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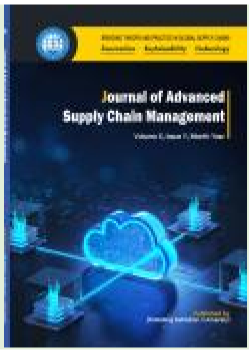

Article

Manufacturer's Strategy for Investing in Low-carbon Technology and Blockchain:Investment Subsidy vs. Output Subsidy

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Abstract: This paper analyses the impact of government subsidy policies on manufacturers' investment strategies in blockchain and low-carbon technologies under carbon tax regulations. A game model of a two-stage supply chain with a manufacturer and retailer is utilized to examine different effects of technology and output subsidy policies. Findings: With low technology subsidy ratio, a low (high) low-carbon technology investment cost factor causes better (smaller) emission reduction than output subsidy policy, while high technology subsidies result in greater emission reduction. Furthermore, technology subsidy policy with a low investment cost factor enhances blockchain adoption, demand, and profits for manufacturers and retailers. Finally, the blockchain adoption, emission reduction, demand, and profits for manufacturers and retailers are all decreasing in blockchain and low-carbon technologies investment cost factors.

Keywords: Low-carbon technology; Blockchain technology; Low-carbon subsidies; Carbon tax; Stackelberg game.

1. Introduction

The escalating severity of global climate change, coupled with the establishment of “double carbon” goals in many countries, necessitates the development of the creation of a sound green and low-carbon economic system. Therefore, it is clear that investing in the development of low-carbon technology (LCT) to reduce emissions is not only necessary to address climate change but also crucial for promoting comprehensive green economic and social development. To encourage companies to invest in LCT, governmental subsidy mechanisms have been implemented. Specifically, there are two principal approaches for the government to subsidize companies' LCT investment (hereinafter referred to as the government subsidy policy (GSP)). One is the investment subsidy policy (hereinafter referred to as the TSP) based on the investment behavior of companies [1]. For example, Hangzhou City, China, provides a 30% subsidy for equipment investment during the construction period if firms and institutions build a carbon-neutral scientific and technological innovation service platform. The other is the output subsidy policy of low-carbon products (hereinafter referred to as the OSP) based on the output of firm investment [2]. For example, the final regulation of the 45Q clause in the United States provides a progressive price subsidy per ton of carbon dioxide for firms to use CCUS technology to capture and sequester carbon dioxide [3]. This regulation effectively stimulated high-carbon emission companies to actively reduce emissions and greatly encouraged companies to invest in CCUS projects [4]. Consequently, based on the above real-word observations, there exists an urgent need to examine the differences between these two subsidy policies.

Moreover, blockchain technology (BT) is extensively recognized for its considerable potentiality in supply chain management [5] and has been progressively applied across a spectrum of industries. For example, Beingmate, a Chinese listed milk powder company, records information such as source, production, and sales in the BT network to allow consumers to verify the authenticity of products. Chronicled Inc. implements BT into secure the pharmaceutical supply chain (SC) [6]. In brief, the BT can greatly facilitate the increased profitability of firms in the SC [7]. Further, the implementation of BT also has ability to promote the achievement of a low-carbon SC, which is conducive to overall performance [8]. The application of BT in SC can realize decentralized data storage and digitize the production process, which can dramatically improve the production efficiency of firms to reduce production costs [9,10]. For example, the Chinese e-commerce company JD utilizes logistics-based BT to reduce costs and enhance efficiency. Thus, BT’s characteristics of the improved production efficiency can also be regarded as an indirect way to the achievement of a low-carbon supply chain. Meanwhile, the cost reduction derived from BT’s improved production efficiency can also ameliorate the barriers in the establishment of a low-carbon supply chain. Therefore, from a low-carbon supply chain perspective, it is significant for firms to explore the collaborative impact of BT and LCT on low-carbon economic system transformation.

Further, in the light of the collaborative impact of BT and LCT on low-carbon economic system transformation, it is imperative to conduct an exploration of the impact of the government’s two principal subsidy policies on the investment incentives for BT and LCT.

Accordingly, the main research questions of this paper are as follows:

(1) Which GSP can better promote firms to invest in LCT?

(2) Which GSP can better promote firms to invest in BT?

(3) How will the investment cost factor (ICF) of BT and the LCT affect the optimal decision-making of firms?

From the perspective of improving LCT, this paper finds that when the TSP ratio is small, the LCT's ICF is smaller. Further, the TSP is better, and the LCT's ICF is larger; therefore, the OSP is better. When the TSP ratio is large, the government should implement TSP for manufacturers, which provides a direction for the government to choose appropriate policies. When the LCT's ICF is small, in comparison to the OSP, the BT level, demand, manufacturer profit, and retailer profit under the TSP are higher. In addition, the level of BT, carbon reduction per unit, and demand all decrease with increases in the BT's ICF and the LCT's ICF. Based on the aforementioned problems and findings, our principal contributions are delineated as follows. First, in view of the impact of different GSP on manufacturers' investment strategies in BT and LCT, this paper recommends that manufacturers invest in BT to solve trust issues with consumers. Further, the impact of the application of BT on manufacturers' production costs of low-carbon products is considered. Second, we also extend the literature on the comparison between two different types of GSPs, such as [11] who state TSP can increase the profitability only when the investment cost factor is moderate as well as [12] whose outcomes imply OSP is always better than TPS. Finally, the aforementioned findings offer a theoretical framework for the government to evaluate and ascertain which subsidy policy is more appropriate to facilitate and bolster the growth of low-carbon industries.

The remaining organization of our paper is outlined in the subsequent sections. Specifically, Section 2 comprehensively reviews the related literature including SGPs and investment in LCT and BT. In Section 3, we detailly describe the model. In Section 4, it shows the model equilibrium solution and analysis. Section 5 provides the numerical analysis and discussion. Finally, Section 6 emphasizes principal findings and practical implications of this paper and gives a view of future studies.

2. Literature review

2.1 GSPs and their impact on the SC

Previous literature covers various types of SCs that have applied GSPs for firms.

Yang and Nie [13] studied the impact of TSP on firms in an asymmetric duopoly market. They found that, when the initial marginal cost gap between the two firms is large, subsidies for large companies can more effectively stimulate technology investment. This study analyses the influence of TSP on the technology investment of firms; several other studies focus on issues of different GSPs influencing the investment decision of firms. For example, Nie et al. [14] studied the differences in the effects of fixed subsidies and OSPs on improving energy efficiency. They found that governments that care about the environment or consumers tend to favour output subsidies, while governments that care about producers tend to favour fixed subsidies. Zhang et al. [16] studied the impact of GSPs and SC collaborative innovation on emission reduction levels. They revealed that GSPs combined with cooperative contracts can achieve maximum economic benefits and carbon reduction. Some studies also focus on the influences of different

GSPs on investment decisions of firms in low-carbon closed-loop SC. Zhang and Yu [16] studied the effects of two recycling modes as well as two power structures on the operational decisions of firms in a low-carbon closed-loop SC when considering GSPs and recycling subsidies as well as ruling party. They found that, when the government provides GSPs and recycling subsidies to maximize social welfare, the ruling party can obtain higher profit. Duan et al. [12] studied the impact of three types of GSPs, including low-carbon subsidies and remanufacturing subsidies in production and consumer recycling subsidies in the recycling phase, on the operational decision of low carbon closed loop SC system. They concluded that increasing the intensity of subsidy is conducive to improving the efficiency rate of recycling, promoting carbon reduction and increasing retailers' profits. Furthermore, when subsidies exceed a certain threshold, continuing to increase subsidies will reduce manufacturer profit.

Wang et al. [17] studied how manufacturers' low-carbon production and GSPs impact on carbon emissions of new energy vehicles. They found that GSPs for manufacturers can ease the pressure on manufacturers to transition to low-carbon production. In addition, in the context of carbon regulatory policies, there are also some studies on the impact of the GSP on firms' investment decisions. For example, Li et al. [18] studied the impact of two types of GSPs on firms' green decision-making under the cap-and-trade regulation policy, namely, the fixed-based TSP and emission-reduction subsidy. They found that, under the same subsidy budget, the TSP can lead to higher profits and fewer emissions for manufacturers; however, the emission-reduction subsidy can lead to more profits for retailers. They found that higher carbon taxes or low consumer carbon awareness would make the positive role of government subsidies more obvious.

Although the previous studies revealed how different GSPs affect the low-carbon supply chain's profitability, LCT investment, and carbon emissions, there is still lack of comprehensive research on how these different GSPs affect the investment of BT. We enrich the existing literature by further exploring the impact of GSP on BT investments.

2.2 Investment in LCT

Accordingly, in terms of research on LCT investment, Xu et al. [19] studied the influence of cap-and-trade mechanism on LCT investment strategies. They found that cap-and-trade mechanism encourages manufacturers to invest in LCT only when initial emissions are low. Li et al. [20] studied whether cap-and-trade mechanism mechanism and carbon tax mechanism can promote carbon emission reduction in a closed-loop SC. They found that remanufacturing and LCT could promote carbon emission reduction when carbon trading price was within a certain range. Since the above studies have uncovered effects of carbon regulation policy on firms' LCT investment decisions, some other scholars start to concentrate on the influence of specific models under the cap-and-trade mechanism on firms' LCT investment decisions. For example, Chen et al. [21] studied the related issues in different quota allocation methods under the cap-and-trade mechanism and investigate how they affect LCT investment in the power sector, finding that the benchmark method always leads to higher LCT investment. There is also research on the value of multiple factors in firms' LCT investment decisions. For example, Shi et al. [22] studied whether the co-creation can improve the performance in a LCT innovation ecosystem. They found that when the cost of LCT innovation is less than the profit, the rise in the cost and carbon emission gap can promote LCT collaborative innovation. Ma et al. [23] studied the regulation on LCT decisions of SC members and found that in the case of cost sharing and government intervention, LCT investment always outperforms other scenarios.

Indeed, the abovementioned scholars pay significant attention to the investment of LCT, and however, they ignore a newly introduced approach, i.e., BT, which may indirectly promote LCT investments. We extend the literature via the consideration of the impact of the adoption of BT on LCT investments.

2.3 Investment in BT

This literature reviews the current research on the implementation of BT within a supply chain. Tan et al. [24] explored the strategic adoption of BT in B2C and O2O fresh produce supply chains and reveal that the implementation of BT is most effective when consumer awareness of traceability is high. Gong et al. [25] investigated the adoption of BT in competitive remanufacturing supply chains. Their findings suggest that OEMs should adopt BT when the consumers' valuation is high and the cost of BT adoption is not expensive. Ma et al. [26] studied how a supplier's adoption of BT affects a fresh produce supply chain's information sharing and demonstrate that the retailer will encourage the supplier's adoption once the cost of BT is not high enough. Zhou et al. [27] uncovered the impact of BT-based information traceability systems on supply chains under different power structures and showed that blockchain-based information traceability systems can significantly enhance the supply chain members' performance and these effects depend on the level of consumer goodwill toward it and competitiveness, and cost sharing proportion. Liu et al. [28] studied the competition between green and brown products in the era of BT and concluded that the adoption of BT does not always enhance the competitiveness of green products implying BT should be strategically utilized. Xu et al. [29] underscored the potentiality of BT to enhance green supply chains and highlight how BT can be leveraged to certify green technologies, thereby increasing the market demand for eco-friendly products. This paper finds that BT not only makes products greener but also promises more profits for manufacturers and platforms. Li et al. [30] studied the issue of LCT investment in sustainable SC in the context of BT and found that this technology can encourage LCT investment only if the incremental level of consumer green sensitivity is relatively high. Li et al. [11] studied the impact of GSPs and BT on LCT investment strategy during port operation. They found that, in comparison to TSP schemes, OSP schemes provide greater benefits to stakeholders, and the introduction of BT leads to increased traffic demand, increased social welfare, and increased profits for all stakeholders.

Although some scholars such as Liu et al. [28] and Xu et al. [29] have noticed the impact of BT on low-carbon supply chains, they now ignore the effects of GSPs on the investment of BT. Only several studies like Li et al. [11] focus on the impact of GSPs on BT on LCT investments and however, they still neglect the endogenous decisions of BT investments.

3. Model

3.1 Problem description

This paper constructs a two-echelon SC consisting of a manufacturer and a retailer, with the manufacturer investing in building a BT platform (See Figure 1). Manufacturers use the invested LCT to produce products and sell them at wholesale prices to retailers, who sell them at retail prices to consumers. According to the information disclosed by the BT platform, the government chooses to provide technical subsidies or production subsidies to manufacturers. Consumers make purchases by querying the information provided by the BT platform. The application of BT can refine manufacturers' production processes, optimize the production process, and improve production efficiency. Its point-to-point real-time recording information can reduce the cost of manual supervision in the production process and turn to real-time supervision through platform data, thereby reducing production costs. The specific assumptions of this paper are as follows:

(1) With the increasing attention of consumers to low-carbon environmental protection practices, there has been an obvious change in consumption preferences, and more consumers are willing to bear more low-carbon premiums [31]. Consequently, Walmart has begun using BT to trace information about food products, which has greatly increased food sales [32]. That is, it is assumed that demand is jointly determined by the sales price, emission reduction rate, consumer preference for low carbon, BT level, and consumer acceptance of BT [33]. Further, compared with brown products, consumers prefer to buying products with low carbon properties, and the consumer acceptance of blockchain is $0<\delta<1$ [34].

(2) Carbon emissions occur only at the production stage, and manufacturers achieve emission reduction by investing in LCT.

(3) The application of BT can reduce the production costs of firms.

(4) The market information structure between the manufacture and retailer is symmetrical, and manufacturers' output of products are the same as the demand, and the market can be completely cleared.

(5) The utility of government is social welfare, which consists of four parts: government financial expenditure, environmental improvement and producer and consumer surplus.

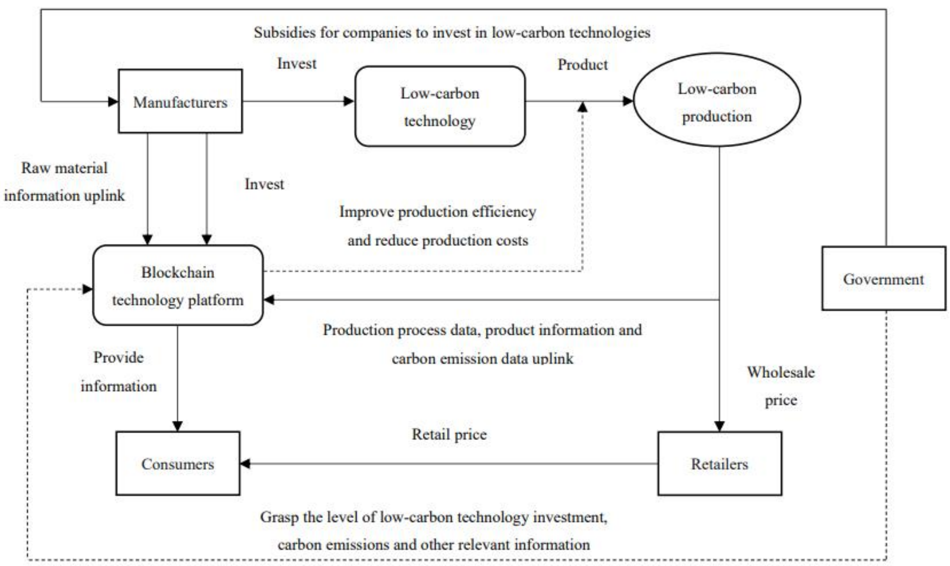

Figure 1. A low-carbon SC operation diagram based on BT

3.2 Symbols

The symbols used in this paper are shown in Table 1, alongside their meanings.

Table 1. Description of symbols used in this paper

Symbol	Description
a	Base demand
b	Consumers' low-carbon preference (LCP) coefficient ($0<b<1$)
k	LCT's investment cost factor (ICF)
θ	Coefficient of government subsidies to manufacturers for LCT investment ($0<\theta<1$)
e	Unit carbon emission
d	BT's investment cost factor (ICF)
μ	Amount of government subsidies to manufacturers for producing individual low-carbon products
z	Manufacturer's initial unit cost of production
f	Efficiency factor of BT to reduce production costs
δ	Consumer acceptance of blockchain ($0<\delta<1$)
t	Unit carbon tax
Decision variable	
w	Wholesale price
p	Retail price
q	Demand
η	BT level ($\eta\geq 0$)
e_0	Unit carbon reduction
Other symbols	
π_m,π_r,π_g	Profits for manufacturers and retailers, and social welfare

3.3 Model description

The demand of consumers with a LCP increases due to the increase in the LCP coefficient, carbon reduction per unit product, consumer acceptance of BT, and the level of BT. Therefore, the demand function is given by:

$$q=a-p+be_0+\delta\eta, \tag{1}$$

where a is the base demand, p is the retail price, b is the consumers' low-carbon preference (LCP) coefficient, e_0 is the unit carbon reduction, δ is the consumer acceptance of BT and η represents the BT level.

The LCT investment of firms is a one-time investment. With increases in the LCT investment, the unit emission reduction input becomes lower and lower, which conforms to the law of diminishing marginal effects. Therefore, the cost function of LCT investment for manufacturers is as follows: $C(e_0)=\frac{1}{2}ke_0^2$, where k is the LCT's ICF. This technology investment cost function has been widely used in previous studies [35].

Similarly, following Jiang and Liu [36] the cost function of BT investment for the manufacturers is as follows: $G(\eta)=\frac{1}{2}d\eta^2$, where d is the BT's ICF.

The cost function of production for the manufacturer is as follows: $z-\eta f$, where z is manufacturer's initial unit cost of production and ηf is the BT level with the cost efficiency factor $0<f<1$.

In addition to these assumptions, to ensure that there is a unique equilibrium solution and that the equilibrium solution is non-negative, it is assumed that $k>max\{k_1,k_2,k_3\}$, $d>\delta(f+\delta)$, $a>et+z$, $e>\frac{-2d(a+z)+(af+z\delta)(f+\delta)}{t(2d-\delta(f+\delta))}+\frac{\mu}{t}$, $z>\mu$, $f<\delta$, where $k_1=\frac{d(b+t)^2}{\left(4d-(f+\delta)^2\right)(1-\theta)}$, $k_2=\frac{d(b+t)(at+b(et+z))}{\left(a(2d-f(f+\delta))+(et+z)(2d-\delta(f+\delta))\right)(1-\theta)}$, and $k_3=\frac{d(b+t)(at+b(et+z-\mu))}{a(2d-f(f+\delta))+(2d-\delta(f+\delta))(et+z-\mu)}$.

4. Model equilibrium solution and analysis

This paper mainly explores the differences between two GSPs models: the TSP and the OSP. In detail, TSP can reduce the investment cost of LCT while OSP declines the carbon tax for manufacturers. The sequence of event is presented by: First, manufacturers will determine the wholesale price w of products, the level of BT η, and the unit carbon reduction e_0 to maximize its profits. Next, retailers will determine the retail price p of low-carbon products to maximize its profits. Finally, the symbols A^* and B^* represent the game equilibrium solution of the technical subsidy policy model and the output subsidy policy model, respectively.

4.1 Model equilibrium solution

4.1.1 TSP model

Under this model, the government implements technology subsidies for manufacturers' investment in LCT, with a technology subsidy ratio of θ. At this time, the profit functions of the manufacturer and retailer are

$$\pi_m^A=\left(w-z+\eta f-t(e-e_0)\right)q-\frac{1}{2}(1-\theta)ke_0^2-\frac{1}{2}d\eta^2, \tag{2}$$

$$\pi_r^A=(p-w)q, \tag{3}$$

Proposition 1: In the TSP model, the equilibrium wholesale price w^{A*}, BT level η^{A*}, a unit of carbon-emission reductions e_0^{A*}, retail price p^{A*}, demand q^{A*}, profit of manufacturer π_m^{A*}, and profit of retailer π_r^{A*} can be obtained using formulas (A3) - (A9), respectively.

4.1.2 OSP model

Under this model, the government implements an output subsidy for manufacturers' investment in LCT, and the unit subsidy amount of the product is μ. At this time, the profit functions of the manufacturer and retailer are

$$\pi_m^B=\left(w-z+\eta f+\mu-t(e-e_0)\right)q-\frac{1}{2}ke_0^2-\frac{1}{2}d\eta^2, \tag{4}$$

$$\pi_r^B=(p-w)q, \tag{5}$$

Proposition 2: In the OSP model, the equilibrium wholesale price w^{B*}, BT level η^{B*}, a unit of carbon-emission reductions e_0^{B*}, retail price p^{B*}, demand q^{B*}, profit of manufacturer π_m^{B*}, and profit of retailer π_r^{B*} can be calculated using formulas (A12) - (A18), respectively.

4.2 Model analysis

When the government implements the TSP or the OSP, there exists a unique equilibrium solution respectively. Based on the equilibrium results, we make following analysis: (1) Investigating the impact of the BT's ICF and the LCT's ICF on the equilibrium solution; (2) Adopting comparative analysis of the technology subsidy policy model and output subsidy policy model. In the following analysis, let $M=\{A,B\}$. The specific conclusions are shown below.

4.2.1 Impact analysis

In this section, the following analysis will be presented: (1) Exploring the impact of the BT's investment cost factor (ICF) d on the equilibrium BT level, carbon reduction per unit, demand, and profit of manufacturers and retailers; (2) Analyzing the impact of the LCT's ICF k on the equilibrium BT level, carbon reduction per unit, demand, wholesale price, retail price, and profit of manufacturers and retailers.

Proposition 3: ***The impacts of*** d ***on the equilibrium solution are as follows:*** $\frac{\partial \eta^{M*}}{\partial d}<0$, $\frac{\partial e_0^{M*}}{\partial d}<0$, $\frac{\partial q^{M*}}{\partial d}<0$, $\frac{\partial \pi_m^{M*}}{\partial d}<0$, ***and*** $\frac{\partial \pi_r^{M*}}{\partial d}<0$.

Proposition 3 analyses the impact of the BT's investment cost factor (ICF) d on the equilibrium level of BT, carbon reduction per unit, product demand, profit of the manufacturer, and profit of the retailer. The results show that, under both TSP and OSP models, the level of BT, carbon reduction per unit, demand, and profit of manufacturers and retailers all decrease with increases in the BT's ICF (d). Specifically, the increase in BT's ICF (d) means that the efficiency of manufacturers investing in BT is low. The low BT investment efficiency leads that the effect of BT on information disclosure is insufficient, thereby reducing the incentives of manufacturers to invest in BT, which directly leads to the decline of the level of BT. According to the demand function given by Eq. (1), the lower level of BT can immediately result in the reduction in the product demand. Accordingly, the decline in the demand directly results in the decrease in the retailer's profit. Due to the low level of BT, manufacturer also has the incentive to reduce the investment in LCT since the lower level of BT leads to smaller improved production efficiency that mitigates less impediments in investment in LCT. Hence, the unit carbon emission of products decreases and carbon taxes rise. Further, together with higher production costs, lower demand, and higher carbon taxes, the increase in the BT's ICF (d) implies that the profitability for the manufacturer will be reduced.

The abovementioned conclusions show that, from the perspective of profit, the higher BT's ICF (d) will decrease the profits of firms in the SC, similar to a conclusion found in a previous study [37]. From the perspective of emission reduction, the prohibitively high BT's ICF (d) will reduce the willingness of firms to invest in LCT through an indirect mechanism. In detail, it will reduce improvements to the production efficiency, resulting in increased carbon emissions and cost production in the production process, which is not conducive to the realization of carbon neutrality. Therefore, the government should control the costs of firms in the construction, maintenance, and upgrading of the BT platform. This is not only motivating firms to invest in

LCT, but also promote the application of BT in the low-carbon SC. Meanwhile, this can also lead to an increasing number of consumers who own environmental awareness, thereby conducting the growth and expansion of of low-carbon market.

Proposition 4*：*The impacts of K on the equilibrium solution are as follows: (1) $\frac{\partial \eta^{M*}}{\partial k}<0$, $\frac{\partial e_0^{M*}}{\partial k}<0$, $\frac{\partial q^{M*}}{\partial k}<0$, $\frac{\partial \pi_m^{M*}}{\partial k}<0$, ***and*** $\frac{\partial \pi_r^{M*}}{\partial k}<0$***; (2) When*** $t\leq t_1$, $\frac{\partial p^{M*}}{\partial k}\leq 0$, ***and otherwise,*** $\frac{\partial p^{M*}}{\partial k}>0$.

Proposition 4 reveals the impact of the LCT's investment cost factor (ICF) k on the equilibrium BT level, carbon reduction per unit, product demand, retail price, profit of the manufacturer, and profit of the retailer. Proposition 4 (1) shows that, under both TSP and OSP models, an increase in the LCT's ICF (k), can lead that the level of BT, carbon reduction per unit, demand, profit of manufacturer, and profit of retailer all decrease. the increase in LCT's ICF (k) means that the efficiency of investment in LCT is low. It is straightforward that the manufacturer has less incentives to invest in LCT, thus reducing the product demand (Seeing Eq. (1)). Due to the decrease in the number of consumers who have environmental awareness, the manufacture can not benefit from investing more in BT, so it is motivated to reduce the investment in BT. Moreover, this reduction in the demand immediately causes falls in profits for the manufacturer and retailer. The above results agree with Li et al. [30] and Xu et al. [29].

Proposition 4 (2) demonstrates that, when the unit carbon tax t is small ($t\leq t_1$), the retail prices under both models decreases when the LCT's ICF (k) rises. When the unit carbon tax t is large ($t>t_1$), the retail price under both models increases with increases in the LCT's ICF (k). Specifically, the large unit carbon tax t motivates the manufacturer to invest in LCT to reduce carbon taxes to improve its profit. Further, with increases in k, the investment efficiency of LCT decreases and the manufacturer will face higher barriers to LCT investment and invest more to ahieve the same level of the unit carbon reduction. Hence, the manufacturer will ultimately pass the investment cost of LCT to consumers by setting high prices. Conversely, when the unit carbon tax is small, although the investment efficiency of LCT decreases with the increase of k, the manufacturer does not have to invest as heavily in LCT. Therefore, to avoid a significant reduction in the product demand, the SC members are then motivated to set a lower price. This result differs from Li et al. [20] who demonstrate that the impact of the LCT's ICF (k) on the retail price only depends on which GSP is adopted.

The abovementioned conclusions uncover that a large LCT's ICF is not conducive to carbon emission reduction and will reduce the profits of supply chain members. Additionally, a large LCT's ICF (k) is also not conducive to the improvement of BT in a low-carbon SC. A high unit carbon tax will urge firms to set higher prices to pass the investment cost of LCT to consumers. Conversely, a small unit carbon tax requires lower investment in LCT and firms need not pass the investment cost of LCT to consumers. Thus, firms are incentivized to choose a lower price to avoid a significant reduction in the product demand. Moreover, from the perspective of emission reduction, increasing carbon tax may not be effective to increase firms' investment in LCT especially when the LCT's ICF (k) is large.

4.2.2 Comparative analysis

In this section, we further conduct the comparison of equilibrium solution between TSP and OSP as follows: (1) comparing the equilibrium LCT investments under two GSPs; (2) comparing the equilibrium levels of BT under the two GSPs; (3) comparing equilibrium retail prices under the two models; (4) comparing equilibrium product demands under two subsidy policies; (5) comparing equilibrium profits of the manufacturer and retailer under TSP and OSP.

Proposition 5：The order of equilibrium LCT investments under the two models satisfies: (1) When $0<\theta<\theta_1$***, if*** $k\le k_2^{\#}$, $e_0^{A*}\ge e_0^{B*}$ ***and if*** $k>k_2^{\#}$, $e_0^{A*}<e_0^{B*}$***;(2) When*** $\theta_1\le\theta<1$, $e_0^{A*}>e_0^{B*}$.

Proposition 5 compares the equilibrium LCT investments under the two GSPs. Proposition 5 (1) highlights that when the subsidy ratio θ of the TSP is small ($0<\theta<\theta_1$), the manufacturer can gain less subsidy for LCT investment from the government. Then, if the LCT's investment cost factor (ICF) k is small ($k\le k_2^{\#}$), the TSP is more conducive to increasing LCT investment (i.e., the unit emission reduction of the product). If the LCT's ICF (k) is large ($k>k_2^{\#}$), the output subsidy policy (OSP) brings a better unit emission reduction. This reflects that when θ is small, which subsidy policy can promote more investment in LCT will be affected by the degree of the LCT's ICF (k). In detail, when k is small, the investment efficiency of LCT is high. In comparison to the OSP, TSP represents a more direct and efficacious method for the manufacturer to reduce LCT's investment cost, therebying motivating the manufacturer to invest more in LCT. On the contrary, when k is large, LCT's ICF is high which means LCT's investment efficiency becomes low, leading that the manufacturer's level of LCT is low, so the incentive of the TSP for the manufacturer to invest in R&D of LCT is insufficient. Here, OSP, which represents a subsidy strategy towards the output side, has the potential to more effectively stimulate the manufacturer to invest more in LCT than TSP.

Proposition 5 (2) states that, when the subsidy ratio θ of the TSP is larger ($\theta_1\le\theta<1$), the TSP is always more conducive to increasing the unit emission reduction of the product. This is because, when θ is large, the TSP for the manufacturer of LCT research and development input cost subsidies is always larger. The manufacturer only needs to bear relatively low costs to invest in LCT. Therefore, it always invests more LCT facing TSP.

These above conclusions illustrate that, when the proportion of cost input subsidy is low, the TSP that focuses on encouraging firms to invest in the R&D of LCT is not necessarily more conducive to increasing the unit emission reduction. From the perspective of improving the market carbon-emission reduction level, the government (with limited financial expenditure) needs to choose the appropriate subsidy strategy regarding the level of the LCT's ICF (k). Specifically, when the LCT's ICF (k) is small, the TSP will be more conducive to increasing product emission reduction. In contrast, when the LCT's ICF (k) is large, the output subsidy is more appropriate. Furthermore, when the proportion of cost input subsidy is large, the TSP always facilitates more investment in LCT.

Proposition 6：The order of the equilibrium levels of BT under the two models satisfies: When $k\le k_1^{\#}$, $\eta^{A*}\ge\eta^{B*}$***; Otherwise,*** $\eta^{A*}<\eta^{B*}$.

Proposition 6 compares the equilibrium levels of BT under the two GSPs. The results demonstrate that when the LCT's investment cost factor ((ICF) k is small ($k \le k_1$), the TSP is more conducive to improving the technical level of firms' investment in BT. When the LCT's ICF (k) is large ($k > k_1$), the OSP is better. According to proposition 5 (1), when k is small, the TSP is more conducive to increasing the unit emission reduction of the product. This implies that the manufacturer is more motivated to invest in BT to disclose the emission reduction information of the product, which will not only increase the demand but also reduce the production cost. When k is large, the OSP is more conducive to increasing the unit emission reduction of of product, so the manufacturer is more motivated to invest in BT under the OSP. Moreover, we further provide a new view which reflects which GSPs can bring more BT investments for scholars such as Li et al. [30] and Li et al. [11].

The abovementioned conclusions indicate that the level of the LCT's ICF will affect the incentive effect of the two types of subsidy policies for firms to invest in the R&D of LCT, and, also, indirectly promote the investment in the R&D of BT. Therefore, in the blockchain SC, the low-carbon supply chain manager should carefully choose the subsidy policy based on the type of LCT (i.e., the cost factor of LCT investment) facing the government's different subsidy policies to response to environmental regulation.

Proposition 7: The order of equilibrium retail prices under the two models satisfies: (1) When $b \le b_1$, if $z \le z_1$, $p^{A*} \le p^{B*}$ and if $z > z_1$, $p^{A*} > p^{B*}$; (2) When $b > b_1$, if $z \le z_1$, $p^{A*} \ge p^{B*}$ and if $z > z_1$, $p^{A*} < p^{B*}$.

Proposition 7 compares the equilibrium retail prices under the two GSPs. Proposition 7 (1) shows that, when the consumers' LCP coefficient b is small ($b \le b_1$), if the initial unit production cost z is small ($z \le z_1$), the retail price under the TSP is lower than that under the OSP. If the initial unit production cost z is large ($z > z_1$), the price under the OSP is lower. This is because, when both b and z are small, the investment in LCT has less impact on the demand. Under the TSP, even if the investment in LCT receives corresponding subsidies, the manufacturer still bears large costs when the investment in LCTis high. Thus, the increased level of emission reduction (due to LCT) may not bring a profit growth. Further, in such situation, the manufacturer will be more inclined to reduce the price strategy to improve profits. If the initial unit production cost of the product is low, the OSP provides more incentive for the manufacturer to produce new low-carbon products. Therefore, firms will set relatively lower prices under the TSP. When b is small and z is large, consumers' LCP coefficient is small, and the cost of production is large. The incentive effect of the OSP on the manufacturer' R&D of new products with low carbon emissions is weak. In comparison to the TSP, firms will be more motivated to reduce product prices under the OSP.

Proposition 7 (2) shows that, when the consumers' LCP coefficient b is large ($b > b_1$), if the initial unit production cost z is small ($z \le z_1$), the price under the OSP is lower than that under the TSP. If the initial unit production cost z is larger ($z > z_1$), the price under the TSP is lower. Specifically, when b is large, investment in LCT will have a greater impact on the demand and therefore on profits. The manufacturer has a greater willingness to invest in LCT. If z is small, the manufacturer will increase its investment in LCT, and TSP will provide greater incentives for the manufacturer to invest in LCT. The retailer, who observes that products own a higher low-carbon level, has an incentive to set higher prices. If z is large, the manufacturer will consider investing in BT to reduce high production costs. At this time, the manufacturer will be motivated to invest more in LCT and BT in order to raise profits, which will lead to a substantial increase in demand and a substantial reduction in unit production costs. Therefore, the OSP is a good incentive for the manufacturer to continue to promote the carbon reduction level. In comparison to the TSP, the retailer, who observes higher low-carbon levels of products under the OSP, has an incentive to set higher prices.

These conclusions show that the incentive effect of the two types of GSPs on firms will be affected by the consumers' LCP coefficient and initial unit production cost, which will consequently affect the product pricing decision of firms. These results can herein provide the manager of the low-carbon supply chain with a guide based on the consumers' LCP coefficient and initial unit production cost, which aids in the adjustment of product pricing strategies when facing diverse GSPs.

Proposition 8：The order of equilibrium demands under the two models satisfies: (1) When $k\le k_3^{\#}$, $q^{A*}\ge q^{B*}$***; (2) When*** $k>k_3^{\#}$, $q^{A*}<q^{B*}$***.***

Proposition 8 compares the equilibrium demands under the two GSPs. The outcomes state that when the LCT's investment cost factor (ICF) k is small ($k\le k_3$), the TSP is more conducive to increasing the demand. When the LCT's ICF (k) is large ($k>k_3$), the OSP can catch more consumers' attention. The price of the product, the unit emission reduction of the product, and the level of BT are the main factors affecting the demand. Further, the level of BT has a greater impact on the demand than the unit production cost ($f<\delta$). According to Proposition 6, when k is small, the TSP is more conducive to firms' investment in BT, so the TSP is more conducive to increasing the demand. When k is large, the OSP is more conducive to increasing the demand. When consumers' LCP coefficient is large, the unit emission reduction of the product and the BT are the key factors affecting demand. According to the Proposition 5 (1) and Proposition 6, when k is small, the TSP is more conducive to firms investing in LCT and BT; therefore, the TSP is more conducive to increasing the demand. When k is large, the OSP is more conducive to increasing the demand. Together with the differences in investments in LCT and BT between TSP and OSP which can affect the demand function, we can deduce that there exists a threshold of k below which the demand under TSP is larger. Our results are also different from Li et al. [11] who demonstrate the equilibrium demand under TSP is always smaller than that under OSP.

Proposition 9：The order of equilibrium profits of the manufacturer and retailer under the two GSPs satisfies: When $k<k_4$, $\pi_m^{A*}>\pi_m^{B*}$***; When*** $k>k_4$, $\pi_m^{A*}<\pi_m^{B*}$***. In addition, when*** $k<k_5$, $\pi_r^{A*}>\pi_r^{B*}$***; when*** $k>k_5$, $\pi_r^{A*}<\pi_r^{B*}$***.***

Proposition 9 compares the profit of the manufacturer and the profit of the retailer in equilibrium under the two GSPs. To be more specific, when the LCT's investment cost factor (ICF) k is small ($k<k_4$ or $k<k_5$), the TSP can make the manufacturer or retailer gain more profits

than the OSP. When the LCT's ICF (k) is large ($k>k_4$ or $k>k_5$), the OSP brings the manufacture or retailer more profits. Further, the demand is the key factor that affects the profit of firms. According to Proposition 8, when k is small, the TSP is more conducive to raising the demand. Therefore, the profits of firms under the TSP are larger. When k is large, the OSP is more conducive to increasing the demand, so the OSP is more effective in increasing the profits of firms. The results in Proposition 8 can also serve to reinforce and validate the integrity of current conclusions in Proposition 9. Additionally, the outcomes in Proposition 9 are different from Li et al. [11] who state TSP can increase the profitability only when the ICF is moderate, and the differences stem from the endogenous decisions of the investment of BT as well as Duan et al. [12] whose outcomes imply OSP is always better than TPS.

Proposition 9 can further provide a view for the low-carbon supply chain firms to evaluate and determine the optimal subsidy policy selection if the government offers a variety of subsidy policies which only one can be chosen. Moreover, from a perspective of the government, the aforementioned findings offer a theoretical framework for the government to evaluate and ascertain which subsidy policy is more appropriate to facilitate and bolster the growth of low-carbon industries.

5. Numerical analysis and discussion

To better explain the effect of the GSP on investment decisions of firms in the SC, this part uses the numerical analysis method to analyse how the BT's and LCT's ICFs affect the equilibrium solution. The parameter values in the analysis process are in accordance with the relevant constraints of theoretical analysis. In addition, the social welfare functions under the two models involved in this part of the analysis are as follows:

$$\pi_g^A=\pi_m^A+\pi_r^A+\frac{(a+be_0+\delta\eta-p)q-\theta ke_0^2}{2}-(e-e_0)q, \tag{6}$$

$$\pi_g^B=\pi_m^B+\pi_r^B+\frac{(a+be_0+\delta\eta-p)q}{2}-\mu q-(e-e_0)q, \tag{7}$$

5.1 Impact of BT investment cost factor d on the equilibrium solution

This section analyses the impact of the BT investment cost factor (ICF) d on the level of BT, carbon reduction per unit, demand, retail price, manufacturer profit, retailer profit, and social welfare. Exogenous variables are fixed for a=20, b=0.6, e=8, f=0.6, k=3, z=5, θ=0.6, δ=0.6, t=1.1, μ=3, and $d\in[4,5]$. From Figures 2 to 8, the following conclusions can be drawn.

Figures 2, 3, 4, and 5 show that, as the BT's ICF (d) increases, the equilibrium BT level, carbon reduction per unit, demand, and retail price all decrease under both subsidy policies. The increase in the BT's ICF (d) means that the efficiency of investment in BT decreases, which directly leads to the decrease of manufacturers' willingness to invest in BT. The reduced effect of information disclosure reduces the return on the investment in LCT, and the manufacturer has the incentive to reduce investment in LCT, which reduces the demand. At this point, the retailer observes a reduction in carbon emissions per unit and responds by reducing retail prices. When $k<k_1$ (k=3, $k_1\in[4.36,4.47]$) and $\theta>\theta_1$ (θ=0.6, θ_1=0.33), the BT level, unit carbon-emission reduction, and demand under the TSP are higher than that under the OSP, which verifies the accuracy of Propositions 5, 6, and 8.

Figures 6 and 7 analyse the influence of the BT's ICF (d) on the profits of the manufacturer and retailer. The results show that, firstly, as the BT's ICF (d) increases, the profits of the manufacturer and retailer decrease. From this analysis, the increase in the BT's ICF (d) will indirectly lead to a decrease in the demand, resulting in a decrease in the profits of the manufacturer and retailer. Secondly, when $k_4<k<k_5$ ($k=3$, $k_5\in[4.36,4.47]$, $k_4\in[2.92,2.98]$), the profit of the manufacturer under the OSP is higher, and the profit of the retailer under the TSP is higher. Thus, the accuracy of Proposition 9 is verified. With increases in the BT's ICF (d), the profits of the manufacturer and retailer under the TSP are more negatively affected. Clearly, the subsidy ratio θ under the TSP is larger, and the LCT's ICF (d) is smaller. Therefore, in comparison to the OSP, the manufacturer under the TSP invests more in LCT. Herein, with increases in the BT's ICF (d), the higher price under the TSP will make its profit suffer more.

Figure 8 highlights that social welfare decreases as the BT's ICF (d) increases. The reduction in the manufacturer's and retailer's profits and the decrease in carbon emission per unit are the main factors leading to the reduction in social welfare. As the BT's ICF (d) continues to increase, the social welfare under the TSP will be lower than the OSP. Therefore, the government can should promote more technology innovation of BT to decline the negative effects of the high cost factor.

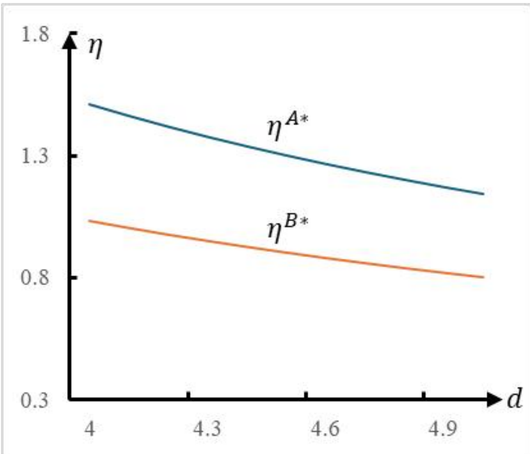

Figure 2. Influence of BT investment cost factor *d* on BT level

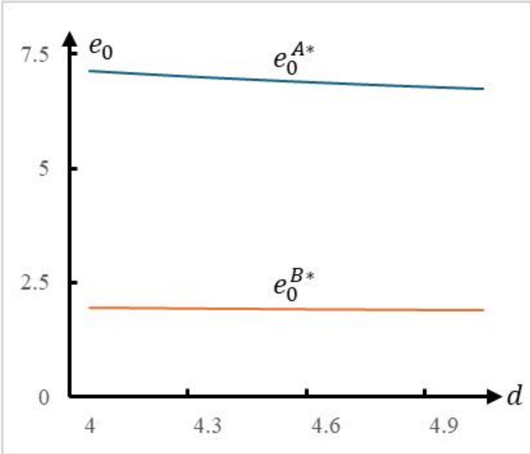

Figure 3. Influence of BT investment cost factor *d* on carbon reduction per unit

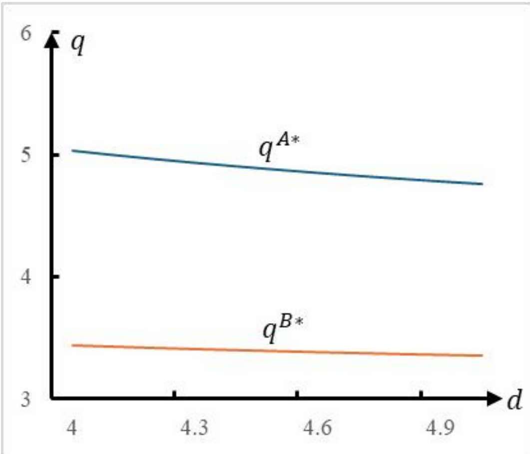

Figure 4. Influence of BT investment cost factor *d* on demand

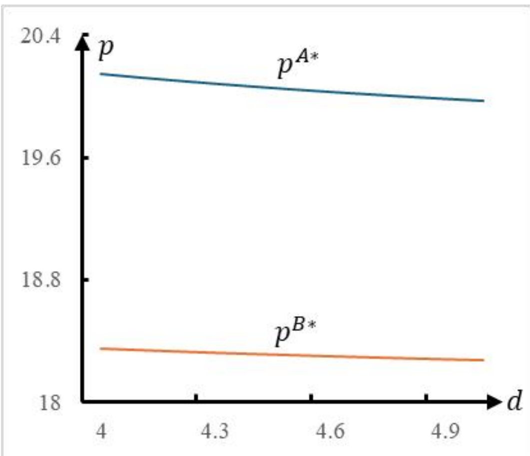

Figure 5. Influence of BT investment cost factor *d* on retail price

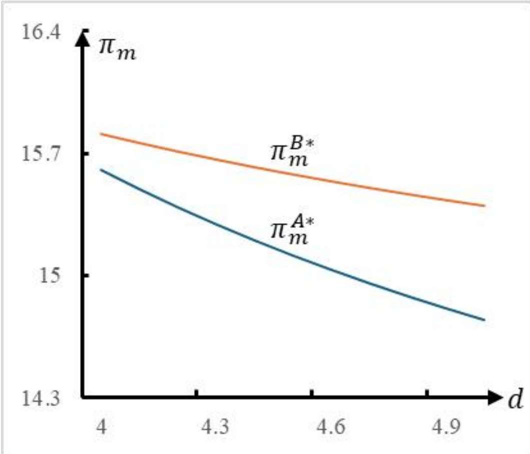

Figure 6. Influence of BT investment cost factor *d* on profit of the manufacturer

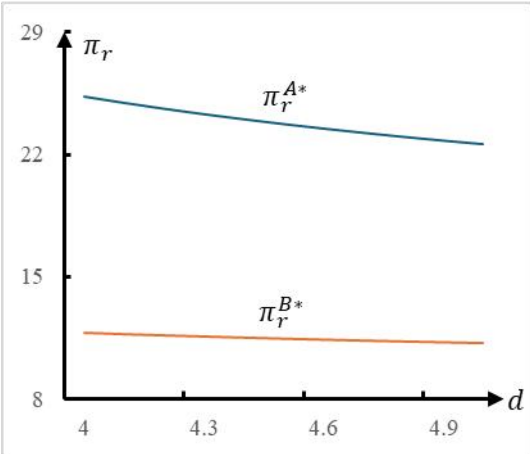

Figure 7. Influence of BT investment cost factor *d* on profit of the retailer

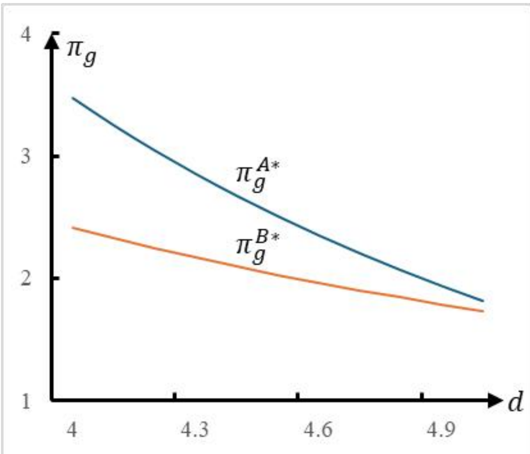

Figure 8. Influence of BT investment cost factor *d* on social welfare

5.2 Impact of LCT investment cost factor k on the equilibrium solution

This subsection analyses the impact of the LCT investment cost factor (IFC) k on retail prices, manufacturer's and retailer's profits, and social welfare. Exogenous variables were fixed for a=20, b=0.6, d=4, e=8, f=0.8, z=5, θ=0.4, δ=0.6, t=1, μ=3, and $k\in[4,5]$. From Figures 9 to 12, the following conclusions can be drawn.

Figure 9 shows that, when $t<t_1$ (t=1, t_1=2.07), the retail price decreases as the LCT's ICF (k) increases. When the unit carbon tax is small, the manufacturer is less willing to reduce the carbon tax via increasing the investment in LCT. In this case, the increase in demand is the main factor for manufacturers to invest in LCT. However, as the LCT's ICF (k) increases, the efficiency of investment in LCT decreases, and the manufacturer's willingness to invest in LCT will also decline, which verifies the accuracy of proposition 4. Figure 9 shows that, when $b>b_2$ (b=0.6, b_2=0.29) and $z<z_2$, the TSP will lead to higher retail prices, which verifies the accuracy of Proposition 7.

Figure 10 and Figure 11 show that, as the LCT's ICF (k) increases, the profits of the manufacturer and retailer both decrease, which indicates that the decrease in LCT investment will immediately result in a fall in profits. When $k>k_4$ and $k>k_5$ ($k\in[4,5]$, k_4=1.68, k_5=2.35), the profit of the manufacturer and the retailer under the OSP are higher, which verifies the accuracy of Proposition 9. Combined with the abovementioned analysis, when the LCT's ICF (k) is high, the unit emission reduction is low, and meanwhile, higher pricing will reduce firm profits to a certain extent.

Figure 12 shows that social welfare will decrease with increases in the LCT's ICF (k), and when the LCT's ICF is $\bar{k}$, social welfare under the TSP is equal to that under the OSP. This shows that higher profits of the manufacturer and retailer do not necessarily lead to higher social welfare. To improve social welfare, the government and market regulators need to lead the technology innovation of the LCT to reduce the LCT's investment cost factor to bring higher social welfare.

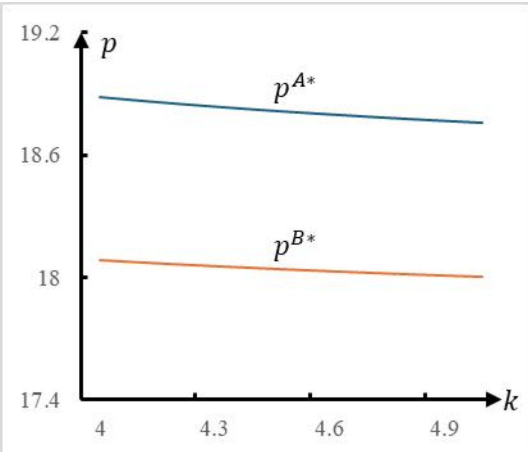

Figure 9. Influence of LCT investment cost factor k on retail price

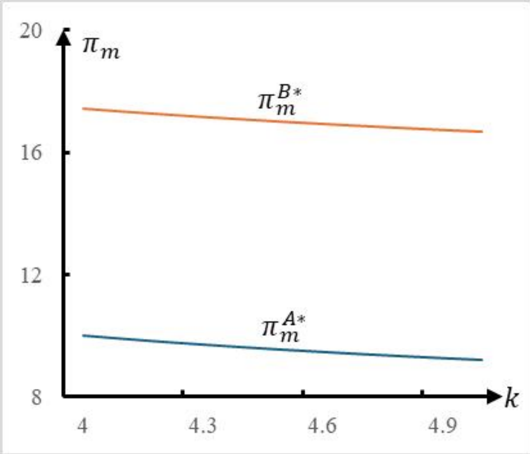

Figure 10. Influence of LCT investment cost factor *k* on profit of the manufacturer

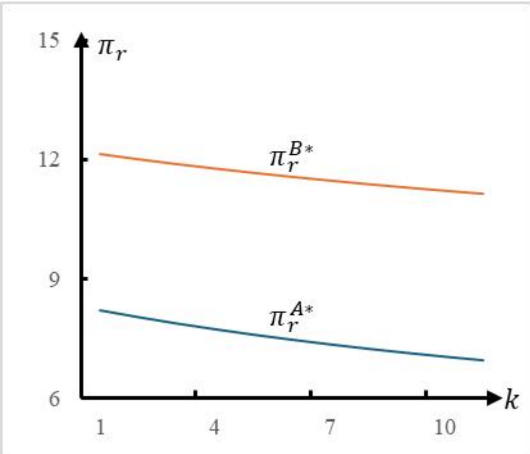

Figure 11. Influence of LCT investment cost factor *k* on profit of the retailer

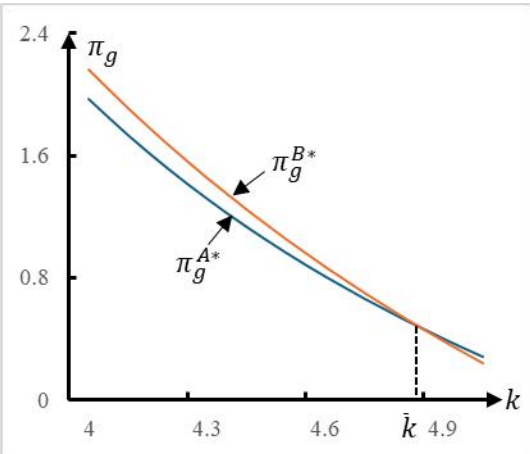

Figure 12. Influence of LCT investment cost factor *k* on social welfare

6. Conclusion

The establishment of "double carbon" goal urges the government to implement the government subsidy policy (GSP) to promote the low-carbon technology (LCT) investment of a supply chain (SC) to reduce carbon emissions. Meanwhile, the blockchain technology (BT) is also considered as a potential method to improve production efficiency which implies that the adoption of BT can indirectly promote the low-carbon level of a supply chain. However, there lacks relevant research on the impact of different GSP on the investment decisions of firms in a low-carbon SC with the BT. Therefore, to uncover the inherent impact mechanism, this paper constructs a low-carbon SC composed of a manufacturer and a retailer to analyse the differences between two types GSPs, i.e., TSP and OSP, on the investments of LCT and BT. Via comparing the equilibrium solutions of different policies, the main conclusions are as follows: (1) When the subsidy ratio under the TSP is small, if the LCT investment cost factor (ICF) is low, the TSP can provide higher unit emission reduction and if the LCT's ICF is high, the OSP can reduce more carbon emissions. When the subsidy ratio under the TSP is larger, the TSP can always provide higher unit emission reduction. (2) When the LCT's ICF is low (high), the level of BT under the TSP (OSP) is higher. (3) The level of BT, unit emission reduction, and demand all decrease with increases in the BT's ICF and the LCT's ICF. (4) When the LCT's ICF is small, the TSP is always superior to the OSP from the perspective of the profitability of the manufacturer and retailer.

These findings provide some management implications for the low-carbon supply chain manager and the government. Firstly, the government should lead the industrial innovation to control the ICFs of LCT and BT which can immediately promote the application of BT and LCT in the low-carbon SC to reduce more carbon emissions to attract an increased number of consumers with environmental awareness. This implication also enriches existing literature such as Li et al. (2022) and Li et al. (2024b) who assume the investments of BT are exogenous through endogenous decisions of BT investments. Secondly, when the supply chain manager faces two different types of GSPs, he needs to carefully choose the subsidy policy based on the LCT's and BT's ICFs in response to the environmental regulations. This managerial insight also extends the literature on the comparison between two different types of GSPs, such as Li et al. (2024b) who state TSP can increase the profitability only when the ICF is moderate as well as Duan et al. (2023) whose outcomes imply OSP is always better than TPS. Thirdly, this paper further provides the manager of the low-carbon supply chain with a guide based on the consumers' LCP coefficient and initial unit production cost, which aids in the adjustment of product pricing strategies when facing diverse GSPs. Finally, the aforementioned findings offer a theoretical framework for the government to evaluate and ascertain which subsidy policy is more appropriate to facilitate and bolster the growth of low-carbon industries. Further, this paper also leverages the numerical analysis method to reveal the impacts of the LCT's and BT's ICFs on the social welfares under two types of GSPs respectively. The findings first demonstrate that the social welfares are decreasing in the increases of the LCT's and BT's ICFs. Interestingly, the results also uncover that when the LCT's ICF is high (low), the TSP (OSP) can bring better social welfare. These findings suggest that which type of GSP chosen by the government needs to previously evaluate the LCT's ICF.

However, there exist some certain limitations in our study. First, we merely focus on the impact of BT on the consumer information traceability and production costs. In the future, the impact of BT on the transaction efficiency and costs between upstream and downstream of the SC can be considered. Secondly, although this paper focuses on the investment in BT and LCT, it only considers the investment under a monopoly situation and neglects the investment cooperation and competition under an oligopoly situation. Finally, the impact of GSP with different priorities on different firms in the low-carbon SC on investment decisions in BT and LCT is also worth investigating.

AUTHOR CONTRIBUTIONS

Qian Zhao and Matthew Quayson： Conceptualization; writing—review and editing. Qian Zhao：Methodology; supervision; funding acquisition. Yuankun Chen：Software; data curation. Hao Lou: Resources. Matthew Quayson： Formal analysis; investigation; project administration. Yuankun Chen,Hao Lou and Qian Zhao:validation. Qian Zhao,Matthew Quayson and Yuankun Chen:writing—original draft preparation. Hao Lou and Yuankun Chen:Visualization.All authors have read and agreed to the published version of the manuscript.

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DATA AVAILABILITY STATEMENT

The authors confirm that the data supporting the findings of this study are available within the article and/or its supplementary materials.

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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