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Enhancing efficiency in supply chain management: A synergistic approach to production, logistics, and green investments under different carbon emission policies

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ABSTRACT

The study examines the influence of different carbon policies and the incorporation of green technologies in a two-echelon supply chain, with a focus on carbon emissions generated during transportation, production, and storage phases. The study evaluates three strategies for controlling carbon emissions: setting a maximum limit on total emissions, implementing carbon-taxation, and adopting a cap-and-trade framework. The proposed model assists businesses determine the optimal production and delivery volumes, as well as calculate the most effective investment in green technologies to reduce costs in the context of different carbon emission regulations. Furthermore, this study offers practical guidance for policymakers, highlighting the importance of balancing environmental sustainability with economic growth. Results indicate that companies are more inclined to pursue advanced green technology solutions under a carbon tax policy. The analysis highlights that carbon emissions per unit of production and transportation distance significantly impact overall emissions. The imposed emission cap has a stronger influence than the emission reduction potential of green technologies. The study recommends that governments establish realistic emission limits in cap-and-trade schemes to prevent excessive trading of emission allowances by suppliers.

1. Introduction

With the escalating severity of climate change and global warming, numerous countries have implemented environmental regulations and policies to control the excessive discharge of wastewater and air pollutants by companies and manufacturers. This scenario presents challenges for both governments and companies. Governments are responsible for verifying and monitoring the carbon emissions of energy consumers. They might also establish systems for trading carbon emissions or provide incentives for environmentally friendly investments to mitigate the release of carbon emissions. Meanwhile, companies aim to maximize their benefits while operating within the framework of government regulations, mechanisms, and incentives.

Typically, governments adopt one of three policies to address carbon emissions as follows: (1) Limited Carbon Emissions: This policy involves the government allocating a fixed allowance of carbon emissions to companies. This limit serves to restrict excessive carbon emissions resulting from production or business activities. (2) Carbon-taxation: This form of pollution tax imposes a fee on each ton of carbon emissions, which is then applied to electricity, gas, or oil consumption. The carbon tax incentivizes companies to decrease unnecessary consumption, enhance energy efficiency, and shift to cleaner energy sources. (3) Cap-and-trade: This system involves taxing companies that exceed their carbon emission allowances, while also allowing them to sell or trade any unused allowances. For instance, the California emissions trading system,

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established in 2013, demonstrates the management of an economy-wide cap-and-trade system. Additionally, investing in green technology often becomes a more cost-effective option than purchasing permits. These policies are implemented in many developed and developing countries. However, for developing countries, pursuing car-bon emission reduction without considering economic growth is impractical. Most of these countries face a trade-off between protecting the environment and promoting economic growth. Therefore, this study examines inventory management strategies within a supply chain, taking into account three different carbon emission policies. Unlike previous research, which often focused on single perspectives, this study takes an integrated approach by considering both ends of the supply chain, with a specific focus on carbon emissions. This perspective represents a significant departure from the existing literature.

The growing environmental awareness has resulted in widespread public under-standing of the need to reduce carbon emissions and conserve energy. In response, various countries have enacted regulations to manage carbon emissions and decrease greenhouse gases, affecting the energy strategies of businesses (Gharaie et al., 2013; Toptal et al., 2014). Consequently, companies are now more focused on reducing carbon emissions throughout the entire product lifecycle, from design to disposal. They are incorporating environmental concerns into their cost structures and business decision-making processes. Governments often impose carbon emission caps and regulations, such as carbon taxes, trading schemes, and offsets, to promote environmental sustainability. Krass et al. (2013) suggested that companies should implement a range of green technologies to com-ply with regulations and carbon taxes, thereby reducing greenhouse gas emissions and minimizing their environmental impact. Carbon trading policies have incentivized companies to reduce emissions by selling excess allowances. Gong & Zhou (2013) proposed a production planning model in which manufacturers can trade emission allowances at fluctuating prices within the planning period, thereby ensuring compliance with emission limits. García-Alvarado et al. (2017) investigated strategies for reducing carbon emissions in continuous production firms that are permitted to participate in carbon trading. They found that the optimal emission reduction can be achieved through trading. Cap-and-trade policies have been proven to reduce emissions and increase profits. Lukas & Welling (2014) conducted research on the effects of ecological and efficiency economics within multi-stage supply chains. Their findings revealed that variations in carbon trading prices positively impact economic efficiency while simultaneously having a detrimental effect on ecological efficiency. Furthermore, several studies have examined pricing and production decision-making in situations involving cap-and-trade and carbon tax systems. These studies concluded that the optimal production quantities are significantly influenced by the current prices of carbon emission trading and the levels of carbon taxes. García-Alvarado et al. (2017) integrate remanufacturing into cap-and-trade systems. They emphasized that firms' decisions are influenced by carbon prices. Hu et al. (2020) investigate the trade-offs between carbon tax and cap-and-trade systems, with a specific focus on China's remanufacturing industry. The study concludes that the cap-and-trade approach is more suitable for controlling carbon emissions in the remanufacturing industry. These results provide valuable guidance for developing effective carbon emission reduction strategies customized for re-manufacturing and related industries. Mirzaee et al. (2022) proposed a stochastic game theoretical framework for analyzing the essential compromises needed to optimize specific goals under this policy. The framework involves manufacturers, a third-party carbon emissions verifier, and the government. Feng (2024) explored pricing strategies in recycling and remanufacturing supply chains, focusing on the impact of consumer preferences for online shopping and recycled product quality. The study showed that these preferences greatly affect logistics service levels, pricing strategies, market demand, and the overall profitability of the supply chain.

Bozorgi et al. (2014) emphasized that refrigeration and transportation are significant sources of greenhouse gases, highlighting the importance of both transportation distance and load weight in the latter. Supporting this idea, Jabali et al. (2012) emphasized the significant impact of transportation on carbon emissions within supply chains. Demir et al. (2014) identified freight transportation as a major source of carbon emissions in production activities. They pointed out that factors such as vehicle speed and load weight have a significant impact on fuel consumption and carbon emissions. Tang et al. (2015) investigated the reduction of carbon emissions through a decrease in transportation frequency. Leenders et al. (2017) examined carbon emissions allocation in transportation routing and found that simple allocation methods can result in equitable and carbon-efficient distribution, regardless of errors in estimating shipment size. Tornese et al. (2018) investigated the relationship between carbon emissions and economic factors in inventory and logistics decisions within pallet supply chains. Recent attention to environmental protection and social responsibility has sparked interest in sustainable supply chain management (SSCM). Studies by Hao et al. (2018), Rabbani et al. (2018, 2019), and Awasthi & Omrani (2019) demonstrate how SSCM helps firms effectively manage environmental and social issues within their supply chains. Stroumpoulis and Kopanaki (2022) explored how SSCM inter-sects with digital transformation, focusing on the integration of particular technologies like Block chain, big data analytics, and the Internet of Things. Shekarian et al. (2022) con-ducted a comprehensive review of industrial practices in SSCM. They presented a sustainable framework outlining various industrial strategies for achieving sustainable supply chains, categorizing them into 38 specific practices across 11 major categories. In summary, SSCM involves environmental management, resource conservation, carbon emission reduction, financial sustainability, and social responsibility.

In the issue of supply chain coordination, businesses are shifting their focus from individual cost structures, such as inventory, to the costs of the entire supply chain. This broader perspective enables the development of integrated inventory models, which in turn helps in formulating strategies to enhance competitive advantages (Hu et al., 2018; Lin et al., 2018; Fu & Ma, 2019; Seyedhosseini et al., 2019; Huang et al., 2020; Khorshidvand et al., 2021; Gupta et al., 2023; Liu et al., 2024). Growing environmental awareness is driving supply chains to assess the impact of environmental protection regulations on their cost. In response to growing concerns about global warming and the necessity of adhering to comply with government regulations, companies are investigating different production methods to minimize carbon emissions, which can occur at any point in the supply chain (Tsao, 2015; Wang & Qie, 2018; Nidhi & Pillai, 2019; Roy et al., 2020; Compernolle & Thijssen, 2022; Zhang et al., 2022; Guo & Xi, 2023; Li & Wang, 2023). However, previous research has rarely addressed the integrated inventory issue, which considers carbon emissions during production, delivery, and storage within a supply chain context (Glock, 2012; Jha & Shanker, 2013; Kazemi et al., 2018; Huang et al., 2020; Yuniarti et al., 2023). Some companies are moving beyond simply complying with carbon emission limits and penalties, opting to proactively invest in green technology to reduce emissions (Lukas & Welling, 2014; Costa-Campi et al., 2017; Bu & Shi, 2021; Xu & Xu, 2022; Xia et al., 2023). In 1997, the Kyoto Protocol urged 38 industrialized nations to cut carbon emissions, creating a challenge in balancing environmental protection with economic growth. Promoting investment in green technologies continues to be a significant hurdle for these countries. The adoption of green technology involves substantial capital costs for companies, requiring government incentives to promote pollution reduction through increased green investments. Essentially, companies can offset their green investment costs with government incentives, leading to a reduction in carbon emissions as a result of these investments.

The structure of this study is organized as follows: Section 2 presents a comprehensive discussion of the research problem, along with the key assumptions that guide the study. Section 3 details the model development process and examines the impact of carbon emissions on overall costs. In Section 4, a numerical example is provided, followed by a sensitivity analysis to assess various scenarios. Finally, Section 5 summarizes the findings and offers recommendations for future research directions. Addressing the challenges associated with the adoption of green technologies is essential. Implementing these technologies often requires substantial capital investment from companies, making government incentives vital for encouraging pollution reduction and promoting sustainable practices. Such incentives can assist businesses mitigate the financial burden of green investments, ultimately resulting in reduced carbon emissions as companies enhance their commitment to environmentally friendly solutions. This study aims to investigate the most effective inventory management strategy that integrates green technology investments to minimize carbon emissions throughout the supply chain. It can balance the pursuit of profit maximization with a commitment to environmental sustainability.

2. Three Carbon Emission Policy Scenarios and Green Investment

This study investigates an integrated inventory model that considers carbon emissions arising from transportation, storage, and production activities. Carbon emissions during the production setup and product manufacturing are denoted as E_S and E_P, respectively. Additionally, E_T represents the emissions per unit of product per unit of distance during transportation, taking into account the impacts of delivery distance and lot size. The study also acknowledges that fixed delivery distances between suppliers and retailers influence the number of shipments and transportation lot sizes, thereby impacting emissions. Special products, such as frozen foods, which generate significant emissions during storage, are denoted as E_H. The study considers three carbon emissions policy scenarios.

1. Carbon-taxation: A government-imposed tax, TX, per unit of emissions from production, transportation, and storage, which varies across industries. For example, the energy sector might encounter lower or no taxes in certain countries.
2. Cap-and-trade: Modeled after systems in the U.S. and Europe, where firms receive initial emission allowances that can be traded. The total quota of allowable emissions are capped at UX, with the excess of UX being tradable at EX per unit. Exceeding the carbon emissions limit necessitates purchasing additional allowances or investing in green technology.
3. Limited Carbon Emissions: In this context, the combined emissions from production, transportation, and storage must not exceed a specified limit UC, which varies depending on the industry and country.

The study also examines investments in green technology (IV) with the aim of reducing emissions, lowering carbon trading costs, and offsetting the expense of selling emission allowances. The objective is to optimize the number of shipments (n^*), transportation lot size (Q^*), and green investment (IV^*) in order to minimize total costs. This includes setup, storage, transportation, carbon tax, revenue from carbon trading, and investment in green technology. Fig. 1 illustrates the conceptual framework. The framework proposes a relationship in which the costs associated with carbon emissions could be reduced through strategic investments in green technology. This, in turn, affects the operational costs and decisions made by both suppliers and retailers. The study aims to quantify these relationships and provide insights into the most cost-effective and environmentally sustainable strategies under different policy scenarios. This study is based on the following assumptions:

1. The supply chain is centralized, involving a single supplier and retailer for a specific product, and is not affected by seasonal demand fluctuations.
2. The production rate is constant and exceeds the retailer's demand, and the storage and transportation capacities are adequate, and extreme cases are not taken into account.
3. The model does not differentiate between types of trucks or shipment weights, instead using average values to estimate carbon emissions.
4. Carbon emissions are only considered in terms of production, transportation, and storage. Green investment does not completely eliminate emissions, but its impact is measurable and based on historical data.

The notations are explained in detail below.

D_R	Retailer's Demand Rate
P_S	Supplier's Production Speed (the production rate P_S must exceed the demand rate D_R)
Q	The economic order quantity
Q_m	The level of safe stock held by the retailer
A_S	The cost incurred by the supplier for setting up production
A_R	The expense incurred by the retailer for processing orders
H_S	Supplier's Product Holding Charge
H_R	Retailer's Product Holding Fee
n	Frequency of Shipments per Production Cycle
F_S	The cost of transportation per kilometer for the supplier
K_S	The average distance of each transportation
E_H	The carbon emissions associated with storing each product for the retailer and the supplier
E_T	Carbon emissions per delivery by the supplier
E_P	Carbon emissions from producing each product
E_S	Carbon emissions generated during a production setup
IV	The investment for green technology
$G(\cdot)$	The function of green technology for reducing carbon emissions
TX	Carbon tax per unit of carbon emission
EX	The price of acquiring carbon credits under a cap-and-trade policy
UX	The quota of carbon emissions
UC	The allowance of carbon emissions

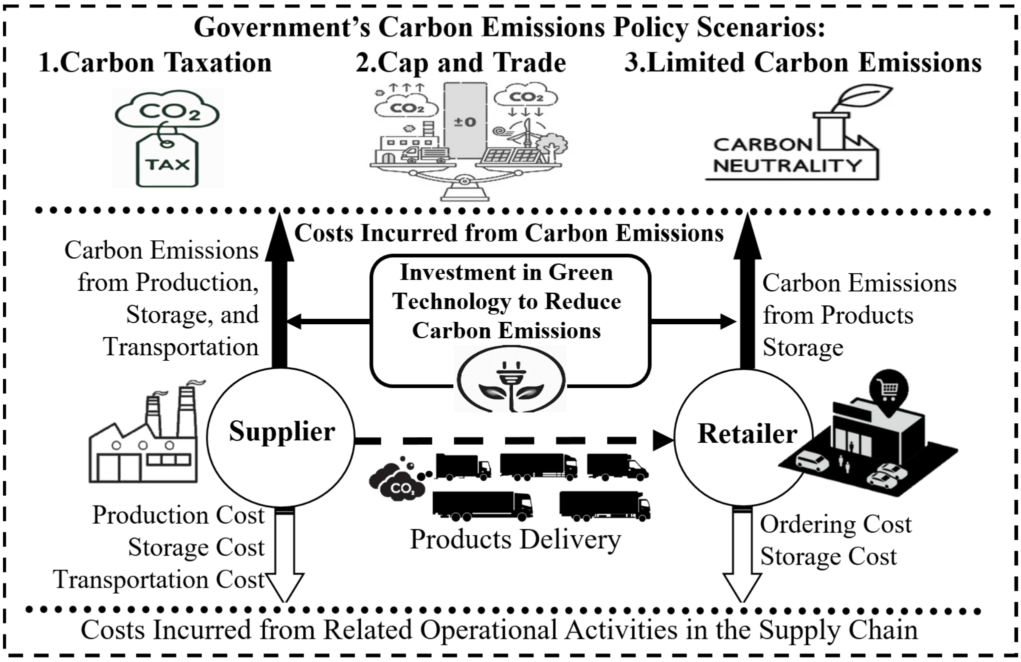


Fig. 1. Conceptual Framework of the Study

3. Three carbon emission policy scenarios and green investment

3.1 Basic model without considering carbon emissions

In this model, the retailer's demand rate is specified as D_R, while the supplier's production rate is P, which must exceed D_R for operational efficiency. The supplier's delivery system is designed to deliver Q units per delivery cycle to the retailer. Consequently, the duration of each delivery cycle is represented by Q/D_R, corresponding to the rate of demand. During the production phase, the supplier maintains a continuous production rhythm, replenishing stock after delivery to the retailer until the designated production volume is achieved. Within each production cycle, the supplier makes n deliveries, each consisting of Q units, to the retailer. The time span of the entire production cycle is calculated as $\frac{nQ}{D_R}$, effectively covering multiple delivery cycles. The end of a cycle is marked when the supplier's inventory is completely depleted. To understand the relationship between production and consumption rates, consider the production time as $\frac{nQ}{P_S}$. The consumption period can be determined by deducting the time of production from the total production cycle duration. This is expressed as $nQ\left(\frac{1}{D_R}-\frac{1}{P_S}\right)$, where D_R represents the retailer's demand rate and P_S represents the supplier's production rate. This period essentially represents the time when the retailer uses the delivered products in comparison to the supplier's production schedule. The model considers various operational dynamics. The supplier needs to carefully monitor inventory levels to align production output with retailer demand. This optimization minimizes storage costs and prevents stock out or overstock situations. We also consider the environmental impact of production and delivery processes, with the aim to minimize carbon emissions and adhere to sustainable practices. The economic analysis of the study assesses the cost implications of different production and delivery strategies, aiming to optimize economic efficiency. The model is designed to be adaptable, allowing for adjustments in production and delivery schedules in response to fluctuating market demands or unforeseen supply chain disruptions. By integrating these elements, the model becomes a comprehensive tool for managing production rates, delivery schedules, and demand fulfillment within the context of a supply chain. In this model, the supplier's costs are divided into three primary components: production setup, transportation, and inventory holding. Each cost element is calculated based on various operational parameters, leading to a comprehensive understanding of the supplier's annual expenditures.

1. Supplier's Production Setup Cost and Retailer's Order Processing Cost: The annual cost of setting up production is determined by considering the demand rate (D_R), the transportation lot size (Q), and the number of shipments (n). The formula $\frac{D_R}{nQ}A_S$ represents this, where A_S denotes the cost incurred for each production setup cycle. Besides, the retailer's annual cost for order processing is calculated by first dividing the total demand by the transportation lot size. This result is then multiplied by the cost per order processed (A_R). The formula $\frac{2D_R}{Q}A_R$ represents the frequency of orders and the corresponding cost per order.
2. Transportation Cost: The cost is calculated by dividing the demand (D_R) by the transportation lot size (Q), then multiplying the result by the distance of each delivery (K_S) and the average cost of transportation per kilometer (F_S). The resulting formula, $\frac{D_R}{Q}F_SK_S$, represents the frequency and cost of transportation per unit distance.
3. Inventory Holding Cost for Supplier and Retailer: The annual cost of holding inventory is calculated by dividing the supplier's inventory area by the duration of the production cycle $(\frac{nQ}{D_R})$. Therefore, the average level of the supplier's inventory throughout the production cycle is $\frac{Q}{2}(1+n(\frac{P_S-D_R}{P_S}))$. In addition, the retailer needs to consider maintaining a minimum level of safety stock (Q_m), and therefore the retailer's average level of inventory will be $\frac{Q+2Q_m}{2}$. The supplier and the retailer's unit holding costs during the production cycle are H_S and H_S, respectively. Based on the above consideration, the inventory holding cost for the supplier and the retailer is $(\frac{Q+2Q_m}{2})H_R+\frac{Q}{2}(1+n(\frac{P_S-D_R}{P_S}))H_S$. Therefore, the cost is given by

$$TC_0(n,Q)=\frac{D_R}{nQ}A_S+\frac{D_R}{Q}K_SF_S+\frac{Q}{2}\left(1+n\left(\frac{P_S-D_R}{P_S}\right)\right)H_S+\frac{D_R}{Q}A_R+\left(\frac{Q}{2}+Q_m\right)H_R. \tag{1}$$

Lemma 1*: In the fundamental integrated inventory model, let's assume that the total cost, denoted as $TC_0(n,Q)$, demonstrates a convex nature with a minimal value. The optimal lot size of a transportation can be expressed by the following equation:*

$$Q_0{}^*(n)=\sqrt{\frac{2D_RP_S\big(A_S+n(A_R+nF_SK_S)\big)}{n\big((H_R+(1+n)H_S)P_S-nD_RH_S\big)}}, \tag{2}$$

Furthermore, n is determined to be a positive integer, conforming to the inequality as follows:

$$n_0^*(n_0^*-1)\le\frac{(H_R+H_S)A_SP_S}{H_S(P_S-D_R)(A_R+F_SK_S)}\le n_0^*(n_0^*+1). \tag{3}$$

Proof of Lemma 1*:*

In this scenario, we examine a basic inventory model where the total cost depends on both Q and n. The total cost function is continuous and differentiable, and its first-order derivatives with respect to n and Q are as $\frac{\partial TC_0(n,Q)}{\partial n}=\frac{(P_S-D_R)H_SQ}{2P_S}-\frac{A_SD_R}{n^2Q}$ *and* $\frac{\partial TC_0(n,Q)}{\partial Q}=\frac{1}{2}\left(H_R+(1+n)H_S-\frac{nD_RH_S}{P_S}-\frac{2D_R(nA_R+A_S+nF_SK_S)}{nQ^2}\right)$.

Setting these derivatives to zero to solve them simultaneously, we find: $n_0^*=\sqrt{\frac{(H_R+H_S)A_SP_S}{H_S(P_S-D_R)(A_R+F_SK_S)}}$ *and* $Q_0{}^*=\sqrt{\frac{2D_RP_S\left(A_S+n(A_R+nF_SK_S)\right)}{n\left((H_R+(1+n)H_S)P_S-nD_RH_S\right)}}$. *Since n must be an integer and can be either the floor or ceiling of n_0^*, depending on which* *gives a lower total cost. Moreover, the determinant value of the Hessian matrix of* $TC_0(n,Q)$ *is greater than 0. Furthermore, due to* $\frac{\partial^2 TC_0(n,Q)}{\partial n^2}$ *and* $\frac{\partial^2 TC_0(n,Q)}{\partial n^2}$ *are positive, it implies that the cost function is a convex nature with a minimal value.*

3.2 Carbon emissions incurred from supply chain and investments in green technology

In this analysis, the study assumes a steady production rate, denoted as P_S. For every unit of product manufactured, carbon emissions, represented by E_P, are generated. Furthermore, the start of each production cycle requires the setup of production equipment, resulting in carbon emissions, denoted as E_S. Consequently, the annual carbon emissions attributable to the production process are calculated as $D_R E_P + \frac{D_R}{nQ} E_S$. The distance of delivery and the size of transportation lots significantly influence carbon emissions. The annual carbon emissions from transportation are calculated by multiplying the emissions per unit of distance (E_T) by the demand rate (D_R), and then dividing the result by the transportation lot size (Q). Finally, this value is multiplied by the delivery distance (K_S). This results in the formula $\frac{D_R}{Q} E_T K_S$ for annual transportation-related emissions. Carbon emissions also occur during the storage of products, particularly those that remain undelivered or unsold, a situation influenced by specific product characteristics and other external factors. To quantify these emissions, the carbon emissions per stored unit product (E_H) are multiplied by the sum of the average inventory held by both the supplier and the retailer, resulting the annual storage-related emissions formula:

$$\left(Q/2 + Q_m + Q/2\left(1 + n\left(\frac{P_S - D_R}{P_S}\right)\right)\right)E_H.$$

Moreover, in order to reduce excessive carbon emissions, the study considers investing in green technology. The carbon reduction function of green technologies can be expressed as $G(IV|\theta_0, \theta_1, \theta_2) = \theta_0 - \theta_1 IV + \theta_2 (IV)^2$, where θ_1 represents the carbon reduction efficiency factor, while θ_0 and θ_2 are related to offsetting carbon reduction. This function implies that investing in green technology (IV) yields a $\theta_1 IV$ reduction in emissions, but also produces additional emissions represented by $\theta_2(IV)^2$ due to energy consumption. The parameters θ_0, θ_1, and θ_2 can be derived by analyzing historical data related to reductions in carbon emissions and the amounts invested in green technologies. Taking into account the carbon emissions from all processes and investments in green technology, we can determine the total cost and total carbon emissions using the following equations:

$$TC(n,Q,IV) = \frac{A_S D_R}{nQ} + \frac{K_S F_S D_R}{Q} + \frac{Q}{2}\left(1 + n\left(\frac{P_S - D_R}{P_S}\right)\right)H_S + \frac{A_R D_R}{Q} + \left(\frac{Q}{2} + Q_m\right)H_R + IV \tag{4}$$

and

$$CE(n,Q,IV) = D_R E_P + \frac{D_R}{nQ}(E_S + nK_S E_T) + \left(\frac{Q}{2} + Q_m\right)E_H + \frac{Q}{2}\left(1 + n\left(\frac{P_S - D_R}{P_S}\right)\right)E_H + G(IV|\theta_0, \theta_1, \theta_2). \tag{5}$$

These equations comprehensively capture the relationship between carbon emissions, investment in green technology, and various operational parameters within the supply chain.

3.3 Carbon-taxation policy

In the context of a carbon tax policy, where a specific tax rate (TX) is imposed for each unit of carbon emitted, the overall cost within the supply chain is directly affected by the total carbon emissions. This scenario provides an opportunity for both suppliers and retailers to invest in green technology, aimed at reducing their carbon emissions, thereby diminishing their carbon tax obligations. The total costs included in this comprehensive inventory model include the supplier's costs for setting up production, the retailer's costs for order processing, transportation-related costs, inventory holding costs for both parties, the combined carbon tax, and investments in green technology. Total carbon emissions are determined by summing the emissions generated from production, transportation, and inventory storage. Afterward, this total is adjusted by subtracting the emissions reduction resulting from investments in green technology, reflecting the overall environmental impact after considering sustainability efforts. As a result, the overall cost implications of complying with a carbon tax policy are formulated as follows:

$$\begin{aligned} TC_1(n,Q,IV) = {} & \frac{1}{2}\left((Q + 2Q_m)H_R + (1+n)QH_S + \frac{2D_R(nA_R + A_S + nF_S K_S)}{nQ} - \frac{nQD_R H_S}{P_S}\right) + IV \\ & + TX\left(D_R E_P + \frac{D_R}{nQ}(E_S + nK_S E_T) + \left(\frac{Q}{2} + Q_m\right)E_H + \frac{Q}{2}\left(1 + n\left(\frac{P_S - D_R}{P_S}\right)\right)E_H + (\theta_0 - \theta_1 IV + \theta_2 (IV)^2)\right). \end{aligned} \tag{6}$$

***Lemma 2**: In this carbon-tax scenario, the total cost function $TC_1(n, Q, IV)$ is convex with a well-defined minimum. Therefore, specific formulas can be used to determine the optimal transportation lot size and the optimal number of shipments. Furthermore, the optimal level of investment in green technology can also be calculated to minimize the total cost.*

$$Q_1^*(n_1^*) = \sqrt{\frac{2D_R(n_1^*A_R + A_S + E_STX + n_1^*(E_TTX + F_S)K_S)P_S}{\begin{matrix}((2 + n_1^*)E_HTX + H_R + (1 + n_1^*)H_S)P_S) \\ -n_1^*(n_1^*D_R(E_HTX + H_S)\end{matrix}}}. \tag{7}$$

Since n_1^* is determined to be a positive integer, it needs to conform to the following inequality:

$$n_1^*(n_1^* - 1) \leq \frac{(A_S + E_STX)(2E_HTX + H_R + H_S)P_S}{(E_HTX + H_S)(A_R + (E_TTX + F_S)K_S)(P_S - D_R)} \leq n_1^*(n_1^* + 1). \tag{8}$$

The optimal investment of the green investment is as follows:

$$IV_1^* = \frac{\theta_1TX - 1}{2\theta_2TX}. \tag{9}$$

***Proof of Lemma 2**:*

Lemma 2 involves demonstrating that the total cost function is continuous, differentiable, and convex, with the first-order derivatives leading to the optimal solutions for n, Q, and IV. The proof uses the Hessian matrix to establish convexity and demonstrates that the total cost has a minimum value under the carbon tax policy. The Hessian matrix of $TC_1(n, Q, IV)$ and determinant value can be given as follows:

$$H = \begin{bmatrix} \frac{2D_R(A_S+E_STX)}{n^3Q} & \frac{1}{2}\left(E_HTX + H_S + D_R\begin{pmatrix}\frac{2(A_S+E_STX)}{n^2Q^2} \\ -\frac{E_HTX+H_S}{P_S}\end{pmatrix}\right) & 0 \\ \frac{1}{2}\left(E_HTX + H_S + D_R\begin{pmatrix}\frac{2(A_S+E_STX)}{n^2Q^2} \\ -\frac{E_HTX+H_S}{P_S}\end{pmatrix}\right) & \frac{2D_R(nA_R+A_S+E_STX+n(E_TTX+F_S)K_S)}{nQ^3} & 0 \\ 0 & 0 & 2\theta_2TX \end{bmatrix}.$$

Since all the parameters' value are all positive numbers, the determinant value of $|H|$ will be greater than 0. Moreover, the diagonal elements of the matrix H ($\frac{\partial^2TC_1(n,Q,G)}{\partial n^2}$, $\frac{\partial^2TC_1(n,Q,G)}{\partial Q^2}$, and $\frac{\partial^2TC_1(n,Q,G)}{\partial G^2}$) are positive, and it implies that the cost function is convex and has a minimal value. In order to obtain the optimal solution for n, Q, and IV, the first-order derivatives with respect to n, Q, and IV can be set to zero and solved simultaneously.

Following this, the study analyzes how the effectiveness of carbon emissions reduction and carbon tax rates impact overall inventory costs and carbon emissions. Proposition 1 suggests that investing in green technology can significantly reduce both the costs and the emissions under a carbon-tax policy.

***Proposition 1**: In the carbon-taxation scenario, investing in green technology can effectively reduce the cost by $\frac{(\theta_1TX-1)^2}{4\theta_2TX}$, and decrease carbon emissions by $\frac{(\theta_1)^2(TX)^2-1}{\theta_2(2TX)^2}$.*

***Proof of Proposition 1**:*

The proof is based on analyzing the differences in total costs and emissions with and without the green technology investment. When comparing the emission levels $CE(n_1^*, Q_1^*, 0)$ (without green technology) and $CE(n_1^*, Q_1^*, IV_1^*)$ (with green technology), it is observed that the reduction in emissions is quantified as $\frac{(\theta_1)^2(TX)^2-1}{\theta_2(2TX)^2}$. Similarly, comparing the total costs $TC_1(n_1^*, Q_1^*, 0)$ and $TC_1(n_1^*, Q_1^*, IV_1^*)$ reveals a cost reduction of $\frac{(\theta_1TX-1)^2}{4\theta_2TX}$, which is greater than zero.

Proposition 1 emphasizes an important insight about the effectiveness of green technology investments under a carbon tax system, with a specific focus on the fixed carbon emissions reduction factor (θ_1) and the offsetting carbon reduction factor (θ_2). In scenarios where these factors remain constant, indicating consistent effectiveness of green technologies, an increase in the carbon tax rate (TX) significantly influences the decision to invest in green technologies. The main point of this proposition is that as the carbon tax price increases, the relative advantage of investing in technologies that reduce carbon emissions becomes more significant compared to just paying the carbon tax. This trend suggests that, as carbon tax rates increase, investing in green technology not only reduces carbon emissions more effectively but also becomes a more financially viable option compared to incurring higher carbon tax expenses. Therefore, in light of carbon taxation, investing in green technology to reduce carbon emissions has become a viable and increasingly beneficial strategy. This insight is particularly relevant for decision-makers in industries where carbon emissions are a significant factor, guiding them toward investment choices that prioritize sustainability while also being economically viable.

3.4 Cap-and-trade policy

Under this policy, the combined carbon emissions of the supplier and retailer are regulated to not exceed a predefined upper limit, denoted as UC. If their carbon emissions fall below this limit, resulting in a surplus, they can sell this excess capacity at a rate of EX per unit, which helps to mitigate some of their operational costs. Conversely, if emissions exceed the limit UC, firms must either purchase additional allowances from the market or invest in green technologies to meet the mandated emissions cap. This policy is based on the premise that any surplus or deficit in carbon allowances is only relevant within the current period and cannot be carried over. The carbon trading price, EX, reflects the market's average rate, and it is assumed that there is ample availability of the allowances in the market for firms looking to purchase them. In this scenario, the total cost for the supply chain includes various components. These costs include the supplier's expenses, the retailer's costs for order processing, transportation expenses, inventory holding costs for both parties, payments related to carbon trading, and the financial investment in green technologies. The total integrated cost in a cap-and-trade environment is determined by various cost elements, such as operational expenses, the effects of carbon emissions trading, and investments in green technology. This cost structure encourages firms to strategically reduce their carbon footprint and effectively manage their financial resources under this policy. Therefore, the total cost is as follows:

$$\begin{aligned}TC_2(n,Q,IV) = {} & \frac{1}{2}\left((Q+2Q_m)H_R+(1+n)QH_S+\frac{2D_R(nA_R+A_S+nF_SK_S)}{nQ}-\frac{nQD_RH_S}{P_S}\right)+IV+EX\left(D_RE_P+\frac{D_R}{nQ}(E_S+\right.\\ & \left. nK_SE_T)+\left(\frac{Q}{2}+Q_m\right)E_H+\frac{Q}{2}\left(1+n\left(\frac{P_S-D_R}{P_S}\right)\right)E_H+(\theta_0-\theta_1IV+\theta_2(IV)^2)-UX\right).\end{aligned} \tag{10}$$

Lemma 3: *In the cap-and-trade scenario, the cost function $TC_2(n,Q,IV)$ is convex with a minimum point. The optimal transportation lot size, the optimal number of shipments, and the optimal investment in green technology can be determined as follows:*

$$Q_2^*(n_2^*)=\sqrt{\frac{2D_R(n_2^*A_R+A_S+E_SEX+n_1^*(E_TEX+F_S)K_S)P_S}{\begin{array}{c}((2+n_2^*)E_HEX+H_R+(1+n_1^*)H_S)P_S)\\ -n_2^*(n_2^*D_R(E_HEX+H_S)\end{array}}}, \tag{11}$$

$$n_2^*(n_2^*-1)\le\frac{(A_S+E_SEX)(2E_HEX+H_R+H_S)P_S}{(E_HEX+H_S)(A_R+(E_TEX+F_S)K_S)(P_S-D_R)}\le n_2^*(n_2^*+1), and \tag{12}$$

$$IV_2^*=\frac{\theta_1EX-1}{2\theta_2EX}. \tag{13}$$

Proof of Lemma 3:

The cost function is continuous, differentiable, and convex. Its first-order derivatives lead to the optimal solutions for n, Q, and IV. Accordingly, the proof can apply the Hessian matrix to establish convexity and demonstrates that the cost function has a minimal value. The Hessian matrix of $TC_2(n,Q,IV)$ and its determinant value can be given as follows:

$$H=\begin{bmatrix}\frac{2D_R(A_S+E_SEX)}{n^3Q} & \frac{1}{2}\left(E_HEX+H_S+D_R\left(\frac{2(A_S+E_SEX)}{n^2Q^2}-\frac{E_HEX+H_S}{P_S}\right)\right) & 0\\ \frac{1}{2}\left(E_HEX+H_S+D_R\left(\frac{2(A_S+E_SEX)}{n^2Q^2}-\frac{E_HEX+H_S}{P_S}\right)\right) & \frac{2D_R\left(\begin{array}{c}nA_R+A_S+E_SEX\\+n(E_TEX+F_S)K_S\end{array}\right)}{nQ^3} & 0\\ 0 & 0 & 2\theta_2EX\end{bmatrix}.$$

Since all the parameter values are positive, the determinant value of $|H|$ is also positive. Moreover, the diagonal elements of the matrix H ($\frac{\partial^2TC_2(n,Q,G)}{\partial n^2}$, $\frac{\partial^2TC_2(n,Q,G)}{\partial Q^2}$, and $\frac{\partial^2TC_2(n,Q,G)}{\partial G^2}$) are positive, indicating that the cost function is convex and has a minimal value. In order to obtain the optimal solution for n, Q, and IV, the first-order derivatives with respect to n, Q, and IV can be set to zero and solved simultaneously.

We further examine how the effectiveness of carbon emissions reduction and the average carbon trading price influence overall inventory costs and carbon emission levels. This analysis assesses the impact of investments in green technology aimed at reducing carbon emissions. Proposition 2 aims to quantify and clarify the effects of these investments within the supply chain, particularly within a carbon trading framework.

***Proposition 2**: In the cap-and-trade scenario, investing in green technology can significantly lower both total costs and carbon emissions. The reduction in total cost is quantified as* $\frac{(\theta_1 EX-1)^2}{4\theta_2 EX}$*, and the decrease in carbon emissions is calculated as* $\frac{(\theta_1)^2(EX)^2-1}{\theta_2(2EX)^2}$.

***Proof of Proposition 2**:*

The proof involves comparing the total costs and emissions before and after the investment in green technology. By incorporating the optimal lot size of transportation and number of shipments into the cost calculations, it's observed that the carbon emissions decrease from $CE(n_2^*, Q_2^*, 0)$ *to* $CE(n_2^*, Q_2^*, IV_2^*)$ *by* $\frac{(\theta_1)^2(EX)^2-1}{\theta_2(2EX)^2}$*. Similarly, the total cost reduces from* $TC_2(n_2^*, Q_2^*, 0)$ *to* $TC_2(n_2^*, Q_2^*, IV_2^*)$ *by* $\frac{(\theta_1 EX-1)^2}{4\theta_2 EX}$*, which is a positive value.*

Proposition 2 indicates that in this scenario, where firms can trade carbon allowances and increase green investment to reduce emissions is not only environmentally beneficial but also economically advantageous, as it can lead to significant cost savings and emissions reductions.

3.5 Limited carbon emissions policy

In a scenario where carbon emissions are subject to a strict cap, both suppliers and retailers are required to adjust their strategies to meet the set carbon emissions limit (UC). If their activities result in carbon emissions exceeding this limit, they have the option to increase green investment as a measure to reduce their carbon footprint. In this scenario, the total cost comprises several elements: the supplier's production costs, the retailer's costs for processing orders, expenses related to product transportation, inventory holding costs for both entities, and the investments in green technologies. The total carbon emissions are determined by aggregating the emissions generated from production processes, product transportation, and inventory management activities of both sites. From this total, the reduction in emissions achieved through investments in green technology is subtracted. The goal is to align the final total carbon emissions with the upper limit, UC, in order to maximize the effectiveness of the green technology investment. This leads to the following programming model for minimizing total costs within the constraints of limited carbon emissions, and it can be represented as follows:

$$min\, TC_3(n,Q,IV) = \frac{1}{2}\left((Q+2Q_m)H_R + (1+n)QH_S + \frac{2D_R(nA_R + A_S + nF_SK_S)}{nQ} - \frac{nQD_RH_S}{P_S}\right) + IV \tag{14}$$

$subject\ to:$

$$D_RE_P + \frac{D_R}{nQ}(E_S + nK_SE_T) + \left(\frac{Q}{2} + Q_m\right)E_H + \frac{Q}{2}\left(1 + n\left(\frac{P_S - D_R}{P_S}\right)\right)E_H + (\theta_0 - \theta_1 IV + \theta_2(IV)^2) = UC \tag{15}$$

To determine the minimum total cost and identify the optimal values for transportation lot size, number of shipments, and green investment, the Lagrange multiplier method is applied. This method enables the identification of decision variables that minimize costs while satisfying specific constraints. Accordingly, the programming model has been reformulated to incorporate the Lagrange multiplier, a method that helps optimize the model under specified constraints. The programming model can be presented as follows:

$$\begin{aligned} &min\, TC_3(n,Q,IV,\lambda) \\ &\quad = \frac{1}{2}\left((Q+2Q_m)H_R + (1+n)QH_S + \frac{2D_R(nA_R + A_S + nF_SK_S)}{nQ} - \frac{nQD_RH_S}{P_S}\right) + IV \\ &\quad + \lambda\Bigg(D_RE_P + \frac{D_R}{nQ}(E_S + nK_SE_T) + \left(\frac{Q}{2} + Q_m\right)E_H + \frac{Q}{2}\left(1 + n\left(\frac{P_S - D_R}{P_S}\right)\right)E_H \\ &\quad + (\theta_0 - \theta_1 IV + \theta_2(IV)^2) - UC\Bigg) \end{aligned} \tag{16}$$

***Lemma 4**: Under a limited carbon emissions policy, the cost function $TC_3(n,Q,IV,\lambda)$ is convex. The optimal lot size, number of shipments, and green investments are determined as follows:*

$$Q_3^*(n_3^*,\lambda)=\sqrt{\frac{2P_SD_R(n_3^*A_R+A_S+\lambda E_S+n_3^*(\lambda E_T+F_S)K_S)}{n_3^*\begin{pmatrix}((2+n_3^*)\lambda E_H+H_R+(1+n_3^*)H_S)P_S\\-n_3^*D_R(\lambda E_H+H_S)\end{pmatrix}}}. \tag{17}$$

The number n_3^* is a positive integer that satisfies following inequality

$$n_3^*(n_3^*-1)\le\frac{P_S(A_S+\lambda E_S)(H_R+H_S+2\lambda E_H)}{(H_S+\lambda E_H)\big(A_R+K_S(F_S+\lambda E_T)\big)(P_S-D_R)}\le n_3^*(n_3^*+1). \tag{18}$$

The optimal investment of green technology is given by

$$IV_3^*(n_3^*,Q_3^*)=\frac{\theta_1+\sqrt{\theta_1^2+2\theta_2\left(2UC-\frac{2D_R(n_3^*Q_3^*E_P+E_S+n_3^*E_TK_S)}{nQ_3^*}+E_H\left(\frac{n_3^*Q_3^*D_R}{P_S}-\left((2+n_3^*)Q_3^*\right)-2Q_m\right)-2\theta_0\right)}}{2\theta_2}. \tag{19}$$

***Proof of Lemma 4**:*

To order to prove Lemma 4, we initially assume that the number of shipments, n, is a continuous variable. The first-order derivatives of the total cost function $TC_3(n,Q,IV,\lambda)$ with respect to n, Q, IV, and λ have been calculated. By setting these derivatives to zero, we can find the optimal values for the number of shipments, transportation lot size, and green investment amount, which are represented by complex mathematical expressions ($\frac{\partial TC_3(n,Q,IV,\lambda)}{\partial n}=\frac{\partial TC_3(n,Q,IV,\lambda)}{\partial Q}=\frac{\partial TC_3(n,Q,IV,\lambda)}{\partial IV}=\frac{\partial TC_3(n,Q,IV,\lambda))}{\partial\lambda}=0$). However, because of the intricate nature of these equations, it is challenging to obtain closed-form solutions for the optimal values. Nonetheless, it is established that the optimal green investment must be non-negative ($IV_3^*(n_3^*,Q_3^*)\ge 0$), and the number of shipments must be an integer. Given these constraints, numerical methods are recommended to determine the exact optimal number of shipments that minimizes the total cost for the given scenario. This approach enables a practical solution for determining the most cost-effective and environmentally compliant operational parameters within the constraints of limited carbon emissions.

4. Numerical application and sensitive analysis

4.1 Numerical examples and the impacts of different carbon emissions policies

This case study aims to analyze the impact of different carbon emission policies on the total inventory costs in a supply chain, focusing specifically on the medical industry. Furthermore, it examines the feasibility of investing in green technology within this framework. The narrative revolves around a medical instrument supplier collaborating with a local retailer to produce and distribute a specific medical product, forecasting a demand of 27,000 units in the supply chain. The supplier boasts a production capacity of 30,000 units per year, with the cost for setting up each production cycle set at $1,250. Furthermore, the supplier incurs a holding cost of $50 for every unit in inventory. The logistics narrative describes the transportation of goods over a distance of approximately 100 kilometers from the supplier to the retailer, incurring a cost of $10 per kilometer. This setup offers a foundation to evaluate the strategic and financial consequences of implementing environmentally-friendly practices in light of regulatory carbon emission standards. The retailer faces an order processing cost of $120 for each order and an inventory holding cost of $70 per unit. From an environmental perspective, the carbon emissions generated are significant. The supplier's production setup emits 10 units of carbon, with each produced unit contributing an additional 3 units of carbon emissions. Furthermore, transporting these units generates 5 units of carbon emissions per kilometer. Additionally, each unit stored for a year contributes 4 units of carbon emissions. The study also examines the effectiveness of green technology in reducing these emissions. In this case, the carbon reduction efficiency factor is set at 35, with an offsetting carbon reduction factor of 0.005. This indicates that while green technology is beneficial in reducing emissions, it also has a slight adverse effect by generating additional emissions. All of these operational and environmental details are meticulously documented in Table 1, providing a comprehensive framework for the analysis. This example sets the foundation for evaluating the impacts of different policies on the overall cost structure of the supply chain in the medical instruments sector. Moreover, it explores the feasibility of green technology as a sustainable option. Finally, the study aims to provide insights to achieve a balance between cost efficiency and environmental responsibility in supply chain management.

Table 1
Model Parameter Settings

Parameter	Value	Parameter	Value
D_R	27,000	E_H	4
P_S	30,000	E_T	5
Q_m	20	E_P	3
A_S	\$1,250	E_S	10
A_R	\$120	$\theta_0, \theta_1, \theta_2$	1600, 35, 0.005
H_S	\$50	TX	\$1.9
H_R	\$70	EX	\$1.4
F_S	\$10	UX	8,000
K_S	100km	UC	12,000

Based on the details in Section 3, the computed findings are displayed in Table 2. These findings suggest that the cap-and-trade policy produces the most advantageous outcomes for the supply chain. The projected overall cost under this policy amounts to $176,860, with the most efficient order quantity for the retailer estimated at 865 units. Moreover, the frequency of shipments within the supplier's production cycle is determined to be 4. It has also been established that the supply chain should allocate approximately $3,614 to invest in environmentally friendly technology to reduce carbon emissions.

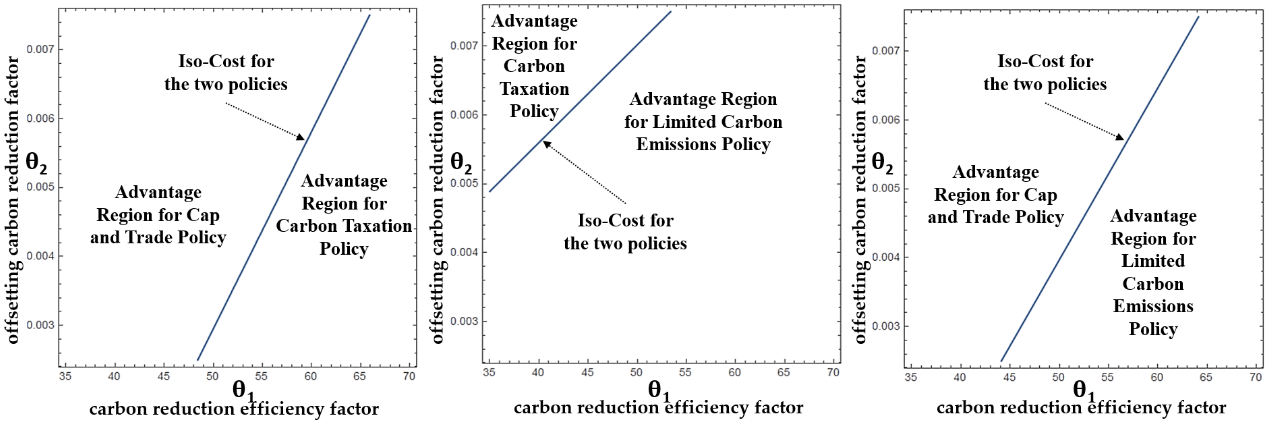
Table 2
Computation Results of Different Carbon Emission Policies

Carbon-taxation Policy	Cap-and-trade Policy	Limited Carbon Emissions Policy
n*≈3.7934→4, Q*=909, IV*=\$3,442, TC1=\$215,752	n*≈4.0483→4, Q*=865, IV*=\$3,428, TC2=\$176,860	n*≈3.7151→4, Q*=913, IV*=\$3,614, TC3=\$221,973

Supply chains operating in different regions are subject to varying carbon emissions policies, requiring a thorough analysis of how these regulations impact their cost structures. One important factor to consider is the potential for investments in green technology to decrease overall costs by reducing carbon emissions. This study explores the feasibility of such investments within three different regulatory frameworks: carbon-taxation, cap-and-trade, and limited carbon emissions. The analysis focuses on the different levels of the carbon emissions reduction factor (θ_1) and the offsetting factor (θ_2). The study presents propositions and visual aids to assist decision-makers in evaluating the effectiveness of different carbon emissions policies. Utilizing data from Table 2, Fig. 2 visually represents the iso-cost line that marks the zones where certain decisions are more favorable, linking the carbon emissions reduction factor (θ_1) with the offsetting factor (θ_2). In the left plot, two separate zones are highlighted, indicating the advantageous areas for both the Cap-and-trade Policy and the Carbon-taxation Policy. An iso-cost line demarcates the equilibrium point of costs between these policies, with the Cap-and-trade Policy being more advantageous to the left of this line, and the Carbon-taxation Policy to the right. This suggests that a higher θ_1 factor encourages the supply chain to boost green technology investments, thus reducing carbon tax payments and effectively balancing the increased investment costs.

The central plot contrasts the Limited Carbon Emissions Policy with the Carbon-taxation Policy. Given the strict emission limits of the Limited Carbon Emissions Policy, the supply chain cannot engage in carbon trading to mitigate emission-associated costs. Consequently, the main solution to avoid exceeding emission limits is to increase investment in green technologies. As the θ_1 factor becomes more effective, increasing investments in green initiatives becomes increasingly beneficial for the supply chain. The following plot compares the Limited Carbon Emissions Policy with the Cap-and-trade Policy. In this area, the majority supports the Cap-and-trade Policy. While carbon trading is an option for reducing costs, its impact is somewhat limited. Comparing this plot with the central one reveals that the region where the Limited Carbon Emissions Policy is advantageous is relatively smaller, indicating a lesser impact of the θ_1 factor. In essence, the θ_1 factor must exceed a certain threshold for the supply chain to be incentivized to increase green investments under the Limited Carbon Emissions Policy. The study provides a nuanced perspective on how different carbon emissions policies influence supply chain decisions related to investments in green technology, emphasizing the significance of strategic adaptation to policy environments.

Furthermore, members of the supply chain are closely focused on understanding the intricate relationship between carbon taxes and the cost of carbon credits under different carbon emissions policies. A crucial aspect of this analysis is depicted in Fig. 3, which illustrates the iso-cost lines. These lines effectively delineate areas where specific decision-making strategies become more advantageous, depending on the interaction between the carbon tax and the cost of carbon credits. In the left section of the figure, the dynamics under the Cap-and-trade Policy are highlighted. The study demonstrates that this policy is more favorable for supply chain entities when the carbon tax is high, while the price of carbon credits is relatively lower. Under these circumstances, many companies would consider acquiring carbon credits from the international carbon trading market as a strategic move to avoid the burden of higher carbon taxes. The main plot of the figure provides a different perspective. This suggests that when the carbon tax exceeds a certain critical threshold, it becomes more advantageous for supply chain operations to adopt the Limited Carbon Emissions Policy. This shift is attributed to the stringent regulations on carbon emissions imposed by this policy, which incentivize companies to increase their investments in green technology. This approach is preferred over the alternatives of either paying the carbon tax or purchasing carbon credits. The right section of the figure depicts another scenario. Here, it is suggested that the Cap-and-trade Policy becomes beneficial for the supply chain when the price of carbon credits remains below a specific threshold. In this context, most companies are likely to purchase carbon credits to comply with government environmental regulations, as they consider it more cost-effective than paying the carbon tax. However, if the price of carbon credits rises significantly, these companies might be forced to either absorb the cost of domestic carbon taxes or increase their investment in green technology. This comprehensive analysis emphasizes the importance of adopting a strategic approach to navigate the landscape of carbon emissions policies. The statement highlights the significant impact of carbon taxes and carbon credits on the cost dynamics within supply chains. This influence affects decision-making processes and steers them toward various environmental compliance strategies. As a result, it emphasizes the importance of supply chain members staying informed and adaptable in response to fluctuating market conditions and policy changes.



Cost Advantage Regions for Different Policies in Terms of Factors θ_1 and θ_2.

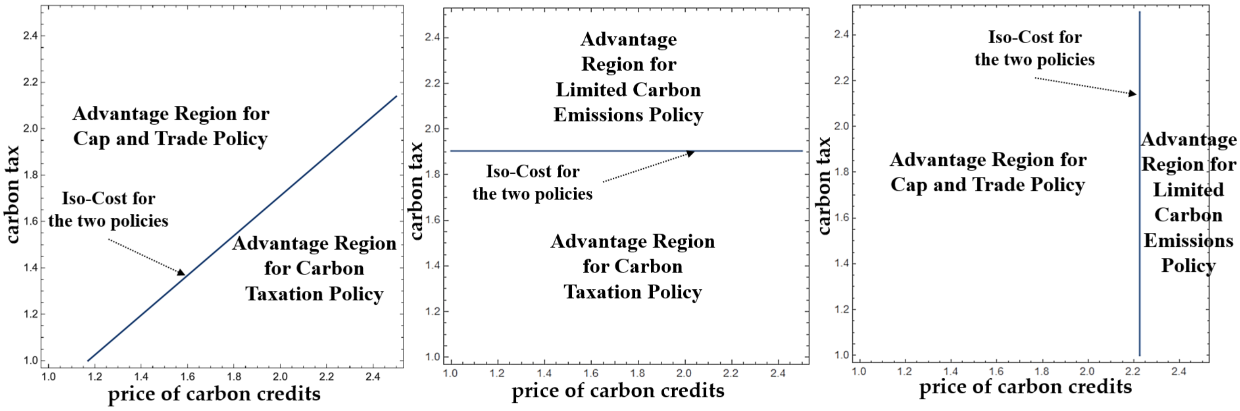


Fig. 2. Cost Advantage Regions for Different Policies in Terms of Carbon Tax and Price of Carbon Credits

In conclusion, this analysis illuminates the complex relationship between carbon emissions reduction strategies and inventory costs under different environmental policies. When the reduction factor for carbon emissions is significant, the inventory costs under the Limited Carbon Emissions Policy are lower compared to those under the Carbon Tax Policy or the Cap-and-Trade Policy. This finding emphasizes the potential financial benefits of investing in green technology. Larger investments aimed at reducing emissions can generate higher returns, strengthening the economic feasibility of eco-friendly practices. However, the situation changes when the carbon emissions offsetting factor is increased. In such cases, the inventory costs under the Cap-and-Trade and Limited Carbon Emissions Policies tend to converge. This convergence suggests that under these conditions, choosing the Cap-and-trade Policy could be more advantageous. In this situation, suppliers must conduct a thorough cost-benefit analysis to determine if the additional investment in green technology is economically justified. This is crucial because the financial benefits of reduced carbon emissions may not always outweigh the advantages of trading in carbon allowances, along with the costs of investing in green technologies. In situations where the effectiveness of reducing carbon emissions is relatively low and the offsetting factor is high, the Carbon Tax Policy may emerge as the more suitable choice. As the efficiency of carbon emissions reduction improves, the cost difference between the Carbon Tax and Cap-and-Trade Policies begins to narrow. The changing cost dynamic could potentially make the Carbon Tax Policy a more attractive option for organizations. This nuanced analysis emphasizes the importance of adapting environmental policies to specific circumstances and evaluating the effectiveness of strategies for reducing emissions. It also emphasizes the importance of businesses staying flexible and responsive to changing environmental and economic landscapes. This information is also helpful for governments when formulating related environmental policies.

To implement these policies successfully, it is important to determine which policy is most likely to motivate firms to increase green investment by aligning economic incentives with environmental objectives. Therefore, policy decisions should be crafted to maximize the attractiveness of green investments to businesses, thereby promoting both environmental sustainability and economic benefits.

4.2 Sensitivity Analysis

In this comprehensive study, a detailed sensitivity analysis is conducted to assess the impact of various parameters within the context of two environmental policy frameworks: the Limited Carbon Emissions Policy and the Cap-and-trade Policy. This analysis systematically categorizes a range of parameters to methodically evaluate their impact on two critical aspects: the total inventory cost and the cumulative carbon emissions. The main focus of this research is illustrated in Fig. 4, which graphically depicts the complex relationship between these parameters and the total inventory cost under both policies. This figure is particularly insightful as it reveals a clear positive correlation between various associated costs and the overall inventory cost. Notably, the study identifies several key factors that significantly influence the total inventory cost. Among these are the transportation costs per unit incurred by the supplier and the inventory holding costs borne by both the supplier and the retailer. A key finding of this analysis is the significant impact of transportation costs, which are greatly influenced by the geographical distance between the supplier and retailer. This aspect is particularly relevant in the context of the environmental policies in question, as it is directly linked to carbon emissions. The transportation phase is a critical component of the logistical process and inherently contributes to carbon emissions, connecting logistical efficiency with environmental impact. This comprehensive analysis provides crucial insights into the dynamics of inventory management costs and environmental implications under different policy scenarios. It emphasizes the importance of strategic planning and policy compliance in supply chain operations. The study also notes that suppliers may want to consider extending their production cycle time, especially when dealing with high production setup costs in comparison to relatively low inventory holding costs. This strategy is feasible as long as it does not interfere with the retailer's warehouse capabilities and safety stock levels. However, as Fig. 4 suggests, the rate at which the supplier's holding costs increase outpaces the rate of production setup costs. This implies that extending the production cycle may lead to higher holding costs, which could be economically disadvantageous for the supplier. This dynamic is further elaborated with detailed data presented in Table 3. Fig. 5 and Table 4 presents an analysis of the influence of different parameters on carbon emissions in the supply chain. This confirms a positive relationship between the parameters (K_S, P_S, Q_m, E_H, E_T, and E_S) and increased carbon emissions. Specifically, the parameters K_S (transportation distance) and E_T (carbon emissions for each delivery) have a substantial impact on the overall increase in carbon emissions. This reflects that the increased carbon emissions mainly originated from logistical issues in the supplier chain. Therefore, if the supplier can utilize new energy vehicles for delivery work under the government's subsidy and incentives, carbon emissions can be effectively reduced. Furthermore, the production rate, P_S, is particularly critical as it can result in significant fluctuations in the total inventory cost with any changes in the number of shipments. However, it does not mean that the increase of P_S leads to carbon emissions. Besides, carbon emissions from storing products are also significant in this case. It implies that it is worthy to improve the strategy of holding products since it is beneficial to reduce carbon emissions. When it comes to investing in green technologies, we can observe that the impact of the carbon emissions reduction factor (θ_1) on reducing carbon emissions is highly effective. The reduction in carbon emissions due to the influence of the parameter θ_1 almost balanced out the increase in carbon emissions from other parameters. In summary, lower transportation costs have made frequent deliveries an attractive option for minimizing inventory holding costs. However, this approach may no longer be feasible due to the heightened emphasis on carbon emissions produced during transportation. Additionally, with a wider variety of transportation methods and vehicles now available, companies need to be more discerning about their transport choices, considering the associated carbon emissions. The modern supply chain must balance costs with environmental impact by considering the emissions footprint of various logistics options.

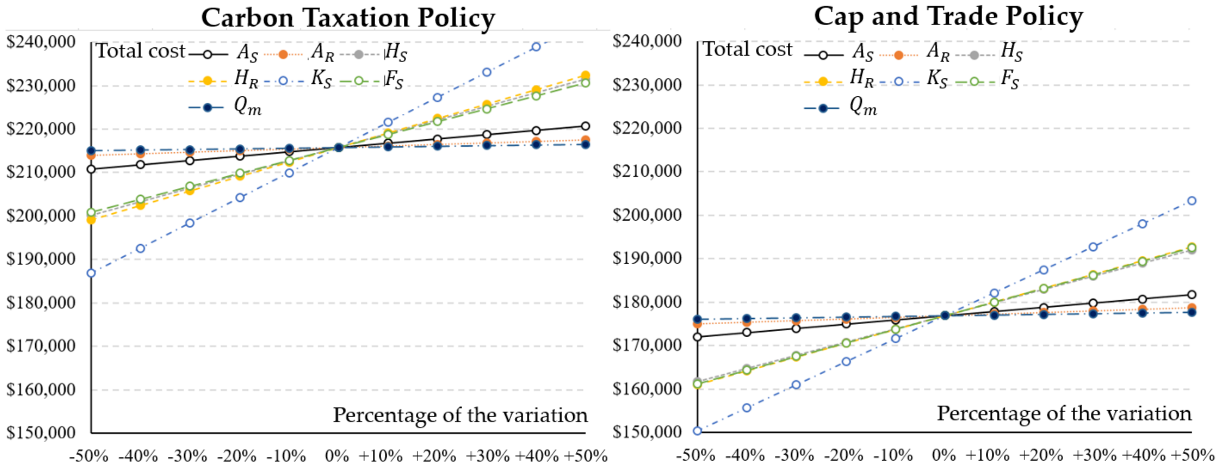


Fig. 3. The Relationship between Related Cost Parameters and Total Inventory Cost

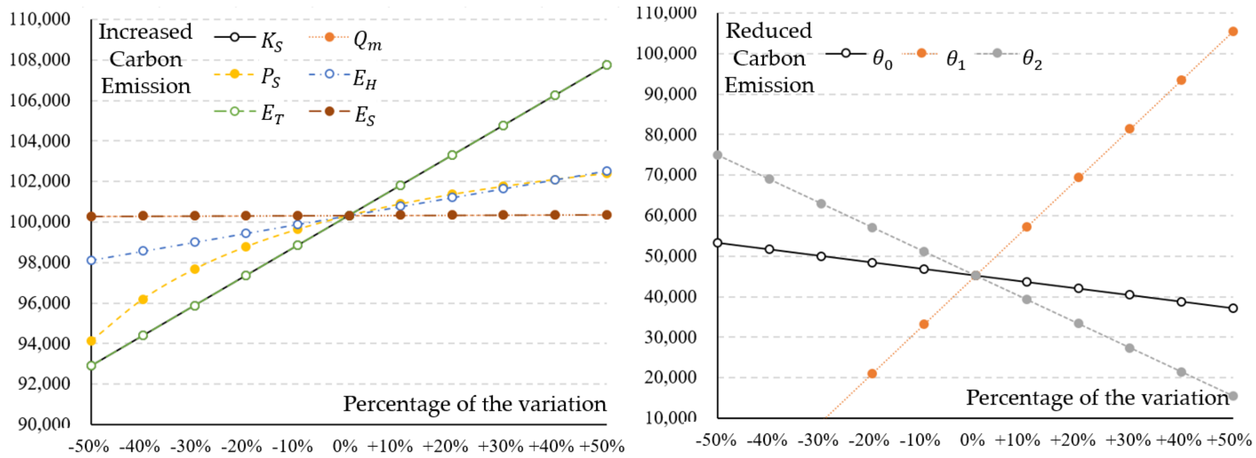


Fig. 4. The Effects of Related Parameters on Carbon Emissions

Table 3

The Impact of Related Cost Parameters on Total Inventory Cost

	Carbon-taxation Policy							Cap-and-trade Policy						
Variation	A_S	A_R	H_S	H_R	K_S	F_S	Q_m	A_S	A_R	H_S	H_R	K_S	F_S	Q_m
-50%	\$210,859	\$213,970	\$200,074	\$199,139	\$186,800	\$200,904	\$214,976	\$172,044	\$174,989	\$161,662	\$161,014	\$150,344	\$161,262	\$176,104
-40%	\$211,838	\$214,326	\$203,210	\$202,462	\$192,590	\$203,874	\$215,131	\$173,007	\$175,363	\$164,702	\$164,183	\$155,647	\$164,382	\$176,256
-30%	\$212,816	\$214,683	\$206,345	\$205,784	\$198,380	\$206,843	\$215,286	\$173,971	\$175,737	\$167,741	\$167,353	\$160,950	\$167,502	\$176,407
-20%	\$213,795	\$215,039	\$209,481	\$209,107	\$204,171	\$209,813	\$215,441	\$174,934	\$176,112	\$170,781	\$170,522	\$166,254	\$170,621	\$176,558
-10%	\$214,773	\$215,395	\$212,616	\$212,429	\$209,961	\$212,782	\$215,596	\$175,897	\$176,486	\$173,821	\$173,691	\$171,557	\$173,741	\$176,709
0%	\$215,752	\$215,752	\$215,752	\$215,752	\$215,752	\$215,752	\$215,752	\$176,860	\$176,860	\$176,860	\$176,860	\$176,860	\$176,860	\$176,860
+10%	\$216,730	\$216,108	\$218,887	\$219,074	\$221,542	\$218,721	\$215,907	\$177,824	\$177,235	\$179,900	\$180,030	\$182,164	\$179,980	\$177,012
+20%	\$217,709	\$216,464	\$222,022	\$222,396	\$227,332	\$221,690	\$216,062	\$178,787	\$177,609	\$182,940	\$183,199	\$187,467	\$183,100	\$177,163
+30%	\$218,687	\$216,821	\$225,158	\$225,719	\$233,123	\$224,660	\$216,217	\$179,750	\$177,983	\$185,979	\$186,368	\$192,770	\$186,219	\$177,314
+40%	\$219,665	\$217,177	\$228,293	\$229,041	\$238,913	\$227,629	\$216,372	\$180,713	\$178,358	\$189,019	\$189,537	\$198,074	\$189,339	\$177,465
+50%	\$220,644	\$217,533	\$231,429	\$232,364	\$244,703	\$230,599	\$216,528	\$181,677	\$178,732	\$192,059	\$192,707	\$203,377	\$192,458	\$177,616

Table 4

The Impact of Related Parameters on Carbon Emissions

	Carbon-taxation Policy						Cap-and-trade Policy					
Variation	K_S	Q_m	P_S	E_H	E_T	E_S	K_S	Q_m	P_S	E_H	E_T	E_S
-50%	92,909	100,292	94,124	98,129	92,909	100,293	93,119	100,878	94,611	98,796	93,119	100,879
-40%	94,393	100,300	96,193	98,569	94,393	100,301	94,679	100,886	96,713	99,221	94,679	100,887
-30%	95,878	100,308	97,671	99,010	95,878	100,309	96,238	100,894	98,215	99,645	96,238	100,895
-20%	97,363	100,316	98,780	99,451	97,363	100,317	97,798	100,902	99,341	100,069	97,798	100,902
-10%	98,848	100,324	99,642	99,892	98,848	100,324	99,358	100,910	100,217	100,493	99,358	100,910
0%	100,332	100,332	100,332	100,332	100,332	100,332	100,918	100,918	100,918	100,918	100,918	100,918
+10%	101,817	100,340	100,897	100,773	101,817	100,340	102,478	100,926	101,491	101,342	102,478	100,925
+20%	103,302	100,348	101,367	101,214	103,302	100,348	104,037	100,934	101,969	101,766	104,037	100,933
+30%	104,786	100,356	101,765	101,654	104,786	100,356	105,597	100,942	102,373	102,191	105,597	100,941
+40%	106,271	100,364	102,106	102,095	106,271	100,364	107,157	100,950	102,720	102,615	107,157	100,949
+50%	107,756	100,372	102,402	102,536	107,756	100,371	108,717	100,958	103,020	103,039	108,717	100,956

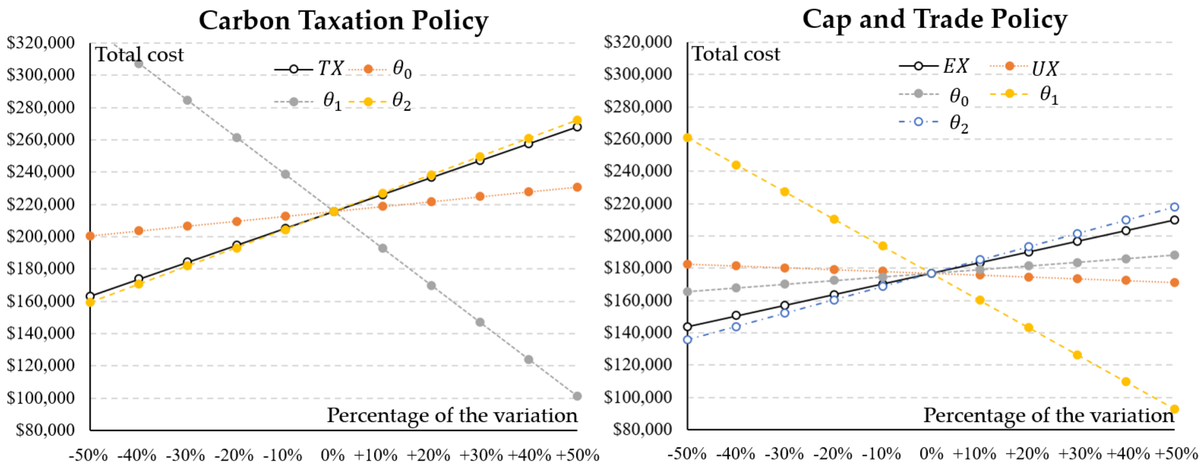


Fig. 5. The Impact of Parameters $\boldsymbol{TX}$, $\boldsymbol{EX}$, $\boldsymbol{UX}$, $\boldsymbol{\theta_0}$, $\boldsymbol{\theta_1}$, and $\boldsymbol{\theta_2}$ on Total Inventory Cost.

Fig. 5 illustrates that both the carbon emissions reduction factor (θ_1) and the carbon emissions quota (UX) are inversely related to the overall inventory cost. In contrast, the offsetting carbon emissions reduction factor (θ_2) exhibits a direct relationship with the total inventory cost. Table 5 presents the computation results in detail. The impact of carbon emissions quota on the total inventory cost needs to be noted. This effect can be attributed to the substantial variation in the number of shipments and the scale of investments in green technology, which leads to considerable fluctuations in the total inventory cost. When the carbon emissions limit is lower, managers are compelled to invest more in green technologies to meet regulatory standards, which leads to higher total inventory costs. As the emissions limit increases incrementally, there is a corresponding decrease in the total inventory cost. Besides, it is intuitive that the carbon tax (TX) and the carbon trading price (EX) are positively correlated to the total inventory cost. The fluctuation of the carbon tax and carbon trading prices is influenced by government regulations and international carbon trading markets. Nevertheless, companies in the supply chain still need to remain attentive and responsive to these external changes.

Table 5
The Impact of Parameters TX, EX, UX, θ_0, θ_1, and θ_2 on Total Inventory Cost

	Carbon-taxation Policy				**Cap-and-trade Policy**				
Variation	TX	θ_0	θ_1	θ_2	EX	UX	θ_0	θ_1	θ_2
-50%	\$163,410	\$200,552	\$330,377	\$159,301	\$143,475	\$182,460	\$165,660	\$260,860	\$135,718
-40%	\$173,878	\$203,592	\$307,452	\$170,591	\$150,152	\$181,340	\$167,900	\$244,060	\$143,946
-30%	\$184,347	\$206,632	\$284,527	\$181,881	\$156,829	\$180,220	\$170,140	\$227,260	\$152,175
-20%	\$194,815	\$209,672	\$261,602	\$193,171	\$163,506	\$179,100	\$172,380	\$210,460	\$160,403
-10%	\$205,283	\$212,712	\$238,677	\$204,461	\$170,183	\$177,980	\$174,620	\$193,660	\$168,632
0%	\$215,752	\$215,752	\$215,752	\$215,752	\$176,860	\$176,860	\$176,860	\$176,860	\$176,860
+10%	\$226,220	\$218,792	\$192,827	\$227,042	\$183,537	\$175,740	\$179,100	\$160,060	\$185,089
+20%	\$236,688	\$221,832	\$169,902	\$238,332	\$190,214	\$174,620	\$181,340	\$143,260	\$193,318
+30%	\$247,156	\$224,872	\$146,977	\$249,622	\$196,892	\$173,500	\$183,580	\$126,460	\$201,546
+40%	\$257,625	\$227,912	\$124,052	\$260,912	\$203,569	\$172,380	\$185,820	\$109,660	\$209,775
+50%	\$268,093	\$230,952	\$101,127	\$272,202	\$210,246	\$171,260	\$188,060	\$92,860	\$218,003

5. Conclusion

This research explores the feasibility of integrating green technology investments into a comprehensive strategy that balances environmental and economic benefits. It aims to provide valuable insights for supply chains, enabling them to optimize operations in a manner that benefits all aspects of the supply chain. Furthermore, the findings of this study are essential for offering direction to governments, assisting them develop effective policies that protect the environment while considering the impacts on industry. Amidst growing environmental awareness, an increasing number of developing countries are implementing environmental regulations. These regulations often include environmental taxes as penalties or subsidies as incentives to encourage companies to reduce carbon emissions. As a result, companies are now obligated to align their strategies with these government regulations and incentives in order to optimize their interests. This study examines the feasibility of green technology investment to establish an integrated approach that harmonizes environmental and economic benefits. It provides essential managerial insights for optimizing the supply chain and also offers significant guidance for governments in developing effective environmental policies.

The principal conclusions of this study suggest that businesses generally prefer either a carbon tax or a limited carbon emissions policy, particularly when the effectiveness of green technology implementation is substantial. A critical aspect to consider is that a company's production and transportation operations are major contributors to its overall carbon emissions. As a result, businesses should focus on acquiring more efficient facilities or adopting new energy-efficient vehicles to reduce these emissions before focusing on optimizing inventory management. Furthermore, within the cap-and-trade policy framework, the predetermined cap limit has a greater impact on a company's operations than the potential emissions reduction achievable through green technology. This underscores the importance of companies adhering to governmental regulations.

Besides, the government also plays a crucial role in establishing appropriate carbon emissions caps under the cap-and-trade policy, and in ensuring that suppliers do not engage in excessive trading of their carbon emission allowances. Looking ahead, future research could extend to developing an integrated inventory model that encompasses multiple retailers, more accurately reflecting real-life situations where suppliers serve a variety of retail entities. Additionally, since firms often focus primarily on their own benefits, there is a tendency to only meet the minimum requirements of environmental regulations rather than fully committing to environmental stewardship. This highlights the importance of governments to devise regulations that are not only effective but also attractive, using incentives or subsidies, to encourage companies to take a more proactive approach to environmental protection.

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