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Research Article

The Multi-Period Dynamic Optimization with Carbon Emissions Reduction under Cap-and-Trade

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Under low carbon environment, a multi-period emissions reduction problem for manufacturer is investigated in the paper, where we assume that the government sets mandatory carbon emissions limit to all the enterprises by free of charge and allows the carbon emission quota to be traded or banked inter-temporally in the carbon trading market. Using discrete-time optimal control theory, the optimal emission reduction strategies for each period are firstly explored for maximizing the sum of net profit under cap-and-trade. The optimal carbon emissions, permit trading quantity, and the number of buying Certified Emission Reduction (CER) are obtained in each period. Furthermore, the effects of carbon price and initial carbon quota given by the government on the firm's emission reduction strategies are discussed. Finally, numerical examples are illustrated to verify the proposed model, and some managerial inferences for a multi-period emission reduction are provided in conclusions.

1. Introduction

Recently, the reliance on carbon-based energy in industry and economic activities has led to excessive carbon dioxide emissions, posing unprecedented challenges to the global economy and ecosystem. Nowadays, governments and international organizations are actively taking some measures to reduce emissions; for example, cap-and-trade mechanism is considered as one of the most effective emission reduction mechanisms in practice. The mechanism sets mandatory emissions limit to all the enterprises by free of charge or auction at the beginning of the regulation period and allows the carbon emission quota to be traded in the carbon trading market. Under this mechanism, enterprise's carbon emissions cannot exceed the mandatory quota set by the government; once actual carbon emissions exceed this limit set by government, enterprises have to buy carbon emission permits in the trading market. On the contrary, when the regulated enterprises have surplus allowance after compliance, they can also sell them in external emission trading market. Therefore, the emission trading can effectively slow the emitting of greenhouse gases by using market mechanism.

Considerable research and practice [1–4] also indicate that the carbon emissions trading system can control the carbon emissions of enterprises by market mechanism, effectively reducing the emissions of greenhouse gases and making a great contribution on the global reduction of carbon emissions. In theory, Hass and Dales [5] firstly proposed the idea of market mechanism to deal with pollution issues. Hereafter, some scholars [6, 7] have began to focus on economical and social problems of carbon trading permit. In practice, European Union is considered as the pioneering organization in emission reduction. In early 2005, to achieve the emission reduction aim made in Kyoto Protocol, they developed European Union Emission Trading Scheme (EU-ETS), which is the first multinational participation emission trading scheme in the world. At present, EU-ETS had conducted two stages; the third stage is in progress. Based on the experience from EU-ETS, some other countries or regions like Japan, Korea, and China also began to implement similar carbon trading system for slowing greenhouse gases emission. Among them, since 2013, China has built seven emission trading pilot cities like Shenzhen, Beijing, Shanghai, Tianjin, etc. And on November 2017, trading permit of carbon dioxide in China has been more than 200 million tons, and turnover has reached about 4.6 billion CNY, which makes China rank the second largest emission trading market. It is worth noting that China's carbon emissions trading system officially launched on December 19, 2017. Up to now, China has ranked the largest carbon trading market in the world.

In order to encourage enterprises to voluntarily develop energy saving and emission reduction activities, some countries and international organizations like European Union allow enterprises to adopt a voluntary emission reductions mechanism to offset the carbon emissions (usually, there are two basic types of carbon emissions permit that need to be considered in emission trading market: one is permit that the policy-maker allocates to firms in the beginning; the other is CER that is a credit for reducing greenhouse gas emissions through environmental protection project). That is, the regulated enterprises can not only buy quotas from the carbon market, but also purchase Certified Emission Reduction (CER) to fulfill their contracts. In 2012, China government also released Chinese Certified Emission Reduction (CCER) mechanism, which can be used for regulated firms. Meanwhile, to reduce the emission of polluting enterprises, China's pilot carbon emission trading markets all have strict requirements on the use of CCER (i.e., the certified emission cannot exceed 5% to 10% of the actual annual carbon emissions of enterprises). In this paper, we do not distinguish CER between European Union and China market; therefore we uniformly adopt CER.

In the process of compliance, if enterprises exceed the carbon quotas given by government, they need to purchase quotas from other enterprises in external market, and then a carbon transaction is formed. Of course, they can also voluntarily reduce their emissions by using other new energy projects; then a voluntary reduction that needs to be certified by government can be treated as a CER. Therefore, under cap-and-trade, whether or not to buy CER to offset and how to choose the compliance strategy will be the first concern of the enterprises.

As a special commodity, it is noteworthy that permit can be tradable in emission trading. However, due to the inconsistency of the compliance period in different the regulatory stage (i.e., the first stage of the implementation of the EU carbon trading market, the compliance period is 3 years; In the second stage, the compliance period is 5 years, and in the third stage, the compliance period is 8 years), this causes the inter-temporal trading problems of carbon emission rights. In practice, inter-temporal emissions trading can not only make better use in carbon emissions allocation, but also reduce transaction costs and decrease the influence of market forces [7–9]. To be specific, in the end of a compliance period, the enterprises can choose to keep unused emission quotas for future use (also known as inter-temporal banking), and also take the future emission quota as present use (also known as inter-temporal borrowing), but in the end of this stage, they must be paid off overdraft emissions, and meanwhile, unused emission quota should not be less than the current total carbon emissions. But in China's current carbon emissions trading market, pilot cities have carried out the first stage (i.e., the compliance period is 3 years), and each market allows carbon quotas inter-temporal banking, but does not allow the quota of inter-temporal borrowing.

As mentioned above, under cap-and-trade, firms can adopt permit or CER when their carbon emissions permit cannot offset their emissions. What is more, the firms can also participate in emission reduction activities, directly, and then sell their surplus permit, and even they can also adopt inter-temporal banking permit for next use within multi-compliance periods. In this paper, noting the emergence of carbon trading markets and the particularity of emission rights as commodities in the market, we here mainly focus on how to use carbon quotas within multi-compliance periods at a regulation stage, where the carbon quota given by the government is assumed to be allocated free of charge in the beginning, and this quota can also be replaced by CER. We intend to understand what the incentives of adopting multi-period carbon reduction strategy under cap-and-trade are. Many researchers have given considerable attention in cap-and-trade, but few papers provide the carbon emissions strategy for each compliance period in a regulatory stage. Specifically, we will cover this gap by investigating the following questions:

(1) how do enterprises make the optimal strategy of multi-period carbon emissions reduction at a regulation stage when carbon emissions rights are allowed to be carried forward for next use under cap-and-trade?

(2) how does the purchase of CER to offset emission reduction affect carbon quotas allocation in different compliance periods?

(3) What factors will influence the regulated firms carbon emissions reduction strategy in each compliance period and how do these factors affect this optimal strategy under cap and trade?

The remainder of the paper is as follows. In Section 2, a literature review is given. The problem prescription, model notations, and related assumptions are described in Section 3. The optimal control model with firms production and emission reduction in multi-period under cap-and-trade are discussed in Section 4. Numerical examples and analyses are given in Section 5. Finally, summary and conclusions of the paper are provided in Section 6.

2. Related Literature

To highlight our contributions, we mainly review two streams of emissions trading literature relevant to our work, namely, inter-temporal permit trading and operation optimization of enterprises under cap-and-trade.

2.1. Inter-Temporal Permit Trading. According to whether the time interval is continuous or not, existing research on inter-temporal permit trading can in general be classified into discrete time model and continuous time model.

For discrete time case, earlier research on this model under emission trading can be traced back to Montgomery [6]; however, he failed to consider the issues of inter-temporal permits. From the perspective of emissions information asymmetry, Yates and Cronshaw [10] found that asymmetric emission information is an important motivation of allowing inter-temporal permit trading, and the permit trading could reduce greenhouse gases. Different from previous study, based on a random simulation and coordination technique, Rong and Lahdelma [11] developed algorithm to solve stochastic optimization problems under emissions trading. Hereafter, Liski and Montero [12, 13] studied pollution permit banking and market power and explored forward permit trading and incomplete observability of permit holdings. Using discrete dynamic programming model under stochastic emission, Yu and Mallory [14] studied how regulator decided equilibrium emission cap and price ceiling in a short run and long run. More recently, considering that speculators have an imperfect cross-period arbitrage, Chen and Tanaka [15] not only explored the market power of permit market with permit trading, but also took market power of product into consideration. Our paper is highly related to Cronshaw and Cruse [16], in which they theoretically analyzed inter-temporal permit problems using discrete time model with banking and considered the effect of bankable permit for next stage using on firms decisions in permit market. However, their research was based on the perspective of government and did not mention a single enterprise's strategic behavior.

For continuous time cases, during the past two decades, more and more scholars have studied the models with the permit trading. For example, considering inter-temporal borrowing and banking, Rubin [17] extended the research of Cronshaw and Cruse [16] and analyzed the firm's optimal permit price and emission decisions. From the perspective of regulator, Laiby and Rubin [7] also investigated a decision of inter-temporal trading rate for banking and borrowing; their results showed that optimal permit trading rate is related to marginal abatement cost, marginal stock-holding damages, and the decay rate of emission. Different from the aforementioned studies, Liski and Montero [18] were the first to consider the effect of market power on equilibrium path of emission permits in imperfect competitive market with a dominant firm; the results showed that this path depends on base-stock of permit and long-run market power of permit and allowance.

Compared with the continuous time model, when storing carbon emissions permit varies with time, the discrete time model may be more suitable to describe a single enterprise's operation behavior in the real world. However, most of researches on the discrete time model discussed emission trading permit from the perspective of policy makers. In this paper, we incorporated CER into inter-temporal trading issues and explored enterprise's operation strategy with multi-period production and emission reduction.

2.2. Enterprise's Operation under Cap-and-Trade. With the popularization of carbon trading in many countries, more and more enterprises are regulated by government in carbon emissions. Especially when the emission right is tradable or even stored in the market, the issues of resource allocation for enterprises become more complicated. In recent years, more and more scholars have given considerable attention in the enterprises' operation under the carbon trading mechanism.

Many scholars have studied the single-cycle production and operation decision-making under the carbon trading mechanism. For example, Subramanian et al. [19] studied the abatement investment and production under three-stage game. Under cap-and-trade, Huang and Chen [20] investigated manufacturer's dynamic production-inventory strategy with stochastic market demand and allowance price. Under some carbon emissions regulations like tax policy and cap-and-trade, He et al. [21] investigated economic order lot-sizing issues. For decentralized and centralized supply chains, Dong et al. [22] developed the sustainability investment on product under emission regulation, gained the optimal production quantity and sustainability investment, and found that the sustainability investment efficiency has a significant impact on the optimal solutions. Later, Li et al. [23] compared the issues of pricing and green production of channel members in single channel or dual-channel supply chain, and they discussed supply chain coordinate issues. Recently, some scholars also focused on some other production and operation problems, including manufacturer-to-consumer [24], consumers service level [25], emission abatement and green technology investment [26–28], product's lifetime [29], joint production and pricing [30], and reciprocal preferences and consumers' low carbon willingness [31].

For multi-period business operations under cap-and-trade, Dobos [32, 33] firstly investigated the effect of tradable permit on production-inventory strategies by using Arrow-Karlin model. Later, Li [34] also explored the effect of inter-temporal permit banking on optimal production-inventory decision. By introducing emission permit banking and pollution abatement, Li [35] developed a dynamic model and discussed the effect of emission permit banking and pollution abatement on the optimal strategy. Hereafter, Li [36] also provided dynamic control model of pollution abatement with permits banking and investigated the relationships between investment and emissions permits quantity. Different from Li [34–36], we consider a issue of carbon emissions permit banking under cap-and-trade, where regulated companies can buy CER when they fulfill their contracts.

For the studies of cap-and-trade from the viewpoint of supply chain management, many scholars explored single enterprise's operation decisions under cap-and-trade. Under cap-and-trade or taxation policy, Zhang and Xu [37] analyzed a single regulated manufacturing firm's production planning of multiple products when he/she faced random market demand. Zhang et al. [38] investigated a product pricing and emission reduction behavior of China allowance allocation rule including grandfathering, self-declaration, and auctioning; the result indicated that distinct allowance allocation rules had a great impact on emission reduction strategy and development of the regulated firm; the regulator may adopt proper allocation rule according to the property of different industries. Du et al. [39] focused on production of carbon footprint and low-carbon preference and established the optimal production model. Xu et al. [40] studied the issue of joint production and pricing on multiple products. Gong and Zhou [41] also considered the polluting firm's multi-stage production planning under cap-and-trade and discussed the

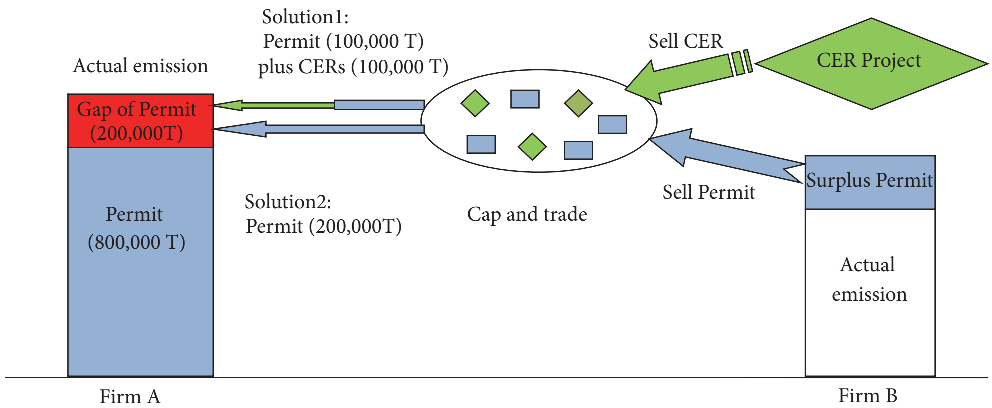

Figure 1: The compliance program of firm A.

trading price of emission rights in forward contracts that satisfies the random Markov chain.

Based on carbon market experience in China, we explore multi-period optimization decision of firms under cap-and-trade. Our work is different from Gong and Zhou in the following four aspects: (1) we consider that emissions permit can just be banked within multi-period, but it cannot be overdraft in advance; (2) we do not explore low carbon technology choices, but intend to study how to allot carbon quotas within multi-period; (3) we use optimal control model instead of the Markov chain model; (4) we mainly focus on how to make decision of purchasing CER when firms implement carbon emissions reduction.

As far as we know, under cap-and-trade, previous researches on firm's operation optimization mainly focus on production, inventory, pricing, and abatement investment, but most of them have almost exclusively discussed that the regulated firm can buy carbon emission allowance directly and also purchase CER to offset the carbon emissions. However, it is very common under this mechanism in some countries and regions like EU and China. Therefore, we will mainly explore the inter-temporal issue by investigating the use of carbon quotas, inter-temporal banking, and buying CER, etc.

3. Model Notations and Basic Assumptions

3.1. Model Description. The paper investigates a single firm's multi-period decision of emission reduction and optimization under cap-and-trade. To intend to understand firm's inter-temporal issues, we here assume that the government regulates the total emission quantity in each period and the firm can choose to increase investment in reducing emissions and sell the surplus permit, and also adopt inter-temporal banking within regulated emission allowance for future using, but if his/her allowance is less than actual carbon emissions, the firm can buy permit or buy a certain amount of CER to offset carbon emission within the regulation periods. In order to clearly show the implementation plans of firms under cap-and-trade mechanism, we take two enterprises of carbon emissions reduction as example and describe the implementation plans under the following two different cases.

Case 1. A regulated firm A owns permit of 800,000 tons, and his real emission quantity is 1 million tons; therefore his permit is less than emission quantity; that is, there is a gap of 200,000 tons. There exist two compliance programs:

Solution 1: The firm can directly choose to buy permit of 200,000 tons in emission trading market for accomplishing compliance.

Solution 2: Noting the fact that the government allows offset carbon emissions by using CER (i.e.,ten percent of the actual annual carbon emissions), the firm can also choose to purchase CER of 100,000 tons (1,000,000 × 10 %) and extra permit of 100,000 tons in emission trading. The firms real permit after buying is 900,000 tons (800,000 plus 100,000), and CER used is 100,000 tons; then he can also achieve compliance.

The compliance program of regulated firm A is shown in Figure 1.

Case 2. A regulated firm C owns permit of 1 million tons, and his real emission quantity is 800,000 tons, so his permit is more than emission quantity; namely, there is a surplus of 200,000 tons, and therefore there exist three compliance programs:

Solution 1: The firm can sell 200,000 tons permit, directly.

Solution 2: The firm can bank 200,000 tons permit for next use.

Solution 3: The firm can offset emission using CER (i.e.,ten percent of the actual annual carbon emissions), that is, buying CER of 80,000 tons (800,000 × 10%). The real permit of the firm is 1 million tons and using CER is 80,000 tons, so the firm has just 280,000 tons permit over after compliance. Then the firm can also choose to sell the permit or bank for future use.

The compliance program of regulated firm C is shown in Figure 2.

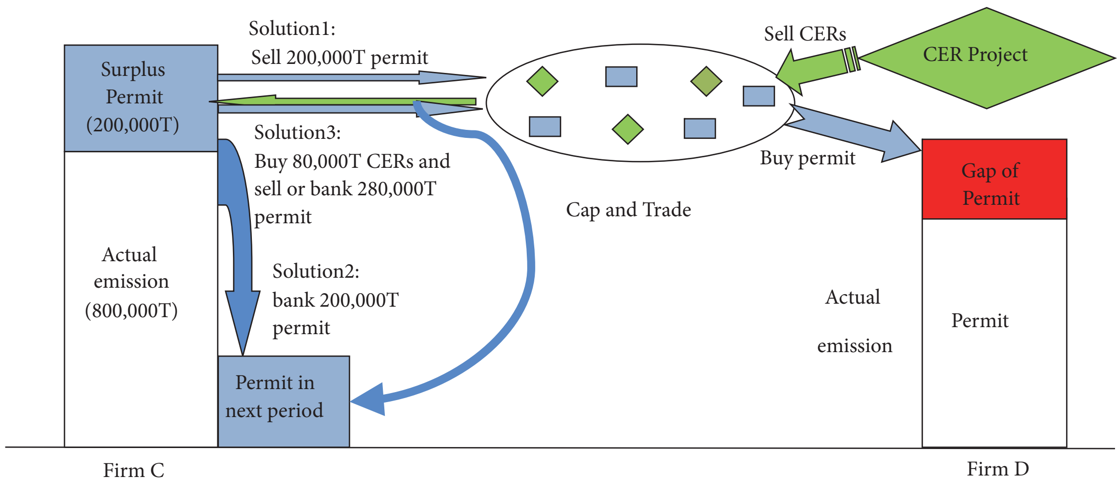

Figure 2: The compliance program of firm C.

In general, for regulated enterprises, comparing current carbon price per unit carbon emission and the price of the CER per unit carbon emission (i.e., the carbon price is usually higher than the CER price, but in the second half of 2015, the opposite case also happened in Shanghai, China), they can make the current compliance plans based on their own interest.

Based on the above description, under cap-and-trade mechanism, multi-period emission reduction can bring more strategic choices for enterprises. In this paper, we mainly consider some realistic factors like carbon quota given by government at different periods, price of per unit carbon emission, the market price of the CER per unit, and market demand affected by consumer environmental awareness, etc. Each of them will affect the enterprise production decisions and emissions reduction. Therefore, we are mainly concerned about which strategies would make enterprise more higher net profit within the regulated period.

3.2. Model Notations. To develop our optimal control model, we introduce the following parameters, decisions variables, and state variable and co-state variable:

(i) Exogenous Parameters

T: the permit operating period regulated by the government (for example, the first stage of EU-ETS is from 2005 to 2007 in EU; then their compliance period is 3 years in this study; namely, $T = 3$);

t: the compliance of permit period during operating process, where $t = 1, 2, \ldots, T$;

U: the profit per unit product;

α the proportion of using CER permit deduction in carbon emission, where $0 \leq \alpha \leq 1$;

e_0: the initial emission quantity of per unit product;

ρ: the discount rate (we here assume that this discounted rate is the same within compliance period T);

$P(t)$: the price of permit at t period under cap-and-trade;

$P_c(t)$: the price of CER at t period under cap-and-trade;

$g(t)$: the emission permit of unit product allocated by the government at the beginning of t period.

(ii) Endogenous Variables

$e(t)$: the emission quantity of per unit product at t period, where $e(t) \geq 0$;

$y(t)$: the firm's trading permit quantity at t period, where $y(t) > 0$ means buying permit, the opposite means selling permit;

$y_c(t)$: the buying quantity of CER at t period, where $y_c(t) \geq 0$;

(iii) State Variable and Co-State Variable

$S(t)$: the banking quantity of permit at t period (it should be pointed out that $S(t) \geq 0$ means the cap and trade mechanism allows inter-temporal banking but forbidding inter-temporal overdraft. We thus assume that the quantity of initial permit is 0; that is, $S(1) = 0$. Considering the government usually clears the firm's allowance after a compliance period, we therefore assume $S(T + 1) = 0$);

$\lambda(t)$: co-state variable.

Combining with Sections 3.1 and 3.2, the multi-period production and emission reduction decisions process of a single firm under cap-and-trade are described in Figure 3.

3.3. Model Assumption. (1) Note that, with the gradual warming of the global climate, low-carbon products are favored by consumers in the market. Numerous studies have confirmed that more and more consumers are willing to pay more for environmentally friendly products [42]. That is, the market demand for low-carbon products increases as the product's carbon emissions decrease. However, similar to new product's investment in the process of enterprise operation, the marginal efficiency of demand affected by emission reduction decreases, and the effect of demand affected by emission reduction decreases; namely, the demand increment brought by unit emission reduction gradually decreases. We thus assume the market demand is influenced by emission quantity of product (see Figure 4). In particular, $D(e(t))$ decreases in $e(t)$ such that $D'(e(t)) < 0$, $D''(e(t)) < 0$, $D(e_0) = D_0$, and $D(0) < D_h$ (see Xia and He, 2014 [43]).

(2) The input cost of unit emission reduction is assumed to be related to the expected emission reduction effect; that is, compared with the initial carbon emission, the larger the emission reduction range is, the higher the cost of emission reduction will be, and vice versa. However, there is no linear relationship between them. According to the principle of marginal effect in economics, as the cost of emission reduction increases, more cost of emission reduction is needed to achieve the same effect as before. Similar cost function has been used in existing literatures [44, 45]. In this paper, as shown in Figure 5, the cost of firm's unit emissions reduction $C(e(t))$ is assumed to be decreasing in $e(t)$ and satisfies the following properties: $C'(e(t)) < 0$, $C''(e(t)) > 0$, $C(e_0) = 0$, and $\lim_{e_t \longrightarrow 0} C(e_t) = +\infty$.

(3) We here refer to China's pilot cities such as Shanghai on carbon quota implementation and assume that the carbon quota set by the government for each enterprise is allocated by using the historical intensity method and adjusted according to firm's output at the beginning of each period, appropriately.

(4) Note that, in some China's cities like Shanghai, Beijing, Shenzhen, Guangdong, and Hubei, emission trading laws all stipulate that CER of local firms cannot be used to offset carbon emissions or clear carbon quotas in their own cities; we here assume that the investment for CER project is not allowed. And thus, the firm does not produce additional CER.

(5) We assume that the manufacture firm produces low carbon product according to market demand, and the effect of inventory and out of stock on firm's operation decisions is neglected.

(6) We do not consider inter-temporal speculation behavior, and in each period, the firm initially owns the amount of carbon emission $S(t)$ that satisfies the following state equation: $S(t+1) = S(t)+g(t)e(t)-e(t)D(e(t))+y(t)+y_c(t)$, $t = 1, 2, \ldots, T$, where $S(1) = 0$, $S(t) \geq 0$, and $S(T+1) = 0$.

4. The Model

Based on the above description and assumptions, we give the following dynamic control model within the compliance period T.

$$\begin{aligned}
\text{Model}: \quad & J^* = \max_{e(t), y(t), y_c(t)} \sum_{t=1}^{T} (1+\rho)^{-t} \left[UD(e(t)) - C(e(t)) D(e(t)) - P(t) y(t) - P_c(t) y_c(t) \right], \\
\text{s.t.} \quad & S(t+1) = S(t) + g(t) e(t) - e(t) D(e(t)) + y(t) + y_c(t); \\
& S(t+1) \geq 0; \\
& S(1) = 0; \\
& S(T+1) = 0; \\
& e(t) \geq 0; \\
& y_c(t) \geq 0; \\
& y_c(t) \leq \alpha e(t) D(e(t)); \\
& t = 1, 2, \ldots, T,
\end{aligned} \tag{1}$$

where, *in the objective function of the model*, J^* denotes the optimal objective value of the total net profit for the regulated firm within compliance period T and the emission quantity of per unit product $e(t)$, the firms trading permit quantity $y(t)$, and the buying quantity of CER $y_c(t)$ are control variables, *while, in the constraints of the model*, the banking quantity of permit $S(t)$ is state variable; $S(t+1) \geq 0$ shows that the firm can inter-temporally bank but not overdraw in advance; $S(1) = 0$ indicates that the permit owned by the firm is zero at the beginning of the first period; $S(T+1) = 0$ implies that there is no excess permit at the end of the planning period; $e(t) \geq 0$ represents non-negative permit of each period t; $y_c(t) \geq 0$ means that the regulated firm does not produce (sell) CER, and $y_c(t) \leq \alpha e(t)D(e(t))$ represents that the firm cannot exceed the proportion of using CER regulated by the government.

Our aim is to maximize the regulated firm's total net profit within compliance period T; we thus have the following theorem.

Theorem 1. *For $t = 1, 2, \ldots, T$, we can get the model's optimal solution pair $(y_c^*(t), e^*(t), y^*(t), S^*(t+1))$, where*

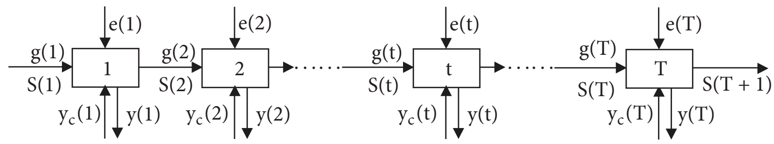

FIGURE 3: Multi-period production and emission reduction process.

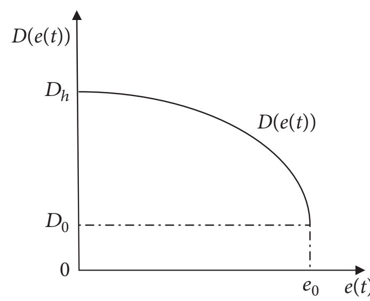

FIGURE 4: The function graphic of $D(e(t))$.

(1) *(i) when* $P(t) > P_c(t)$, *then* $y_c^*(t) = \alpha e(t)D(e(t))$;
(ii) when $P(t) = P_c(t)$, *then* $y_c^*(t) \in [0, \alpha e(t)D(e(t))]$;
(iii) when $P(t) < P_c(t)$, *then* $y_c^*(t) = 0$.
(2) *the optimal* $e^*(t)$ *satisfies the conditions* $UD'(e(t)) - C'(e(t))D(e(t)) - C(e(t))D'(e(t)) + P(t)g(t)D(e(t)) - [P(t)(1-\alpha) + P_c(t)\alpha][D(e(t)) + e(t)D'(e(t))] = 0$ *and* $(\partial^2 L(t)/\partial e^2(t))|_{e(t)=e^*(t)} = [U + P(t)g(t)]D''(e(t)) - C''(e(t))D(e(t)) - 2C'(e(t))D'(e(t)) - C(e(t))D''e(t)) - [P(t)(1-\alpha) + P_c(t)\alpha][2D'(e(t)) + e(t)D''(e(t))] < 0$.
(3) *(i) when* $P(t) > (1+\rho)^{-1}P(t+1)$, *then* $y^*(t) = e^*(t)D(e^*(t)) - S(t) - g(t) - y_c^*(t)$;
(ii) when $P(t) = (1+\rho)^{-1}P(t+1)$, *then* $y^*(t) = 0$ *and* $y^*(T) = e^*(T)D(e^*(T)) - S(T) - g(T) - y_c^*(T)$, *where* $t = 1, 2, \ldots, T-1$.
(4) $S^*(t+1) = S^*(t) + g(t) - e^*(t)D(e^*(t)) + y^*(t) + y_c^*(t)$.

Proof of Theorem 1. Firstly, to solve the optimal control problem with constraints, let Hamiltonian function be $H_t = (1+\rho)^{-t}[UD(e(t)) - C(e(t))D(e(t)) - P(t)y(t) - P_c(t)y_c(t)] + \lambda(t+1)[S(t) + (g(t) - e(t))D(e(t)) + y(t) + y_c(t) - S(t+1)]$. Combining with $S(t+1) \geq 0$ and $y_c(t) \leq \alpha e(t)D(e(t))$, we introduce Lagrange multiplies $\omega_1(t)$ and $\omega_2(t)$ and build Lagrange function of the optimal control model as follows:

$$\bigwedge_t = H_t + \omega_1(t+1)S(t+1) + \omega_2(t+1)[\alpha e(t)D(e(t)) - y_c(t)]. \tag{2}$$

Likewise, (2) can be further written as

$$\bigwedge_{t-1} = H_{t-1} + \omega_1(t)S(t) + \omega_2(t)[\alpha e(t-1)D(e(t-1)) - y_c(t-1)]. \tag{3}$$

From (2) and (3), Euler Equation with respect to $S(t)$ can be expressed by

$$\frac{\partial \bigwedge_t}{\partial S(t)} + \frac{\partial \bigwedge_{t-1}}{\partial S(t)} = 0, \tag{4}$$

Equation (4) can be further written as

$$\lambda(t+1) - \lambda(t) + \omega_1(t) = 0. \tag{5}$$

Owing to the inequality constraints of $e(t)$ and $y_c(t)$, all the inequality constraints are linear, so they satisfy constraint qualification [46]. Furthermore, combining with Pontryagin's maximum principle, canonical equations of the optimal control problem can be described as follows:

$$\begin{aligned}\frac{\partial \bigwedge_t}{\partial e(t)} &= (1+\rho)^{-t}\left[UD'(e(t)) - C'(e(t))D(e(t)) - C(e(t))D'(e(t))\right] + \lambda(t+1)g(t)D'(e(t)) \\ &\quad + \omega_2(t+1)\alpha\left[D(e(t)) + e(t)D'(e(t))\right] - \lambda(t+1)\left[D(e(t)) + e(t)D'(e(t))\right] \leq 0.\end{aligned} \tag{6}$$

$$\frac{\partial \bigwedge_t}{\partial y(t)} = \lambda(t+1) - (1+\rho)^{-t}P(t) = 0. \tag{7}$$

$$\frac{\partial \bigwedge_t}{\partial y_c(t)} = \lambda(t+1) - (1+\rho)^{-t}P(t) - \omega_2(t+1) \leq 0. \tag{8}$$

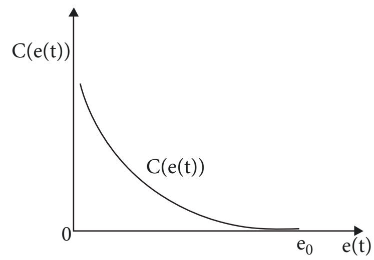

Figure 5: The function graphic of $C(e(t))$.

$$\frac{\partial \bigwedge_t}{\partial \omega_1 (t+1)} = S(t+1) \geq 0. \quad (9)$$

$$\frac{\partial \bigwedge_t}{\partial \omega_2 (t+1)} = \alpha e(t) D(e(t)) - y_c(t) \geq 0. \quad (10)$$

$$e(t) \geq 0. \quad (11)$$

$$e(t) \frac{\partial \bigwedge_t}{\partial e(t)} = 0. \quad (12)$$

$$y_c(t) \geq 0. \quad (13)$$

$$y_c(t) \frac{\partial \bigwedge_t}{\partial y_c(t)} = 0. \quad (14)$$

$$\omega_1 (t+1) \geq 0. \quad (15)$$

$$\omega_1 (t+1) S(t+1) = 0. \quad (16)$$

$$\omega_2 (t+1) \geq 0, \quad (17)$$

$$\omega_2 (t+1) \left[\alpha e(t) D(e(t)) - y_c(t)\right] = 0. \quad (18)$$

And the boundary condition is $S(1) = 0$ and $S(T+1) = 0$. We have the following results:

(1) The Solution of $y_c^*(t)$. According to (7), we have

$$\lambda(t+1) = (1+\rho)^{-t} P(t). \quad (19)$$

and

$$\lambda(t) = (1+\rho)^{-(t-1)} P(t-1). \quad (20)$$

From $\partial \bigwedge_t / \partial S(t) = \lambda(t+1)$, we get that $\lambda(t+1)$ is the shadow price of permit banking $S(t+1)$, which indicates that investing a unit permit banking can generate the increment of total net profit at the ending of t period. Equation (19) represents that when the firm increases a unit permit banking, the increment of net profit equals the permit price in the current.

Substituting (19) into (8), we have

$$(1+\rho)^{-t} P(t) - (1+\rho)^{-t} P_c(t) - \omega_2 (t+1) \leq 0. \quad (21)$$

From (14), we get the following discussion:

(1) when $y_c(t) > 0$, $\partial \bigwedge_t / \partial y_c(t) = 0$, then (21) can be converted to

$$\omega_2 (t+1) = (1+\rho)^{-t} \left(P(t) - P_c(t)\right). \quad (22)$$

From (17) we have $\omega_2(t+1) \geq 0$, and then $P(t) \geq P_c(t)$. Therefore, we have the following two results:

(i) when $P(t) > P_c(t)$, then $\omega_2(t+1) > 0$; this implies that CER has the positive shadow price, and thus CER has been completely used. Therefore, according to (10) we have $\alpha e(t) D(e(t)) - y_c(t) = 0$, that is, $y_c^*(t) = \alpha e(t) D(e(t))$;

(ii) when $P(t) = P_c(t)$, then $0 < y_c^*(t) < \alpha e(t) D(e(t))$.

These two results indicate that when the current price of carbon is higher than the price of CER, if the CER is allowed to be used to offset carbon emissions, then the optimal number of buying CER just equals $\alpha e(t) D(e(t))$; when the current price of carbon is just equal to the price of CER, the optimal number of buying CER is less than $\alpha e(t) D(e(t))$.

In addition, (iii) when $P(t) < P_c(t)$, one case is $\alpha = 0$, which means CER is not allowed to be used to offset carbon emissions; another one is $\alpha > 0$; the government allows buying CER, but the optimal number of buying CER for the firm is zero. And thus, according to (10), we have $\omega_2(t+1) = 0$. Combining with (21), we have $(1+\rho)^{-t}(P(t) - P_c(t)) \leq 0$; then $P(t) \leq P_c(t)$. This shows that when the price of CER in the current is no less than the carbon price, the optimal decision for the firm is not to buy any number of CER; that is, $y_c^*(t) = 0$.

(2) The Solution of $e^*(t)$. According to (6), when $e(t) > 0$, then $\partial \bigwedge_t / \partial e(t) = 0$. Substituting (19) and (22) into (6) and using two-order sufficient condition, we can get $e^*(t)$ with the following conditions: $UD'(e(t)) - C'(e(t))D(e(t)) - C(e(t))D'(e(t)) + P(t)g(t)D(e(t)) - [P(t)(1-\alpha) + P_c(t)\alpha][D(e(t)) + e(t)D'(e(t))] = 0$ and $(\partial^2 \bigwedge_t / \partial e^2(t))|_{e(t)=e^*(t)} = [U + P(t)g(t)]D''(e(t)) - C''(e(t))D(e(t)) - 2C'(e(t))D'(e(t)) - C(e(t))D''e(t)) - [P(t)(1-\alpha) + P_c(t)\alpha][2D'(e(t)) + e(t)D''(e(t))] < 0$.

(3) The Solution of $y^*(t)$. Substituting (19) and (20) into (5), we have

$$\omega_1 (t) = (1+\rho)^{-(t-1)} \left(P(t-1) - (1+\rho)^{-t} P_c(t)\right). \quad (23)$$

Noticing that $\omega_1(t+1) \geq 0$, we have

$$(1+\rho)^{-t} P(t-1) \geq (1+\rho)^{-(t+1)} P(t). \quad (24)$$

This implies that carbon price in the current is not less than the net value of the carbon price in the next period, but if the net value of the next carbon price is greater than the present carbon price, enterprises will hold more carbon quotas in the current period and wait for the speculation in the next phase. Therefore, the present carbon price is not less than the net value of the next carbon price in the normal carbon market.

From (8) and (22), when surplus quotas in the current are carried over to the next phase (i.e.,$S(t+1)>0$), then $\omega_1(t+1)=(1+\rho)^{-t}P(t)-(1+\rho)^{-(t+1)}P(t+1)=0$; we thus gain

$$P(t)=(1+\rho)^{-1}P(t+1). \quad (25)$$

In other words, when the current carbon price equals the net value of carbon price in the next period, the enterprise will carry forward the remaining carbon quotas for the next use. Due to the fact that total net profit function (i.e., objective function) is monotone decreasing on quantity of carbon trading $y(t)$, if the carbon quotas appear as surplus, the enterprises tend to carry forward all the surplus quotas for the next use; namely, $y^*(t)=0$.

On the contrary, if the current carbon price is greater than the net value of carbon price in the next period (i.e.,$P(t)>(1+\rho)^{-1}P(t+1)$), then from (23), we have $\omega_1(t+1)>0$. Furthermore combining with (16), we get $S(t+1)=0$. Considering the condition of the state transfer $S(t+1)=S(t)+g(t)e(t)-e(t)D(e(t))+y(t)+y_c(t)$, the number of trading carbon quota in the current can be written as

$$y^*(t)=e^*(t)D(e^*(t))-S(t)-g(t)-y_c^*(t). \quad (26)$$

In addition, combining with the boundary condition $S(t+1)=0$, we also get the optimal quantity of carbon quota trading $y^*(T)=e^*(T)D(e^*(T))-S(T)-g(T)-y_c^*(T)$.

(4) The Solution of $S^*(t)$. Substituting the above-mentioned $y_c^*(t)$, $e^*(t)$, and $y^*(t)$ into the state transfer equation $S(t+1)=S(t)+g(t)e(t)-e(t)D(e(t))+y(t)+y_c(t)$, we have $S^*(t+1)=S^*(t)+g(t)-e^*(t)D(e^*(t))+y^*(t)+y_c^*(t)$, where $S(1)=0; S(T)=0, t=1,2,\ldots,T$.

These complete the proof of Theorem 1. □

The following corollaries will discuss how the optimal decisions for the firms change with key parameters in the above model.

Corollary 2. *For the optimal $y_c^*(t)$, we have*

(i) if the enterprise prefers to buy CER in the current period, the price of carbon quota in the current period is not less than that of CER.

(ii) if the enterprise does not buy CER, there are two different cases: one case is that the government does not allow companies to use CER to offset carbon emissions; the other is that the price of carbon quota in the current is not higher than that of CER.

Proof of Corollary 2. (i) If this enterprise chooses to buy CER (i.e., $y_c(t)>0$), according to complementary relaxation condition $y_c(t)\cdot\partial L(t)/\partial y_c(t)=0$, we get $\partial\bigwedge_t/\partial y_c(t)=0$, and further substituting (19) into (8), we have $P(t)-P_c(t)=\omega_2(t+1)\geq 0$; that is, $P(t)\geq P_c(t)$.

(ii) If the enterprise does not buy CER (i.e., $y_c(t)=0$), we have the following two cases: one case is $\alpha=0$; namely, in this case, the government bans the enterprises from buying CER to offset carbon emissions; the other is $\alpha>0$; namely, the government permits the enterprises to buy CER to offset that one, but for the enterprise, the optimal number of buying CER is 0; then $\alpha e(t)D(e(t))-y_c(t)>0$. Using similar procedures, we get $P(t)\leq P_c(t)$. □

Corollary 3. *For the optimal solution $y^*(t)$ in Theorem 1, when the enterprise has surplus carbon quotas, we have the following results:*

(i) when the enterprise decides to carry forward the surplus quotas to the next period, the net value of the next period carbon quota price just equals carbon quota price in the current.

(ii) when the current carbon price is higher than the net value of the next carbon quota price, the enterprise will make the decision of selling the remaining carbon quotas in the current.

Proof of Corollary 3. (i) If the enterprise decides to carry forward the quota to the next period, then $S(t+1)>0$. And furthermore, combining with the constraints (16), we get $\omega_1(t+1)=0$. From (23), we have $P(t)=(1+\rho)^{-1}P(t+1)$; namely, the net value of carbon quota price in the next period is just equal to the price of carbon quota in the current.

(ii) If the current carbon price is higher than the net value of the next carbon quota price (i.e., $P(t)>(1+\rho)^{-1}P(t+1)$), we have $\omega_1(t+1)>0$, from (16); we get $S(t+1)=0$; namely, the optimal strategy for the enterprise is to sell the surplus carbon quotas in the current. □

Corollary 4. *For enterprises, the impact of each additional unit carbon quota from the government on the net value of profits in the whole regulatory period is just in quantity equal to the product of the net value of carbon price and the customer's demand in each period.*

Proof of Corollary 4. Using Benvensite-Scheinkman's formula [46], the effect of parameter changes in state equation on the optimal value function is equivalent to the effect of parameter changes on the Lagrangian function, and taking the first partial derivative with respect to $g(t)$ on both sides of (6), we have

$$\frac{\partial\bigwedge_t}{\partial g(t)}=\lambda(t+1)D(e(t)). \quad (27)$$

Substituting (19) into (27), we get

$$\frac{\partial\bigwedge_t}{\partial g(t)}=(1+\rho)^{-1}P(t)D(e(t)). \quad (28)$$

□

5. Numerical Example

To illustrate our model, the base values of the parameters are listed as follows: $T=5$, $\alpha=0.05$, $\rho=0.1$, $U=200$, $D(e(t))=80-e^2(t)$, and $C(e(t))=500/e(t)$, and we refer to the spot price and quota allocation of the EU's

Table 1: $P(t)$,$P_c(t)$ and $g(t)$ for t.

t	1	2	3	4	5
$P(t)$	40	35	30	33	35
$P_c(t)$	20	18	32	32	35
$g(t)$	7	6.5	6	5.5	5

carbon trading market and China's carbon trading market; the carbon quota price $P(t)$, CER's price $P_c(t)$, and the amount of carbon quota $g(t)$ allocated by the government are given for each phase in Table 1 (the data of carbon price and CER's price in Table 1 refer to real-time carbon market data in Shanghai and Shenzhen, respectively. While carbon quota is not set for any industry in advance, the data is given with the help of historical data in combination with the policies of seven pilot cities in China; see the following websites: http://k.tanjiaoyi.com; http://www.tanpaifang.com/tanshichang/201707/0559913.html.)

Substituting the above parameter values into Corollary 2, the optimal decision of multi-period production emission reduction under cap-and-trade can be obtained as shown in Table 2. Specific results are shown in items (1) and (2).

(1) When the price of the carbon quota is larger than the price of CER (i.e., in period 2, $P(2) > P_c(2)$), the optimal enterprise's emission reduction strategy is to purchase CER within the allowable policy range, firstly; when the price of the carbon quota is less than that one (i.e., in period 3, $P(3) < P_c(3)$), the optimal strategy for enterprise is not to buy any CER (i.e.,$y_c^*(3) = 0$).

(2) When the current carbon quota price is higher than the net value of the next carbon quota price (i.e., $P(1) < (1 + 0.1)^{-1}P(2)$), the enterprise does not choose to carry forward the surplus carbon quotas, but selling the ones in the current period (i.e., $y^*(1) = -294.7293$); when the current carbon quota price just equals the present value of the next carbon quota price (i.e., $P(3) = (1+0.1)^{-1}P(4)$), the enterprise prefers to hold over excess carbon quotas (i.e., $y^*(3) = 177.4705$). It should be pointed out that, using optimal control theory, this paper only investigates an optimal decision of production and emission reduction and does not consider the speculation in carbon trading market. However, in the actual market, if the current carbon quota price is less than the net value of the next carbon quota price (i.e., $P(t) < (1 + 0.1)^{-1}P(t + 1)$), the enterprise will choose to buy more carbon quotas to speculate, but this situation is not going to happen in this paper.

And furthermore, to get more comparison, using Excel 2016, 6 groups of production emission reduction strategies are randomly produced in the feasible region of the proposed model; we compare the net profit value J with the optimal profit value J^* (see Table 3). From Table 3, under the optimal production and carbon emissions reduction strategy, the sum of the enterprise's net profits in multi-period is higher than that of the other strategies. This illustrates the validity of the control model and also plays a theoretical role in guiding the enterprise's production and emission reduction decisions under cap-and-trade.

6. Conclusion

Under the carbon trading mechanism, as a new resource of production input, the introduction of carbon quota has changed the operating cost and profit structure of enterprises. In the actual carbon trading market, enterprises may make tradeoff between carbon emission reduction capability and carbon reduction cost to find more suitable emission reduction path. Noting that carbon emission rights in some countries and regions like China and European Union can be carried forward for next use, enterprises usually make multi-period production plans and emission reduction decisions for achieving the maximization of total profits. In this paper, using the optimal control theory, a multi-period production problem is firstly investigated under cap-and-trade mechanism and an inter-temporal optimization model is developed for maximizing the total net profit during planning period, where the number of carbon emissions, the number of emission trading, and the number of buying CER are viewed as decision variables, and the initial carbon emissions for each storage are considered as state variables. And then the optimal carbon reduction strategy including the number of carbon emission quota and the buying of CER in each period is explored. Finally, numerical examples are used to illustrate the proposed model.

Some key conclusions can be obtained as follows.

For buying CER, when the current price of carbon is higher than the price of CER, the optimal number of buying CER just equals permissible maximum upper bound; when the current price of carbon is just equal to the price of CER, the optimal number of buying CER is less than that upper bound, while when the price of CER in the current is no less than the carbon price, the optimal decision for the firm is not to buy any number of CER. For inter-temporal banking, when the current carbon price equals the net value of carbon price in the next period, the enterprise will carry forward the remaining carbon quotas for the next use; when carbon quota price in the current just equals the net value of the next period carbon quota price, the enterprise decides to carry forward the surplus quotas to the next period, while when the current carbon price is higher than the net value of the next carbon quota price, the enterprise will make the decision of selling the remaining carbon quotas in the current.

Under cap-and-trade, this paper discusses a multi-period optimization decision problem by investigating the number of carbon trading and CER buying, which mainly rely on the comparison between carbon prices in different periods and the comparison between carbon quota price and CER price. But in the actual carbon trading market, the price of carbon quota and CER per period may be affected by the market factors with some uncertainty; this article does not investigate this predicting problem in carbon price; it will be one of our future research directions. In addition, this article only explores a problem of multiple-cycle production

Table 2: Optimal decisions of multi-cycle emission reduction.

t	1	2	3	4	5
$e^*(t)$	2.9992	3.1952	3.4055	3.3418	3.3184
$y_c^*(t)$	10.6479	11.1498	0	11.5012	11.4465
$y^*(t)$	-294.7239	-241.7941	0	-337.5257	-127.4571
$S(t+1)$	0	0	177.4705	0	0

Table 3: Comparison of multi-cycle emission reduction decisions.

$e(t)$	$t=1$	$t=2$	$t=3$	$t=4$	$t=5$	J or J^*
$e^*(t)$	2.9992	3.1952	3.4055	3.3418	3.3184	$J^*=43012.5452$
$e_1(t)$	3.5316	3.0018	3.9683	3.5289	3.2928	$J=42308.3051$
$e_2(t)$	3.1614	3.0188	3.2425	3.6059	3.9793	$J=42579.1947$
$e_3(t)$	3.3223	2.7018	3.2770	3.2659	2.7929	$J=42239.1699$
$e_4(t)$	2.9707	1.8372	2.9947	2.5663	2.7957	$J=38099.9842$
$e_5(t)$	5.7439	5.9347	6.1082	6.1991	5.6141	$J=23695.9033$
$e_6(t)$	2.3162	5.7471	6.0788	1.4537	1.2334	$J=18687.2033$

and carbon emission reduction, and the pricing issues for low-carbon products are not discussed; we will also do further research in combining with this pricing feature in the future.

Data Availability

The data used to support the conclusions of this paper are included within this study.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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