ELECTRICITY SUPPLY CHAIN COORDINATION WITH CARBON ABATEMENT TECHNOLOGY INVESTMENT UNDER THE BENCHMARKING MECHANISM

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Abstract. The introduction of the benchmarking mechanism into the electricity industry has influenced whether utility firms choose to invest in carbon abatement technology. This study presents an electricity supply chain that includes a utility firm as the leader and a retailer as the follower to decide on the electricity price and carbon abatement technology investment. The study discusses the impact of the benchmarking mechanism on the decision-making of the electricity supply chain enterprises. The main conclusions are as follows: (1) Investing in carbon abatement technology increased electricity demand, customer surplus, and profits of the electricity supply chain enterprises. (2) Carbon abatement technology investment and profits of the supply chain enterprises increased with the unit carbon quota. (3) A revenue-sharing and cost-sharing contract could be used to coordinate the electricity supply chain.

1. Introduction. Previous studies have shown that increased carbon emissions have resulted in the greenhouse effect [18]. Several organizations are committed to reducing the greenhouse effect, such as the United Nations Framework Convention on Climate Change established in 1992, which was supplemented by the Kyoto Protocol in 1997; subsequently, China acceded to the Paris Agreement. The Chinese government announced its aim to decrease carbon intensity by approximately 40–45% from 2005 to 2020 [41]. A decrease in carbon emissions from the electricity industry is required because these emissions account for approximately 48% of the total carbon emissions in China [27]. In addition, each unit of electricity emits approximately 627 g of carbon dioxide in China, whereas in Germany only 560 g is emitted [6].

By the end of 2017, the Chinese government had established seven carbon trading pilot regions to trade carbon quotas. Most of these regions, such as Beijing,
Guangzhou, and Shenzhen, are driven by the benchmarking mechanism (BM), where a firm can buy/sell its carbon quota from the carbon trading market when the unit carbon emission is in surplus/when there is a lack of unit carbon quota provided by the government [42]. The unit carbon quota is set by the government based on the emission level of the industry, which is fundamental to the design of the BM [25].

Faced with the BM, firms must undertake measures to satisfy these requirements for their survival [23]. Buying carbon quotas and investing in carbon reduction technology are examples of effective measures [39]. With these measures, the carbon emissions of the unit electricity in China decreased by 21.6% from 2005 to 2016 [7]. The present study compared two strategies, 1) buying the carbon quota and not investing in carbon abatement technology (N-strategy) and 2) buying the carbon quota and investing in carbon abatement technology (I-strategy).

BM can provide incentives for efficient firms as well as punish inefficient companies [9]. Several previous studies have examined investment in carbon abatement technology to improve carbon emission efficiency. For example, [8] discussed renewable energy investment under the BM. Furthermore, [42] studied emission reduction behavior under a multi-stage model under different carbon regulations. The electricity market has also been discussed in [10, 19, 29, 36], and [37]. Supply chain and supply chain management have been studied in [1, 3, 15, 16, 20, 30], and [40].

How to meet the BM requirements is extremely important for the development and survival of an enterprise with profit maximization. The present study aimed to answer the following questions:

(a) What strategy is beneficial to the profits and customer surplus under the BM?

(b) What is the impact of the unit carbon quota on investing in carbon abatement technology?

The present study used a Stackelberg game model to compare the two-stage supply chain between the N-strategy and I-strategy, as this game is able to solve the practical problem [4]. The utility firm was used as the leader to decide the carbon abatement technology investment and electricity wholesale price, and the retailer was used as the follower to decide the electricity price. Thus, this study focused on the impact of different strategies on the investment in carbon abatement technology.

This study has three primary contributions to the field. Firstly, based on the BM adopted in China, the utility firm could invest in low-carbon technology and could buy a carbon quota to meet the BM requirements. This paper identifies whether the utility firm should invest in low-carbon technology or not, and under which conditions. Secondly, many studies have discussed low-carbon technology investment; however, there are limited studies of low-carbon management in the electricity supply chain under the BM. This paper contributes to enrichment of the low-carbon field. Thirdly, this paper examines the impact of the BM on investment in carbon abatement technology and how this influences electricity demand, customer surplus, and profit. The results show that investment in carbon abatement technology increased electricity demand, customer surplus, and profits. These findings provide a reference base for electricity supply chain enterprises.

2. Model framework. This study first examined the responses of the N-strategy and I-strategy to the BM and then established a two-stage electricity supply chain which included a utility firm as the leader and a retailer as the follower. The utility
firm invested in carbon abatement technology on the existing conventional energy source and sold the electricity to the retailer at a wholesale electricity price, after which the retailer sold the electricity to consumers. The analysis detailed in this paper is based on certain conditions. Utilizing the characteristics of the electricity market (illustrated in Fig. 1), the following assumptions are made:

**Assumption 1.** The electricity demand is \( q = a - bp \), where \( a \) is the potential market demand, \( b \) is the price sensitive coefficient, and \( p \) is the electricity price. The consumer is price sensitive, i.e., the higher the price, the lower the electricity demand.

**Assumption 2.** We used a quadratic function to describe the cost of carbon abatement technology investment; this approach is common in previous studies \([13]\) and \([33]\). Thus, the cost of carbon abatement technology investment is \( F(\xi) = \frac{1}{2}k\xi^2 \), where \( k \) is the cost-coefficient of the carbon abatement technology investment. A higher \( k \) indicates that the utility firm bears more of the investment cost. The parameter \( \xi \) is the carbon abatement technology investment, with the investment cost increasing with \( \xi \).

**Assumption 3.** The utility firm first dispatches the high-efficiency unit followed by the low-efficiency unit, as per the assumptions in \([2]\) and \([24]\). Thus, we assumed that the cost of electricity production is \( G(q) = \frac{1}{2}cq^2 \), where \( c \) is the generated cost-effectiveness of the conventional energy sources. A higher \( c \) indicates that the utility firm bears more of the generating costs.

**Assumption 4.** We assumed that the carbon price \( t \) is an exogenous variable in the carbon trading market, the unit carbon emission \( e \) is from conventional energy resources, and the unit carbon quota set by the government is \( e_0 \). To ensure that the optimal decision variables were greater than zero, we assumed that \( 0 < e \leq \frac{a}{b} \) and \( t^2 \leq \frac{4k+c+kh}{b} \). Similar assumptions were adopted in \([28]\) and \([38]\).

The notation used and definitions of all the parameters in the present study are shown in Table 1.
Table 1. Notation and description of parameters

| Notation | Description                                      |
|----------|-------------------------------------------------|
| $q$      | Electricity demand                              |
| $a$      | Potential electricity demand                    |
| $b$      | Sensitivity coefficient of electricity price     |
| $c$      | Cost coefficient of electricity production      |
| $k$      | Cost coefficient of carbon abatement technology investment |
| $e_0$    | Unit carbon emission-free quota under the BM     |
| $e$      | Initial unit carbon emission                    |
| $t$      | Carbon price                                    |
| $\pi_R$ | Profit of the electricity retailer              |
| $\pi_U$ | Profit of the utility firm                      |
| $\pi_S$ | Profit of the supply chain                      |

| Decision Variables | Description                                      |
|--------------------|-------------------------------------------------|
| $p$                | Electricity price                               |
| $w$                | Electricity wholesale price                      |
| $\xi$              | Carbon abatement technology investment           |

3. Model analysis. When the government introduced the BM into the electricity market, the utility firm could buy a carbon quota from the carbon trading market or invest in carbon abatement technology to deal with this mechanism. The present study focused on two strategies (N-strategy and I-strategy) and then examined a centralized system and decentralized system in the electricity supply chain. Superscripts N, I, and B represent the N-strategy, I-strategy, and the coordination strategy (B-strategy), respectively. Subscripts C and D represent the centralized system and decentralized system, respectively. Subscripts U, R, and S represent the utility firm, electricity retailer, and supply chain, respectively.

3.1. N-strategy with a decentralized system (ND). Under the ND, the utility firm buys the carbon quota from the carbon trading market without investing in carbon abatement technology. Thus, the utility firm decides the wholesale price $w$ and then the electricity retailer decides the electricity price $p$. The profits of the retailer and utility firm are as follows:

$$\pi_{DR}^N = (p - w)q,$$

$$\pi_{DU}^N = wq - \frac{1}{2}eq^2 - tq(e - e_0).$$

Using Eqs. (1)–(2), we can obtain the optimal wholesale price and optimal electricity price:

$$w_{DU}^* = \frac{a(2 + cb) + 2bt(e - e_0)}{b(4 + cb)},$$

$$p_{DR}^* = \frac{3a + acb + bet - be_0t}{b(4 + cb)}.$$}

Using the electricity demand function and Eqs. (1)–(2), we can obtain the optimal electricity demand and the profits of the electricity retailer, utility firm, and supply chain as follows:

$$q_{DR}^* = \frac{a - bet + be_0t}{4 + cb},$$
\[ N_\text{DS} = (6 + cb)(a - bet + be_0t) \left/ 2b(4 + cb)^2 \right. \] (8)

**Lemma 3.1.** Under the ND, the optimal electricity price, electricity demand, and the profits of the electricity retailer, utility firm, and supply chain are given by Eqs. (4)–(8), respectively.

3.2. N-strategy with a centralized system (NC). Under the NC, which considers the utility firm and electricity retailer together, the supply chain makes decisions on the electricity price to maximize its profit. The profit of the supply chain enterprises is as follows:

\[ \pi_{CS}^N = pq - \frac{1}{2} cq^2 - tq(e - e_0). \] (9)

Using Eq. (9), we can obtain the optimal electricity price as follows:

\[ p_{CR}^* = \frac{a + acb + bt(e - e_0)}{b(2 + cb)}. \] (10)

Using the electricity demand function and Eq. (9), we can obtain the optimal electricity demand and supply chain profit as follows:

\[ q_{CR}^* = \frac{a - bet + be_0t}{2 + cb}, \] (11)

\[ \pi_{CS}^* = \frac{(a - bet + be_0t)^2}{2b(2 + cb)}. \] (12)

**Lemma 3.2.** Under NC, the optimal electricity price, electricity demand, and profit of the supply chain are given by Eqs. (10)–(12), respectively.

3.3. I-strategy with a decentralized system (ID). Under the ID, the utility firm invests in carbon abatement technology. The utility firm first decides the wholesale price \( w \) and carbon abatement \( \xi \) and then the retailer decides the electricity price \( p \). The profits of the retailer and utility firm are given as follows:

\[ \pi_{DR}^I = (p - w)q, \] (13)

\[ \pi_{DU}^I = wq - \frac{1}{2} cq^2 - tq(e - e_0 - \xi) - \frac{1}{2} k\xi^2. \] (14)

Using Eqs. (13) and (14), the optimal wholesale price, carbon abatement technology investment, and electricity price can be calculated as follows:

\[ w_{DU}^* = \frac{2kbt(e - e_0) + a[k(4 + cb) - bt^2]}{b[k(4 + cb) - bt^2]}, \] (15)

\[ \xi_{DU}^* = \frac{k[a + bt(e_0 - e)]}{k(4 + cb) - bt^2}, \] (16)

\[ p_{DR}^* = \frac{3ak + acb + kbt - kbe_0t - abt^2}{b(4k + ckb - bt^2)}. \] (17)
Using the electricity demand function and Eqs. (13) and (14), we can obtain the optimal electricity demand and the profits of the electricity retailer, utility firm, and supply chain as follows:

\[ q^{I*}_{DR} = \frac{ak - kbet + kbe_0t}{4k + kbc - bt^2}, \]  
\[ \pi^{I*}_{DR} = \frac{k^2[a - bt(e - e_0)]^2}{b(4k + kbc - bt^2)}, \]  
\[ \pi^{I*}_{DU} = \frac{k[a - bt(e - e_0)]^2}{2b[k(4 + cb) - bt^2]}, \]

\[ \pi^{I*}_{DU} + \pi^{I*}_{DR} = \pi^{I*}_{DS} = \frac{k[a + bt(e_0 - e)]^2[k(6 + cb) - bt^2]}{2b[k(4 + cb) - bt^2]}. \]

**Lemma 3.3.** Under ID, the optimal carbon abatement technology investment, electricity price, electricity demand, and profits of the electricity retailer, utility firm, and supply chain are given by Eqs. (16)–(21), respectively.

### 3.4. I-strategy with a centralized system (IC).

Under IC, which regards the utility firm and retailer as a whole, decisions are made on the electricity price and carbon abatement technology investment to maximize the supply chain profit. Thus, the profit of the supply chain is given as follows:

\[ \pi^{I*}_{CS} = pq - \frac{1}{2}cq^2 - tq(e - e_0 - \xi) - \frac{1}{2}k\xi^2. \]  

Using Eq. (22), the optimal carbon abatement technology investment and electricity price are as follows:

\[ \xi^{I*}_{CU} = \frac{t[a + bt(e_0 - e)]}{k(2 + cb) - bt^2}, \]  
\[ p^{I*}_{CR} = \frac{bt(e - e_0) + a(k + ckb - bt^2)}{b[k(2 + cb) - bt^2]}. \]

Using the electricity demand function and Eq. (22), we can obtain the optimal electricity demand and profit of the supply chain as follows:

\[ q^{I*}_{CR} = \frac{ak - kbet + kbe_0t}{2k + kbc - bt^2}, \]  
\[ \pi^{I*}_{CS} = \frac{k[a - bt(e - e_0)]^2}{2b[k(2 + cb) - bt^2]}. \]

**Lemma 3.4.** Under IC, the optimal carbon abatement technology investment, electricity price, electricity demand, and profit of the supply chain are given by Eqs. (23)–(26), respectively.

### 4. Impact of unit carbon quota.

With Lemma 3, the following results are obtained, as summarized in Proposition 1.

**Proposition 1.** (1) \( \frac{\partial \pi_{JR}}{\partial e_0} < 0; \) (2) \( \frac{\partial \pi_{DU}}{\partial e_0} > 0; \) (3) \( \frac{\partial \pi_{DS}}{\partial e_0} > 0, \) \( \frac{\partial \pi_{JR}}{\partial e_0} > 0, \) \( \frac{\partial \pi_{DU}}{\partial e_0} > 0, \) \( \frac{\partial \pi_{DS}}{\partial e_0} > 0, \) where \( j = \{C, D\}. \)

Proposition 1 shows the impact of the unit carbon quota on the electricity price, the carbon abatement technology investment, and profits of the supply chain enterprises. It shows that the electricity price \( (p^{I*}_{JR}) \) decreases with the unit carbon quota \( (e_0) \). A larger \( e_0 \) means that the government gives a greater subsidy to the
utility firm, which reduces the carbon emission cost. Therefore, the supply chain enterprises can set a lower electricity price with the unit carbon quota.

Proposition 1 shows that carbon abatement technology investment \((\xi_{IU}^*)\) increases with \(e_0\). A larger \(e_0\) can result in a greater reduction in the cost of carbon emissions for the utility firm. Thus, the utility firm has more motivation to invest in carbon abatement technology to obtain greater profits. It suggests that the government should set a reasonable unit carbon quota for the utility firm to increase carbon abatement technology investment.

5. **Comparison of different strategies.** Here, we discuss the benefits and drawback of each strategy. Firstly, we compared the electricity price and carbon abatement technology between the IC (NC) and ID (ND). Using Lemmas 1–4, the following results (summarized in Theorem 1) were obtained.

**Theorem 5.1.** When comparing IC (NC) and ID (ND), the order of electricity price, carbon abatement technology, and profits is as follows, with \(M = \{I, N\}\).

1. \(p_{M*}^{CR} < p_{M*}^{DR}\);  
2. \(\xi_{IU}^{M*} > \xi_{DU}^{M*}\);  
3. \(\pi_{M*}^{CS} > \pi_{M*}^{DS}\).

Theorem 1 shows the comparisons of electricity price between IC and ID. Compared with ID, the electricity price is lower under IC because there is no “double marginalization” under IC, i.e., the electricity supply chain under IC does not consider the wholesale electricity price. Thus, the consumer can get a lower electricity price. It suggests that the government should encourage the electricity supply chain enterprises to adopt IC.

Theorem 1 shows that carbon abatement investment under IC is higher than that under ID. Compared to ID, the electricity supply chain under IC avoids insider trading (wholesale electricity price). Thus, there is more motivation to invest in carbon abatement technology. In summary, a lower electricity price and higher carbon abatement technology investment help the electricity supply chain to achieve greater profits.

Next, the consumer surplus and demand were compared between IC (NC) and ID (ND). Using Lemmas 1–4, the following results (summarized in Theorem 2) were obtained.

**Theorem 5.2.** When comparing IC (NC) and ID (ND), the order of consumer surplus and demand is as follows, with \(M = \{N, I\}\).

1. \(C_{M*}^{CS} > C_{M*}^{DS}\);  
2. \(q_{CR}^{M*} > q_{DR}^{M*}\).

Theorem 2 compares the consumer surplus and electricity demand between the decentralized system and centralized system. Compared to the decentralized system, the centralized system encourages utility firms to produce more electricity and customer surplus because the centralized system sets a lower electricity price. It suggests that the centralized system can bring greater benefits to consumers. The government should consider reducing unnecessary supply chain links while preventing enterprises from gaining excess profits.

Next, the electricity price was compared between NC (ND) and IC (ID). Using Lemmas 1–4, the following results (summarized in Theorem 3) were obtained.
Theorem 5.3. When comparing the I-strategy and N-strategy, the order of electricity price is as follows:

1. \( p_{DR}^I < p_{DR}^N \)
2. \( p_{CR}^I < p_{CR}^N \)

Theorem 3 compares the electricity price and electricity demand between the I-strategy and N-strategy. Compared to the N-strategy, the electricity price is always lower in the I-strategy. This is because in the I-strategy, investment in carbon abatement technology will have two effects: to the first is to increase the cost for the utility firm and the other is to provide a new competitive advantage for the utility firm, i.e., decreasing the cost of carbon emissions for the utility firm. The cost of carbon emissions savings is higher than the cost of investing in carbon abatement technology. Therefore, the electricity retailer sets a lower price in the I-strategy. It suggests that the government should set up a reasonable mechanism to encourage enterprises to invest in carbon abatement technology, as the consumer would then pay a lower electricity price.

Next, consumer surplus and electricity demand were compared between NC (ND) and IC (ID). Using Lemmas 1-4, the following results (summarized in Theorem 4) were obtained.

Theorem 5.4. When comparing the I-strategy and N-strategy, the order of consumer surplus and electricity demand is as follows:

1. \( C_{DR}^I > C_{DR}^N, C_{CR}^I > C_{CR}^N \)
2. \( q_{DR}^I > q_{DR}^N, q_{CR}^I > q_{CR}^N \)

Theorem 4 compares the consumer surplus and electricity demand between the I-strategy and N-strategy. Compared to the N-strategy, the I-strategy encourages the utility firm to set a lower electricity price, leading to more electricity demand and customer surplus. Therefore, the utility firm invested in carbon abatement technology is better for the government and consumer.

Next, profits were compared between NC (ND) and IC (ID). Using Lemmas 1-4, the following results (summarized in Theorem 5) were obtained.

Theorem 5.5. When comparing the I-strategy and N-strategy, the order of profits is as follows:

1. \( \pi_{DU}^I > \pi_{DU}^N, \pi_{DR}^I > \pi_{DR}^N \)
2. \( \pi_{DS}^I > \pi_{DS}^N, \pi_{CS}^I > \pi_{CS}^N \)
3. \( \pi_{CS}^I > \pi_{DR}^I + \pi_{DU}^I, \pi_{CS}^I > \pi_{DR}^N + \pi_{DU}^N \)

Theorem 5 compares the profits of the supply chain enterprises between the I-strategy and N-strategy. Adoption of carbon abatement technology is always profitable for the supply chain enterprises in both the decentralized system and centralized system. The utility firm with carbon abatement technology can create a Pareto improvement because the cost-saving of carbon emissions reduction is greater than the cost of carbon abatement technology investment. The profits in the centralized system are higher than those in the decentralized system. Therefore, it is a great choice for the utility firm to invest in carbon abatement technology and coordinate the supply chain system.

Theorem 5.6. When comparing the benefits and drawbacks of each strategy, more carbon abatement technology, consumer surplus, and profit of the electricity supply chain are obtained under IC.
Theorem 6 compares the benefits and drawbacks of each strategy. The results show that, compared with NC and ND, under IC and ID, it is better for the utility firm to invest in carbon abatement technology. The choice of carbon abatement technology for large enterprises is more conducive to long-term development, while small and medium-sized enterprises are limited by funds, so they can only buy carbon emission indicators and have little incentive to invest in carbon abatement technology. Moreover, compared with ID, IC is better for the utility firm. Therefore, the utility firm would invest more in carbon abatement technology under IC.

Compared with NC and ND, IC and ID result in more consumer surplus, which shows that investment in low-carbon technology can bring benefits to consumers. Specifically, consumer surplus is the highest under IC.

Compared with NC and ND, IC and ID allow the electricity supply chain enterprises to obtain more profits. Specifically, profit is highest under IC. If there is no investment in low-carbon technology, the profits of enterprises will be reduced. Therefore, under IC it is best to invest more in carbon abatement technology, generate more consumer surplus, and obtain more profit for the electricity supply chain. However, IC may lead to monopoly profits. We suggest that the government should encourage the utility firm to adopt IC to spread the benefits, while the government should prevent utility firm from obtaining excess profits.

6. Coordination. The present study analyzed the coordination of the I-strategy. Theorem 1 showed that the supply chain profits in the centralized system were better than those in the decentralized system. Thus, the electricity supply chain can be coordinated. A revenue-sharing and cost-sharing contract is widely used, i.e., the utility firm pays a lower wholesale price to the retailer and the retailer has to bear a proportional $1 - \gamma_1$ cost of the carbon abatement technology investment and give a proportion $\gamma_2$ of the sales revenue to the utility firm. Therefore, the utility firm pays $\frac{1}{2} \gamma_1 k \xi_2$ of the carbon abatement technology investment cost and the retailer pays $\frac{1}{2} (1 - \gamma_1) k \xi_2$; then, the retailer receives the sales revenue $\gamma_2 pq$ and the utility firm receives $(1 - \gamma_2) pq$.

The profits of the utility firm and retailer are as follows:

$$\pi_{BI}^{\text{DR}} = (\gamma_2 p - w)q - \frac{1}{2} (1 - \gamma_1) k \xi_2,$$  \hspace{1cm} (27)

$$\pi_{BI}^{\text{DU}} = wq - G(q) - tq(e - e_0 - \xi) + (1 - \gamma_2) pq - \frac{1}{2} \gamma_1 k \xi_2.$$  \hspace{1cm} (28)

Lemma 6.1. There exists optimal profits for the supply chain enterprises as follows:

$$\pi_{DI_s}^{\text{DR}} = \frac{k^2 r_2 [a - bt(e - e_0)]^2}{b[k(2 + cb) - bt]^2},$$  \hspace{1cm} (29)

$$\pi_{DI_s}^{\text{DU}} = \frac{k[a - bt(e - e_0)]^2 [k(2 + cb - 2r_2) - bt^2]}{2b[k(2 + cb) - bt]^2},$$  \hspace{1cm} (30)

$$\pi_{DI_s}^{\text{DR}} + \pi_{DI_s}^{\text{DU}} = \pi_{CS} = \frac{k[a - bt(e - e_0)]^2}{2b[k(2 + cb) - bt^2]}.$$  \hspace{1cm} (31)

Theorem 6.2. A revenue-sharing and cost-sharing contract can coordinate the supply chain profit and can be implemented.

(1) When $r_1 = 1$ and $\pi_{DI_s}^{\text{DU}} = \frac{r_2 [a c(k + 2k)(e - e_0) - ar^2]}{k(2 + cb) - bt^2}$, the revenue-sharing and cost-sharing contract can coordinate the supply chain profit.
(2) When \( \frac{k^2(2+cb)^2-2kbt^2(2+cb)+b^2t^4}{k^2(4+cb)^2-2kbt^2(4+cb)+b^2t^4} \leq r_2 \leq \frac{4k+ckb-bt^2}{2k+ckb-bt^2} \), this contract can be implemented.

Theorem 6 shows the availability and feasibility of the revenue-sharing and cost-sharing contract. When \( r_1 = 1 \) and \( w_{BI}^* = \frac{r_2(a+c+2(k(e-e_0)-at^2))}{k(2+cb)}-br^2 \), the profit of the supply chain under the revenue-sharing and cost-sharing contract is the same as that in the centralized system. Moreover, when \( \frac{k^2(2+cb)^2-2kbt^2(2+cb)+b^2t^4}{k^2(4+cb)^2-2kbt^2(4+cb)+b^2t^4} \leq r_2 \leq \frac{4k+ckb-bt^2}{2k+ckb-bt^2} \), the profit of the supply chain enterprise in the coordination system is higher than that in the decentralized system; therefore, the supply chain enterprise is willing to implement the contract providing \( r_2 \) is within the range.

The revenue-sharing and cost-sharing contract set in this paper has certain characteristics. First, revenue-sharing is the retailer’s electricity sales revenue, excluding the electricity purchase cost, in order to make-up for the low carbon investment cost. Second, cost-sharing is the cost of investing in low-carbon technology, excluding the cost of production, to prevent the retailer from bearing more cost. Third, the availability and feasibility of this contract are illustrated by setting reasonable proportions of revenue and investment cost.

7. Numerical study. A numerical analysis was undertaken to confirm the above conclusions and provide further management insight. The unit carbon quota plays an important role in the BM; therefore, the impact of the unit carbon quota on the decision-making of the supply chain was examined. Based on the relevant conditions, the parameter values were as follows: \( a = 10, c = 1.2, a_1 = 1, b = 0.4, e = 1, t = 1, \) and \( e_0 \subset [0, 1] \).

7.1. The impact of the unit carbon quota. Figure 2 shows the relationship between electricity prices \( (p_{CR}^*, p_{DR}^*) \) and the unit carbon quota \( (e_0) \). Electricity prices \( (p_{CR}^*, p_{DR}^*) \) decreased with the unit carbon quota \( (e_0) \), i.e., the higher the unit carbon quota, the lower the cost of the carbon emission. Thus, the supply chain

![Figure 2. Electricity price p as e_0.](image-url)
enterprises would naturally lower their price. Figure 2 also shows that the electricity price in the centralized system \( (p^*_{C^R}) \) was lower than that in the decentralized system \( (p^*_{DR}) \) because the former system avoids “double marginalization”. Double marginalization can reduce the operational efficiency of the electricity supply chain because the supply chain enterprises pursue one-sided maximization for their own benefit. Therefore, the government can set higher carbon quotas to decrease the electricity price.

Figure 3 shows the impact of the unit carbon quota \( (e_0) \) on electricity demand \( (q^*_C, q^*_D) \). First, the electricity demand increased \( (q^*_C, q^*_D) \) with the unit carbon quota \( (e_0) \), as the electricity retailer set a lower electricity price. Second, the electricity demand in the centralized system \( (q^*_C) \) was higher than that in the decentralized system \( (q^*_D) \), because of the lower electricity prices in the centralized system \( (p^*_C) \).

Figure 4 shows the impact of the unit carbon quota \( (e_0) \) on the carbon abatement technology investment \( (\xi^*_C, \xi^*_D) \). First, increasing the unit carbon quota \( (e_0) \) increased the carbon abatement technology investment \( (\xi^*_C, \xi^*_D) \). Increasing the unit carbon quota \( (e_0) \) implies that the utility firm pays a lower carbon emission cost. Thus, the utility firm has more motivation to invest in carbon abatement technology. Second, the carbon abatement technology investment in the centralized system \( (\xi^*_C) \) was higher than that in the decentralized system \( (\xi^*_D) \). Therefore, centralized decision-making is conducive to carbon abatement technology investment.

Figure 5 compared the impact of the unit carbon quota on the profits of the supply chain enterprises between the centralized and decentralized systems. First, the profits \( (\pi^*_C, \pi^*_D, \pi^*_B, \pi^*_B) \) increased with the unit carbon quota \( (e_0) \) under the I-strategy and B-strategy. Increased unit carbon quota \( (e_0) \) decreased the carbon emission cost by buying lower carbon emissions for the utility firm, thus increasing the electricity demand. Second, the profits under the I-strategy \( (\pi^*_B, \pi^*_B) \) were lower than those under the I-strategy and B-strategy \( (\pi^*_B, \pi^*_B) \).
which supports the feasibility of the revenue-sharing and cost-sharing contract, i.e., the utility firm and electricity retailer are willing to accept the contract. Third, the profit of the utility firm $(\pi_{DU}^*, \pi_{BI}^*DU)$ was higher than that of the electricity retailer $(\pi_{DR}^*, \pi_{BI}^*DR)$ because the utility firm is the leader in the electricity supply chain who can make decisions first to obtain more profits, whereas the electricity retailer is the follower who obtains less profit.

7.2. **Sensitivity analysis.** We analyzed price sensitivity and carbon abatement technology sensitivity to examine their stability. We defined $S = \frac{\partial p}{\partial e_0} \frac{c_0}{p}$ and $Z = \frac{\partial \xi}{\partial e_0} \frac{c_0}{\xi}$ to represent the sensitivity.
Figure 6 shows the price sensitivity. It can be seen that $-0.05 < S_{DR}^{IP} < 0.05$ and $-0.05 < S_{CR}^{IP} < 0.05$, which implies that our results are reliable. Moreover, the results show that the electricity price decreases with the unit carbon quota. When the unit carbon quota is increased, the utility firm obtains a greater carbon subsidy; thus, the electricity supply chain enterprises are motivated to reduce the electricity price.

![Figure 6. Price sensitivity.](image)

Figure 7 shows the carbon abatement technology sensitivity. It can be seen that $-0.05 < Z_{CU}^{IC} < 0.05$ and $-0.05 < Z_{DU}^{IC} < 0.05$, which suggests that our results

![Figure 7. Carbon abatement technology sensitivity.](image)
are reliable. Moreover, the results show that the carbon abatement technology investment increases with the unit carbon quota. By increasing the unit carbon quota, the utility firm obtains a greater carbon subsidy. Thus, the electricity supply chain enterprises are motivated to invest in carbon abatement technology.

8. Discussion. Our paper considers deterministic demand and can be expanded to uncertain demand. Thus, we set the electricity demand $\hat{q} = a - bp + \eta$, where $\eta \sim N(\mu, \sigma^2)$. Superscript M represents the case of uncertain demand.

Under ID, the utility firm invests in carbon abatement technology. The utility firm first decides the wholesale price $w$ and carbon abatement $\xi$ and then the retailer decides the electricity price $p$. The profits of the retailer and utility firm are given as follows:

$$\pi_{MI}^{DR} = (p - w)\hat{q},$$ (32)

$$\pi_{MI}^{DU} = \hat{q}w - \frac{1}{2} c(\hat{q})^2 - \frac{1}{2} c\xi^2 - t\hat{q}(e - e_0 - \xi).$$ (33)

Under IC, which regards the utility firm and retailer as a whole, decisions are made on the electricity price and carbon abatement technology investment to maximize the supply chain profit. Thus, the profit of the supply chain is given as follows:

$$\pi_{MI}^{CS} = \hat{q}p - \frac{1}{2} c(\hat{q})^2 - \frac{1}{2} c\xi^2 - t\hat{q}(e - e_0 - \xi).$$ (34)

Theorem 8.1. When comparing IC and ID, the order of carbon abatement technology is as follows: $\xi_{DU}^{MI*} < \xi_{CU}^{MI*}$.

Theorem 8 shows that the carbon abatement investment under IC is higher than that under ID. Compared to ID, the electricity supply chain under IC avoids insider trading (wholesale electricity price). Thus, there is more motivation to invest in carbon abatement technology. This further demonstrates the stability of our conclusion.

9. Conclusion. To date, the literature discussing the BM under a low-carbon environment is limited. The current study examines the BM in the electricity supply chain, contributing to enrichment of the low-carbon literature. In this study, we considered the following problems: (1) whether the utility firm should invest in carbon abatement technology investment or not; (2) the impact of the BM on the behavior of the electricity supply chain enterprises; (3) the design of a contract to improve supply chain efficiency. We found that investing in carbon abatement technology increased electricity demand, customer surplus, and profits of the electricity supply chain enterprises. Moreover, a revenue-sharing and cost-sharing contract could be used to coordinate the electricity supply chain.

This paper discusses the impact of the BM on carbon abatement technology and these findings can provide guidance for supply chain participants. However, there are also some limitations. These limitations can provide directions for further study. Firstly, future study can consider inventory management as analyzed in [31] and [34]. Secondly, dynamic game approaches discussed in [17, 22], and [26] may also be future research opportunities. Thirdly, multi-objective constrained optimization provided by [11, 12, 14, 21, 32], and [35] may be appropriate for future study consideration.
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Appendix.

Proof of Lemma 1. With a backward induction, the electricity retailer as the follower should first determine the electricity price and then the utility firm as the leader decides the wholesale price. With Eq. (1), we have \( p^N_{DR} = \frac{a + bw}{2b} \). Substituting \( p^N_{DR} \) into Eq. (2), we have \( \frac{\partial^2 E(\pi^N_{DU})}{\partial w^2} < 0 \). Hence, \( \pi^N_{DU} \) is concave on the electricity wholesale price. From the first-order conditions, \( \frac{\partial \pi^N_{DU}}{\partial w} = 0 \), we obtain the optimal electricity wholesale price \( w^{N*}_{DU} = \frac{a(2+b)+2b(c-e_0)}{6(4+cb)} \), substituting \( w^{N*}_{DU} \) into \( p^N_{DR} = \frac{a + bw}{2b} \), and we have \( p^N_{DR} = \frac{3a+ach+bet-be_0}{6(4+cb)} \).

Using the electricity demand function and Eqs. (1)–(2), we can obtain the optimal electricity demand and the profits of the electricity retailer, utility firm, and supply chain, respectively, as follows: \( q^N_{DR} = \frac{a - bet + be_0}{4+cb} \), \( \pi^N_{DR} = \frac{(a+bet+be_0)^2}{b(4+cb)} \), \( \pi^N_{SU} = \frac{(a+bet+be_0)^2}{2b(4+cb)^2} \), and \( \pi^N_{DS} = \frac{(a+bet+be_0)^2}{2b(4+cb)^2} \).

Proof of Lemma 2. The proof is similar to that for Lemma 1. Thus, we have not included it here.

Proof of Lemma 3. Using Eqs. (13) and (14), we have \( \frac{\partial^2 E(\pi^I_{DU})}{\partial w^2} = -\frac{b(4+a)b}{4} < 0 \), \( \frac{\partial^2 E(\pi^I_{DU})}{\partial \xi^2} = -\frac{b}{4} \). Let \( H \) be a Hessian of \( E(\pi^I_{DU}) \), \( H = \begin{pmatrix} -a_1 & -bt \\ -bt & \frac{b}{4} \end{pmatrix} \). \( H \) is a negative definite. Hence, \( E(\pi^I_{DU}) \) is jointly concave on the carbon abatement technology investment and wholesale price. Let \( \frac{\partial E(\pi^I_{DU})}{\partial w} = 0 \), \( \frac{\partial E(\pi^I_{DU})}{\partial \xi} = 0 \). We have, \( w^{I*}_{DU} = \frac{2kt(e-e_0)+a(k+be_0) - bt^2}{b(k+be_0) - bt^2} \) and \( \xi^{I*}_{DU} = \frac{tk(a+bt(e-e_0))^2}{b(k+be_0) - bt^2} \).

Substituting \( w^{I*}_{DU} \) into \( p^I_{DR} = \frac{a + bw}{2b} \), with electricity demand function and Eqs. (13) and (14), we can obtain the optimal electricity price, electricity demand, and the profits of the retailer electricity, utility firm, and supply chain, respectively, as follows: \( p^{I*}_{DR} = \frac{3ak+ckb+kbet-kbe_0-ad^2}{6(k+be_0) - bt^2} \), \( q^{I*}_{DR} = \frac{a-kt-kbet+kbet-be_0}{4k+ckb - bt^2} \), \( \pi^{I*}_{DR} = \frac{k^2(a+bt(e-e_0))^2}{2b(k+be_0) - bt^2} \), \( \pi^{I*}_{SU} = \frac{k^2(a+bt(e-e_0))^2}{2b(k+be_0) - bt^2} \), and \( \pi^{I*}_{DS} = \frac{k^2(a+bt(e-e_0))^2}{2b(k+be_0) - bt^2} \).

Proof of Lemma 4. The proof is similar to that for Lemma 3. Thus, we have not included it here.

Proof of Proposition 1. Using Lemma 3, we have \( \frac{\partial \xi^{I*}_{DU}}{\partial e_0} = \frac{bt^2}{k(4+be_0) - bt^2} \), and \( \frac{\partial \xi^{I*}_{DU}}{\partial e_0} = \frac{k^2(a+bt(e-e_0))^2}{2b(k+be_0) - bt^2} \).

That is, \( \frac{\partial \xi^{I*}_{DU}}{\partial e_0} > 0 \), \( \frac{\partial \xi^{I*}_{SU}}{\partial e_0} < 0 \), and \( \frac{\partial \pi^{I*}_{DU}}{\partial e_0} > 0 \), \( \frac{\partial \pi^{I*}_{SU}}{\partial e_0} > 0 \), and \( \frac{\partial \pi^{I*}_{DS}}{\partial e_0} > 0 \).
Using Lemma 4, we have \( \frac{\partial p_t^*}{\partial c_0} = -\frac{kt}{(2+cb)-bt}^2 \), \( \frac{\partial \pi_t^*}{\partial c_0} = \frac{bt}{(2+cb)-bt}^2 \), and \( \frac{\partial \xi_t^*}{\partial c_0} = \frac{kt(a+bt(e_c-e))}{(2+cb)-bt}^2 \).

That is, \( \frac{\partial p_t^*}{\partial c_0} > 0 \), \( \frac{\partial \pi_t^*}{\partial c_0} < 0 \), and \( \frac{\partial \xi_t^*}{\partial c_0} > 0 \).

\[ \square \]

**Proof of Theorem 1.** Using Lemma 1 and 2, we have \( p_{CS}^{N*} - p_{DR}^{N*} = \frac{2(a-bt(e_c-e))}{b(2+cb)} < 0 \), \( q_{CS}^{N*} - q_{DR}^{N*} = \frac{2(a-bt(e_c-e))}{b(2+cb)} < 0 \), and \( \pi_{CS}^{N*} - \pi_{DS}^{N*} = \frac{2(a-bt(e_c-e))}{b(2+cb)}^2 < 0 \).

That is, \( p_{CS}^{N*} < p_{DR}^{N*}, q_{CS}^{N*} > q_{DR}^{N*}, \pi_{CS}^{N*} > \pi_{DS}^{N*} \).

Using Lemmas 3 and 4, we have \( p_t^{I*} - p_{DR}^{I*} = -\frac{2k^2(a-bt(e_c-e))}{b(2+cb)}\frac{kt}{(2+cb)-bt}^2 \xi_{CS}^{I*} \), \( q_t^{I*} - q_{DR}^{I*} = \frac{2k^2(a-bt(e_c-e))}{b(2+cb)}\frac{kt}{(2+cb)-bt}^2 \xi_{DS}^{I*} \), and \( \pi_t^{I*} - \pi_{DS}^{I*} = \frac{2k^2(a-bt(e_c-e))}{b(2+cb)}\frac{kt}{(2+cb)-bt}^2 \xi_{DS}^{I*} \).

That is, \( p_t^{I*} < p_{DR}^{I*}, q_t^{I*} < q_{DR}^{I*}, \xi_t^{I*} > \xi_{DS}^{I*}, \pi_t^{I*} > \pi_{DS}^{I*} \).

\[ \square \]

**Proof of Theorem 2.** Using \( q = a - bp, C_s = \frac{(a-bp)^2}{2b} \), for Theorem 2, we have \( p_t^{I*} < p_{DR}^{I*} \) and \( C_s t_{DR}^* < C_s t_{DR}^* \).

\[ \square \]

**Proof of Theorem 3.** Using Lemmas 1 and 4, we have \( p_t^{I*} - p_{DR}^{N*} = -\frac{2k^2(a-bt(e_c-e))}{b(2+cb)}\frac{kt}{(2+cb)-bt}^2 \xi_{CS}^{I*} \), \( q_t^{I*} - q_{DR}^{N*} = \frac{2k^2(a-bt(e_c-e))}{b(2+cb)}\frac{kt}{(2+cb)-bt}^2 \xi_{DS}^{I*} \).

Using Lemmas 2 and 3, we have \( p_t^{I*} - p_{DR}^{N*} = \frac{2k^2(a-bt(e_c-e))}{b(2+cb)}\frac{kt}{(2+cb)-bt}^2 \xi_{DS}^{I*} \), and \( q_t^{I*} - q_{DR}^{N*} = \frac{2k^2(a-bt(e_c-e))}{b(2+cb)}\frac{kt}{(2+cb)-bt}^2 \xi_{DS}^{I*} \).

That is, \( p_t^{I*} < p_{DR}^{I*}, q_t^{I*} < q_{DR}^{I*} \).

\[ \square \]

**Proof of Theorem 4.** The proof of Theorem 4 is the same as Theorem 3.

\[ \square \]

**Proof of Theorem 5.** Using Lemmas 3 and 4, we have \( \pi_{DS}^{I*} - \pi_{DS}^{N*} = \frac{t^2(a-bt(e_c-e))}{2(2+cb)^2(4+cb)}(4+cb)(2+cb-bt) \), \( \pi_{DS}^{I*} - \pi_{DS}^{N*} = \frac{t^2(a-bt(e_c-e))}{2(2+cb)^2(4+cb)}(4+cb)(2+cb-bt) \).

That is, \( \pi_{DS}^{I*} > \pi_{DS}^{N*} \) and \( \pi_{DS}^{I*} > \pi_{DS}^{N*} \) and \( \pi_{DS}^{I*} > \pi_{DS}^{N*} \). Moreover, \( \pi_{DS}^{I*} > \pi_{DS}^{N*} \), \( \pi_{DS}^{I*} > \pi_{DS}^{N*} \), and \( \pi_{DS}^{I*} > \pi_{DS}^{N*} \).

Thus, \( \pi_{DS}^{I*} > \pi_{DS}^{N*} \) and \( \pi_{DS}^{I*} > \pi_{DS}^{N*} \).

\[ \square \]

**Proof of Theorem 6.** With \( \frac{\partial \pi_{CS}^{I*}}{\partial p} = 0 \), we have \( p_{CS}^{I*} = \frac{1}{2} (a + w + \frac{2a}{r_2}) \). Placing \( p_{CS}^{I*} \) in Eq. (27), with \( \frac{\partial \pi_{CS}^{I*}}{\partial c_0} = 0 \), we have \( \xi_{CS}^{I*} = \frac{1}{r_1(2+cb-bt)} \).

Let \( p_{CS}^{I*} = p_{CS}^{I*} \), \( \xi_{CS}^{I*} = \xi_{CS}^{I*} \). We have \( r_1 = 1 \) and \( w = \frac{r_2}{2k(2+cb-bt)} \).

Thus, \( \pi_{DR}^{I*} = \frac{k^2}{2b(2+cb-bt)} \), \( \pi_{DS}^{I*} = \frac{k^2}{2b(2+cb-bt)}(2+cb-bt) \), and \( \pi_{DS}^{I*} + \pi_{DR}^{I*} + \pi_{DS}^{I*} = \frac{k^2}{2b(2+cb-bt)} \).

\[ \square \]

**Proof of Theorem 7.** Using Lemmas 3 and 5, \( \pi_{DS}^{I*} - \pi_{DS}^{I*} > 0 \) and \( \pi_{DS}^{I*} - \pi_{DS}^{I*} > 0 \).

We have \( r_1 = 1, w = \frac{r_2}{2k(2+cb-bt)} \) and \( k^2/(2+cb-bt) + k^2/(2+cb-bt) \leq r_2 \leq \frac{2k(2+cb-bt)}{2k(2+cb-bt)} \).

\[ \square \]
Then, we can get \( \xi_{CU}^* - \xi_{DU}^* = \frac{2kt(a-bet+\mu+bt+c\theta)}{(2+t+c)k-bt^2} > 0. \)

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