Decision Analysis with Green Awareness and Demand Uncertainties under the Option-available ETS System

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Abstract: Besides the emission trading scheme (ETS), a mandatory measure to reduce carbon emission, the increasing green awareness encourages the manufacturing industry to invest in green upgrades for reducing its emission. Under the increasingly stringent low-carbon environment, the manufacturer needs to restructure its production by holding emission reserves or investing in greener production.

Relatively few research works have discussed how the risk-bearing manufacturer performs in consideration of the emission options to achieve low-carbon production, although its contributions to the long-run success of ETS have been proven. This paper fills this research gap by combining the method of Lagrange Multipliers and Karush-Kuhn-Tucker (KKT) conditions to obtain production optimality under emission constraints. Although this method is famous in economics, it has rarely been used in emission reduction.

The objective of this research is to investigate the emission and production strategy with green awareness under an emission-limited market, where emission options are available and uncertainties exist. Analytical and numerical results show that emission options make scheduling production beyond the emission cap beneficial under almost all the conditions. Specifically, the firm may gain under reasonable emission restrictions than under emission-free market. Setting reasonable emission caps helps the manufacturer achieve higher profitability and larger emission reduction, out of the green-inclined demand and low-carbon restrictions. This helps reduce resistance to the emission reduction regulations and encourages the manufacturer to join in low-carbon production.

Keywords: Decision Analysis, Green Awareness, Option Contracts, Demand Uncertainty, Price Volatility, Lagrange Optimization

I. INTRODUCTION

The manufacturing industry has reportedly been weighing heavily on carbon emission (International Energy Agency, 2017), while customers' green awareness of products continuously makes them more environmentally responsible, and has become vitally important in guiding their purchasing decisions on the green-labelled products (Suki, 2013). With the spread of green awareness, the manufacturing operators recognize the urgency and importance to upgrade their production for greener products. For instance, H&M has launched green-labelled products produced with a lower emission level by adopting green technology. Some other companies, such as Marks & Spencer and Levis, have all promised to cut their carbon footprint for sustainability (Dong et al., 2016). Furthermore, these global concerns for environmental sustainability drive the regulatory bodies to take action for reducing carbon emission substantially. Among the existing emission abatement principles, the emission trading scheme (ETS) was first launched in 2005 and has remained the largest against environment deterioration (Ellerman & Buchner, 2007). The regulatory bodies contribute to the success of the ETS via enforcing scarcity and ensuring trading. The emission scarcity is enforced by reducing the amount of the emission allowance as required. High-polluting firms pay more for the emission, while the less-pollution ones benefit from selling the spare quotas as a by-product.

The objective of this research is to investigate the best emission and production strategy with green awareness under the emission-limited market, where emission options are available for dealing with uncertainties. Regarding emission as a kind of dominant raw material, the production decision-making under ETS becomes a procurement problem that enjoys a certain amount of free emission credits. Uncertainties refer to the demand uncertainty and price volatility, which are regarded as the major issues in the procurement problem that cause profit haemorrhage. Since production decisions depend critically on accurate information derived from demand forecast, failures to do so often result in product shortage or leftover. Demand uncertainty should thus be explicitly taken into account in the decision process. Since the opening of the European Union ETS (EU ETS), the emission credit price has diverted significantly from its theoretical optimum (Balietti, 2016). Emission price volatility is persistent and clustered, and has become the primary ETS-related risk for industries (Chevallier et al., 2011). It challenges the efficiency of ETS and threatens the profitability of the emission-limited entities. Fortunately, some properly designed financial instruments on emission credits can effectively hedge this volatility risk together with the overall emission reduction, such as options, the most powerful risk hedging tools in view of the financial derivatives to reduce uncertainties (Arani et al., 2016).

Emission options are actively traded in the ETS program and have been proven to be strongly resilient against the demand uncertainty and price volatility (Xu et al., 2016). It is widely used in the field of operations management and is conducive to reducing emission costs from the demand and price uncertainties in the emission-capped market. However, previous research works have mainly focused on the role and implications of emission options on the emission policy design, with little consideration of its use on the decision-making process to reduce the manufacturing emission-related cost.

This research bridges this gap with originality in using a call option contract to obtain the optimality for production decision-making subject to emission constraints and developing a new method that combines the Lagrange Multipliers and KKT conditions. Besides the green investment level, the manufacturer needs to schedule its production under, at or over the free emission credits. Newsvendor models are adopted to address the proposed production and purchasing problem. A call option contract is proposed in the option-available scenario to hedge the demand uncertainty and emission price volatility. It gives the option holder a contracted right to purchase a certain asset of emission at a certain price, regardless of the future price of the credits before the expiration date. A premium for the emission reservation is required, and the firms can choose to exercise it or not at an exercising price according to the emission demand and price feasibility. The option-void scenario in which the manufacturer makes routine decisions without options serves as a benchmark. Spare emission or unsatisfied demand may occur due to demand mis-forecast in the benchmark scenario, while a higher unit emission cost is charged when the options are allowed. Scheduling the optimal investment and production strategy is a key question for the emission-capped manufacturer, and it is solved by the use of Lagrange Multipliers and Karush-Kuhn-Tucker (KKT) conditions.

This research contributes to production sustainability and profitability in the following aspects: (1) A new method is developed to solve the production and investment problem under the emission reduction policy; (2) Low-carbon upgrades due to customers' green awareness are considered for sustainability and profitability; (3) A call option contract is proposed to release the manufacturer's financial burden out of emission constraints and uncertainties; (4) It gives some insights for the manufacturers to manage their emission assets and schedule their production; (5) Results show that low-carbon constraints can increase profitability with reasonable emission caps, rather than cause absolute economic loss.

The rest of this paper is organized as follows: Section II briefly reviews the related literature. Assumptions and notations are presented in Section III, which builds newsvendor models and solves it by Lagrange Multipliers and KKT conditions under ETS with options. Numerical studies are presented in Section IV, while Section V draws conclusions and highlights managerial insights.

II. LITERATURE REVIEW

This section briefly reviews the previous literature and concludes the theoretical bases and existing research gaps which can be resolved by this study.

Suki (2013) defined green awareness as the customer's environmental concerns which continually changes our lifestyle into being more environmentally responsible. It influences customer behaviours in many ways, such as reducing consumption, raising preference for green products, and selective waste collection. It has been exploited by many firms to produce products for green-sensitive markets (Baines et al., 2012). Such products that espouse positive social and environmental principles have received considerable attention and become increasingly popular among green customers. Based on surveys conducted in Europe and the USA, Brécard (2013) concluded that 83% of European purchasers consider the product environmental impact and 75% tend to buy green products even if a higher price is charged, while 82% of US buyers continue to buy green products. Moon et al. (2002) stated that the green customer's willingness to pay for the green product encourages the producer to convert to environmentally-friendly production with a higher premium. Chitra (2007) said the need for green products increases with the persistent rise in the eco-friendly concerns. For example, Reinhardt (1998) conducted a survey for StarKist tuna and found that the customers with green awareness desired to pay a premium of $0.21 per can for the dolphin-safe tuna. Yakita (2009) concluded that an average 19.25% increase in the sales of hybrid cars, although it charges more than 1.5 times of the price. The sales of hybrid-cars had contributed to reducing 3.5 million tons of carbon emission in April 2007. Therefore, a considerable number of major companies take environmental factors into their company strategy. For instance, Siemens, Danone, P&G, Carrefour have regarded low-carbon production and sustainable development as their brand orientations (Du et al., 2016).

Reducing the carbon footprints of products is one way to attract more green-sensitive customers while meeting the emission reduction requirements (Jiang & Chen, 2016). As low-carbon preference practically raises the market demand, academic researchers take it into account when solving purchasing and production problems. Luchs et al. (2010) discussed the impacts of green awareness on the customers' preference, and they pointed out that the degree to which the customers are inclined to the green products relies on the type of benefits that the consumers most value for the product category. Similar works on production with green awareness have been conducted by Liu et al. (2012), Zhang et al. (2015), Yang and Chen (2018), etc., considering the low-carbon efforts. Researchers have discussed the impact of product sustainability on the customers' demand, and manufacturers are increasingly producing sustainable products. However, relatively little is known about the emission and production strategy which balances the demand increase and green premium with an option contract. The manufacturer needs to better shape its production and emission structure, holding emission reserve or investing in greener production.

Moschini and Lapan (1995) pointed out that commodity producers face profit uncertainty due to price volatility and demand risks. Demand risks would likely cause profit loss due to a gap between forecast and actual demand. Any mis-match between production and demand would lead to either unsatisfied orders and then to the loss of market share or excessive inventory cost (Petkov & Maranas, 1997). It is prevailing in the rapidly changing market environment and considered as one of the major supply chain risks in the field of operation research. Weisbrod (1964) first argued that the option value arises out of demand uncertainty, and the firms can achieve additional benefits from the option value. Cicchetti and Freeman III (1971) further strengthened Weisbrod's insights by demonstrating that option values exist where the uncertainty is more complicated and individuals are risk-averse. Price risk makes it difficult to make decisions and predict final profits in particular market situations. Prices typically fluctuate across the trading seasons as new information regarding expected production and demand variables reaches the market, including the emission prices. Profit haemorrhage occurs due to this price uncertainty and mis-prediction. Moschini and Lapan (1995) pointed out that price risk leads to a hedging role for option, and interest in the hedging role of options under price risks has been highlighted by current government initiatives and academic researchers.

So far, the option contract is regarded as a financial derivative instrument widely used to hedge different kinds of risks. The option value in the optimal hedging decisions has been the object of considerable research works (Hua et al., 2018; Xu, 2010). Researchers have proved that the option contract can bring benefits to all the parties in a supply chain and concluded that options are put forward to improve the supply chain performance (Cai et al., 2016; Wang & Liu, 2007). Indeed, many manufacturing enterprises have realized the value of option contracts in hedging risks from demand uncertainty and price volatility. For instance, it was reported that 35% of Hewlett-Packard's (HP) procurement value is incurred in option contracts (Chen et al., 2014) which reaped 425 million dollars in cumulative cost-saving (Nagali et al., 2008). Intel Corporation saved tens of millions of dollars by implementing an option procurement strategy (Peng et al., 2012). The Chinese famous e-commerce retailer, Suning Commerce Group, also adopts option contracts to avoid excess stock (Cai et al., 2016).

The regulatory bodies of carbon emission also see the significance of options in risk management. The European Climate Exchange (ECX) has introduced option instruments in October 2006 after regulatory authorization to improve risk management in the European Union Emission Trading Scheme (EU ETS) (Chevallier et al., 2011). Although previous research works have discussed the hedging role of options in demand and price risks, relatively few researchers have considered this problem under the emission reduction context. As some regulatory bodies have reported the significance of options in emission abatement, it is worth discussing how the risk-bearing manufacturer behaves and performs considering the emission options to achieve the low-carbon production. Wang et al. (2018) explored a production problem under a specific ETS which reduces its significance, while this research focuses on the common ETS by Lagrange optimization. Wang and Choi (2019) discussed the emission ordering and green investment strategy under ETS, but it ignored the impact of economic instrument, options, to relieve the emission pressure and then enlarge the final profit.

This paper bridges these research gaps by considering the options to gain the manufacturer optimality under the emission reduction policy -- the ETS system. Risk management is considered in this research with the aim to achieve the optimal emission abatement investment level and provide guidance for production under, at, or over the emission cap. It is of great significance for the emission-capped manufacturers to better develop in the green-concerned environment.

III. MODEL FORMULATION

Newsvendor models are built in this section to study the decision behaviours and profit performance of a risk-bearing manufacturer, considering the emission options to achieve the low-carbon production. Green investment level is analysed in this research to balance the emission abatement requirements and profit maximization.

3.1 Notations and Assumptions

The following notations are employed throughout this research.

Table 1. Notations for Demand Function

Demand Function	Description
$D(i,\varepsilon)$	Green-driven demand function, which is stochastic and differentiable. $D(i,\varepsilon)=y(i)+\varepsilon$.
$y(i)$	Increasing demand function with green level. $y(i)=a+bi$.
i	Green level of the product related to emission.
a	Market scale. $a>0$.
b	Green sensitivity to the demand. $b>0$.
ε	Random variable related to uncertainty. $\varepsilon\in[A,B], E(\varepsilon)=\mu$. $A>-a$.
$f(\cdot)$	Probability density function for uncertainty ε.
$F(\cdot)$	Distribution function for uncertainty ε, which is non-negative and invertible.

Table 2. Notations for Parameters

Parameters	Description
p	Unitary selling price.
e	Emission level of the product.
K	Emission cap under ETS.
c	Unitary cost, including production, inventory, and managerial cost, etc.
s	Emission resold price.
g	Unitary goodwill cost for the unsatisfied demand.
H	Cost factor for green investment.
w_o	Emission option price.
w_b	Emission credit price.
w_e	Emission exercising price.
λ	The Lagrange Multipliers.
η^2	The slack variables.

x^+	Larger value comparing zero with x, $x^+ = \max(0, x)$.
$p > c + w_o + w_e > c + w_b$, $w_o + w_e > w_b > w_o + s$, $w_e > s$	

Table 3. Notations for Decision Variables

Decision Variables	Description
i	Emission abatement level.
q	Total emission quantity needed.
q_o	Emission option quantity.
q_b	Emission credit quantity.
q_s	Spare emission quantity.
Q	Production quantity.
r	Stocking factor when $q \geq 0$.
z	Stocking factor when $q \leq 0$.

Some specific assumptions are made as follows:

Assumption 1: The manufacturer has no capacity limit.

Assumption 2: The demand is positive and the profit is non-negative.

Assumption 3: The green-driven demand function is additive with uncertainty.

$$D(i,\varepsilon) = y(i) + \varepsilon \, , y(i) = a + bi \;\; (a > 0, b > 0), \; \varepsilon \in [A, B] \, , A > -a \, , E(\varepsilon) = \mu \, .$$

Assumption 4: The resold price of spare emission is less than the exercising price, $w_e > s$.

Assumption 5: The total cost of exercising one-unit option is larger than that of directly purchasing one-unit emission credit, that is, $w_o + w_e > w_b$.

Assumption 6: the cost of reselling the spare emissions is less than the emission credit price, that is, $w_o + s < w_b$.

Assumption 7：Green investment is subject to a quadratic function, Hi^2.

This implies that the firm cannot infinitely reduce its emission level with an increasing marginal cost, based on the research works by Yalabik and Fairchild (2011), Jiang and Chen (2016), Basiri and Heydari (2017), Yang and Chen (2018).

3.2 Model Building

This research seeks the optimal production and emission strategy with emission constraints when the manufacturer decides whether to purchase the emission credits and/or options or not. Demand uncertainty and green inclination are considered. The manufacturer can invest in green upgrades, like innovations in its production technologies, investment in cleaner technologies, or education from employee training (Yalabik & Fairchild, 2011). The green investment level is one of the decision variables solved in this research. Emission options are available but not mandatory, and the manufacturer is free to make emission purchasing decisions with/without options. A premium is prepaid for emission reservation under the call option contract, and some or all of these emission options can be exercised upon receiving larger orders. This may enlarge the emission cost, but can avoid losing orders, and hence the brand and profit. Buying or not buying options refers to two scenarios to solve this production problem under which the manufacturer can compare these two final profit results and make the best decisions.

3.2.1 Basic Scenario

Under the basic scenario, the manufacturer decides to just purchase emission credits regardless of the emission options. The batch production is scheduled upon the emission credits received, and green investment is necessary to capture more customer demand. The firm decides to invest Hi^{n2} in reducing i^n emission abatement level for more green-inclined demand. q^n emission credits are needed for producing $\left(q^n+K\right)/\left(e-i^n\right)$ units with p unitary selling price. Losing demand costs g per unit and the emission leftovers can be disposed of at the resold price s. The profit model is given as:

$$\begin{cases} \Pi\left(q^n,i^n\right)=\left(p-c\right)\cdot\min\left[D,\dfrac{q^n+K}{e-i^n}\right] \\ +s\cdot\left(e-i^n\right)\cdot\left[\dfrac{q^n+K}{e-i^n}-D\right]^+-g\cdot\left[D-\dfrac{q^n+K}{e-i^n}\right]^+-w_b\cdot q^n-H\cdot i^{n2} \\ s.t.\;\; q^n\geq 0,\, 0\leq i<e \end{cases} \tag{1}$$

A stocking factor is adopted as $r^n=\dfrac{q^n+K}{\left(e-i^n\right)}-y\left(i^n\right)$ under this scenario to simplify the calculation. It refers to the riskless leftover regardless of demand uncertainty. Emission leftover occurs when $r^n > \varepsilon$, and shortage when $r^n < \varepsilon$, where ε means the solved uncertainty. This stocking factor helps solve this problem as follows:

$$\begin{aligned}\Pi\left(r^n, i^n\right) = &\left(p-c\right)\cdot \min\left[y\left(i^n\right)+\varepsilon, y\left(i^n\right)+r^n\right] - H\cdot i^{n2} \\ &+ s\cdot\left(e-i^n\right)\cdot\left[r^n-\varepsilon\right]^+ + w_b\cdot K - g\cdot\left[\varepsilon - r^n\right]^+ \\ &- w_b\cdot\left(e-i^n\right)\cdot\left[\left(y\left(i^n\right)+r^n\right)\right]\end{aligned} \tag{2}$$

$\Lambda\left(r^n\right)=\int_A^{r^n}\left(r^n-x\right)f\left(x\right)dx$ is defined for the expected product leftover and $\Gamma\left(r^n\right)=\int_{r^n}^{B}\left(x-r^n\right)f\left(x\right)dx$ for the expected product shortage. $\psi\left(i^n\right)$ refers to the riskless profit and $\chi\left(r^n, i^n\right)$ to the uncertainty cost. Then the expected profit under emission restrictions, denoted $E\left[\Pi\left(r^n, i^n\right)\right]$, can be written as follows:

$$\begin{cases} E\left[\Pi\left(r^n, i^n\right)\right] = \psi\left(i^n\right) - \chi\left(r^n, i^n\right) \\ s.t.\quad K-\left(e-i^n\right)\cdot\left(y\left(i^n\right)+r^n\right)\le 0\end{cases} \tag{3}$$

With

$$\begin{aligned}&\psi\left(i^n\right)=\left[p-c-w_b\cdot\left(e-i^n\right)\right]\cdot\left[y\left(i^n\right)+\mu\right]+w_b\cdot K-H\cdot i^{n2} \\ &\chi\left(r^n, i^n\right)=\left(w_b-s\right)\cdot\left(e-i^n\right)\cdot\Lambda\left(r^n\right)+\left[p-c+g-w_b\cdot\left(e-i^n\right)\right]\cdot\Gamma\left(r^n\right)\end{aligned} \tag{4}$$

This optimization problem subject to emission constraints can be addressed by Lagrange Multipliers (LM) with Karush-Kuhn-Tucker (KKT) conditions. Rockafellar (1993) defined Lagrange Multipliers as auxiliary variables introduced in a constrained minimization/maximization problem in order to formally write KKT conditions, which are the first-order necessary conditions for a solution in non-linear programming to get optimality, given some regularity conditions are satisfied. Due to one constraint in this problem, λ_1 is adopted as the Lagrange Multiplier. A slack variable η_1^2 is used to satisfy the equality constraints required. This quadratic format ensures the non-negative slack variable. Then the LM-formed profit function is given as:

$$\begin{cases} L\left(r^n, i^n, \eta_1, \lambda_1\right) = -\psi\left(i^n\right)+\chi\left(r^n, i^n\right)+\lambda_1\cdot\left[K-\left(e-i^n\right)\cdot\left(y\left(i^n\right)+r^n\right)+\eta_1^2\right] \\ s.t.\ \lambda_1\ge 0\end{cases} \tag{5}$$

Now, the KKT conditions can be written as follows:

$$\begin{cases} \dfrac{\partial L}{\partial i^n} = 2\left(H - w_b \cdot b\right) \cdot i^n - w_b \cdot \left(a - b \cdot e + \mu\right) - b \cdot \left(p - c\right) + w_b \cdot \Gamma - \left(w_b - s\right) \cdot \Lambda \\ \qquad + \lambda_1 \cdot \left(a + 2b \cdot i^n - b \cdot e + r^n\right) = 0 \\ \dfrac{\partial L}{\partial r^n} = -\left[p - c + g - w_b \cdot \left(e - i^n\right)\right] + \left[p - c + g - s \cdot \left(e - i^n\right)\right] \cdot F\left(r^n\right) \\ \qquad - \lambda_1 \cdot \left(e - i^n\right) = 0 \\ \dfrac{\partial L}{\partial \eta_1} = 2\eta_1 \cdot \lambda_1 = 0 \\ \dfrac{\partial L}{\partial \lambda_1} = K - \left(e - i^n\right) \cdot \left(y\left(i^n\right) + r^n\right) + \eta_1^2 = 0 \end{cases} \tag{6}$$

This optimization problem can be solved when $\lambda_1 = 0$ and $\eta_1 = 0$. The results help the manufacturer schedule its production over, at, or under the emission cap.

(a) $\lambda_1 = 0$. No spare emissions exist.

The expression of i^n can be obtained by solving the first equation $\frac{\partial L}{\partial i^n} = 0$, and then $i^n = \varphi\left(r^n\right)$ is achieved. Combining $i^n = \varphi\left(r^n\right)$ with the second equation $\frac{\partial L}{\partial r^n} = 0$, the optimal r^{n*} is given by solving $\frac{\left[p - c + g - s \cdot \left(e - \varphi\left(r^n\right)\right)\right]}{e - \varphi\left(r^n\right)} = w_b - s$. Then the optimal i^{n*} is solved as $i^{n*} = \varphi\left(r^{n*}\right)$ and the optimal total emission quantity q^{n*} as $q^{n*} = \eta_1^2 = \left(e - i^{n*}\right) \cdot y\left(i^{n*}\right) + r^{n*} - K$.

Result 1: When $\lambda_1 = 0$, the optimal stocking factor r^{n*} is uniquely determined by the equation $\frac{\left[p - c + g - s \cdot \left(e - \varphi\left(r^n\right)\right)\right]}{e - \varphi\left(r^n\right)} = w_b - s$.

Result 2: The firm invests in $i^{n*} = \varphi\left(r^{n*}\right)$ emission abatement level and requires $q^{n*} = \left(e - i^{n*}\right) \cdot y\left(i^{n*}\right) + r^{n*} - K$ emission credits from the emission credits supplier.

Lemma 1: The firm schedules its production over the emission cap when $\lambda_1 = 0$.

(b) $\eta_1 = 0$. No emissions are required.

If $\eta_1 = 0$, the firm just schedules its production within allowable emissions and can benefit from selling the spare emission quotas. Under this situation, the firm can ignore the emission credits and the model can be re-built as:

$$\begin{cases} \Pi(Q,i) = (p-c)\cdot \min[D,Q] - H\cdot i^2 + s\cdot\left[K-(e-i)\cdot Q\right]^+ - g\cdot[D-Q]^+ \\ s.t.\quad (e-i)\cdot Q \le K \end{cases} \tag{7}$$

The stocking factor is $z = Q - y(i)$. $\Phi(z) = \int_A^z (z-x)\, f(x)dx$ is defined for the expected product leftover and $\Upsilon(z) = \int_z^B (x-z)\, f(x)dx$ for the expected product shortage. $\psi(i)$ refers to the riskless profit and $\chi(z,i)$ to the uncertainty cost. Then the expected profit, denoted $E\left[\Pi(z,i)\right]$, can be written as follows:

$$\begin{cases} E\left[\Pi(z,i)\right] = \psi(i) - \chi(z,i) \\ s.t.\ \ (e-i)\cdot\left(y(i)+z\right) - K \le 0 \end{cases} \tag{8}$$

With

$$\begin{aligned} \psi(i) &= \left[p-c-s\cdot(e-i)\right]\cdot\left[y(p)+\mu\right] + s\cdot K - H\cdot i^2 \\ \chi(z,i) &= \left[p-c+g-s\cdot(e-i)\right]\cdot\Upsilon(z) + s\cdot(e-i)\cdot\Phi(z) \end{aligned} \tag{9}$$

Due to one constraint in this problem, λ_2 is adopted as the Lagrange Multiplier and η_2^2 as the slack variable. Then the LM-formed profit function is given as:

$$\begin{cases} L(z,i,\eta_2,\lambda_2) = -\psi(p,i) + \chi(z,p,i) + \lambda_2\cdot\left[(e-i)\cdot\left(y(i)+z\right) - K + \eta_2^2\right] \\ s.t.\ \ \lambda_2 \ge 0 \end{cases} \tag{10}$$

Now, the KKT conditions can be written as follows:

$$
\begin{cases}
\dfrac{\partial L}{\partial i} = 2\left(H - s\cdot b\right)\cdot i - \left(p-c\right)\cdot b + s\cdot\left[\Upsilon\left(z\right) - \Phi\left(z\right) - a + b\cdot e - \mu\right] \\
\qquad -\lambda_2\cdot\left(2b\cdot i + a + z - b\cdot e\right) = 0 \\
\dfrac{\partial L}{\partial z} = -\left(p - c + g\right)\cdot \overline{F}\left(z\right) + s\cdot\left(e - i\right) \\
\qquad +\lambda_2\cdot\left(e - i\right) = 0 \\
\dfrac{\partial L}{\partial \eta_2} = 2\lambda_2\cdot\eta_2 = 0 \\
\dfrac{\partial L}{\partial \lambda_2} = \left(e - i\right)\cdot\left(a + b\cdot i + z\right) - K + \eta_2^2 = 0
\end{cases}
\tag{11}
$$

This optimization problem can be solved when $\lambda_2 = 0$ and $\eta_2 = 0$. The results help the manufacturer schedule its production at or under the emission cap.

(c) $\lambda_2 = 0$. Spare emissions exist.

The firm can benefit from re-selling spare emissions.

The expression of i can be obtained by solving the first equation $\frac{\partial L}{\partial i} = 0$, and then $i = \varsigma\left(z\right)$ is achieved. Combining $i = \varsigma\left(z\right)$ with the second equation $\frac{\partial L}{\partial z} = 0$, the optimal z^* is given by solving $\left(p - c + g\right)\cdot\overline{F}\left(z\right) = s\cdot\left(e - \varsigma\left(z\right)\right)$.

Then the optimal i^{S*} is solved as $i^{S*} = \varsigma\left(z^*\right)$, the optimal spare emission quantity q^{S*} as $q^{S*} = \eta_2^2 = K - \left(e - i^{S*}\right)\cdot\left(a + b\cdot i^{S*} + z^*\right)$, and the optimal total production quantity Q^{S*} as $Q^{S*} = a + b\cdot i^{S*} + z^*$.

Result 3: When $\lambda_2 = 0$, the optimal stocking factor z^* is uniquely determined by the equation $\left(p - c + g\right)\cdot\overline{F}\left(z\right) = s\cdot\left(e - \varsigma\left(z\right)\right)$.

Result 4: The firm invests in $i^{S*} = \varsigma\left(z^*\right)$ emission abatement level to produce $Q^{S*} = a + b\cdot i^{S*} + z^*$ products and resells $q^{S*} = K - \left(e - i^{S*}\right)\cdot\left(a + b\cdot i^{S*} + z^*\right)$ spare emissions to the emission market.

Lemma 2: The firm schedules its production under the emission cap and benefits from the emission-resold income when $\lambda_2 = 0$.

(d) $\eta_2 = 0$. The emission-capped quantity is just produced.

The optimal production quantity Q^{K*} as $Q^{K*} = \frac{K}{e - i^{K*}}$.

The expression of i can be obtained by solving the first equation $\frac{\partial L}{\partial \eta_2} = 0$, and then $i = \upsilon(z)$ is achieved. Combining $i = \upsilon(z)$ with the second equation $\frac{\partial L}{\partial i} = 0$, the optimal z^{K*} is given by solving the expression $\Theta(z)$ as:

$$\frac{2(H - s\cdot b)\cdot\upsilon(z) + s\cdot\left[\Upsilon(z) - \Phi(z) - a + b\cdot e - \mu\right] - (p - c)\cdot b}{2b\cdot\upsilon(z) + a + z - b\cdot e} = \frac{(p - c + g)\cdot\overline{F}(z) - s\cdot(e - \upsilon(z))}{(e - \upsilon(z))} \tag{12}$$

Thus, the optimal i^{K*} is solved as $i^{K*} = \upsilon(z^{K*})$ and the optimal production quantity Q^{K*} as $Q^{K*} = \frac{K}{e - i^{K*}}$.

Result 5: When $\eta_2 = 0$, the optimal stocking factor z^{K*} is uniquely determined by the equation $\Theta(z)$.

Result 6: The firm invests in $i^{K*} = \upsilon(z^{K*})$ emission abatement level to produce $Q^{K*} = \frac{K}{e - i^{K*}}$ products.

Lemma 3: The firm just produces the emission-capped quantity when $\eta_2 = 0$.

Based on the results, the profits obtained under these three scenarios ($\lambda_1 = 0$, $\lambda_2 = 0$, $\eta_2 = 0$) can be presented as $Profit1$, $Profit2$, and $Profit3$, respectively. Strong profitability can be achieved by comparing these three profits, and then the manufacturer reaches the corresponding production and purchasing strategy, over, at, or under the emission cap.

Proposition 1: Provided emission options are ignored, the firm can schedule its production over, under, or at the emission cap by comparing the profits achievable when $\lambda_1 = 0$, $\lambda_2 = 0$, and $\eta_2 = 0$.

3.2.2 Option Scenario

This option scenario is the target model in this research, which discusses the emission and production strategy with green awareness under an emission-limited market, where emission options are available and uncertainties exist. It investigates the options' ability to hedge the demand uncertainty and price fluctuation to increase the profitability, which may relieve the pressure of the manufacturers to achieve the low-carbon target.

Under the option scenario, the manufacturer is allowed to order emission options for risk hedge in addition to emission credits. Exercising options helps produce more to satisfy the urgent need for larger orders over prediction. A premium is prepaid for this emission reservation. The firm decides to invest Hi^{o2} in reducing i^o emission abatement level for more green-inclined demand. q_b^o emission credits and q_o^o emission options are purchased for production and the maximum is $q^o = q_o^o + q_b^o$. w_o option price is charged for a premium and exercising it claims w_e exercising price. The manufacturer can resell the spare emission credits with s, but benefits nothing from the spare emission options. The profit model is given as:

$$\begin{cases} \Pi\left(q_o^o, q^o, i^o\right) = (p-c)\cdot\min\left[D, \dfrac{q^o+K}{e-i^o}\right] + s\cdot\left[q^o - q_o^o + K - \left(e-i^o\right)\cdot D\right]^+ - w_o\cdot q_o^o \\ -w_b\cdot\left(q^o - q_o^o\right) - w_e\cdot\left[\min\left[\left(e-i^o\right)\cdot D - K - \left(q^o - q_o^o\right), q_o^o\right]\right]^+ - g\cdot\left[D - \dfrac{q^o+K}{e-i^o}\right]^+ - Hi^{o2} \\ s.t. \quad q^o \ge 0,\ q_o^o \ge 0,\ e > i^o \ge 0 \end{cases} \tag{13}$$

A stocking factor, $r^o = \dfrac{q^o+K}{\left(e-i^o\right)} - y\left(i^o\right)$, helps solve this problem under this scenario as follows:

$$\begin{aligned} \Pi\left(q_o^o, r^o, i^o\right) &= (p-c)\cdot\min\left[y\left(i^o\right)+\varepsilon, y\left(i^o\right)+r^o\right] - Hi^{o2} \\ &+ s\cdot\left[\left(e-i^o\right)\cdot\left(r^o-\varepsilon\right) - q_o^o\right]^+ - w_o\cdot q_o^o - w_b\cdot\left[\left(e-i^o\right)\cdot\left(y\left(i^o\right)+r^o\right) - K - q_o^o\right] \\ &- w_e\cdot\left[\min\left[\left(e-i^o\right)\cdot\left(\varepsilon - r^o\right) + q_o^o, q_o^o\right]\right]^+ - g\cdot\left[\varepsilon - r^o\right]^+ \end{aligned} \tag{14}$$

$\Lambda\left(q_o^o, r^o, i^o\right) = \int_A^{r^o - \frac{q_o^o}{e-i^o}} \left(r^o - \frac{q_o^o}{e-i^o} - x\right) f(x)\,dx$ is defined for the expected product leftover, $\Omega\left(q_o^o, r^o, i^o\right) = \int_{r^o - \frac{q_o^o}{e-i^o}}^{r^o} \left(r^o - x\right) f(x)\,dx$ for the expected option leftover, and $\Gamma\left(r^o\right) = \int_{r^o}^{B} \left(x - r^o\right) f(x)\,dx$ for the expected product shortage. $\psi\left(i^o\right)$ refers to the riskless profit and $\chi\left(q_o^o, r^o, i^o\right)$ to the uncertainty cost. Then the expected profit under emission restrictions, denoted $E\left[\prod\left(q_o^o, r^o, i^o\right)\right]$, can be written as follows:

$$\begin{cases} E\left[\prod\left(q_o^o, r^o, i^o\right)\right] = \psi\left(i^o\right) - \chi\left(q_o^o, r^o, i^o\right) \\ s.t. \quad K - \left(e - i^o\right)\cdot\left(y\left(i^o\right) + r^o\right) \le 0 \end{cases} \tag{15}$$

With

$$\begin{aligned} \psi\left(i^o\right) &= \left[p - c - w_b \cdot \left(e - i^o\right)\right]\cdot\left[y\left(i^o\right) + \mu\right] + w_b \cdot K - H i^{o2} \\ \chi\left(q_o^o, r^o, i^o\right) &= w_o \cdot q_o^o \cdot \int_A^{r^o - \frac{q_o^o}{e-i^o}} f(x)\,dx + \left(w_o - w_b + w_e\right)\cdot q_o^o \cdot \int_{r^o - \frac{q_o^o}{e-i^o}}^{B} f(x)\,dx \\ &\quad + \left(w_b - s\right)\cdot\left(e - i^o\right)\cdot\Lambda\left(q_o^o, r^o, i^o\right) + \left(w_b - w_e\right)\cdot\left(e - i^o\right)\cdot\Omega\left(q_o^o, r^o, i^o\right) \\ &\quad + \left[p - c + g - w_b \cdot \left(e - i^o\right)\right]\cdot\Gamma\left(r^o\right) \end{aligned} \tag{16}$$

Due to one constraint in this problem, λ_3 is adopted as the Lagrange Multiplier and η_3^2 as the slack variable. Then the LM-formed profit function is given as:

$$\begin{cases} L\left(q_o^o, r^o, i^o, \eta_3, \lambda_3\right) = -\psi\left(i^o\right) + \chi\left(q_o^o, r^o, i^o\right) + \lambda_3 \cdot \left[K - \left(e - i^o\right)\cdot\left(y\left(i^o\right) + r^o\right) + \eta_3^2\right] \\ s.t. \ \lambda_3 \ge 0 \end{cases} \tag{17}$$

Now, the KKT conditions can be written as follows:

$$
\begin{cases}
\dfrac{\partial L}{\partial q_o^o} = \left(w_o - w_b + w_e\right) - \left(w_e - s\right) \cdot F\left(r^o - \dfrac{q_o^o}{e - i^o}\right) = 0 \\
\dfrac{\partial L}{\partial r^o} = -\left[p - c + g - w_b \cdot \left(e - i^o\right)\right] + \left[p - c + g - w_e \cdot \left(e - i^o\right)\right] \cdot F\left(r^o\right) \\
\qquad + \left(w_e - s\right) \cdot \left(e - i^o\right) \cdot F\left(r^o - \dfrac{q_o^o}{e - i^o}\right) - \lambda_3 \cdot \left(e - i^o\right) = 0 \\
\dfrac{\partial L}{\partial i^o} = -w_b \cdot (a + bi^o + u) - b \cdot \left[p - c - w_b \cdot \left(e - i^o\right)\right] + 2Hi^o + s \cdot \Lambda + w_e \cdot \Omega \\
\qquad + s \cdot \dfrac{q_o^o}{e - i^o} \cdot F\left(r^o - \dfrac{q_o^o}{e - i^o}\right) + \lambda_3 \cdot \left(a + bi^o + r^o\right) - \lambda_3 \cdot b \cdot \left(e - i^o\right) = 0 \\
\dfrac{\partial L}{\partial \eta_3} = 2\lambda_3 \cdot \eta_3 = 0 \\
\dfrac{\partial L}{\partial \lambda_3} = K - \left(e - i^o\right) \cdot \left(y\left(i^o\right) + r^o\right) + \eta_3^2 = 0
\end{cases}
\tag{18}
$$

This optimization problem can be solved when $\lambda_3 = 0$ and $\eta_3 = 0$. The results help the manufacturer schedule its production over, at, or under the emission cap.

(e) $\lambda_3 = 0$. Extra emissions are needed, including credits and options.

The expression of i^o can be obtained by solving $\left[p - c + g - w_e \cdot \left(e - i\right)\right] \cdot \overline{F}\left(r\right) = w_o \cdot \left(e - i\right)$, and then $i^o = \vartheta\left(r^o\right)$ is achieved. Combining $i^o = \vartheta\left(r^o\right)$ with the first three equations $\frac{\partial L}{\partial q_o^o} = 0, \frac{\partial L}{\partial r^o} = 0, \frac{\partial L}{\partial i^o} = 0$, the optimal r^{o*} can be obtained. The optimal i^{o*} is $i^{o*} = \vartheta\left(r^{o*}\right)$ and the optimal q_o^{o*} can be given by solving $F\left(r^{o*} - \frac{q_o^o}{e - i^{o*}}\right) = \frac{w_o - w_b + w_e}{w_e - s}$. The optimal total emission quantity q^{o*} is solved as $q^{o*} = \eta_3^2 = \left(e - i^{o*}\right) \cdot y\left(i^{o*}\right) + r^{o*} - K$. From $q^o = q_o^o + q_b^o$, the optimal q_b^{o*} is known as $q_b^{o*} = \left(e - i^{o*}\right) \cdot y\left(i^{o*}\right) + r^{o*} - K - q_o^{o*}$.

Result 7: When $\lambda_1 = 0$, the optimal stocking factor r^{n*} is uniquely determined and optimal green investment level is therefore uniquely determined by $i^{o*} = \vartheta\left(r^{o*}\right)$.

Result 8: The firm requires $q^{o*} = \left(e - i^{o*}\right)\cdot y\left(i^{o*}\right) + r^{o*} - K$ emissions from the emission supplier, including $q_b^{o*} = \left(e - i^{o*}\right)\cdot y\left(i^{o*}\right) + r^{o*} - K - q_o^{o*}$ emission credits and q_o^{o*} emission options, which is uniquely determined by $F\left(r^{o*} - \frac{q_o^o}{e - i^{o*}}\right) = \frac{w_o - w_b + w_e}{w_e - s}$.

Lemma 4: The firm schedules its production over the emission cap with emission options when $\lambda_3 = 0$.

(f) $\eta_3 = 0$. No emissions are required.

Under this situation, no emissions, including options and credits, are required. Hence, it refers to the same problem when $\eta_1 = 0$.

Result 9: The result when $\eta_3 = 0$ is consistent with that when $\eta_1 = 0$, which contains two solutions by $\lambda_2 = 0$ and $\eta_2 = 0$.

Based on the results, the profit obtained under $\lambda_3 = 0$ can be presented as $Profit4$. Strong profitability can be achieved by comparing these four profits $Profit1$, $Profit2$, $Profit3$, $Profit4$, and then the manufacturer reaches the corresponding production and purchasing strategy, over, at, or under the emission cap with/without emission options.

Proposition 2: Provided emission options are allowed, the firm can schedule its production over, under, or at the emission cap with/without options by comparing the profits achievable when $\lambda_1 = 0$, $\lambda_2 = 0$, $\lambda_3 = 0$ and $\eta_2 = 0$.

Proposition 3: Once achieving the desired production strategy, the firm can invest in corresponding emission abatement for green-inclined demand.

IV. NUMERICAL ANALYSIS

The results achieved above requires further numerical analysis to validate its utility and efficiency. The Chinese fertilizer industry, which weighs heavily on energy use and emission generation, is the key to reach the emission reduction targets. Therefore, the data set for the following numerical analysis, shown in Table 4, are collected from a Chinese fertilizer company with an average monthly 22500 tons of phosphate fertilizer.

According to the income statement of the company and the market information, it is assumed that the green demand function follows $y(i) = 200 + 50i$ and the demand risk follows a normal distribution with $\mu = 25$ and $\sigma = 50$ when $\varepsilon \in [-100,100]$.

Table 4. Data Set

p	e	K	c	s	g	H	w_b	w_o	w_e
300	0.9	0.8	200	5	10	50000	10	4	8
USD	ton/ ton	USD/ ton	USD/ ton	USD/ ton	USD/ ton	USD	USD/ ton	USD/ ton	USD/ ton

4.1 Numerical Results

Tables 5 indicates the numerical results under the above dataset, which enables the best strategy selection via profit comparison when $\lambda_1 = 0$, $\lambda_2 = 0$, $\eta_2 = 0$, and $\lambda_3 = 0$.

It can be observed that the firm better orders 106.93 emission credits and reserves 58.78 emission options for higher final profits. 0.729 emission abatement level is required to attract more customer surplus. The extra emission initially costs 26.57 (1000USD), less than the 29.80 (1000USD) without options. This is due to the lower option premium for the emission reservation. Besides the profit increase, options help relieve the financial pressure and raise the fund liquidity. Scheduling the production within the emission-cap quantity requires more efforts in green upgrade for production capacity rise, but this halves the end revenue.

Corollary 1: Emission options enable a larger emission reservation with less cost.

Table 5. Numerical Results

	Unit	$\lambda_1 = 0$	$\lambda_2 = 0$	$\eta_2 = 0$	$\lambda_3 = 0$
Emission abatement level	--	0.0772	0.0637	0.2385	0.0729
Emission credits quantity	100ton	160.87	0	0	106.93
Emission options quantity	100ton	0	0	0	58.78

Total emissions	100ton	160.87	0	0	165.71
Spare credits quantity	100ton	0	-165.01	0	0
Production quantity	100ton	317.07	316.89	151.17	--
Investment Cost	1000USD	29.80	20.29	284.41	26.57
Emission Cost /without exercising cost	1000USD	160.87	0	0	130.44
Resulted profit	1000USD	2132.46	2177.09	1262.19	2136.91
Final profit	1000USD	2132.46	0	1262.19	2136.91
Best strategy	--	--	--	--	2136.91 Over K Credits & Options

4.2 Sensitivity to Demand

Figures 1 and 2 demonstrate the changes in the firm's decisions and performance with the green-demand factor and coefficient of variance (CV) for demand uncertainty, respectively.

For the case selection, 1 refers to ordering both emission credits and options; 2 refers to producing under emission cap; 3 refers to just producing the emission-capped quantity; 4 refers to ordering emission credits.

From Figure 1(b), the best strategies in both the basic model and the option model are to order extra emissions in almost all the green sensitivity to demand. Unlike only emission credits in the basic model, emission options are needed in the option scenario.

Figures 1 (a) and 1(c) elaborates that profit and green investment rise with increasing green-demand factor, which refers to customers' green-inclination. Correspondingly, fewer emissions are required, including credits and options, due to a smaller emission level during production, shown in 1(d). Compared the results between with and without options, it is clear that purchasing options earns more with less green investment cost, because options enable a larger emission reservation with less emission cost. The firm can order more emissions instead of low-carbon investment. The green-demand factor significantly affects the firm's decisions and performance with regard to options.

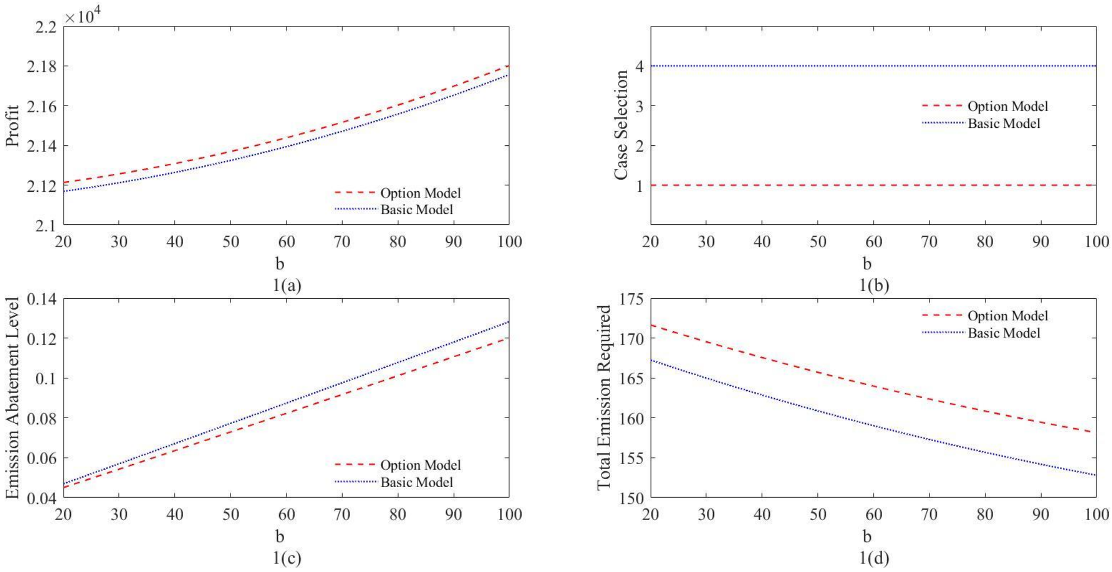

Figure 1. Sensitivity to green-demand factor

Corollary 2: Emission options help the firm earn more with higher green inclination.

Figure 2(b) demonstrates that scheduling production over the emission cap helps the firm achieve its optimality in almost all the demand uncertainty. From Figure 2(a), it shows that ordering options earns superior profits at a lower demand risk but less at a higher level. Due to the higher cost for exercising an option, a higher demand risk incurs larger expense on emissions. Both the emission investment and extra emissions required grow up when the demand suffers more uncertainty, as shown in Figures 2(c) and 2(d), respectively. It is rational to reserve more emission-capped production capacity from low-carbon investment and/or emission reservation with higher demand risk, as it enables the firm to address the demand fluctuation with higher flexibility.

Corollary 3: Options perform better at a lower demand risk.

Corollary 4: The firm needs to address higher demand risks with great effort on green investment and emission reservation.

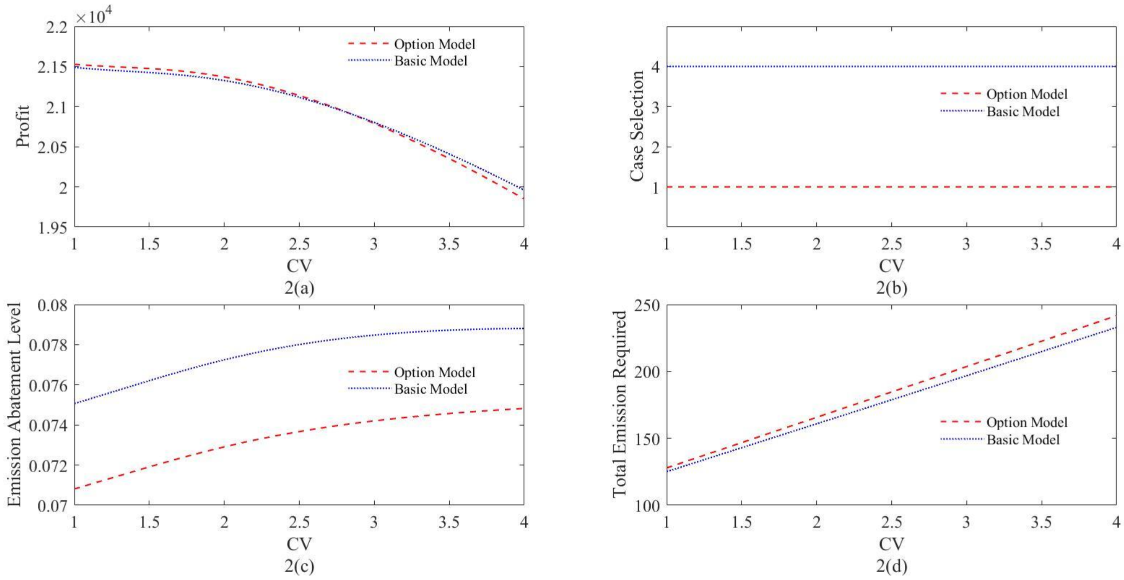

Figure 2. Sensitivity to demand uncertainty (CV)

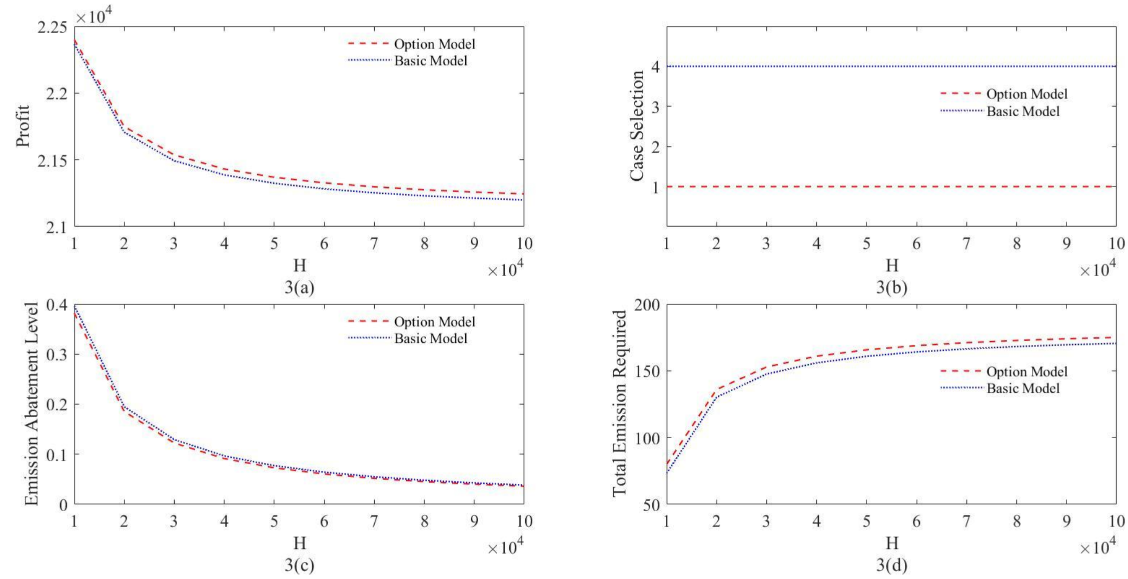

Figure 3. Sensitivity to green investment factor

4.3 Sensitivity to Emissions

Obviously, the higher green investment cost reduces the profitability both in the basic and option models, but the options increase the firm earning compared to the basic model without options, as shown in Figure 3(a). In 3(b), the firm better operates with more emissions out of mandatory cap regardless of the increase in investment cost. From 3(c) and 3(d), the firm prefers to order more emissions instead of green investment when the investment cost factor rises up. This means upgrading the green technology which lowers the investment cost can motivate the emission-dependent firms to produce greener products with a higher emission abatement level.

Figure 4 shows the intricate relationship between the decisions/profitability and the emission cap. From 4(a), it can be seen that the profitability experiences a stable increase until approximately 260, and then a sharp decrease due to the changes in case selection. After that, the profitability gradually increases with the looser emission cap. Profit increase out of options exists before 260. Similarly, case changes (in 4(b)) also substantially drop the low-carbon efforts at 260 in 4(c). Fewer emissions are required with increasing emission cap till to 0 after 260, as shown in 4(d).

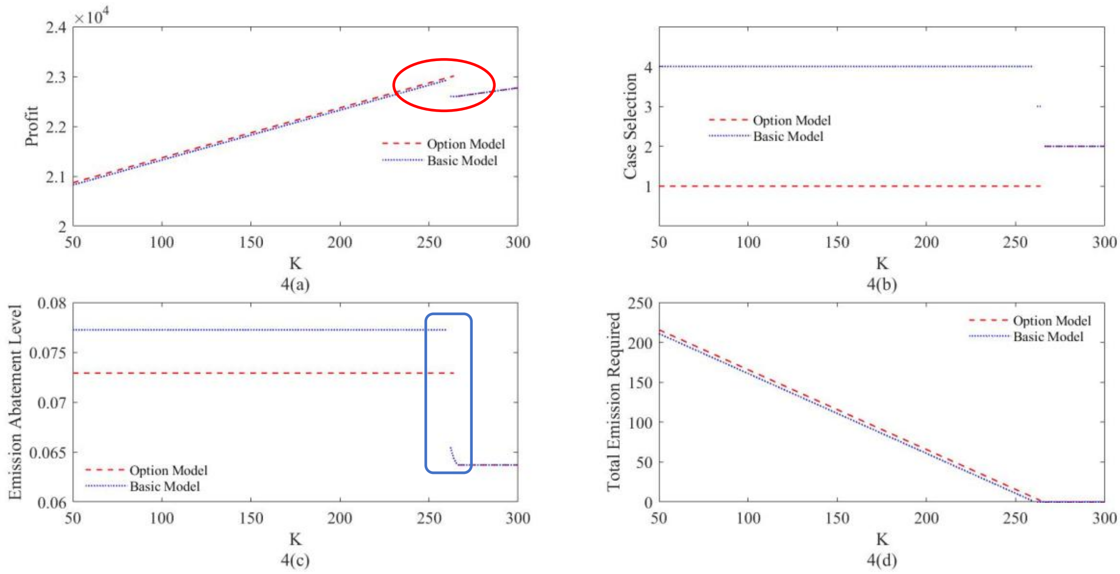

Figure 4. Sensitivity to emission cap

Here, the highlighted part by a red circle in Figure 4(a) indicates that loose or no emission requirements fail to bring better returns, which is against the subjective conjecture that capping the emission incurs extra costs for profit loss. Reasonable emission caps make the manufacturer achieve higher profitability, due to its green promotion effect. This result helps reduce the manufacturers' resistance to the emission reduction regulations and encourages them to join in the low-carbon production. Moreover, the highlighted part by a blue circle in Figure 4(c) indicates that suitable emission caps significantly reduce the carbon emission compared with the emission-free production. Hence, it is concluded that the emission restrictions can achieve emission reduction targets without impairing the manufacturers' profits, and even bring a bonus due to the green-inclined demand.

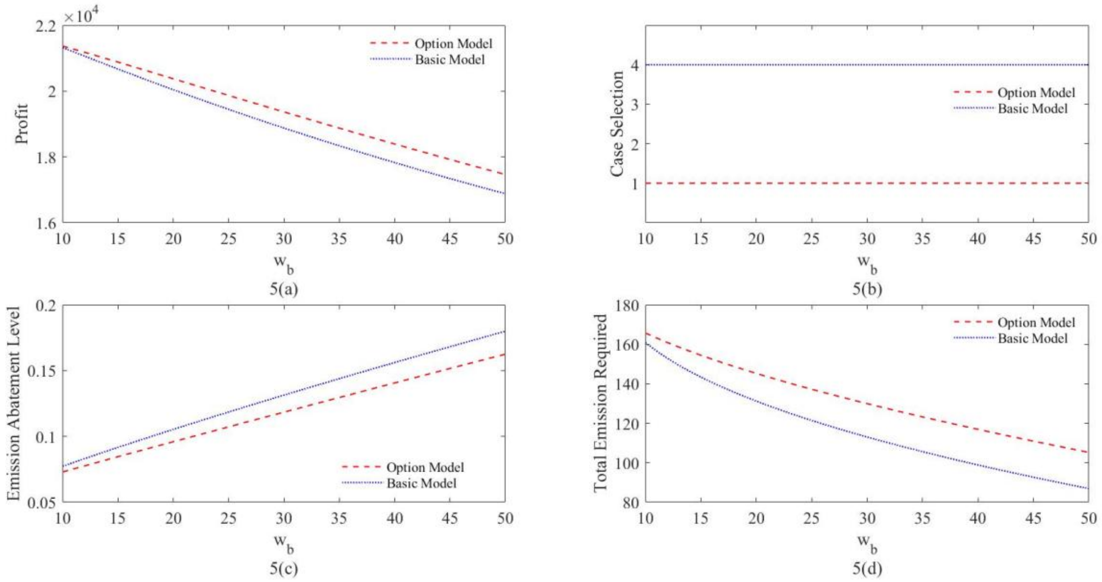

Figure 5. Sensitivity to emission credit price

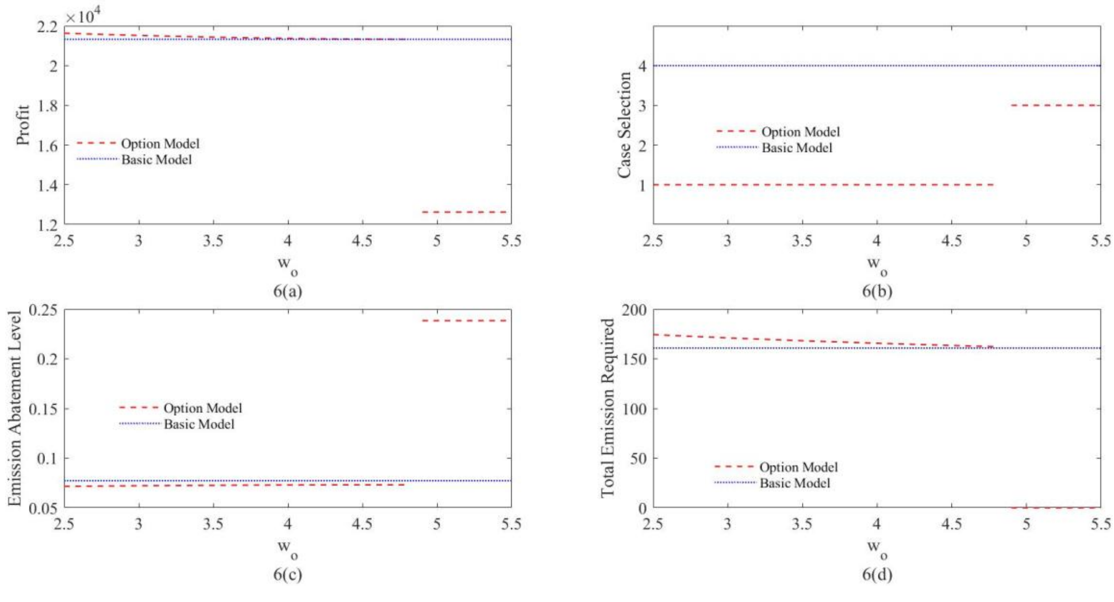

Figure 6. Sensitivity to emission option price

Corollary 5: The firm may gain under reasonable emission restrictions than under emission-free market.

From Figure 5, higher emission credit price leads to the profit decrease and green investment increase with/without options. Purchasing options brings more profits but reduces low-carbon efforts. The increasing emission credit prices enlarge both the profitability and the greenness differences (shown in Figure 5(a) and Figure 5(c), respectively). Figure 5(b) shows that the firm tends to schedule its production over emission cap ignoring the increasing credit price.

However, the emission reservation falls down, and this decreases the production capacity, which subsequently results in profit drops.

From Figure 6, the emission option price is nothing to the basic model. Under option model, the profitability slightly decreases till 4.8, where a sharp plunge emerges and then the profitability remains stable. This plunge occurs due to the case selection change, from over to at the emission cap. Correspondingly, a sharp surge of green investment ensures to produce more at the emission cap in Figure 6(c). Similar to the profitability, the emissions required gradually decrease and abruptly fall to 0 at 4.8.

From Figure 7, the emission exercising price does not affect the basic model as well. Profits with options decrease to the basic level at 9.5 and then become inferior to the basic profit. Purchasing extra emissions remains the best strategy. In Figure 7(c), a higher emission cost drives the firm to invest more in low-carbon production. Therefore, the required emissions observe a downward trend with the increasing emission exercising price.

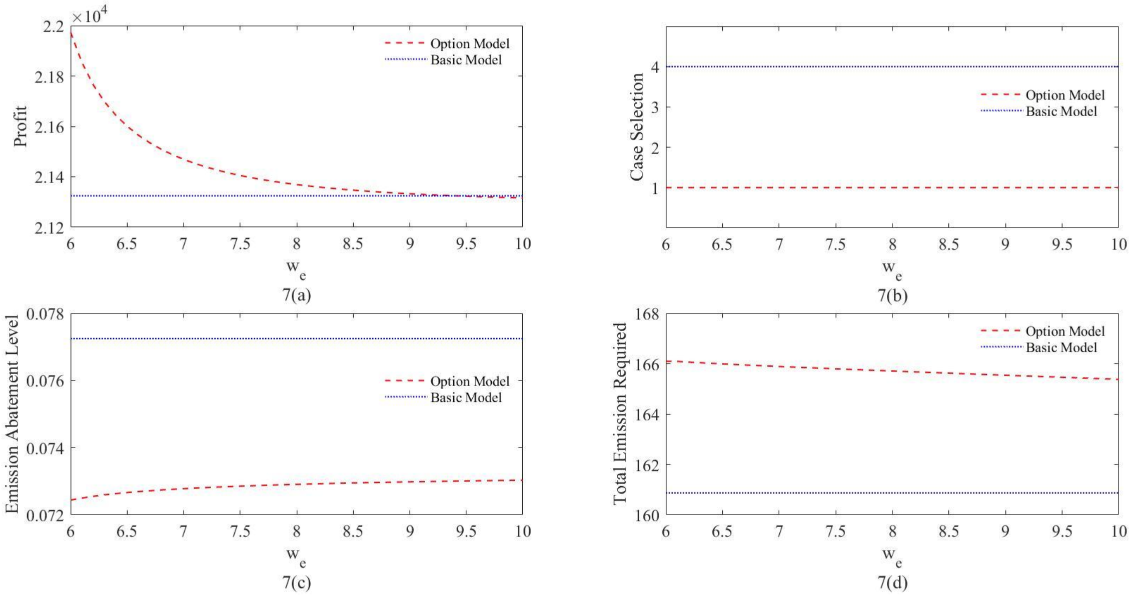

Figure 7. Sensitivity to emission exercising price

Corollary 6: Options perform better with the increasing emission credit price.

Corollary 7: Higher emission-related prices shrink the profitability but drive up the low-carbon investment.

Corollary 8: The premium of the emission options significantly affects the firm's decision-making and profitability.

Figure 8 elaborates the trends of emission options under different market-settings. The increasing green awareness pulls down the option reservation, as more production can be achieved out of the less unit emission level. More options are required for higher demand risk, higher unit green investment cost, and higher selling price. Provide the credit price is below 20, a larger option reservation raises the fund flexibility and then the profitability, but over 20, a larger one shrinks the production and then the profitability. This explains why the emission options increase and then decrease with the rising credit price. The option-related prices, including the option and exercising price draw down the option reservation, as shown in Figure 8(g) and 8(h).

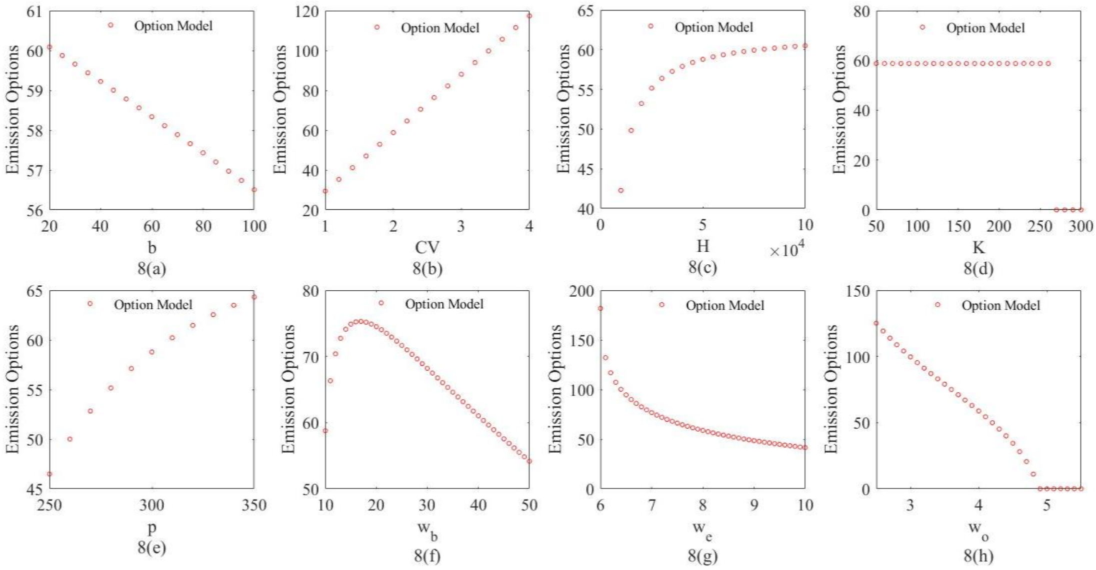

Figure 8. Sensitivity of emission options

4.4 Recommendations

Accordingly, recommendations for emission-constrained firms are proposed based on the above numerical analysis as follows:

For the manufacturers:

Recommendation 1: The firms gain out of options under almost all the market settings, excluding a much higher demand risk.

Recommendation 2: Options perform better facing with higher emission prices.

Recommendation 3: Scheduling over emission cap achieves better performance in most cases.

Recommendation 4: Loose carbon market is not necessarily suitable for a firm's thrive with customers' green awareness.

Recommendation 5: More efforts on green upgrades are needed for lowering the investment cost.

For the regulatory bodies:

Recommendation 6: Setting reasonable emission caps can benefit both economic and environmental development, out of the green-inclined demand.

Recommendation 7: Providing emission options relieves the pressure of the emission-capped manufacturers, which helps the long-run success of ETS.

V. CONCLUSIONS

The novelty of this paper lies in addressing the options-enabled production problem under ETS with green awareness and upgrades. It investigates how the risk-bearing manufacturer behaves and performs considering the emission options to achieve the low-carbon production. Previous research works have focused on the manufacturers' efforts on product sustainability and its impact on customer demand. Relatively little is known about the emission-dependent production strategy considering both the green capital input and emission premium of options with low-carbon awareness. Although there has been a discussion about the hedging role of options in demand and price risks, it has not studied in the context of emission reduction and green awareness. This research fills these research gaps and helps the emission-dependent manufacturer to better shape its production and emission structure under the increasingly stringent low-carbon environment with green awareness, which encourages the firms to invest in green upgrade for curtailing its emission level. It also considers the role of options in addressing the demand uncertainty and price fluctuation, which surges profitability and relieves pressure from emission reduction.

Analytical results provide the best solutions under each condition, and then further propose the optimal emission-relied production strategy. Numerical studies validate these results and offer some recommendations. Specifically, opposite to the traditional concept that emissions impose an extra cost, the manufacturers have a chance to achieve better returns from the emission-motivated production compared to those under the emission-free market. Higher profitability and higher greenness are simultaneously realized, due to the green promotion effect. This relieves the emission-dependent firms' resistance to the emission restrictions and further encourages them to put more efforts into low-carbon production.

These findings call for the manufacturer to better assign its sustainability liability for synergistic achievement in greenness and profitability under emission constraints. Limitations still exist in this paper. Only one-period production and single product are considered. Multi-period scheduling with multi-products deserves further discussion. More constraints can enrich this research. For instance, other emission regulations and multi-supplier conditions should be taken into consideration. Cases in which the selling price affects the customers' surplus should also be addressed in future studies.

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