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# New Carbon Emissions Allowance Allocation Method Based on Equilibrium Strategy for Carbon Emission Mitigation in the Coal-Fired Power Industry

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**Abstract:** The carbon emissions from coal-fired power have become an increasing concern to governments around the world. In this paper, a carbon emissions allowances allocation based on the equilibrium strategy is proposed to mitigate coal-fired power generation carbon emissions, in which the authority is the lead decision maker and the coal-fired power plants are the follower decision makers, and an interactive solution approach is designed to achieve equilibrium. A real-world case study is then given to demonstrate the practicality and efficiency of this methodology. Sensitivity analyses under different constraint violation risk levels are also conducted to give authorities some insights into equilibrium strategies for different stakeholders and to identify the necessary tradeoffs between economic development and carbon emissions mitigation. It was found that the proposed method was able to mitigate coal-fired power generation carbon emissions significantly and encourage coal-fired power plants to improve their emissions performance.

**Keywords:** carbon emission allowance allocation; emission mitigation; coal-fired power generation; cap and tax mechanism

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## 1. Introduction

Because of their major contribution to global climate change, there has been increased research to determine the best ways to reduce carbon emissions, which have been exponentially increasing due to the increased demand for energy [1–3]. Although renewable energy systems are more environmentally friendly than traditional energy systems, two thirds of the world's electricity is still generated using fossil fuel-based generation plants [4,5]; that is, coal, gas and oil-fired thermal power remain the main sources for electricity generation, especially in developing countries (e.g., China and India) [6,7]. Approximately 20% of the global electricity produced in 2016 was supplied by coal-fired power plants (CPP), with some developing countries having an even higher proportion [8]; for example, coal-fired power plants supply more that 65% of China's needs [9]. Therefore, for sustainable social development, it is necessary to mitigate or control CPPs' carbon emissions.

Research has shown that "hard-path" and "soft-path" approaches can be taken to mitigate carbon emissions [10,11]. "Hard-path" methods mainly focus on advanced clean coal technologies (CCT) such as integrated gasification combined cycles (IGCC), carbon capture and storage (CCS), ultra-supercritical technology (USC) and externally-fired combined cycle (EFCC) technologies [12–14]. For example, Hoya and Fushimi evaluated the performance of advanced IGCC power generation systems with low-temperature gasifiers and gas cleaning and found that the lowest net thermal efficiency rose to 57.2% and the minimum carbon emission factors fell to 39.7 kg-$CO_2$ MWh [15]. Kayal and

Chakraborty designed and developed carbon-based metal organic framework (MOF) composite for $CO_2$ capture and concluded that the MAX-MIL composite was able to adsorb a greater quantity of $CO_2$ compared with the original methods [16]. Even though these "hard-path" methods are highly efficient in reducing carbon emissions, commercial-scale applications are still extremely expensive [17,18], especially for developing countries, which tend to prefer "soft-path", less-expensive solutions [19,20]. The "soft-path" approach focuses on policy controls or operations management methods for carbon emissions mitigation. For example, Cao and Xu investigated the effects of cap-and-trade policy (CTP) and low carbon subsidy policy (LCSP) on carbon emissions reduction and concluded that carbon emissions reductions were positively correlated with the carbon trading price, but not with low carbon subsidies [21]. Shih and Frey developed a multi-objective chance-constrained optimization method under certainty to improve emission performance by adjusting coal blending ratios [22]. Wang et al. proposed a multi-objective unit commitment approach to simulate the impacts of manifold uncertainty on system operation with emission concern and suggested operational insights for mixed generation systems [23]. Xu et al. developed an equilibrium strategy based on a hydro-wind-thermal complementary system for carbon emission reduction and obtained some useful suggestions [24]. Although such studies have gone some way to alleviating the human activity caused global climate change effects, the reality is still not satisfactory due to the complexity and uncertainty of human activities; thus, further improvements are necessary.

There has been increased research interest in the carbon emissions allowance allocation (CEAA) method to mitigate carbon emissions [25,26]. Cap and trade and carbon taxes have been the two most popular emissions reduction mechanisms to curb CPP carbon emissions [27]. While cap and trade mechanisms are business friendly, as the trading price is determined by supply and demand, there is increased trading price uncertainty [28]. While carbon tax mechanisms are simpler and easier to implement and the tax increases financial revenue [27], which can be used to sponsoring of green projects such as renewable energy, there is no upper limit to the possible emissions reduction [28]. By combining the advantages of these two mechanisms, a new cap and tax mechanism was developed to mitigate carbon emissions. As a key determinant for the CEAA strategy, the allocation strategy is crucial to ensure carbon emissions mitigation. In this paper, a combination of free and taxable allocation strategies under a carbon emissions cap is adopted for the carbon quota allocations. The free emissions allowances are used to meet the CPP basic operations, and the taxable emissions allowances are employed to meet further CPP development.

Previous CEAA studies have tended to consider only a single CPP participant. However, in actual production activities, carbon emissions mitigation involves both the CPP and the authority, which usually have conflicting targets. For example, the CPP generally has a profit objective, while the authority, as a representative of public benefits, generally has environmental protection as the main starting point; therefore, traditional optimization methods are not effective. The equilibrium strategy, which has been proven to be powerful in addressing such conflicts, has been widely used in many fields. For example, Liu et al. developed a computable general equilibrium (CGE) model to explore the impacts of a carbon tax on the socio-economic system and had some useful results [29]. Tu et al. employed an equilibrium strategy to solve regional water resource allocation conflicts between different sub-areas under multiple uncertainties [30]. Kardakos et al. proposed an equilibrium optimization method to address an optimal bidding strategy problem that considered the mutual interactions between the various stakeholders in the electricity market [31]. The successful application of the equilibrium strategy in these areas motivated the use of this method in this paper to address the conflicts between the authority and CPPs to achieve regional sustainable development. However, as the equilibrium strategy is an abstract concept, a specific, quantitative method is needed to describe the situation. As bi-level programming has been proven to be the most efficient method for expressing equilibrium strategies and describing the interactions between multiple stakeholders, bi-level programming is integrated into the CEAA problem to determine the equilibrium between the authority and the CPPs.

Compared with previous studies, the equilibrium strategy established in this study, which integrates a bi-level multi-objective programming model, a carbon emissions allowance allocation method and uncertainty theory, has the ability to address the equilibrium between the authority and the CPPs, the conflict between economic development and environmental protection and the uncertainties simultaneously. The remainder of this paper is organized as follows. Section 2 discusses the features of the CEAA problem in preparation for establishing the mathematical model. In Section 3, a bi-level multi-objective mathematical model is built based on a real situation, after which in Section 4, a case study is given to demonstrate the practicality and effectiveness of the proposed methodology. Section 5 gives a detailed results analysis and in-depth discussion, and conclusions and future research are given in Section 6.

## 2. Key Problem Statement

With a carbon emissions allowance allocation and a cap and tax mechanism, the CEAA problem is complex for both the authority and the CPPs.

As a public representative, the authority must ensure stable local economic development and mitigate the associated carbon emissions. However, the authority also has the power to develop the policies that must be implemented by the CPP if they wish to keep their power generation rights. However, the authority has an obligation to consider the actual CPP situation when making decisions to avoid non-sustainable CPP development or a cessation of operations, which could be harmful to stable economic development. Therefore, the authority divides the total carbon emissions into free emissions, which allow the CPP to meet its production and operation commitments and ensures fairness, and taxable emissions, which supplement the free emissions and can be used to regulate the market. Therefore, the authority pursues a balance between financial benefits and carbon emissions reduction by satisfying the CPPs' basic rights and meeting the regional electricity needs.

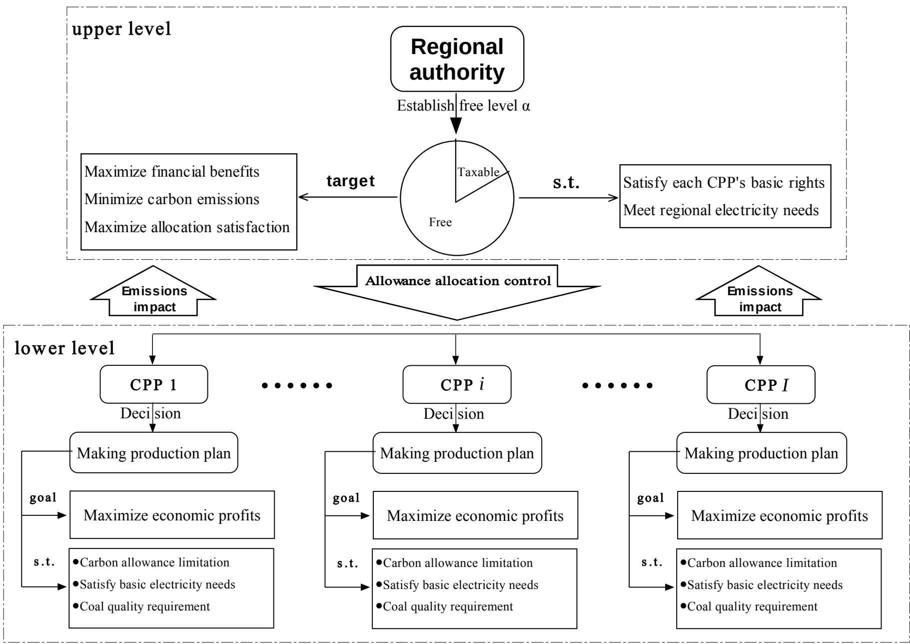



**Figure 1.** Concept model of the bi-level structure for the carbon emissions allowance allocation (CEAA) problem. CPP, coal-fired power plant.

According to the rational person hypothesis, the primary goal of the CPPs is to maximize profits while also considering emissions performance, boiler conditions, social responsibility and the component coal that can be purchased on the market. Therefore, as higher carbon emissions allowances mean higher production and higher profits, each CPP seeks to obtain as high a carbon emissions allowance as possible. However, as the authority seeks to mitigate carbon emissions, the CPPs that have better emissions performance are more competitive. Therefore, CPPs are allocated higher emissions quotas if they put some effort into improving the CPP emissions performance. This relationship between the authority and the CPPs for the CEAA problem is shown graphically in Figure 1.

## 3. Model Development

In this section, a bi-level optimization model for the CEAA problem in the coal-fired power industry is built.

### 3.1. Assumptions

The various assumptions involved in this paper are as follows:

1. The CEAA problem is a single production period decision; at the beginning of the next production period, the decision process is reset.
2. All decision makers are rational and seek to maximize returns under limited resources.

### 3.2. Authoritative Carbon Emissions Allowance Allocations

The complete carbon emissions allowances allocation problem involves authority allocation decisions and CPP coal purchase decisions. Therefore, in this study, the CEAA based on the cap and tax system has two levels (i.e., the authority and the CPPs), the details of which are discussed in the following (the required symbol descriptions are given in Table 1).

**Table 1.** Model variables and parameters.

| **Indices** | **Description** |
|---|---|
| $i$ | Index for coal power plants (CPPs), $i \in \Psi = \{1, 2, ..., I\}$. |
| $j$ | Index for component coal, $j \in \Phi = \{1, 2, ..., J\}$. |
| $k$ | Index for coal quality, $k \in \Omega = \{1, 2, ..., K\}$. |
| Crisp parameters | Description |
| $\mu$ | Taxes that the corporation should pay for each unit of power generation. |
| $\gamma$ | Carbon tax price of the exceeding part when exceeding the allocated free carbon emissions allowances. |
| $CE_c$ | The cap of carbon emissions allowances. |
| $CE_f$ | The allocated free carbon emissions allowances. |
| $CE_t$ | The allocated taxable carbon emissions allowances. |
| $CEA_i^{\min}$ | The minimum carbon emissions allowances demand of CPP $i$. |
| $CEA_i^{\max}$ | The maximum carbon emissions allowances demand of CPP $i$. |
| $D$ | Amount of power needed to maintain regional development. |
| $p$ | Price of a unit of electric power. |
| $CT_{jk}$ | Operation cost of pollutant-control measures for reducing pollutant $k$ in CPP $i$. |
| $\eta_{ik}$ | Removal rate of air pollutant $k$ in the CPP $i$ by taking pollutant-control measures. |
| $ED_i$ | Amount of power that CPP $i$ has the responsibility to produce to meet the basic demand in the region. |
| $Q_{ij}^u$ | Amount of component coal $j$ that can be procured by CPP $i$. |
| Uncertain parameters | Description |
| $\widetilde{T}_i$ | Carbon-power conversion coefficient of a unit of carbon emissions allowances for CPP $i$. |
| $\widetilde{T}_{ij}$ | Coal-power conversion coefficient of component coal $j$ at CPP $i$. |
| $\widetilde{C}_j$ | Procurement cost of component coal $j$. |
| $\widetilde{CEF}_{ij}$ | Carbon emission factor of component coal $j$ to carbon at CPP $i$. |
| $\widetilde{EF}_{jk}$ | Emission factor of component coal $j$ to air pollutant $k$. |
| $\widetilde{LCQ}_{ik}$ | Lower bounds of coal quality $k$ for meeting the operation allowance of the $i$-th CPP. |
| $\widetilde{CQ}_{jk}$ | Coal quality $k$ of component coal $j$. |
| $\widetilde{UCQ}_{ik}$ | Upper bounds of coal quality $k$ for meeting the operation allowance of the $i$-th CPP. |
| Decision variables | Description |
| $X_i$ | Free carbon emissions allowances allocated to CPP $i$, which are determined by the authority. |
| $Y_i$ | Taxable carbon emissions allowance for CPP $i$ allocated by the authority. |
| $Z_{ij}$ | Amount of component coal $j$ burned by CPP $i$. |
| Policy control parameters | Description |
| $\theta$ | Minimal allowance satisfactory degree chosen by the authority. |
| $\alpha$ | The free carbon emission level, which is determined by the authority. |
| $\beta$ | Attitude of the authority towards the historical data. |
| $\lambda$ | Attitude of the authority towards carbon emissions reduction. |

3.2.1. Pursuing Possible Financial Benefits

While protecting the environment, the authority is also responsible for using taxpayer receipts to ensure steady local economic and social development. The goal is to develop an optimal carbon emissions allowance allocation scheme that returns the maximum revenue from both the value added tax (VAT) and the carbon tax.

Let $\widetilde{T}_{ij}$ denote the coal-power conversion coefficient of component coal $j$ at CPP $i$. Even though the uncertain parameters $\widetilde{T}_{ij}$ are very difficult to determine exactly due to many objective factors such as coal quality, based on historical data, the value can be estimated within a certain range; therefore, this type of uncertain situation is considered fuzzy and is described using trapezoidal fuzzy numbers, which are written as $T_{ij} = (r_{ij}^1, r_{ij}^2, r_{ij}^3, r_{ij}^4)$, where $r_{ij}^1 \leq r_{ij}^2 \leq r_{ij}^3 \leq r_{ij}^4$ [32–34]. As the fuzzy parameters cannot be directly calculated, the expected value operator method is employed to transform the trapezoidal fuzzy number into its corresponding expected value [35]; therefore, the corresponding expected value for conversion parameters $T_{ij}$ is calculated, where $\widetilde{T}_{ij} \to E\left[\widetilde{T}_{ij}\right] = \frac{1-\varphi}{2}(r_{ij}^1 + r_{ij}^2) + \frac{\varphi}{2}(r_{ij}^3 + r_{ij}^4)$ and $0 \leq \varphi \leq 1$. The revenue function for the authority is formulated as follows:

$$\max FB = \mu \sum_{i=1}^{I} \sum_{j=1}^{J} E[\widetilde{T_{ij}}] Z_{ij} + \gamma \sum_{i=1}^{I} Y_i \tag{1}$$

where $FB$ is the potential financial benefits function from the CPPs of the authority.

3.2.2. Minimizing Total Carbon Emissions Allowance

As electricity demand is growing because of global economic development, more coal-fired power will be required to meet demand. However, as the carbon emissions produced from the CPP can cause irreversible climate change effects [36], the authority has an important responsibility to protect the environment while at the same time ensuring steady local development. As the total carbon emissions in the region are equal to the carbon emissions allowances cap, the total carbon emissions function can be written as follows:

$$\min TC = CE_c \tag{2}$$

where $TC$ is the total carbon emissions function from the CPPs.

3.2.3. Maximizing Allocation Free Carbon Allowance Satisfaction

Previous research has found that fairness is a critical factor for sustainable development [37]. Therefore, in this allowance allocation problem, a satisfactory degree method is proposed to measure the fairness [25,38]. The higher the free carbon emissions allowances granted to a CPP, the higher the satisfactory degree; therefore, the authority defines the allocation satisfaction function for each CPP as follows:

$$SD_i = \begin{cases} 0, & X_i \leq CEA_i^{\min} \\ \frac{X_i - CEA_i^{\min}}{CEA_i^{\max} - CEA_i^{\min}}, & CEA_i^{\min} \leq X_i \leq CEA_i^{\max} \\ 1, & X_i \geq CEA_i^{\max} \end{cases} \tag{3}$$

where $SD_i$ is the allocation degree of satisfaction for CPP $i$ in this study.

To ensure the sustainable development of the region and allocation fairness for each CPP, an objective function is used to maximize the minimal allocation satisfaction, as shown in Equation (4).

$$\max SD = \min \{SD_i\} \tag{4}$$

where $SD$ is the minimal carbon emissions allowance allocation satisfaction for each CPP.

#### 3.2.4. Allocation Constraints

A carbon emissions allowances cap (i.e., $CE_c$) is determined as part of the allocated free allowances (i.e., $CE_f$) and taxable allowances (i.e., $CE_t$), as shown in Equation (5).

$$CE_c = CE_f + CE_t \tag{5}$$

The free carbon emissions allowances depend on the level of free carbon emissions determined by the authority; therefore, the corresponding free and taxable emissions allowances are allocated to each CPP, as shown in Equations (6)–(8).

$$CE_f = \alpha CE_c \tag{6}$$

$$CE_f = \sum_{i=1}^{I} X_i \tag{7}$$

$$\sum_{i=1}^{I} Y_i \leq CE_t \tag{8}$$

#### 3.2.5. Demand Constraints

To protect taxpayer rights, while the authority cannot allocate carbon emissions allowances the CPP is unable to carry, they have an obligation to ensure the CPP's basic rights (i.e., a minimum carbon emissions allowance that maintains the basic CPP operations), as can be seen in Equation (9).

$$CEA_i^{\min} \leq X_i + Y_i \leq CEA_i^{\max} \quad \forall i \in \Psi \tag{9}$$

#### 3.2.6. Power Supply Constraints

The authority has an obligation to guarantee an adequate supply of electricity. Based on historical data, total electricity production is $\sum_{i=1}^{I} E[\widetilde{T}_i]X_i \geq D$. However, there may be some errors if only historical data are used. As electricity supply is essential for economic and social development, insufficient power supplies could cause economic decline and social panic. In addition, due to the inherent complexity and external uncertainty of power generation and fluctuating demand, electricity production needs to be estimated as accurately as possible. Therefore, the actual predicted electricity production is $\sum_{i=1}^{I}\sum_{j=1}^{J} E[\widetilde{T_{ij}}]Z_{ij}$, and the two parts are then combined using a harmonic parameter. Therefore, this constraint is as shown in Equation (10).

$$\beta \sum_{i=1}^{I} E[\widetilde{T}_i]X_i + (1-\beta)\sum_{i=1}^{I}\sum_{j=1}^{J} E[\widetilde{T_{ij}}]Z_{ij} \geq D \tag{10}$$

where $\beta$ is the attitude of the authority towards the historical data, which allows the authority to comprehensively consider both the historical data and the forecast values.

### *3.3. CPP Coal Purchase Scheme*

#### 3.3.1. Economic Profits

Each CPP seeks the largest possible profit under the restrictions of the carbon emissions allowances allocation. CPP profits are income from electricity sales revenue minus the sales tax and component coal procurement, pollution treatment and the carbon emissions allowance tax. Therefore, the profits function for each CPP is formulated as follows:

$$\max EP_i = (p-\mu)\sum_{j=1}^{J} E[\widetilde{T_{ij}}]Z_{ij} - \sum_{j=1}^{J} E[\widetilde{C_j}]Z_{ij} - \sum_{j=1}^{J}\sum_{k=1}^{K} CT_{jk}E[\widetilde{EF_{jk}}]\eta_{ik}Z_{ij} - \gamma Y_i \quad (11)$$

where $EP_i$ is the potential economic profits function of each CPP; $E[\widetilde{T_{ij}}]$ is the expected value of $T_{ij}$; $E[\widetilde{C_j}]$ is the expected value of $C_j$; $E[\widetilde{EF_{jk}}]$ is the expected value of $EF_{jk}$.

### 3.3.2. Carbon Emissions Allowance Constraints

The total carbon emissions at each CPP must not exceed the free (i.e., $X_i$) and taxed (i.e., $Y_i$) carbon emissions quotas allocated by the authority, otherwise the CPP is severely punished or even deprived of its power generation rights. Therefore, the constraints are expressed as in Equation (12).

$$\sum_{j=1}^{J} E[\widetilde{CEF_{ij}}]Z_{ij} \leq X_i + Y_i \quad \forall i \in \Psi \quad (12)$$

where $E[\widetilde{CEF_{ij}}]$ is the expected value of $CEF_{ij}$.

### 3.3.3. Coal Quality Requirement

For the CPPs, the five properties (i.e., volatile matter content, heat rate, ash content, moisture content and sulfur content) of burning coal need to meet the boiler requirements [39,40]. Therefore, these properties are limited within a special range using a coal blending method to ensure normal boiler operations, as shown in Equation (13):

$$E[\widetilde{LCQ_{ik}}]\sum_{j=1}^{J} Z_{ij} \leq \sum_{j=1}^{J} E[\widetilde{CQ_{jk}}]Z_{ij} \leq E[\widetilde{UCQ_{ik}}]\sum_{j=1}^{J} Z_{ij}, \quad \forall i \in \Psi, \forall k \in \Omega \quad (13)$$

where $k = 1$ denotes volatile matter content, $w = 2$ denotes heat rate, $w = 3$ denotes ash content, $w = 4$ denotes moisture content and $w = 5$ denotes sulfur content.

### 3.3.4. Social Responsibility Limitation

Modern enterprises not only consider profits, but also have necessary social responsibilities. As electricity is essential to social and economic development, the supply of basic electricity is the most basic social responsibility for each CPP. Therefore, this constraint ensures an electricity supply-demand balance, as seen in Equation (14).

$$\sum_{j=1}^{J} E[\widetilde{T_{ij}}]Z_{ij} \geq ED_i \quad \forall i \in \Psi \quad (14)$$

### 3.3.5. Component Coal Purchase Quantity Limitations

There is a limit to each component coal that can be purchased by the CPP, which is affected by the coal production and coal consumption in other industries. There are also nonnegative constraints on the decision variable $Z_{ij}$ as the component coal burned by the CPP cannot be nonnegative. By combining these two parts, this constraint is expressed as follows:

$$0 \leq Z_{ij} \leq Q_{ij}^{u} \quad \forall i \in \Psi, \forall j \in \Phi \quad (15)$$

### 3.4. Global Model

By integrating Equations (1)–(15), the global optimization model for the carbon emissions allowance allocation based on the cap and tax mechanism is built, as shown in Equation (16). There is interaction between the authority and the CPPs as the authority's decisions affect the CPPs' decisions. The authority seeks to mitigate carbon emissions, and the CPPs seek profit maximization. However, as the decisions by each CPP also affect the authority's decisions and the other CPPs, conflicts arise when all stakeholders attempt to achieve an optimal solution based on their own respective optimization targets; therefore, a compromise is necessary to achieve equilibrium between the authority and the CPPs. Initially, based on historical information and its own objectives, the authority decides on an initial carbon emissions allowances allocation scheme, which is sent to the CPPs. Each CPP than formulates its own production plan in line with the allocated carbon emissions allowance, the coal quality requirements, its social responsibility and the market conditions. These CPP plans are then fed back to the authority, which adjusts its initial decisions in consideration of the emissions performance of each CPP, after which an improved allocation plan is sent to the CPPs again. The above process is repeated until all stakeholders reach equilibrium. Therefore, this problem is expressed mathematically as a bi-level programming model, as follows:

$$
\begin{aligned}
&\max FB = \mu \sum_{i=1}^{I} \sum_{j=1}^{J} E[\widetilde{T_{ij}}] Z_{ij} + \gamma \sum_{i=1}^{I} Y_i \\
&\min TC = CE_c \\
&\max SD = \min \{SD_i\} \\
&s.t. \left\{ \begin{array}{l}
CE_c = CE_f + CE_t \\
CE_f = \alpha CE_c, \ \ \alpha \in [0,1] \\
CE_f = \sum_{i=1}^{I} X_i \\
\sum_{i=1}^{I} Y_i \le CE_t \\
CEA_i^{\min} \le X_i + Y_i \le CEA_i^{\max}, \ \ \forall i \in \Psi \\
\beta \sum_{i=1}^{I} E[\widetilde{T_i}] X_i + (1-\beta) \sum_{i=1}^{I} \sum_{j=1}^{J} E[\widetilde{T_{ij}}] Z_{ij} \ge D \\
\max EP_i = (p-\mu) \sum_{j=1}^{J} E[\widetilde{T_{ij}}] Z_{ij} - \sum_{j=1}^{J} E[\widetilde{C_j}] Z_{ij} - \sum_{j=1}^{J} \sum_{k=1}^{K} CT_{jk} E[\widetilde{EF_{jk}}] \eta_{ik} Z_{ij} - \gamma Y_i \\
s.t. \left\{ \begin{array}{l}
\sum_{j=1}^{J} E[\widetilde{CEF_{ij}}] Z_{ij} \le X_i + Y_i, \ \ \forall i \in \Psi \\
E[\widetilde{LCQ_{ik}}] \sum_{j=1}^{J} Z_{ij} \le \sum_{j=1}^{J} E[\widetilde{CQ_{jk}}] Z_{ij} \le E[\widetilde{UCQ_{ik}}] \sum_{j=1}^{J} Z_{ij}, \ \ \forall i \in \Psi, \forall k \in \Omega \\
\sum_{j=1}^{J} E[\widetilde{T_{ij}}] Z_{ij} \ge ED_i, \ \ \forall i \in \Psi \\
0 \le Z_{ij} \le Q_{ij}^{u} \ \ \forall i \in \Psi, \forall j \in \Phi
\end{array} \right.
\end{array} \right.
\end{aligned}
\tag{16}
$$

## 4. Case Study

### 4.1. Case Description

Jiangsu Province, one of the most economically-prosperous areas in China, is located in southeast China. Because of the rapid industrialization and urbanization, the demand for electricity primarily supplied by coal-fired power plants has increased dramatically, leading to a commensurate increase in carbon emissions. Due to the pressure from international bodies and local public opinion, the authority in Jiangsu Province has planned to reduce carbon emissions in the next five-year plan. To reduce the computation burden, only three major CPPs (i.e., the Xiaguan CPP, the Huarun CPP and the Yancheng CPP; the locations for which are shown in Figure 2) in Jiangsu Province were chosen in this case study to demonstrate the practicability and efficiency of the proposed method.

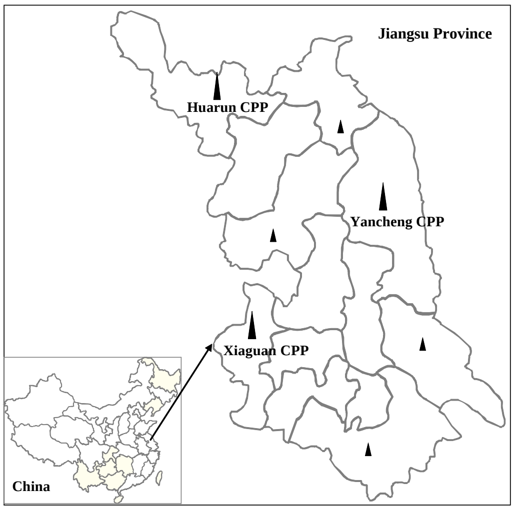



**Figure 2.** Location of the case region.

### 4.2. Model Transformation

Based on the actual background and characteristics of the CEAA problem, this paper transforms the multi-objective optimization problem into a single-objective optimization problem by determining a primary objective and treating the secondary objectives as corresponding constraints with appropriate threshold values according to the research of Zeng et al. [41]. As Jiangsu Province is still developing, continued economic development remains the primary objective of the authority. However, under pressure to ensure sustainable development, the environment must also be protected; therefore, the authority transforms the minimization of the total carbon emissions allowance objective into a corresponding environmental constraint. Analogously, to ensure a fair market environment, the authority transforms the objective to maximize free carbon allowance allocation satisfaction into its corresponding constraint. Therefore, Model (16) is transformed into a corresponding single-objective form, as shown in Equation (17):

$$\max FB = \mu \sum_{i=1}^{I} \sum_{j=1}^{J} E[\widetilde{T}_{ij}] Z_{ij} + \gamma \sum_{i=1}^{I} Y_i$$
$$s.t. \begin{cases} CE_c \leq \lambda CE \\ SD_i \geq \theta \\ CE_c = CE_f + CE_t \\ CE_f = \alpha CE_c, \ \ \alpha \in [0,1] \\ CE_f = \sum_{i=1}^{I} X_i \\ \sum_{i=1}^{I} Y_i \leq CE_t \\ CEA_i^{\min} \leq X_i + Y_i \leq CEA_i^{\max}, \ \ \forall i \in \Psi \\ \beta \sum_{i=1}^{I} E[\widetilde{T}_i] X_i + (1-\beta) \sum_{i=1}^{I} \sum_{j=1}^{J} E[\widetilde{T}_{ij}] Z_{ij} \geq D \\ \max EP_i = (p-\mu) \sum_{j=1}^{J} E[\widetilde{T}_{ij}] Z_{ij} - \sum_{j=1}^{J} E[\widetilde{C}_j] Z_{ij} - \sum_{j=1}^{J} \sum_{w=1}^{W} CT_{jw} E[\widetilde{EF}_{jw}] \eta_{iw} Z_{ij} - \gamma Y_i \\ s.t. \begin{cases} \sum_{j=1}^{J} E[\widetilde{CEF}_{ij}] Z_{ij} \leq X_i + Y_i, \ \ \forall i \in \Psi \\ E[L\widetilde{CQ}_{ik}] \sum_{j=1}^{J} Z_{ij} \leq \sum_{j=1}^{J} E[\widetilde{CQ}_{jk}] Z_{ij} \leq E[U\widetilde{CQ}_{ik}] \sum_{j=1}^{J} Z_{ij}, \ \ \forall i \in \Psi, \forall k \in \Omega \\ \sum_{j=1}^{J} E[\widetilde{T}_{ij}] Z_{ij} \geq ED_i, \ \ \forall i \in \Psi \\ 0 \leq Z_{ij} \leq Q_{ij}^{u} \ \ \forall i \in \Psi, \forall j \in \Phi \end{cases} \end{cases} \quad (17)$$

where $\lambda$ is the attitude of the authority towards carbon emissions reduction; $\theta$ is the minimal allowance satisfactory degree chosen by the authority; and $CE$ is the actual carbon emission amount in the last production cycle. However, the bi-level optimization model is still a non-deterministic polynomial hard problem even in its most simple form. The different levels of the decision makers control or influence the decisions of the others through their own decisions; in other words, equilibrium between the upper and lower levels needs to be achieved through constant stakeholder interaction. Therefore, an interactive algorithm was designed to resolve this complexity. First, a feasible region for the upper level model was built based on the constraints and a feasible solution randomly produced as the initial solution. Then, this initial feasible solution was sent to the lower level and a corresponding solution obtained, which was fed back to the upper level. After receiving the feedback from the lower level, the upper level made corresponding adjustments to obtain an improved solution, which was then sent to the lower level again. This procedure continued to iterate until the termination condition was met. In this paper, the termination condition was set as $\sum_{i=1}^{I} \left( \left| X_i^n - X_i^{n-1} \right| + \left| Y_i^n - Y_i^{n-1} \right| \right) \Big/ \sum_{i=1}^{I} \left( X_i^n + Y_i^n \right) \leq 1\%$. This process was accomplished using the following procedure.

Step 1: Randomly generate a set of initial feasible solutions ($X_i^1$, $Y_i^1$) in the feasible zone of the upper level.

Step 2: Solve the lower level problem using the simplex method by inputting $X_i$ and $Y_i$ into the lower level optimization model.

Step 3: Obtain the optimal solution from $Z_{ij}$, which is fed back to the upper-level optimization model.

Step 4: Solve the upper level problem using the simplex method, and obtain the improved solution ($X_i$, $Y_i$).

Step 5: The improved solution is sent to the lower level model again.

Step 6: Repeat Step 3 and Step 4 until the termination condition is reached.

### 4.3. Data Collection

The basic data shown in Table 2 were obtained from the annual reports of the three power plants. Macro data, such as the actual carbon emissions $CE$ from the last production period were taken from the Statistical Yearbook of Jiangsu Province, China, as shown in Table 3. The uncertain data in the model are described using trapezoidal fuzzy numbers based on fuzzy set theory. These fuzzy data were determined from interviews with experts and engineers, a well as historical data [37]. Therefore, the uncertain parameters in this paper were collected in fuzzy form, as shown in Table 4.

**Table 2.** Crisp parameters of each CPP.

| | Xiaguan CPP | Huarun CPP | Yancheng CPP |
|---|---|---|---|
| Emission reduction measure | | | |
| For $SO_2$ ($w = 1$) | LDS | LDS | LDS |
| For $NO_x$ ($w = 2$) | SCR | SCR | SCR |
| For $PM_{10}$ ($w = 3$) | CDE and EP | EF and EP | EF and EP |
| Emission reduction efficiency, $\eta_{iw}$ | | | |
| For $SO_2$ ($w = 1$) (%) | 96.2 | 96.1 | 95.9 |
| For $NO_x$ ($w = 2$) (%) | 85.9 | 85.7 | 85.4 |
| For $PM_{10}$ ($w = 3$) (%) | 98.8 | 98.5 | 98.4 |
| Emission reduction cost, $CT_{jw}$ | | | |
| For $SO_2$ ($w = 1$) (RMB/kg) | 2.4 | 2.2 | 1.7 |
| For $NO_x$ ($w = 2$) (RMB/kg) | 16.7 | 15.8 | 14.2 |
| For $PM_{10}$ ($w = 3$) (RMB/kg) | 3.5 | 2.8 | 2.1 |
| Minimum power supply, $ED_i$ ($10^9$ kWh) | 2.7 | 4.2 | 1.9 |
| Minimum allowance demand, $CEA_i^{min}$ ($10^6$ tonne) | 3 | 4 | 2 |
| Maximum allowance demand, $CEA_i^{max}$ ($10^6$ tonne) | 6 | 8 | 6 |
| Coal quality requirement, $[LCQ_{ik}, LCQ_{ik}]$ | | | |
| Volatile matter (% weight) | >6 and <27 | >7 and <29 | >9 and <32 |
| Heat rate (GJ/tonne) | >22.3 | >22.1 | >21.9 |
| Ash content (% weight) | <20 | <22 | <23 |
| Moisture content (% weight) | <5 | <6 | <7 |
| Sulfur content (% weight) | <0.8 | <0.9 | <1.0 |

Notes: LDS (i.e., lime spray dryer system), SCR (i.e., selective catalytic reduction), EP (i.e., electrostatic precipitator), CDE (i.e., cyclone dust extractor) and FF (i.e., fabric filter).

**Table 3.** Other parameters employed in the proposed model.

| | |
|---|---|
| Taxable carbon allowance price, $\gamma$ (RMB/tonne) | 30 |
| Added-value tax, $\mu$ (RMB/kWh) | 0.01 |
| Price of unit electric, $p$ (RMB/kWh) | 0.45 |
| Total basic electric supply, D ($10^9$ kWh) | $8.8 \times 10^9$ |
| Actual carbon emission amount in the last production cycle, CE (tonne) | $1.98 \times 10^7$ |

**Table 4.** Parameters of component coals in fuzzy form.

| | Tongmei | Shenhua | Yitai | Zhongmei |
|---|---|---|---|---|
| Coal characteristics, $\widetilde{CQ}_{jk}$ | | | | |
| Volatile matter (% weight) | (6.9, 7.5, 8.3, 9.3) | (35.2, 37.4, 38.9, 40.5) | (23.6, 25.4, 27.1, 27.9) | (24.9, 27.4, 29.8, 29.9) |
| Heat rate (GJ/tonne) | (22.6, 22.9, 23.5, 23.8) | (21.2, 21.7, 22.1, 22.2) | (20.4, 20.9, 21.3, 21.8) | (18.2, 18.6, 20.1, 21.1) |
| Ash content (% weight) | (19.9, 20.6, 21.4, 22.1) | (14.7, 15.8, 16.6, 16.9) | (10.4, 11.5, 12.1, 14) | (16.3, 17.4, 18.9, 19.4) |
| Moisture content (% weight) | (4.3, 4.4, 4.8, 4.9) | (5.1, 5.4, 5.7, 6.2) | (1.9, 2.3, 2.7, 3.1) | (2.4, 2.9, 3.2, 3.9) |
| Sulfur content (% weight) | (0.4, 0.5, 0.7, 0.8) | (0.1, 0.2, 0.3, 0.6) | (0.6, 0.7, 1.1, 1.2) | (0.1, 0.2, 0.2, 0.3) |
| Emission factor, $\widetilde{EF}_{jw}$ | | | | |
| For $SO_2$ ($w = 1$) (kg/tonne) | (4.3, 4.9, 5.3, 7.9) | (5.6, 6.3, 7.4, 7.9) | (6.4, 6.9, 7.6, 8.7) | (8.6,8.8,9.2,10.2) |
| For $NO_x$ ($w = 2$) (kg/tonne) | (1.8, 2.3, 2.8, 3.1) | (2.3, 2.9, 3.5, 3.7) | (6.1, 6.4, 6.7, 6.8) | (8.8, 9.1, 9.4, 9.9) |
| For $PM_{10}$ ($w = 3$) (kg/tonne) | (0.1, 0.2, 0.2, 0.3) | (0.2, 0.4, 0.6, 0.8) | (0.4, 0.7, 1.2, 1.3) | (1.1, 1.3, 1.5, 1.7) |
| Coal-power conversion coefficient, $\widetilde{T}_{ij}$ | | | | |
| Xiaguan CPP (kWh/tonne) | (2490, 2535, 2595, 2660) | (2415, 2425, 2435, 2445) | (2320, 2330, 2340, 2370) | (2120, 2145, 2160, 2175) |
| Huarun CPP (kWh/tonne) | (2485, 2520, 2550, 2565) | (2375, 2390, 2415, 2420) | (2265, 2295, 2315, 2325) | (2090, 2105, 2140, 2145) |
| Yancheng CPP (kWh/tonne) | (2420, 2455, 2480, 2525) | (2325, 2335, 2345, 2355) | (2225, 2240, 2255, 2280) | (2045, 2055, 2085, 2095) |
| Carbon emission factor, $\widetilde{CEF}_{ij}$ | | | | |
| Xiaguan CPP (kg/tonne) | (2045, 2075, 2095, 2145) | (1955, 1965, 1975, 1985) | (1875, 1890, 1905, 1930) | (1730, 1745, 1760, 1765) |
| Huarun CPP (kg/tonne) | (2090, 2105, 2115, 2130) | (1980, 1995, 2010, 2015) | (1905, 1910, 1925, 1940) | (1750, 1760, 1775, 1795) |
| Yancheng CPP (kg/tonne) | (2120, 2130, 2145, 2165) | (1995, 2015, 2030, 2040) | (1940, 1945, 1955, 1960) | (1780, 1785, 1790, 1805) |
| Procurement cost, $\widetilde{C}_j$ (RMB/tonne) | (665, 675, 685, 695) | (630, 635, 645, 650) | (570, 590, 615, 665) | (525, 540, 555, 580) |

## 5. Results and Discussion

### *5.1. Results and Sensitivity Analysis*

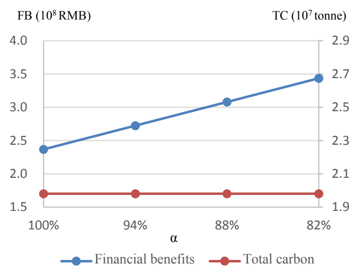
The collected data were input into the proposed model (i.e., Equation (17)) and the solution approach run on MATLAB software, from which the optimal carbon emissions allowance allocation for the authority was determined.

#### 5.1.1. Different Free Carbon Emission Levels

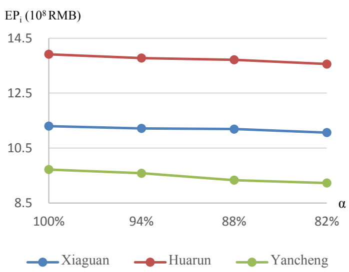
As the authority needs to strengthen the control over the free carbon emissions allocations, a single result is unsatisfactory; therefore, several scenarios are considered. To illustrate the practicality and validity of this method, as a representative situation, Table 5 shows the results of the sensitivity analysis on the free carbon emission levels when $\theta = 0.5$ and $\lambda = 1$. In this situation, for fairness, the authority's attitude towards allocation satisfaction, was set at 0.5, and the carbon emissions reduction level was set at one, the most relaxed carbon emissions reduction attitude. It can be seen that in this situation, the authority earns $3.436 \times 10^8$ RMB when $\alpha = 0.82$, which is the lowest free emissions level. Figure 3 illustrates the changes to the financial benefits for the authority (i.e., $FB$), the total carbon emissions (i.e., $TC$) in the region, each CPP's profits (i.e., $EP_i$), the allocation satisfaction level (i.e., $SD_i$), the free emissions allocation allowance ($X_i$), the taxable emissions allocation allowance ($Y_i$) and the carbon emissions allowance ($X_i + Y_i$) against changing the free carbon emissions level. The financial benefits for the authority gradually increase, and the profits of each CPP decrease as the free carbon emissions level decreases. Further, to maximize profits, all CPPs strive to obtain a higher market share and finally reach equilibrium, at which point, all CPPs have used all their free carbon emission allowances and are seeking to obtain as high an allowance as possible from the authority. In addition, as the free emissions level decreases, the CPPs have lower free carbon emissions allowances and lower satisfactory degrees. From Figure 3, it can be seen that the Huarun CPP remained the most profitable CPP under the different free emissions levels and the highest carbon emissions allowance, which included both the free and taxable emissions allowances. In addition, the Yancheng CPP profits were lower than the Xiaguan CPP profits, although they have roughly equivalent carbon emissions quotas. It was concluded that the Yancheng CPP may be detrimental to the sustainable development of the coal-fired power industry in this region. Therefore, suitable free carbon emissions level can achieve both stable economic development and a fair market environment.

**Table 5.** Sensitivity analysis on free carbon emissions level $\alpha$ when $\theta = 0.5$ and $\lambda = 1$.

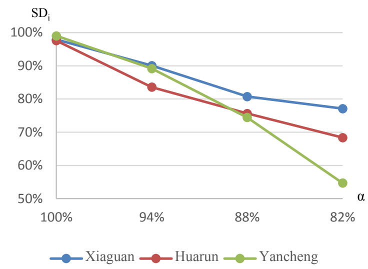
| $\alpha$ | $FB$ ($10^8$ RMB) | CPP | $X_i$ ($10^6$ tonnes) | $Y_i$ ($10^5$ tonnes) | $EP_i$ ($10^8$ RMB) | $Z_{i1}$ ($10^6$ tonnes) | $Z_{i2}$ ($10^6$ tonnes) | $Z_{i3}$ ($10^6$ tonnes) | $Z_{i4}$ ($10^6$ tonnes) | $SD_i$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2.367 | Xiaguan | 5.94 | 0.00 | 11.30 | 2.00 | 0.89 | 0.00 | 0.00 | 0.9789 |
| | | Huarun | 7.90 | 0.00 | 13.91 | 2.00 | 1.00 | 0.88 | 0.00 | 0.9757 |
| | | Yancheng | 5.96 | 0.00 | 9.72 | 1.00 | 1.00 | 0.92 | 0.00 | 0.9901 |
| | | | | | 34.94 | | | | | |
| 0.94 | 2.723 | Xiaguan | 5.70 | 2.25 | 11.22 | 2.00 | 0.89 | 0.00 | 0.00 | 0.9006 |
| | | Huarun | 7.34 | 5.84 | 13.78 | 2.00 | 1.00 | 0.89 | 0.00 | 0.8358 |
| | | Yancheng | 5.57 | 3.79 | 9.59 | 1.00 | 1.00 | 0.92 | 0.00 | 0.8917 |
| | | | | | 34.58 | | | | | |
| 0.88 | 3.080 | Xiaguan | 5.42 | 5.44 | 11.19 | 2.00 | 0.91 | 0.00 | 0.00 | 0.8073 |
| | | Huarun | 7.03 | 9.28 | 13.71 | 2.00 | 1.00 | 0.90 | 0.00 | 0.7563 |
| | | Yancheng | 4.98 | 9.04 | 9.33 | 1.00 | 1.00 | 0.88 | 0.00 | 0.7442 |
| | | | | | 34.24 | | | | | |
| 0.82 | 3.436 | Xiaguan | 5.31 | 5.92 | 11.07 | 2.00 | 0.88 | 0.00 | 0.00 | 0.7711 |
| | | Huarun | 6.74 | 11.64 | 13.56 | 2.00 | 1.00 | 0.87 | 0.00 | 0.6838 |
| | | Yancheng | 4.19 | 18.08 | 9.23 | 1.00 | 1.00 | 0.94 | 0.00 | 0.5469 |



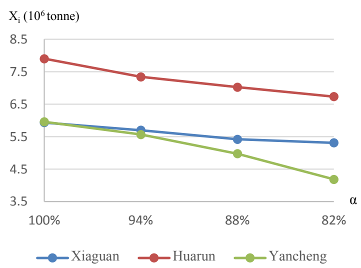

(**a**) Financial benefits and carbon emissions of the authority



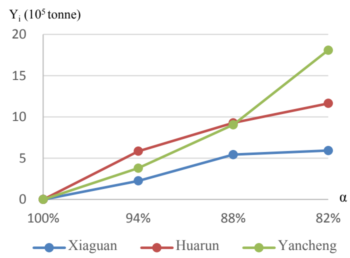

(**b**) CPPs' economic profits



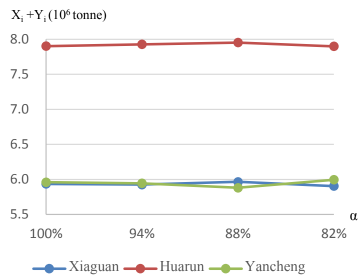

(**c**) CPPs' allocation satisfaction




(**d**) CPPs' free carbon emissions allowance




(**e**) CPPs' taxable carbon emissions allowance

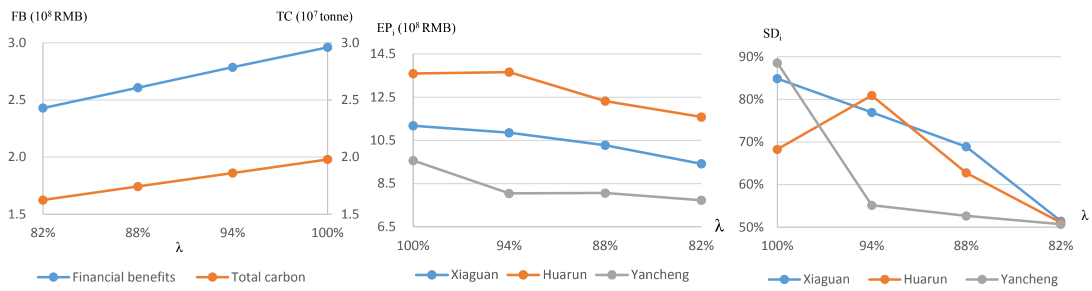



(**f**) CPPs' total carbon emissions allowance

**Figure 3.** Comparative analysis under different free emission levels. (**a**) Financial benefit and carbon emissions of the authority; (**b**) CPPs' economic profits; (**c**) CPPs' allocation satisfaction; (**d**) CPPs' free carbon emissions allowance; (**e**) CPPs' taxable carbon emissions allowance; (**f**) CPPs' total carbon emissions allowance.

### 5.1.2. Different Carbon Emission Reduction Levels

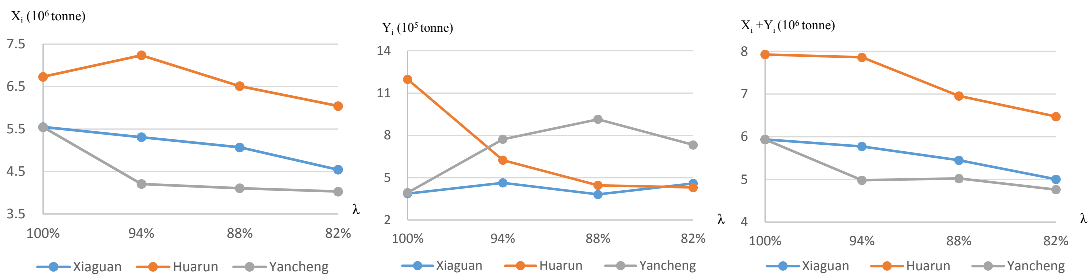
As the carbon emissions reduction level is an another important factor for carbon emissions mitigation by the authority, several scenarios were again considered under different $\lambda$. As a representative example, Table 6 shows the sensitivity analysis results for the carbon emissions reduction levels when $\theta = 0.5$ and $\alpha = 0.9$ to verify the validity of the model. The carbon emissions allowance cap was divided into free and taxable emissions quotas and the free carbon emissions level set at 0.9. The results in Table 6 show that the authority achieves a minimum of $2.43 \times 10^8$ RMB when $\lambda = 0.82$, which was the lowest carbon emissions reduction level. Figure 4 shows the results for the comparative analysis under different carbon emissions reduction levels. From Figure 4a, it can be seen that both the financial benefits and total carbon emissions decrease as the environmental protection constraints are tightened (i.e., changing $\lambda$ from one to its lowest level); however, the decrease in the carbon emissions ratio is larger than the decrease in the financial benefits. For example, when $\lambda = 0.94$ is compared with $\lambda = 1$, the financial benefit ratio decreases by 5.9% and the carbon emissions ratio decreases by 6.4%. Further, the ratios decrease by 6.4% and 6.8% when $\lambda = 0.88$ and by 6.8% and 7.3% when $\lambda = 0.82$ for the two factors. From this analysis, it was concluded that tightening the environmental protection constraints is more beneficial to sustainable development and that more relaxed environmental protection constraints cause more damage to sustainable development. Similar to the different free carbon emissions level scenarios, to maximize economic profits, each CPP is eager to gain a higher market share and eventually reaches equilibrium. In addition, it is clear that the CPP profits decrease with a decrease in the carbon emissions reduction level. The profits and free emissions allowance at the Huarun CPP are still the highest, and the Yancheng CPP is the lowest under the different carbon emissions reduction levels.




(**a**) Financial benefits and carbon emissions of the authority

(**b**) CPPs' economic profits

(**c**) CPPs' allocation satisfaction




(**d**) CPPs' free carbon emissions allowance

(**e**) CPPs' taxable carbon emissions allowance

(**f**) CPPs' total carbon emissions allowance

**Figure 4.** Comparative analysis under different carbon emission reduction levels. (**a**) Financial benefits and carbon emissions of the authority; (**b**) CPPs' economic profits; (**c**) CPPs' allocation satisfaction; (**d**) CPPs' free carbon emissions allowance; (**e**) CPPs' taxable carbon emissions allowance; (**f**) CPPs' total carbon emissions allowance.

**Table 6.** Sensitivity analysis on carbon emission reduction level $\lambda$ when $\theta$ = 0.5 and $\alpha$ = 0.9.

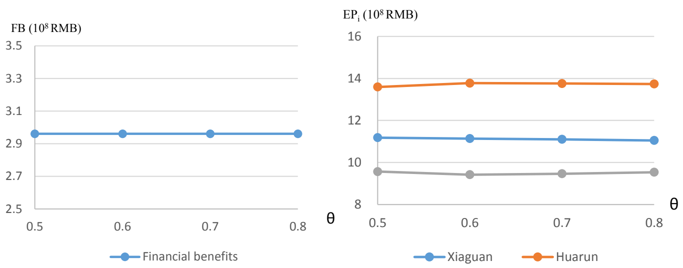
| $\lambda$ | $FB$ ($10^8$ RMB) | CPP | $X_i$ ($10^6$ tonnes) | $Y_i$ ($10^5$ tonnes) | $EP_i$ ($10^8$ RMB) | $Z_{i1}$ ($10^6$ tonnes) | $Z_{i2}$ ($10^6$ tonnes) | $Z_{i3}$ ($10^6$ tonnes) | $Z_{i4}$ ($10^6$ tonnes) | $SD_i$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2.961 | Xiaguan | 5.55 | 3.88 | 11.18 | 2.00 | 0.89 | 0.00 | 0.00 | 0.8488 |
| | | Huarun | 6.73 | 11.97 | 13.59 | 2.00 | 1.00 | 0.89 | 0.00 | 0.6826 |
| | | Yancheng | 5.54 | 3.95 | 9.57 | 1.00 | 1.00 | 0.91 | 0.00 | 0.8858 |
| 0.94 | 2.787 | Xiaguan | 5.31 | 4.64 | 10.86 | 2.00 | 0.81 | 0.00 | 0.00 | 0.7695 |
| | | Huarun | 7.24 | 6.24 | 13.66 | 2.00 | 1.00 | 0.85 | 0.00 | 0.8092 |
| | | Yancheng | 4.21 | 7.73 | 8.04 | 1.00 | 1.00 | 0.42 | 0.00 | 0.5514 |
| 0.88 | 2.608 | Xiaguan | 5.07 | 3.82 | 10.28 | 2.00 | 0.64 | 0.00 | 0.00 | 0.6888 |
| | | Huarun | 6.51 | 4.46 | 12.32 | 2.00 | 1.00 | 0.38 | 0.00 | 0.6275 |
| | | Yancheng | 4.11 | 9.14 | 8.06 | 1.00 | 1.00 | 0.44 | 0.00 | 0.5263 |
| 0.82 | 2.429 | Xiaguan | 4.54 | 4.60 | 9.42 | 1.94 | 0.48 | 0.00 | 0.00 | 0.5142 |
| | | Huarun | 6.04 | 4.31 | 11.59 | 2.00 | 1.00 | 0.13 | 0.00 | 0.5105 |
| | | Yancheng | 4.03 | 7.32 | 7.73 | 1.00 | 1.00 | 0.31 | 0.00 | 0.5069 |

### 5.1.3. Different Allocation Satisfaction Levels

A fair market environment is conducive to regional sustainable development. In this paper, a satisfactory degree method is proposed to measure fairness. Similarly, several scenarios were conducted under different allocation satisfaction levels. As an example, Table 7 shows the results of the sensitivity analysis for the allocation satisfaction levels when $\alpha$ = 0.9 and $\lambda$ = 1, from which it can be seen that the authority achieves a minimum of 2.96066 $\times$ $10^8$ RMB when $\theta$ = 0.8, which is the lowest allocation satisfaction level. Figure 5 illustrates the changes in the financial benefits (i.e., $FB$) for the authority and each CPP's profits (i.e., $EP_i$) when the allocation satisfaction level changes. However, as can be seen, the allocation satisfaction does not significantly impact the financial benefits of the authority or the CPP profits. For example, when $\theta$ = 0.5, the financial benefits are 2.96112 $\times$ $10^8$ RMB, and as $\theta$ changes to 0.6, the financial benefits are 2.96081 $\times$ $10^8$ RMB, a decrease of only 0.011%. When $\theta$ is set at 0.7 and 0.8, the ratio decreases only slightly by 0.004% and 0.001%. From Figure 5, similar situations can be seen for each of the CPP profits.

**Table 7.** Sensitivity analysis on allocation satisfaction level $\theta$ when $\alpha$ = 0.9 and $\lambda$ = 1.

| $\theta$ | $FB$ ($10^8$ RMB) | CPP | $X_i$ ($10^6$ tonnes) | $Y_i$ ($10^5$ tonnes) | $EP_i$ ($10^8$ RMB) | $Z_{i1}$ ($10^6$ tonnes) | $Z_{i2}$ ($10^6$ tonnes) | $Z_{i3}$ ($10^6$ tonnes) | $Z_{i4}$ ($10^6$ tonnes) | $SD_i$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 0.5 | 2.96112 | Xiaguan | 5.55 | 3.88 | 11.18 | 2.00 | 0.89 | 0.00 | 0.00 | 0.8488 |
| | | Huarun | 6.73 | 11.97 | 13.59 | 2.00 | 1.00 | 0.89 | 0.00 | 0.6826 |
| | | Yancheng | 5.54 | 3.95 | 9.57 | 1.00 | 1.00 | 0.91 | 0.00 | 0.8858 |
| 0.6 | 2.96081 | Xiaguan | 5.56 | 3.48 | 11.14 | 2.00 | 0.88 | 0.00 | 0.00 | 0.8519 |
| | | Huarun | 7.40 | 5.14 | 13.78 | 2.00 | 1.00 | 0.88 | 0.00 | 0.8496 |
| | | Yancheng | 4.87 | 11.18 | 9.42 | 1.00 | 1.00 | 0.94 | 0.00 | 0.7165 |
| 0.7 | 2.96068 | Xiaguan | 5.52 | 3.67 | 11.10 | 2.00 | 0.87 | 0.00 | 0.00 | 0.8404 |
| | | Huarun | 7.35 | 5.65 | 13.76 | 2.00 | 1.00 | 0.88 | 0.00 | 0.8369 |
| | | Yancheng | 4.95 | 10.48 | 9.46 | 1.00 | 1.00 | 0.94 | 0.00 | 0.7378 |
| 0.8 | 2.96066 | Xiaguan | 5.40 | 4.76 | 11.05 | 2.00 | 0.86 | 0.00 | 0.00 | 0.8007 |
| | | Huarun | 7.21 | 7.19 | 13.73 | 2.00 | 1.00 | 0.89 | 0.00 | 0.8017 |
| | | Yancheng | 5.21 | 7.85 | 9.54 | 1.00 | 1.00 | 0.94 | 0.00 | 0.8027 |




(**a**) Financial benefits of the authority (**b**) CPPs' economic profits

**Figure 5.** Comparative analysis under different allocation satisfaction levels. (**a**) Financial benefits of the authority; (**b**) CPPs' economic profits.

### 5.2. Discussion

Based on the above results and analysis, the proposed method contributes to research on carbon emissions mitigation in the coal-fired power field and can assist authorities in establishing reasonable carbon emissions allowance allocation policies as the uncertain factors (coal characteristics, emissions factor, coal-power conversion coefficient, carbon emissions factor and procurement costs) are considered. The coal characteristics are uncertain due to the impact of the natural condition and the mining processes, and the uncertain emissions factor depends on the uncertain coal characteristics. The coal-power conversion coefficient and the carbon emissions factor are uncertain because of the uncertain combustion efficiencies. The procurement costs are uncertain because of the impact of price coordination and market fluctuations. At the same time, there are deviations in the collected data; that is, these uncertain parameters are influenced by both subjective and objective factors. There has been significant research conducted in dealing with such uncertainties. For example, Cheng et al. proposed an interval recourse liner programming (IRLP) to mitigate constraint violation problems in resources and environmental systems management (REM) under uncertainties [42]. Huang et al. developed an inexact fuzzy stochastic chance constrained programming (IFSCCP) method to address various uncertainties in evacuation management problems [43]. However, based on the actual background and characteristics of the CEAA problem in this paper, fuzzy theory was employed to fit reality and an expected value operator used to transform the fuzzy variables into corresponding expected values. Through this process, the results of the proposed method are more convincing.

In addition, the proposed method was shown to describe the interactive relationship between the authority and the CPPs effectively and to resolve the conflicts between economic development and environmental protection. Such situations are also found in other carbon emissions mitigation fields. For instance, there are similar interactive relationships between the authority and biomass power plants in the biomass power industry, in which there is also economic development and environmental protection conflicts. To mitigate these carbon emissions, authorities need to apply the appropriate CEAA strategy based on cap and tax mechanisms for biomass power plants, and the biomass power plants should have suitable biomass blending plans to achieve their required profits under the carbon quotas imposed by the authority.

### 5.3. Management Recommendations

Based on the above analysis and discussion, some management recommendations are given.

First, for regions that largely depend on CPP-generated electricity, a new cap and tax mechanism should be established to ensure the required environmental protection. Without such a mechanism, CPPs would arbitrarily emit carbon dioxide as they would lack the motivation to improve their emissions performances. Using the proposed methodology, the cap and tax mechanism is able to motivate CPPs to develop low carbon power generation. Further, under carbon emissions allowance allocation constraints, CPPs may be encouraged to improve their clean-energy technologies to decrease operating costs, which could further mitigate carbon emissions and gain higher profits.

Second, the authority can design suitable carbon emissions allowance allocation plans using the proposed method; that is, the authority can select the desired free carbon emissions levels and carbon emissions reductions levels based on the actual situation. Therefore, when using the proposed model, it is recommended that the authorities in developed regions set the lowest free carbon emissions level and the strictest carbon emissions reduction levels to encourage environmentally-friendly power generation. On the other hand, for developing regions, the authority can set relatively loose emissions reduction goals at the start to ensure steady local economic development. They can then continue to tighten the environmental protection parameter to aim for sustainable development.

## 6. Conclusions

This paper studied a coal-fired power generation carbon emission allowance allocation problem and proposed a bi-level multi-objective model that considered the mutual coordination and conflicts between an authority and CPPs. Using the proposed method, a carbon emissions allowance allocation with a cap and tax mechanism was established to ensure steady economic development and carbon emissions mitigation. This model has the ability to describe the interactions of all stakeholders whose decisions may affect the sustainable development of a region and therefore can assist them to develop corresponding strategies to adapt to the changes made by the other stakeholders. A case study on a coal-fired power generation system with three main CPPs was employed to illustrate the practicality and efficiency of the proposed method. Sensitivity analyses on free emission levels and carbon emissions reduction levels were also conducted, which could assist authorities to select the most appropriate local development strategy. The analysis and discussion demonstrated that considering both free emissions levels and carbon emissions reduction levels is able to assist in balancing economic development and environmental protection and that a cap and tax mechanism could play a significant role in the environmentally-friendly development of coal-fired power generation systems.

The following further research directions could be taken: (1) integrate technical innovation and management optimization to improve coal-fired power generation systems; (2) examine how the carbon emissions trading mechanism could be integrated with the proposed method.

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