$ establish when $e_0$ is greater than and less than a certain threshold. In summary, there exists a threshold $\tilde{e}_{10}$ such that $\pi_M^A - \pi_M^S > 0$ holds if $e_0 < \tilde{e}_{11}$; otherwise, $\pi_M^A - \pi_M^S < 0$ holds.

In a similar way, we can also prove that $\pi_R^A - \pi_R^S < 0$ always holds when $s > t$. However, when $s > t$, it has the following features: there exists a threshold $\tilde{e}_{11}$ such that if $e_0 < \tilde{e}_{12}$, then $\pi_R^A - \pi_R^S > 0$; otherwise, $\pi_R^A - \pi_R^S < 0$.

Similar to the above analysis, we can prove that $E^A - E^S$ is decreasing in $e_0$ when $e_0 \in (0, \bar{e}_0]$. In addition, when $e_0 = 0$, we have

$$(E^A - E^S)\Big|_{e_0=0} = \frac{h(s+u)(a-bc)^2}{(bu^2+2bsu+bs^2-4h)^2} - \frac{h(t+u)(a-bc)^2}{(bu^2+2but+bt^2-4h)^2}.$$

Let $A_5(x) = \frac{h(x+u)(a-bc)^2}{(bx^2+2bxu+bu^2-4h)^2}$. The first derivative of $A_5(x)$ with respect to $x$ is $\frac{dA_5(x)}{dx} = \frac{(h(a-bc)^2(3bx^2+6bxu+3bu^2+4h))}{(4h-bx^2-2bxu-bu^2)^3} > 0$. The above findings imply that if $s > t$, then $(E^A - E^S)|_{e_0=0} > 0$; otherwise, $(E^A - E^S)|_{e_0=0} < 0$. Meanwhile, it is easy to verify that $(E^A - E^S)|_{e_0=\bar{e}_0} < 0$. Combining the above information, we obtain the results stated in Proposition 10.

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