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Optimal Operation of Generation Company's Participating in Multiple Markets with Allocation and Exchange of Energy-Consuming Rights and Carbon Credits

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Abstract: The proposal of the energy-consuming right (ECR) market may lead to generation companies (GenCos) facing the risk of being overcharged due to the inaccurate calculation of carbon emission reduction, since it claims the same credit as the carbon market does. To estimate the carbon emission reduction accurately for the GenCos that participate in electricity, carbon, and ECR markets simultaneously, this paper proposes a market framework where a flexible exchange mechanism between the ECR and carbon markets is specially considered. To investigate the influence of the allocation and exchange of ECR and carbon credits on the behavior of GenCos that participate in multi-type markets, a bi-level model based on the leader–follower game theory is proposed. In the upper level of the proposed model, a decision problem for maximizing the profit of GenCos is developed, which is especially constrained to the primary allocation of ECR and carbon credits. While the multi-type market clearing model and an exchange mechanism between the ECR and carbon credits are proposed in the lower level of the model. The bi-level problem is converted into the mathematical program with equilibrium constraints (MPECs) through the Karush–Kuhn–Tucker (KKT) condition to solve. The results illustrate that the interaction between the ECR market and the carbon market can improve the energy efficiency and reduce the carbon emissions of GenCos.

Keywords: energy-consuming right market; carbon market; electricity market; credit allocation; credit exchange

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1. Introduction

Global warming and excessive energy consumption pose great challenges to the ecological environment [1,2]. As a major carbon emitter, China has adopted various measures to improve energy efficiency, emission reduction, and the transformation to a low-carbon economy [3]. The ECR market was first proposed in China [4] and piloted in the Zhejiang, Fujian, Henan, and Sichuan provinces [5], aiming to control the total regional energy consumption and force enterprises to save energy, while the carbon market is a market-based carbon dioxide emission reduction transaction in the context of the "Kyoto Protocol" [6,7], which has been nationally launched in China. Both claim the same credit—carbon emission reduction, which lays the basis that they can be exchanged with each other.

Take GenCo as an example, it sells electricity in the electricity market as revenue. When GenCo makes a profit by selling electricity in the electricity market, it not only emits carbon dioxide that costs carbon credits but also consumes energy that costs ECR credits. Hence, the more electricity that GenCo generates, the more carbon and ECR credits it needs. Therefore, the ECR market, carbon market, and electricity market that GenCos participate in simultaneously are not independent of each other. As a profit-driven party, GenCo's generation plan is strongly affected by complex market mechanisms and an unknown competitive environment. Considering the synergistic effect of improved energy efficiency and emission reduction, the ability to calculate the carbon emission reduction in the coupled multi-type market becomes essential to the development of GenCos under "double control".

The ECR market is similar to the carbon market because both of them claim the same carbon credit emission, which indicates that they can be exchanged with each other. For research on the coupling of the carbon and electricity markets, the researchers in [8] designed a novel framework to enable the exchange of energy and carbon credits, while those in [9] proposed a Nash bargaining game model to assess the synergy of the carbon market, tradable green certificate (TGC) market, and electricity market on the decision behavior of non-renewable energy and renewable energy GenCos. The researchers in [10] proposed a day-ahead coupled electricity–carbon–TGC market framework based on blockchain technology and electricity purchasers for dealing with the contradiction between the independent operation and the internal connection of the carbon market, TGC market, and electricity market. The existing literature on the carbon market reveals the coupling quantitative relationship between carbon emission and electricity generation.

Compared with the research on the carbon market, the attention on the ECR market is much less because of its limited application in very few countries. ECR was first proposed for motivating businesses to invest in new technologies and increase productivity to obtain economic dividends, which is considered as the supplement to the emission trading plan to alleviate global warming [11,12]. The existing research on the ECR or ECR market is usually qualitative analysis instead of quantitative ones. Th group in [5] analyzed the ECR market and concluded that it could reduce the intensity of CO_2 emissions to cut down carbon emissions with the proposed difference-in-differences method to explore the effect of the ECR trading strategy on carbon emission intensity. The researchers in [13,14] stated that energy consumption and carbon emissions are interrelated and interdependent and further demonstrated the feasibility of the coordination of two markets. The above-mentioned literature proves the effectiveness of ECR to carbon emission.

However, GenCos not only generate additional energy-saving quantity by investing in new green technologies or increasing productivities but also bringing about carbon emission reduction under the ECR control. Such carbon emission reduction caused by the ECR control is usually ignored in the certificated carbon emission reduction measurement, which leads to the overallocation of carbon credits to GenCos. To estimate the carbon emission reduction accurately for the GenCos that participate in the electricity, carbon, and ECR markets simultaneously, based on the above Nash bargaining game model and multi-type markets coupling mechanisms, this paper proposes a market-based model for GenCos who participate in muti-type markets. The detailed contributions are listed as follows:

1. For investigating the influence of the allocation and exchange of the ECR credit and carbon credit on the behavior of GenCos that participate in multi-type markets, a bi-level model based on the leader–follower game theory is proposed, where a decision problem for maximizing the profit of GenCo is developed in the upper level, while the multi-type markets clearing is modeled in the lower level;
2. To prevent the GenCos who took energy-saving measures from being overallocated with the carbon credits, the carbon emission reduction caused by the energy-saving measures that the GenCos has undertaken is deducted from the primary carbon credits in this paper;
3. A flexible exchange mechanism between the ECR and carbon credits is proposed. In this mechanism, the surplus ECR credits can be traded in the ECR market after making its electricity generation plan or be converted later into carbon credit for trading in the carbon market.

2. Market Framework

Figure 1 illustrates the proposed market framework, where the GenCos participate in the electricity, ECR, and carbon markets one day ahead simultaneously. In the electricity market, the independent system operator (ISO) operates the energy market and is responsible for market clearing after the multiple electricity consumers and GenCos submit their demands and offers. As for the ECR and carbon markets, both have been partitioned into primary and secondary markets. The original allocation of ECR and carbon credit issued by the environmental authority via legislative procedures is free of charge and known as the primary market. It is worth mentioning that the ECR focuses on the source of the production process while the carbon emission certification focuses on the end of that. The primary allocation of the ECR and carbon credits may not perfectly match the actual usage of them. Therefore, the secondary market is established for trading ECR and carbon credits among surplus ECR and carbon credit holders.

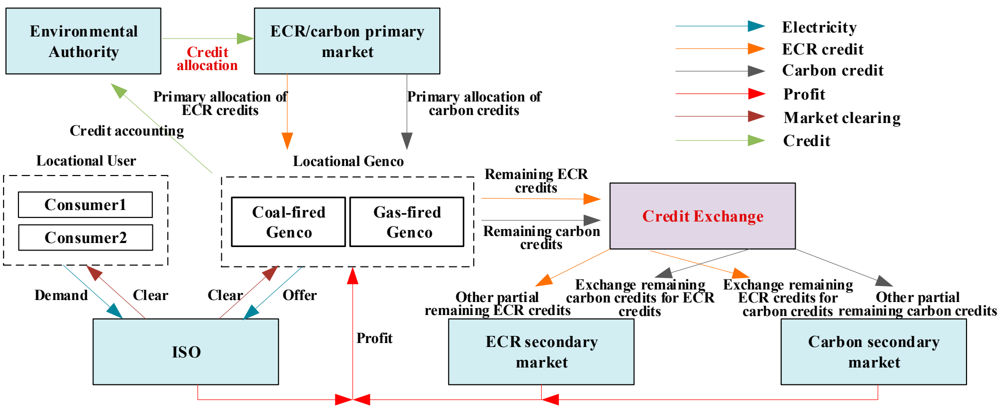

Figure 1. Flow chart of multi-market interaction.

In the secondary market, once there are ECR credits remaining in the primary market, then GenCos may decide whether to trade them in the ECR secondary market or to exchange the remaining ECR credit into the carbon credit and trade them in the carbon secondary market. Reversely, once the ECR credit is insufficient in the primary market when making the electricity generation plan, GenCos will decide to purchase more ECR credits from the ECR secondary market or the carbon secondary market.

3. Modeling of Bi-Level Problem

In this section, a bi-level optimal model is proposed for analyzing the influence of the ECR and carbon markets on the economical behavior of GenCos as indicated in Figure 2, here the upper level takes the profit maximization of GenCo as its objective function, and the lower level takes the social welfare maximization as its objective function. The upper and lower levels constitute a leader–follower game to analyze the market competition [15], where the leader makes offering decision before the followers.

In the electricity market, GenCos, as the upper-level decision maker, submit the offering interval to the lower level. Then, the consumer, as the lower-level decision follower, submits the bidding price to the GenCos. Finally, the ISO clears the electricity market with social welfare maximization and obtains the result of the electricity clearing price at node n, the power produced through block b of generator i, and the power consumed by consumer d of block k at time t. The result of the electricity clearing price and cleared power capacity are later submitted to the upper level. In the ECR and carbon markets, the quantity of the actual ECR and carbon credits used are passed to the two lower-level problems. Then, the clearing prices of the ECR and carbon credits are submitted to the upper level by adopting the Gournot model and credit exchange mechanism. Figure 2 presents the specific model structure and information flows.

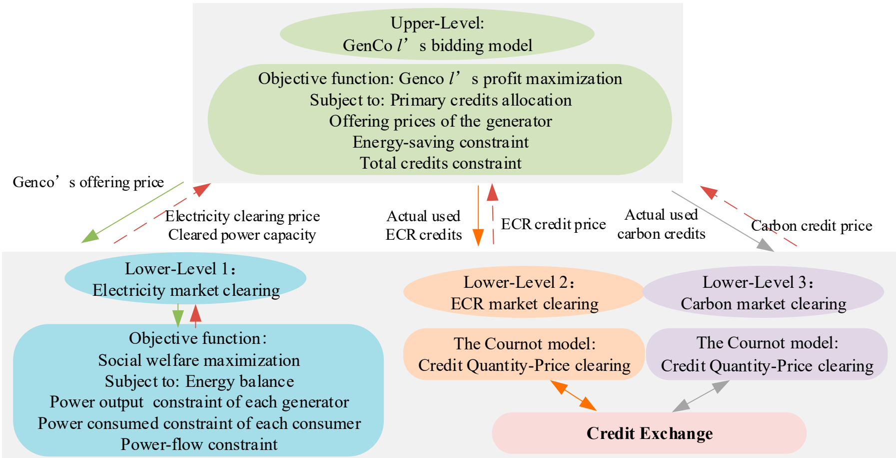

Figure 2. Interactive framework for bi-level model.

3.1. Assumptions

To advance the modeling the GenCos' participation in multi-type markets, the following assumptions should be made:

1. The electricity market is a pool-based one, which is a centralized marketplace where participants can submit their bids and offers for the certain amount of electricity [16]. In actual markets, the ECR and carbon credit markets are typically dominated by a few large participants, especially in the early stages of development. These markets tend to have low liquidity, with transactions primarily concentrated among a small number of large participants. Considering that the ECR and carbon markets are both emerging markets, the GenCos which sell the remaining carbon/ECR credits must have market power. Therefore, the ECR and carbon markets can be considered as oligopoly markets where GenCos compete in credit quantities rather than prices. This is the reason why the Cournot model is adopted for the ECR/carbon market clearing.
2. The premise of the credit exchange mechanism is that the GenCos' primary total credits are sufficient. The ECR and carbon credits are only exchangeable when there is a shortage of any certain type of credit. In other words, when the remaining carbon credit is insufficient and the remaining ECR credit is in surplus, then GenCos can exchange the remaining ECR credit for carbon credit, and vice versa.

3.2. Upper-Level Problem: GenCo's Profit Maximization

The objective function of the upper-level model is to maximize the profit of a GenCo, as shown in Equation (1).

$$\max U_l = (U_l^{\mathrm{DA}} + U_l^{\mathrm{ECR}} + U_l^{\mathrm{CET}} + U_l^{\mathrm{ES}}) \tag{1}$$

where U_l denotes the total profit of GenCo l participating in the electricity market, ECR market, and carbon market; and U_l^{DA}, U_l^{ECR}, and U_l^{CET} are the profits earned by GenCo l in the electricity market, ECR market, and carbon market, respectively. U_l^{ES} denotes the profit of GenCo l for energy efficiency.

The constraints of the upper-level model are listed as follows:

3.2.1. Profit of Selling Electricity

Constraint (2) demonstrates the profit of GenCo l in the electricity market, as follows:

$$U_l^{\mathrm{DA}} = \sum_{i \in \Omega_l} \sum_{b} \sum_{t \in T} [\chi_{(n:i \in \Gamma_n)t} - \chi_{ib}] P_{ibt} \Delta t \tag{2}$$

where $i \in \Omega_l$ and $i \in \Gamma_n$ denote generator i belongs to GenCo l and is located at node n; $\chi_{(n:i\in\phi_n)t}$ is the locational marginal price at node n at time t; χ_{ib} is the marginal cost of block b of generator i; and P_{ibt} is the power produced through block b of generator i at time t.

3.2.2. Profit of Energy Efficiency

Constraint (3) demonstrates the energy-saving benefit of the GenCo, as follows:

$$U_l^{\text{ES}} = \sum_{i\in\Omega_l} (\rho_1 S_i + \rho_2) \tag{3}$$

where S_i is the energy-saving quantity of generator i; and ρ_1 and ρ_2 are the two parameters of the first-order linear function of the energy-saving quantity of generator i, respectively.

3.2.3. Primary Credits Allocation

Constraints (4) and (5) demonstrate the free primary ECR and carbon credits allocated to GenCos. This paper adopts the baseline method for allocating free primary credits to GenCos to encourage them to improve their energy efficiency [5]. Constraint (6) demonstrates the primary carbon credits after deducting the repetitive credits caused by the energy-saving measures taken by GenCo l.

$$E_l^{\text{free}} = RE_{l,\text{ref}} H_l \tag{4}$$

$$C_l^{\text{free0}} = RC_{l,\text{ref}} H_l \tag{5}$$

$$C_l^{\text{free}} = C_l^{\text{free0}} - \sum_{i\in\Omega_l} f_i S_i \tag{6}$$

where E_l^{free} and C_l^{free0} denote GenCo's primary ECR and carbon credits; and C_l^{free} denotes GenCo's primary carbon credits after deducting the repetitive credits. $RE_{l,\text{ref}}$ is the energy consumption baseline; and $RC_{l,\text{ref}}$ is the carbon emission baseline of the generator owned by the GenCo l. H_l represents the historical average output quantity of GenCo l per day; f_i is the carbon emission factor of the generator i; S_i is the energy-saving rate of the generator i.

Assuming that the remaining ECR and carbon credits in the primary market of GenCo l are Q_l^{ECR} and Q_l^{CET}, respectively, when Q_l^{ECR} is greater than zero, the surplus ECR credits can be sold in the ECR secondary market; otherwise, the insufficient ECR credits must be brought from the ECR secondary market., as shown in constraints (7)–(10).

$$Q_l^{\text{ECR}} = E_l^{\text{free}} - E_l^{\text{real}} \tag{7}$$

$$Q_l^{\text{CET}} = C_l^{\text{free}} - C_l^{\text{real}} \tag{8}$$

$$E_l^{\text{real}} = \frac{1}{\theta}\Big(\sum_{i\in\Omega_l}\sum_b\sum_t P_{ibt}\Delta t - \sum_{i\in\Omega_l} S_i\Big) f_i \tag{9}$$

$$C_l^{\text{real}} = \sum_{i\in\Omega_l}\sum_b\sum_t \Big[(Ca)_i + (Cb)_i P_{ibt} + (Cc)_i P_{ibt}^2\Big]\Delta t - \sum_{i\in\Omega_l} S_i f_i \tag{10}$$

where E_l^{real} and C_l^{real} denote the actual ECR and carbon credits used by GenCo l; and θ is the exchange value of the ECR and carbon credits.

3.2.4. Offering Prices of the Generator

Constraints (11) and (12) demonstrate the offering prices, as follows:

$$\alpha_{ib}^{\min} \le \alpha_{ib} \le \alpha_{ib}^{\max} \tag{11}$$

$$\alpha_{i(b-1)} \le \alpha_{ib} \tag{12}$$

where α_{ib} is the offering price for block b of generator i ($b \geq 2$); $\alpha_{ib}^{\max}$ and $\alpha_{ib}^{\min}$ are the upper and lower caps of the offering price for block b of generator i, respectively.

3.2.5. Enengy-Saving Constraint

Constraint (13) guarantees the total quantity of energy saved by the generator, as follows:

$$S_i \leq \sum_b \sum_t P_{ibt}\sigma \tag{13}$$

where σ is the energy-saving rate of the generators.

3.2.6. Total Credits Constraint

Constraint (14) guarantees ample credits in the ECR/carbon market.

$$\sum_l (E_l^{\text{real}} + C_l^{\text{real}}) \leq \sum_l (E_l^{\text{free}} + C_l^{\text{free}}) \tag{14}$$

3.3. Low-Level Problem: Multi-Type Market Clearing

The lower-level model is the multi-type market clearing based on their market characteristics, including the electricity market, ECR market, and carbon market.

3.3.1. Electricity Market Clearing

The optimization object of electricity market clearing is to maximize the social welfare, as shown in (15):

$$\min\left(\sum_i \sum_b \alpha_{ib} P_{ibt} - \sum_d \sum_k \chi_{dk} P_{dkt}\right)\Delta t \tag{15}$$

where χ_{dk} is the consumption utility of bidding block k of consumer d; and P_{dkt} is the power consumed by consumer d of block k at time t.

Subject to the following:

$$\sum_{i\in\Gamma_n^{\text{G}}} \sum_b P_{ibt} - \sum_{d\in\Gamma_n^{\text{D}}} \sum_k P_{dkt} - \sum_{m\in\Gamma_n^{\text{N}}} B_{nm}(\delta_{nt} - \delta_{mt}) = 0 : \chi_{nt} \tag{16}$$

$$P_{ib}^{\min} \leq P_{ibt} \leq P_{ib}^{\max} : \psi_{ibt}^{\min}, \psi_{ibt}^{\max} \tag{17}$$

$$P_{dk}^{\min} \leq P_{dkt} \leq P_{dk}^{\max} : \psi_{dkt}^{\min}, \psi_{dkt}^{\max} \tag{18}$$

$$B_{nm}(\delta_{nt} - \delta_{mt}) \leq P_{nm}^{\text{Lmax}} : \mu_{nmt}^{\text{Lmax}} \tag{19}$$

$$-\pi \leq \delta_{nt} \leq \pi : \omega_{nt}^{\min}, \omega_{nt}^{\max} \tag{20}$$

$$\delta_{1t} = 0 : \xi_t^{\delta 1} \tag{21}$$

Constraint (16) represents the nodal energy balance, where $i \in \Gamma_n^{\text{G}}$, $d \in \Gamma_n^{\text{D}}$, and $m \in \Gamma_n^{\text{N}}$ stand for the generator i, consumer d, and node m located at node n, respectively. B_{nm} is the admittance of the line between node n and node m, δ_{nt} and δ_{mt} are the voltage angle of node n and node m at time t, respectively. χ_{nt} is the dual variable of constraint (16), representing the electricity clearing price. Constraints (17) and (18) represent the power output constraints and the power consumed constraints, where $P_{ib}^{\max}$ and $P_{ib}^{\min}$ are the upper and lower caps of the available capacity of block b in the generator i's offers; and $P_{d,k}^{\text{Dmax}}$ and $P_{d,k}^{\text{Dmin}}$ are the upper and lower levels of the demand quantity of block k in the consumer d's bids. $\psi_{ibt}^{\min}$, $\psi_{ibt}^{\max}$, $\psi_{d,k,t}^{\min}$, and $\psi_{d,k,t}^{\max}$ are the dual variables of constraints (17) and (18). Constraints (19) and (20) are transmission line capacity constraints and power angle constraints, where P_{nm}^{Lmax} is the maximum transmission capacity of line mn. Constraint (21) represents the reference node, where δ_{1t} represents that node 1 is the balanced node. μ_{nmt}^{Lmax}, $\omega_{nt}^{\min}$, $\omega_{nt}^{\max}$, and $\xi_t^{\delta 1}$ is the dual variable of constraints (19)–(21). The derivation of the Lagrangian function of the lower model and the optimality conditions can be seen in Appendix A.

3.3.2. ECR/Carbon Market Clearing

- The Cournot Model

This paper uses the Cournot model to portray the linear relationship between the price and quantity of ECR/carbon credits, the inverse demand function could be calculated as in (22) and (23) [17,18].

$$\begin{cases} \chi_{\mathrm{E}} = \alpha_1 - \beta_1 \sum\limits_{l} E_l^{\mathrm{real}} \\ \alpha_1 = \chi_1 \\ \beta_1 = (1-\varepsilon_0)\chi_1/\gamma_0 Q_0 \end{cases} \tag{22}$$

$$\begin{cases} \chi_{\mathrm{C}} = \alpha_2 - \beta_2 \sum\limits_{l} C_l^{\mathrm{real}} \\ \alpha_2 = \chi_2 \\ \beta_2 = (1-\varepsilon_0)\chi_2/\gamma_0 Q_0 \end{cases} \tag{23}$$

$$Q_0 = \sum_{d,k,t} P_{dkt}^{\max} \Delta t \tag{24}$$

where χ_{E} and χ_{C} are the clearing price of ECR and carbon credit, respectively. α_1, β_1,α_2, and β_2 are two parameters with positive values of the Cournot model in the ECR and carbon market, respectively. χ_1 and χ_2 represent the highest acceptable ECR credit price and carbon credit price for the subject of credit obligation, respectively. ε_0 represents price coefficient; $\varepsilon_0\chi_1$ and $\varepsilon_0\chi_2$ represent the consumers' payment willingness; γ_0 represents the requirement ratio; and Q_0 is the total maximization demand.

- Credit Exchange Mechanism

To prevent GenCos from using excess credits to exchange for insufficient credits without restriction, which may lead to excessive carbon emission or energy waste. The following two provisions are listed: (1) The proportion of carbon credits converted by GenCos from their surplus ECR credits to offset their excess emissions shall not exceed 10% of their primary carbon credits after deducting the repetitive credits; and (2) the proportion of ECR credits converted by GenCos from their surplus carbon credits to offset their excess energy consumption should not exceed 10% of their primary ECR credits.

According to Assumption (2) in Section 3.1, there is no case of $Q_l^{\mathrm{ECR}} < 0$ and $Q_l^{\mathrm{CET}} < 0$ at the same time. The credit exchange mechanism can be expressed as in (25)–(29).

$$U_l^{\mathrm{ECR}} = \chi_{\mathrm{E}}(Q_l^{\mathrm{ECR}} - \Delta Q_l^{\mathrm{ECR}} + \Delta Q_l^{\mathrm{CET}}/\theta) \tag{25}$$

$$U_l^{\mathrm{CET}} = \chi_{\mathrm{C}}(Q_l^{\mathrm{CET}} - \Delta Q_l^{\mathrm{CET}} + \theta \times \Delta Q_l^{\mathrm{ECR}}) \tag{26}$$

$$\begin{cases} -\xi_l^+ M^+ \le Q_l^{\mathrm{ECR}} \le (1-\xi_l^+)M^+ \\ -\xi_l^- M^- \le Q_l^{\mathrm{CET}} \le (1-\xi_l^-)M^- \end{cases} \tag{27}$$

$$\begin{cases} 0 \le \Delta Q_l^{\mathrm{CET}}/\theta \le 10\% \xi_l^+ E_l^{\mathrm{free}} \\ 0 \le \theta \Delta Q_l^{\mathrm{ECR}} \le 10\% \xi_l^- C_l^{\mathrm{free}} \end{cases} \tag{28}$$

$$\begin{cases} \xi_l^+ + \xi_l^- \le 1 \\ \xi_l^+ \in \{0,1\}, \forall \mathrm{l} \\ \xi_l^- \in \{0,1\}, \forall \mathrm{l} \end{cases} \tag{29}$$

where $\Delta Q_l^{\mathrm{CET}}$ denotes the amount of the remaining carbon credits exchanged for ECR credits by GenCo l; $\Delta Q_l^{\mathrm{ECR}}$ denotes the amount of the remaining ECR credits exchanged for carbon credits by GenCo l. M^+, M^- is an enough large number; ξ_l^+ and ξ_l^- are 0–1 variables, which reflect the flow of credit exchange. The specific exchange flows are as follows:

1. When $\xi_l^+ = 0$ and $\xi_l^- = 0$, resulting in $Q_l^{\mathrm{ECR}} > 0$ and $Q_l^{\mathrm{CET}} > 0$, no credit exchange required at this time;
2. When $\xi_l^+ = 1$ and $\xi_l^- = 0$, resulting in $Q_l^{\mathrm{ECR}} < 0$ and $Q_l^{\mathrm{CET}} > 0$, the partial remaining carbon credits ($\Delta Q_l^{\mathrm{CET}}$) shall be exchanged for ECR credits;

3. When $\xi_l^+ = 0$ and $\xi_l^- = 1$, resulting in $Q_l^{\mathrm{CET}} < 0$ and $Q_l^{\mathrm{ECR}} > 0$, the partial remaining ECR credits ($\Delta Q_l^{\mathrm{ECR}}$) shall be exchanged for carbon credits.

4. Solution Technique and Procedure

The original model poses a bi-level programming problem, rendering it unsuitable for direct resolution using existing commercial optimization solvers. In this section, the model is initially reconstructed through KKT conditions [19,20]. The optimality conditions and complementary slackness conditions are derived, facilitating the transformation of the bi-level model into a MPEC. Subsequently, the non-convex constraints are piecewise linearized to obtain a standard mixed integer linear programming model by the strong duality theorem and a binary expansion method [21].

4.1. Mathematical Program with Equilibrium Constraints Reconstruction

By using the KKT condition, the lower-level problem of the electricity market clearing is transformed into the optimality condition as shown in (30)–(32), and the complementary slackness conditions of the lower-level problem are obtained as shown in (33)–(39).

$$\alpha_{ib} - \chi_{(n:i\in\Gamma_n),t} - \psi_{ibt}^{\min} + \psi_{ibt}^{\max} = 0 \tag{30}$$

$$\chi_{(n:d\in\Gamma_n),t} - \chi_{dk} - \psi_{dkt}^{\min} + \psi_{dkt}^{\max} = 0 \tag{31}$$

$$\sum_{m\in\Gamma_n^{\mathrm{N}}} \begin{matrix} B_{nm}(\chi_{nt} \\ -\chi_{mt}) \end{matrix} + \omega_{nt}^{\max} - \omega_{nt}^{\min} + \sum_{m\in\Gamma_n^{\mathrm{N}}} \begin{matrix} B_{nm}(\mu_{nmt}^{\mathrm{Lmax}} \\ -\mu_{mnt}^{\mathrm{Lmax}}) \end{matrix} + \xi_t^{\delta 1} = 0 \tag{32}$$

$$0 \le (P_{ibt} - P_{ib}^{\min}) \perp \psi_{ibt}^{\min} \ge 0 \tag{33}$$

$$0 \le (P_{ib}^{\max} - P_{ibt}) \perp \psi_{ibt}^{\max} \ge 0 \tag{34}$$

$$0 \le (P_{dkt} - P_{dk}^{\min}) \perp \psi_{dkt}^{\min} \ge 0 \tag{35}$$

$$0 \le (P_{dk}^{\max} - P_{dkt}) \perp \psi_{dkt}^{\max} \ge 0 \tag{36}$$

$$0 \le (P_{nm}^{\mathrm{Lmax}} - B_{nm}(\delta_{nt} - \delta_{mt})) \perp \mu_{nmt}^{\mathrm{Lmax}} \ge 0 \tag{37}$$

$$0 \le (\delta_{nt} + \pi) \perp \omega_{nt}^{\min} \ge 0 \tag{38}$$

$$0 \le (\pi - \delta_{nt}) \perp \omega_{nt}^{\max} \ge 0 \tag{39}$$

Then, the original lower-level electricity market clearing model is transformed into a duality problem, and the optimality conditions and complementary slackness conditions are used as constraints of the upper-level model to realize the model reconstruction. Since there is no optimality objective in the lower-level ECR/carbon market clearing model, the constraints (22)–(29) in the lower-level model can be directly integrated into the upper-level model.

4.2. Linearization Technique

There are three kinds of nonlinear forms in the MPEC model, which cannot be directly solved by commercial software. This paper adopts strong dual theory [22], the Big M method [23], and the binary expansion method [24] to linearize the non-convex constraints and obtain a mixed integer linear programming model.

4.2.1. Product of the Cleared Power Capacity P_{ibt} and the Locational Marginal Price $\chi_{(n:i\in\Gamma_n)t}$

The nonlinearities caused by $P_{ibt}\chi_{(n:i\in\Gamma_n)t}$ in (2) can be equivalently transformed by the strong duality theorem in (40) to obtain the equality relation between the objective functions in the original problem and the dual problem.

$$\begin{aligned}
&\sum_i \sum_b \alpha_{ib} P_{ibt} - \sum_d \sum_k \chi_{dk} P_{dkt} + \sum_{n(m\in\Gamma_n^{\mathrm{N}})} P_{nm}^{\mathrm{Lmax}} \mu_{nmt}^{\mathrm{Lmax}} \\
&+\pi \sum_n \begin{pmatrix} \omega_{nt}^{\min} \\ +\omega_{nt}^{\max} \end{pmatrix} + \sum_d \sum_k \begin{pmatrix} \psi_{dkt}^{\max} P_{dk}^{\max} \\ -\psi_{dkt}^{\min} P_{dk}^{\min} \end{pmatrix} + \sum_i \sum_b \begin{pmatrix} \psi_{ibt}^{\max} P_{ib}^{\max} \\ -\psi_{ibt}^{\min} P_{ib}^{\min} \end{pmatrix} = 0
\end{aligned} \tag{40}$$

According to (30), Constraint (2) is equivalently split into H_1 and H_2, as shown in (41) and (42).

$$H_1 = \sum_{i\in\Omega_j} \sum_b \alpha_{ib} P_{ibt} \tag{41}$$

$$H_2 = \sum_{i\in\Omega_j} \sum_b (\psi_{ibt}^{\max} - \psi_{ibt}^{\min} - \chi_{ib}) P_{ibt} \tag{42}$$

H_1 in (41) can be derived by the strong duality theorem in (40), $\psi_{ibt}^{\max} P_{ibt}$ and $\psi_{ibt}^{\min} P_{ibt}$ in H_2 can be replaced by (33)–(39). Finally, the equivalent transformed H_1 and H_2 are added to obtain (43), and the linearization of (2) is completed.

$$\begin{aligned}
U_l^{\mathrm{DA}} &= \sum_d \sum_k \chi_{dk} P_{dkt} - \sum_{i\notin\Omega_j} \sum_b \chi_{ib} P_{ibt} - \sum_{n,m\in\Gamma_n^N} P_{nm}^{\mathrm{Lmax}} \mu_{nmt}^{\mathrm{Lmax}} \\
&-\pi \sum_n \begin{pmatrix} \omega_{nt}^{\min} \\ +\omega_{nt}^{\max} \end{pmatrix} + \sum_{d,k} \begin{pmatrix} \psi_{dkt}^{\min} P_{dk}^{\min} \\ -\psi_{dkt}^{\max} P_{dk}^{\max} \end{pmatrix} + \sum_{i,b} \begin{pmatrix} \psi_{ibt}^{\min} P_{ib}^{\min} \\ -\psi_{ibt}^{\max} P_{ib}^{\max} \end{pmatrix} \\
&+ \sum_{i\in\Omega_j} \sum_b (\psi_{ibt}^{\max} P_{ib}^{\max} - \psi_{ibt}^{\min} P_{ib}^{\min} - \chi_{ib} P_{ibt}) \\
&= \sum_{d,k} \chi_{dk} P_{dkt} - \sum_{i\notin\Omega_j} \sum_b \chi_{ib} P_{ibt} - \sum_{i\in\Omega_j} \sum_b \chi_{ib} P_{ibt} \\
&- \sum_{n,m\in\Gamma_n^N} P_{nm}^{\mathrm{Lmax}} \mu_{nmt}^{\mathrm{Lmax}} - \pi \sum_n \begin{pmatrix} \omega_{nt}^{\min} \\ +\omega_{nt}^{\max} \end{pmatrix} + \sum_{d,k} \begin{pmatrix} \psi_{dkt}^{\min} P_{dk}^{\min} \\ -\psi_{dkt}^{\max} P_{dk}^{\max} \end{pmatrix}
\end{aligned} \tag{43}$$

4.2.2. Product of Credit and Credit Price

The nonlinearities of $\chi_{\mathrm{E}} Q_l^{\mathrm{ECR}}$, $\chi_{\mathrm{E}} \Delta Q_l^{\mathrm{ECR}}$, $\chi_{\mathrm{C}} Q_l^{\mathrm{CET}}$, etc. in (25) and (26) can be solved by the binary expansion method. Take $\chi_{\mathrm{E}} Q_l^{\mathrm{ECR}}$ as an example in (44)–(49), as follows:

$$\chi_{\mathrm{E}} Q_l^{\mathrm{ECR}} \approx \sum_r Q_{lr}^{\mathrm{ref}} \varsigma_{lr}^1 \tag{44}$$

$$Q_l^{\mathrm{ECR}} - \frac{\Delta Q_l^{\mathrm{ref}}}{2} \le \sum_r Q_{lr}^{\mathrm{ref}} \varsigma_{lr}^2 \le Q_l^{\mathrm{ECR}} + \frac{\Delta Q_l^{\mathrm{ref}}}{2} \tag{45}$$

$$\begin{cases} 0 \le \chi_{\mathrm{E}} - \varsigma_{lr}^1 \le M_0 (1 - \varsigma_{lr}^2) \\ 0 \le \varsigma_{lr}^1 \le M_0 \varsigma_{lr}^2 \end{cases} \tag{46}$$

$$\begin{cases} \sum_r \varsigma_{lr}^2 = 1 \\ \varsigma_{lr}^2 \in \{0,1\} \end{cases} \tag{47}$$

$$\Delta Q_l^{\mathrm{ref}} = Q_l^{\max} / R_0 \tag{48}$$

$$Q_{lr}^{\mathrm{ref}} = r \Delta Q_l^{\mathrm{ref}} \tag{49}$$

where Q_{lr}^{ref} is the rth approximative benchmark value of the Q_l^{ECR}; $\Delta Q_l^{\mathrm{ref}}$ is the approximative precision; ς_{lr}^1 and ς_{lr}^2 are 0–1 ancillary variables; M_0 is a large enough number; $Q_l^{\max}$ is the maximization in the approximative process of GenCo l's actual credit quantity used; and R_0 is the total number of bands.

4.2.3. Complementary Slackness Condition

The complementary slackness conditions (33)–(39) can be linearized for form $0 \le f(x) \perp g(y) \ge 0$ by introducing an auxiliary binary variable κ and a sufficiently large constant M, as shown in (50) and (51) as follows:

$$0 \leq f(x) \leq M\kappa \tag{50}$$

$$0 \leq g(y) \leq M(1-\kappa) \tag{51}$$

Finally, the original bi-level model is transformed into a standard form of mixed integer linear programming model with the objective function as in (1) and the constraints as in (2)–(14), (16)–(39), and (43)–(51).

5. Case Study

5.1. Basis Data

The illustrative example is performed on the modified IEEE 33-bus system, as shown in Figure 3. There are six GenCos (C1, C2, C3, C4, G1, G2) and three consumers in the network, where C1, C2, C3, C4 are the conventional coal-fired GenCos who own coal-fired generators and G1, G2 represent gas-fired GenCos. The total generation capacity is 340 MW. All the GenCos participate in the electricity market, ECR market, and carbon market at the same time. Data on the relevant parameters, e.g., primary credit allocation, and carbon emission factors, of each generator are shown in Table 1 [25]. The total demand of the three consumers (D1, D2, D3) is 290MW, the parameters of which are shown in Table 2. An electricity market where the supply exceeds the demand is considered a buyer's market. Here, GenCos and consumers all adopt a stepwise offer curve. According to the quality conservation principle, the exchange coefficient between the ECR credit and carbon credit is 1:2.54, i.e., θ is set as 2.54. Based on reference [26], ε_0 is set as 0.3; γ_0 is set as 40%; the maximum price of ECR credit χ_1 is set as 8; the maximum price of carbon credit χ_2 is set as 10, and the energy-saving rate σ is 50%. The optimization analysis is carried out using the Cplex 12.10 solver based on the GAMS in a Win11 operating system, i7 CPU, and 2.80 GHz processor environment, which costs 2.036 s.

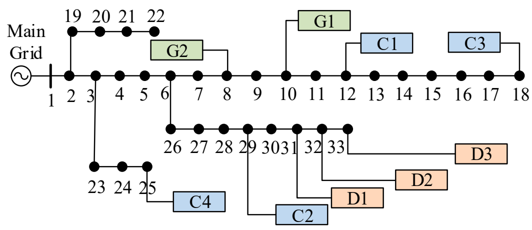

Figure 3. Modified IEEE 33-bus system.

Table 1. Parameters of Generators.

GenCo	Energy Block (MW)	Marginal Cost ($/MWh)	Primary ECR Credit (tCO_2)	Primary Carbon Credit (tCO_2)	Carbon Emission Factor (tCO_2/MWh)
C1	20; 30; 30	18; 40; 44	590	1512	0.8938
C2	25; 25; 30	20; 45.1; 46.5	541	1473	0.8412
C3	15; 15; 20	18; 42; 47	312	921	0.7938
C4	20; 20; 15	21; 41; 47	337	959	0.7438
G1	10; 10; 10	34; 43; 57	95	611	0.3791
G2	15; 15; 15	35; 44; 53	112	669	0.3791

Table 2. Parameters of Consumers' Bidding Strategy.

Consumer	Demand Block (MW)	Bidding Strategy ($/MWh)
D1	30; 20; 20	93.5; 73.5; 63.5
D2	40; 30; 10	88.0; 68.0; 58.0
D3	60; 50; 30	82.5; 62.5; 52.5

5.2. Market Equilibrium Analysis

In order to verify the effectiveness of the optimal behaviors of profit-driven GenCos participating in multi-type market with ECR credit and carbon credit allocation and exchange, the following three scenarios are set up for comparison and analysis:

1. Case 1: GenCos only participate in the electricity market. Neither the ECR nor carbon markets exist;
2. Case 2: GenCos participate in the electricity, ECR, and carbon markets at the same time, while the ECR and carbon credits cannot be exchanged with each other;
3. Case 3: GenCos participate in the electricity, ECR, and carbon markets at the same time, and the ECR and carbon credits can be exchanged with each other.

5.2.1. Analysis of Profit of GenCos

Figure 4 shows the profit of each GenCo in Cases 1–3 proposed in this paper, as well as a comparison of each GenCo's profit percentage change under different cases. For Case 1, where the GenCos only participate in the electricity market, the profit of each GenCo is basically ranked by the capacity of the generators. As shown in Figure 5, for Case 1, coal-fired GenCos have a higher cleared power capacity than that of gas-fired GenCos because of their lower offering price in the bidding strategy for the electricity market, so they are more profitable. However, for coal-fired C1 and C2 with the same generation capacity, the profit of C2 is lower than that of C1 as the cost of C2 is higher than that of C1, resulting in a lower cleared power capacity for C2 compared to that of C1 in Figure 5. When GenCos are required to participate in the ECR and carbon markets (i.e., Cases 2 and 3), the overall profit of GenCos decreases substantially, because the restriction of ECR and carbon credits on the GenCos' bidding strategy in Table 3 leads to a decrease in the locational marginal price, as indicated in Figure 5.

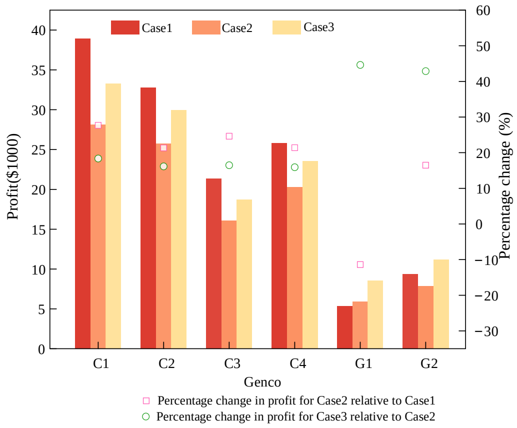

Figure 4. Profit of GenCo and percentage change in profit.

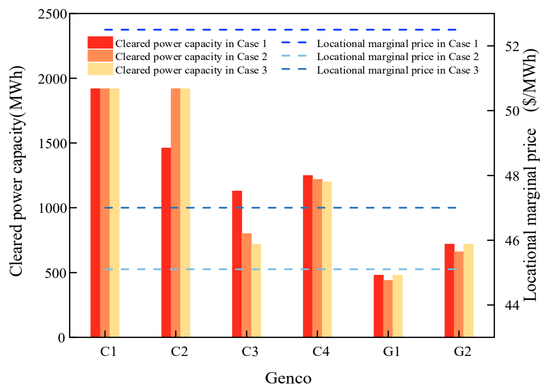

Figure 5. Cleared power capacity and locational marginal price.

Table 3. Bidding Strategy of Each GenCo.

GenCo	Bidding Strategy ($/MWh)		
	Case 1	**Case 2**	**Case 3**
C1	18; 40; 44	18; 40; 44	18; 40; 44
C2	20; 45.1; 46.5	20; 45.1; 46.5	20; 45.1; 46.5
C3	18; 42; 47	18; 42; 45.1	18; 42; 47
C4	21; 41; 47	21; 41; 45.1	21; 41; 47
G1	34; 43; 52.5	34; 43; 45.1	34; 43; 47
G2	35; 44; 52.5	35; 44; 45.1	35; 44; 47

Compared to Case 1, the profits of C1, C2, C3, and C4, who own the coal-fired generator with a higher carbon emission factor, experience a sharper percentage decrease in Case 2 of 27.7%, 21.3%, 24.6%, and 21.4%, respectively. This is because the higher the carbon emission factor of a generator, the more primary ECR and carbon credits it consumes. As a result, the remaining ECR and carbon credits are insufficient and should be purchased more from the secondary market, increasing the additional cost. In contrast, the profit of G2 changes very slightly and that of G1 increases by 11.4%. This is because the gas-fired generator usually has a lower carbon emission factor than coal-fired ones so the gas-fired GenCos are more profitable due to the additional revenue brought on by selling the remaining credit. To sell more ECR and carbon credits in the secondary markets, the gas-fired GenCos reduce their cleared power capacity in Figure 5. It can be seen that the quantity of credits will affect the cleared power capacity. Changes in returns in the carbon market primarily reflect the costs or profitability faced by GenCos in meeting carbon emission requirements. High-carbon emitting power GenCos spend more in the carbon market, especially as the price of carbon credits rises, which can significantly affect their overall profitability. Companies with low carbon emissions can increase their earnings by selling their remaining carbon credits.

In Case 3, where GenCos participate in all three types of markets at the same time, the profits of all GenCos increase compared to Case 2, which demonstrates the effectiveness of the credit exchange mechanism proposed in this paper. The increasing rate of profit of coal-fired C1, C2, C3, C4, and gas-fired G1, G2 are 18.37%, 16.16%, 16.49%, 15.92%, 44.64%, and 42.88%, respectively, which proves that gas-fired GenCos have higher competitiveness and will force coal-fired GenCos to take up energy-saving technologies to reduce the generator's carbon emission factor. Comparing Cases 2 and 3, the specific profits of each GenCo in the three markets are shown in Table 4, respectively. On the one hand, C3, C4, G1, and G2 submit an increased quantity–price bid, whose clearing price is more than their locational marginal price to increase the revenue from the electricity market; on the other hand, the total actual consumed credit decrease results in the increasing prices of ECR and carbon credits, as indicated in Figure 6. Also, the profit of GenCos in both the ECR market and the carbon market increase. But due to the sharp rise in carbon credit prices, C1 and C2 exchange their partial remaining ECR credits for carbon credits for more revenue in the carbon market in Figure 7 (the red dashed line represents the quantity of each GenCo's ECR and carbon credits in the ECR and carbon secondary markets after credit exchange). Thus, the profits of C1 and C2 in the ECR market drop and the profits in the carbon market increase significantly. Furthermore, due to an increase in the locational marginal price, G1 and G2 raise their cleared power capacity and consequently make more profits in the electricity market than in Case 1. As their cleared power capacity rises and their actual credit usage increases, their profits in the ECR and carbon markets both decline marginally, as shown in Table 4, but their overall profit increases significantly.

Table 4. Social Welfare of GenCos in Three Markets.

Social Welfare ($)	GenCo	Case 2	Case 3
Electricity Market	C1	16,016	21,120
	C2	13,604	17,700
	C3	9416	12,240
	C4	12,080	15,360
	G1	1628	4080
	G2	2312	5400
	Total	55,056	75,900
ECR Market	C1	1489.57	1341.12
	C2	1317.57	1165.98
	C3	1104.50	1181.53
	C4	935.44	955.32
	G1	367.18	350.50
	G2	370.62	345.11
	Total	5584.88	5339.56
Carbon Market	C1	−685.80	−473.11
	C2	−477.50	−257.73
	C3	960.88	1192.01
	C4	173.26	226.63
	G1	1492.58	1463.42
	G2	1407.23	1350.91
	Total	2870.65	3502.13

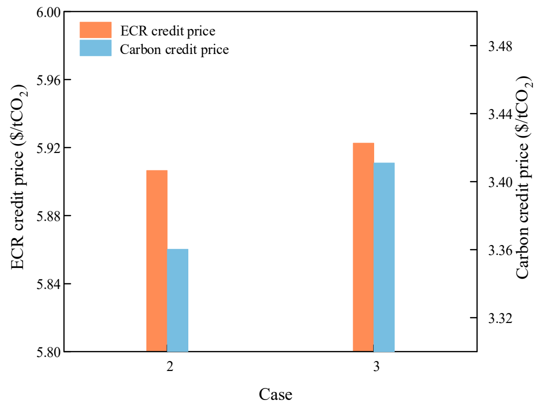

Figure 6. ECR credit price and carbon credit price.

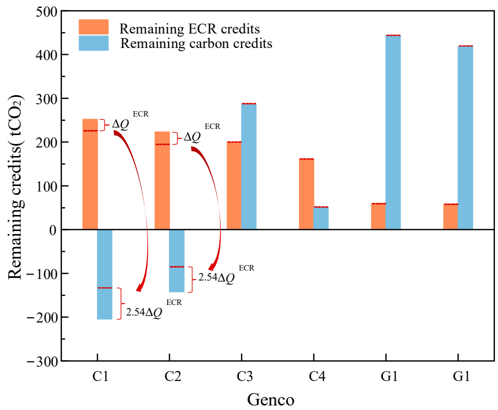

Figure 7. Remaining credit and credit exchange.

The remaining ECR credits, carbon credits, and credit exchange of GenCos are shown in Figure 7. Due to C1 and C2 possessing high carbon emission factor coal generators, their primary carbon credits are unable to meet their actual carbon emissions, which leads to an increase in the additional costs within the carbon market. As can be seen from Figure 6, compared to Case 2, the price of carbon credit increases by 0.0508 $\$/tCO_2$ in Case 3 due to the existence of the exchange mechanism.

5.2.2. Analysis of Credit of the Generation Companies

The actual ECR and carbon credit usage for Cases 2 and 3 are shown in Figures 8 and 9. In Figures 8 and 9, the total actual ECR credit usage in Case 3 is 7.966 tCO_2, which is less than in Case 2. The total actual carbon credit usage is 20.235 tCO_2, which is less than in Case 2, indicating that the proposed credit exchange mechanism can reduce the consumption of ECR and carbon credits, effectively reduce the total energy consumption, and control the total carbon emission to achieve the effect of improved energy efficiency and emission reduction.

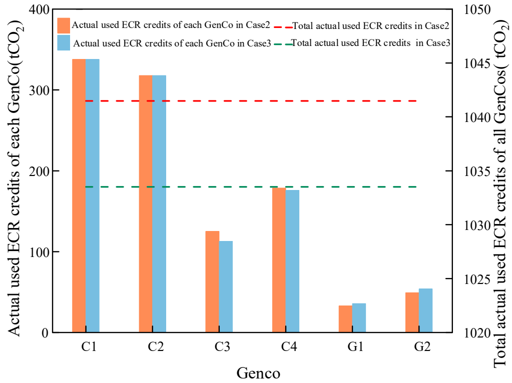

Figure 8. Actual ECR credit used in Cases 2 and 3.

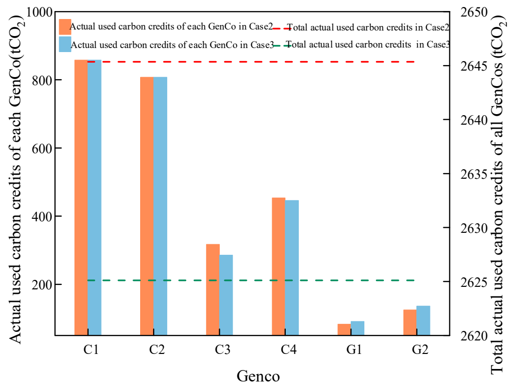

Figure 9. Actual carbon credits used in Cases 2 and 3.

In Figures 8 and 9, for Cases 2 and 3, C1 and C2 do not exchange their actual ECR and carbon credit usage, while C3 and C4 reduce their actual ECR and carbon credit usage, and G1 and G2 both slightly increase their actual ECR and carbon credit usage. Considering that C3 and C4 do not have a significant advantage in terms of their own capacity, cost, and carbon emission factors, they choose to reduce a small amount of cleared power capacity and actual ECR and carbon credit usage to improve the profits within the ECR and carbon markets. And actual credit usage of G1 and G2 increases slightly because they own low carbon emission generators, and they choose to obtain more profit by increasing their cleared power capacity.

5.3. Sensitivity Analysis of Primary Allocation of Credits

Before the beginning of market operations for each trading period, the free primary ECR and carbon credits will be allocated to GenCos. This allocation is established prior to the electricity market and credit trading, ensuring that GenCos have an initial stock of credits available to plan and optimize their generation strategies accordingly.

The primary allocation of the ECR and carbon credits has a great impact on the results of market equilibrium; this subsection focuses on the sensitivity analysis of the influence of different percentage changes in the primary allocation of credits on the total profit, the price of electricity and credit price, improved energy efficiency and emission reduction, and credit exchange. Given that the baseline of the primary allocation of the ECR and carbon credits is 100%, three percentage changes of the primary allocation of credits are considered, e.g., 75%, 125%, and 150%, respectively.

Table 5 shows the impact of the primary credit allocation on the profits of all GenCos. Obviously, the total profits of GenCos increase with quantity as the proportion of credit fluctuation increases. The larger the primary credits obtained by the GenCo, the more the remaining credits can be sold in the secondary market to gain greater competitiveness in the ECR and carbon markets.

Table 5. Impact of Primary Credit on the Total Profit of GenCos, Electricity Price, ECR Credit Price, and Carbon Credit Price.

Credit Type	Percent-Age Change	Electricity Price ($/MWh)	ECR Credit Price ($/t$CO_2$)	Carbon Credit Price ($/t$CO_2$)	Total Profit of GenCos ($10,000)
ECR Credit	75%	47	5.9227	3.411	12.24
	100%	47	5.9227	3.411	12.53
	125%	45.1	5.8693	3.242	10.56
	150%	47	5.9227	3.411	13.12
Carbon Credit	75%	47	5.9197	3.402	12.00
	100%	47	5.9227	3.411	12.53
	125%	47	5.9227	3.411	13.04
	150%	47	5.9227	3.411	13.56

However, when the primary ECR credits increase to 125%, there is an obvious drop in the total profit of the GenCos. This drop is caused by the GenCos' revenue decrease from the electricity market due to a reduction in the locational marginal price by lowering the offering price, as shown in Table 6. In addition, as shown in Figure 10, a sharp increase in the actual ECR and carbon credit usage decreases the prices of the ECR and carbon credits, such that GenCos' profit in the ECR and carbon markets decreases at the same time. Once the amount of primary ECR credits increases by 25%, the total profit of the GenCos decreases significantly, which proves that when the credits are not primarily allocated properly, the GenCos do not have enough motivation to save energy or reduce carbon. This requires the environmental authority to consider the energy efficiency, emission reduction, and the market environment comprehensively when allocating the primary credits for improving the overall profit.

Table 6. Impact of Primary Credit on Credit Exchange.

Credit Type	Percentage Change	C1	C2	C3	C4	G1/G2
ECR Credit	75%	25.75	26.20	/	/	/
	100%	25.75	26.20	/	/	/
	125%	29.27	26.20	/	/	/
	150%	25.75	26.20	/	/	/
Carbon Credit	75%	10.86	11.70	13.60	12.95	/
	100%	25.75	26.20	/	/	/
	125%	/	/	/	/	/
	150%	/	/	/	/	/

Note: / indicates that this part is not available.

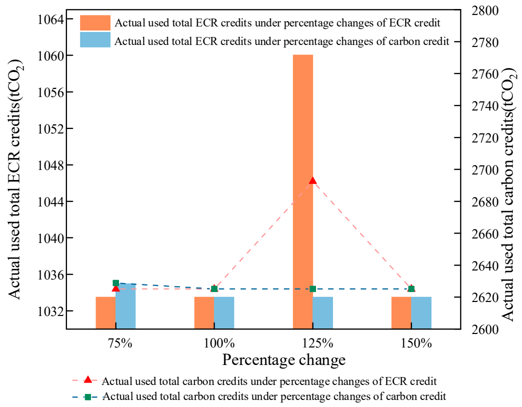

Figure 10. Impact of primary credits on energy efficiency/emission reduction.

The sensitivity analysis of the primary credit allocation to credit exchange is shown in Table 6. Among them, the primary carbon credit has a greater impact on the credit exchange of GenCos, while the primary ECR credit has a smaller impact on the credit exchange of GenCos. When the primary carbon credit is tightened to 75%, the primary carbon credits obtained by the coal-fired GenCos with higher carbon emission factors are lower than the actual carbon credits used, and the partial remaining ECR credits need to be exchanged for carbon credits; when the primary carbon credits are increased to 125% and above, the primary carbon credit is sufficient and no exchange is required; when the primary ECR credit is loosened to 125%, the carbon credit price is reduced, and the carbon cost of coal-fired C1 is reduced, which makes its actual carbon credit usage too high, so a surplus of the remaining ECR credits are exchanged for carbon credits.

5.4. Sensitivity Analysis of Energy-Saving Rate

Within this paper, the carbon credit resulting from the energy-saving measures that GenCos took is deducted from the primary carbon credit to avoid being double counted. Considering that the energy-saving rate of the generators will affect the market equilibrium, this example focuses on the sensitivity analysis of credit price, the actual credit usage, and credit exchange under the energy-saving rates of 0.45, 0.5, 0.55, 0.6, 0.65, and 0.7, respectively.

It can be seen from Figure 11 that when the energy-saving rate of the generator increases, the prices of the ECR and carbon credits both rise, thanks to the energy-saving measurements taken by the GenCos, the actual credits used, the total energy consumption, and the carbon emission; otherwise, they would decrease with the increased electricity generation.

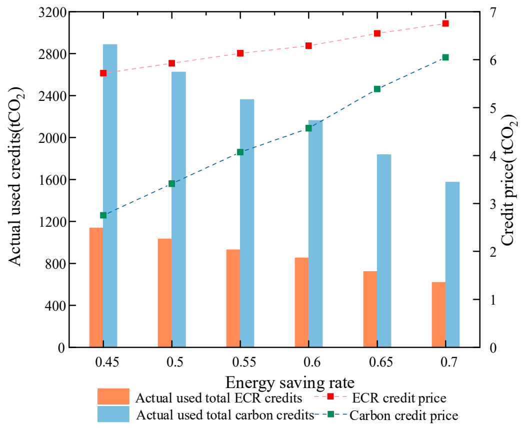

Figure 11. Impact of energy-saving rates on actual credits used and credit price.

Table 7 illustrates the exchange amount between the carbon and ECR credits. In general, the amount of credit exchange decreases as the energy-saving rate of the generators increases. By upgrading the generators, the actual ECR and carbon credit usage of the GenCos decreases and the primary carbon credits of the GenCos after deducting the carbon credits increase, thus the remaining ECR credits and carbon credits increase.

Table 7. Influence of Energy Saving Rate on Credit Exchange.

Energy Saving Rate	Credit Exchange	C1	C2	C3/C4/G1/G2
0.45	Quantity	+29.1243	+29.3781	/
	Percentage change	+13.335%	+15.360%	/
0.5	Quantity	+25.7461	+26.1987	/
	Percentage change	+10.209%	+11.745%	/
0.55	Quantity	+22.368	+23.0194	/
	Percentage change	+7.822%	+9.032%	/
0.6	Quantity	+22.1569	+19.8401	/
	Percentage change	+6.500%	+6.9213%	/
0.65	Quantity	+15.6117	+16.6607	/
	Percentage change	+4.416%	+5.232%	/
0.7	Quantity	+12.2336	+13.4814	/
	Percentage change	+3.159%	+3.849%	/

Note: / indicates that this part is not available; + indicates that the ECR credits are exchanged for the carbon credits.

6. Conclusions

The emergence of ECR credit, which has been put forward for controlling energy consumption, will definitely limit the GenCos' electricity generation plan. To comprehensively assess the influence of GenCos' participation in a multi-type market, including the ECR market, carbon market, and electricity market, on their economic behavior and to accurately quantify carbon emission reductions, this paper proposes a market framework where a flexible exchange mechanism between the ECR and carbon credits is specially considered. The key findings are outlined as follows:

1. The proposed flexible exchange mechanism between the ECR and carbon credits can improve the profit of each GenCo, with an increase of 20.4% in the total profit of all GenCos. In particular, gas-fired GenCos are more competitive and profitable in the market than coal-fired GenCos, which will force the coal-fired GenCos to upgrade and retrofit their generators to save more energy.
2. The credit exchange contributes to improved energy effciency and emission reduction, with the actual total ECR and carbon credit usage decreasing by 7.966tCO_2 and 20.235tCO_2, respectively.

The primary focus of this paper is to address the issue of repetitive credits caused by energy-saving measures and propose a credit exchange mechanism without differentiating the energy consumption characteristics of different types of energy sources for the time being. Future research will concentrate on the credit exchange of ECR and carbon credits for multi-type energy sources to enhance the practicality of the credit exchange mechanism proposed in this paper.

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Conflicts of Interest: Author Ye Zhang was employed by the company Inner Mongolia Power Electric Operations Control Company, Inner Mongolia Electric Power (Group) Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Appendix A

Firstly, the Lagrangian function of the lower model is constructed by weighted combination, as shown in (A1):

$$\begin{aligned} L(n) = & \sum_i \sum_b \alpha_{ib} P_{ibt} - \sum_d \sum_k \chi_{dk} P_{dkt} + \chi_{nt} \Big(\sum_{d \in \Gamma_n^{\mathrm{D}}} \sum_k P_{dkt} \\ & - \sum_{i \in \Gamma_n^{\mathrm{G}}} \sum_b P_{ibt} + \sum_{m \in \Gamma_n^{\mathrm{N}}} B_{nm}(\delta_{nt} - \delta_{mt}) \Big) + \psi_{ibt}^{\min}(P_{ib}^{\min} - P_{ibt}) \\ & + \psi_{ibt}^{\max}(P_{ibt} - P_{ib}^{\max}) + \psi_{dkt}^{\min}(P_{dk}^{\min} - P_{dkt}) + \psi_{dkt}^{\max}(P_{dkt} - P_{dk}^{\max}) \\ & + \mu_{nmt}^{\mathrm{Lmax}}(B_{nm}(\delta_{nt} - \delta_{mt}) - P_{nm}^{\mathrm{Lmax}}) \\ & + \omega_{nt}^{\min}(-\pi - \delta_{nt}) + \omega_{nt}^{\max}(\delta_{nt} - \pi) + \delta_{1t} \xi_t^{\delta 1} \end{aligned} \tag{A1}$$

The optimality conditions can be obtained by deriving the Lagrangian function through the following:

$$\frac{\partial L(n)}{\partial P_{ibt}} = \alpha_{ib} - \chi_{(n:i \in \Gamma_n),t} - \psi_{ibt}^{\min} + \psi_{ibt}^{\max} = 0 \tag{A2}$$

$$\begin{aligned} \frac{\partial L(n)}{\partial \delta_{nt}} = & \sum_{m \in \Gamma_n^{\mathrm{N}}} B_{nm}(\chi_{nt} - \chi_{mt}) + \omega_{nt}^{\max} \\ & - \omega_{nt}^{\min} + \sum_{m \in \Gamma_n^{\mathrm{N}}} B_{nm}(\mu_{nmt}^{\mathrm{Lmax}} - \mu_{mnt}^{\mathrm{Lmax}}) + \xi_t^{\delta 1} = 0 \end{aligned} \tag{A3}$$

$$\frac{\partial L(n)}{\partial P_{dkt}} = \chi_{(n:d \in \Gamma_n),t} - \chi_{dk} - \psi_{dkt}^{\min} + \psi_{dkt}^{\max} = 0 \tag{A4}$$

The complementary slackness conditions in (33)–(39) are derived from constraints (17)–(20). Thus, the lower-level problem is transformed into optimality conditions and complementary slackness conditions, which act as constraints of the upper-level problem.

References

1. Say, N.P.; Yücel, M. Energy Consumption and CO_2 Emissions in Turkey: Empirical Analysis and Future Projection Based on an Economic Growth. *Energy Policy* **2006**, *34*, 3870–3876. [CrossRef]
2. Köne, A.Ç.; Büke, T. Forecasting of CO_2 Emissions from Fuel Combustion Using Trend Analysis. *Renew. Sustain. Energy Rev.* **2010**, *14*, 2906–2915. [CrossRef]
3. Qiu, J.; Dong, Z.Y.; Zhao, J.H.; Meng, K.; Zheng, Y.; Hill, D.J. Low Carbon Oriented Expansion Planning of Integrated Gas and Power Systems. *IEEE Trans. Power Syst.* **2015**, *30*, 1035–1046. [CrossRef]
4. Xue, G.; Wu, C.; Zhang, M.; Wu, Y. Energy-Consuming Right Trading: Architectures, Practices and Challenges. In Proceedings of the 2022 IEEE/IAS Industrial and Commercial Power System Asia (I&CPS Asia), Shanghai, China, 8–11 July 2022; pp. 2107–2112. [CrossRef]
5. Wang, K.; Su, X.; Wang, S. How Does the Energy-Consuming Rights Trading Policy Affect China's Carbon Emission Intensity? *Energy* **2023**, *276*, 127579. [CrossRef]
6. Song, Y.; Liang, D.; Liu, T.; Song, X. How China's Current Carbon Trading Policy Affects Carbon Price? An Investigation of the Shanghai Emission Trading Scheme Pilot. *J. Clean. Prod.* **2018**, *181*, 374–384. [CrossRef]
7. Zhao, Y.; Wang, C.; Sun, Y.; Liu, X. Factors Influencing Companies' Willingness to Pay for Carbon Emissions: Emission Trading Schemes in China. *Energy Econ.* **2018**, *75*, 357–367. [CrossRef]
8. Xu, Z.; Wu, Y. Environmental Economic Co-Benefits and Offsets Effects of China's Unified Energy-Carbon Market. *J. Environ. Manag.* **2023**, *331*, 117268. [CrossRef]
9. Zhang, X.; Guo, X.; Zhang, X. Assessing the Policy Synergy among Power, Carbon Emissions Trading and Tradable Green Certificate Market Mechanisms on Strategic GENCOs in China. *Energy* **2023**, *278*, 127833. [CrossRef]

10. Wang, Y.; Xie, H.; Sun, X.; Tang, L.; Bie, Z. A Cross-Chain Enabled Day-Ahead Collaborative Power-Carbon-TGC Market. *Energy* **2022**, *258*, 124881. [CrossRef]
11. Chen, T.-L.; Hsu, H.-M.; Pan, S.-Y.; Chiang, P.-C. Advances and Challenges of Implementing Carbon Offset Mechanism for a Low Carbon Economy: The Taiwanese Experience. *J. Clean. Prod.* **2019**, *239*, 117860. [CrossRef]
12. Ye, F.; Xiong, X.; Li, L.; Li, Y. Measuring the Effectiveness of the Chinese Certified Emission Reduction Scheme in Mitigating CO_2 Emissions: A System Dynamics Approach. *J. Clean. Prod.* **2021**, *294*, 125355. [CrossRef]
13. Zhang, X.; Zhang, M.; Su, C. Research on the Coordination of Carbon Emission Trading Mechanism, Energy Use Trading Mechanism and Electric Power Trading Mechanism. *Environ. Prot.* **2022**, *50*, 21–24.
14. Menegaki, A.N.; Ahmad, N.; Aghdam, R.F.; Naz, A. The Convergence in Various Dimensions of Energy-Economy-Environment Linkages: A Comprehensive Citation-Based Systematic Literature Review. *Energy Econ.* **2021**, *104*, 105653. [CrossRef]
15. Zhang, T.; Li, Y.; Yan, R.; Abu-Siada, A.; Guo, Y.; Liu, J.; Huo, R. A Master-Slave Game Optimization Model for Electric Power Companies Considering Virtual Power Plant. *IEEE Access* **2022**, *10*, 21812–21820. [CrossRef]
16. Guan, Y.; Yue, X.; Xu, B.; Fan, Z. The Bilateral Negotiation or Centralized Bidding? How to Choose the Transaction Mode with Power Users for Power Plants. *IEEJ Trans. Electr. Electron. Eng.* **2021**, *16*, 1174–1186. [CrossRef]
17. Guo, H.; Chen, Q.; Xia, Q.; Kang, C. Market Equilibrium Analysis with High Penetration of Renewables and Gas-Fired Generation: An Empirical Case of the Beijing-Tianjin-Tangshan Power System. *Appl. Energy* **2018**, *227*, 384–392. [CrossRef]
18. Long, J.; Huang, H. Stability of Equilibrium Production-Price in a Dynamic Duopoly Cournot-Bertrand Game with Asymmetric Information and Cluster Spillovers. *MBE* **2022**, *19*, 14056–14073. [CrossRef]
19. Li, G.; Wang, C.; Lei, S.; Wang, X. Bi-level optimal allocation of power system considering carbon capture technology. *Electr. Power Autom. Equip.* **2023**, *43*, 25–31. [CrossRef]
20. Pan, Z.; Song, Y.; Jing, Z. A Visualization Method for Bidding Games in the Electricity Spot Market. *Energy Rep.* **2022**, *8*, 1305–1312. [CrossRef]
21. Ghilardi, L.M.P.; De Pascali, M.L.; Casella, F.; Barbati, D.; Palazzo, R.; Martelli, E. A MILP Approach for the Operational Optimization of Gas Networks. *IFAC-PapersOnLine* **2022**, *55*, 321–326. [CrossRef]
22. Guo, H.; Chen, Q.; Shahidehpour, M.; Xia, Q.; Kang, C. Bidding Behaviors of GENCOs under Bounded Rationality with Renewable Energy. *Energy* **2022**, *250*, 123793. [CrossRef]
23. Bhattacharjee, S.; Sioshansi, R.; Zareipour, H. Energy Storage Participation in Wholesale Markets: The Impact of State-of-Energy Management. *IEEE Open J. Power Energy* **2022**, *9*, 173–182. [CrossRef]
24. Kazempour, S.J.; Conejo, A.J.; Ruiz, C. Strategic Generation Investment Considering Futures and Spot Markets. *IEEE Trans. Power Syst.* **2012**, *27*, 1467–1476. [CrossRef]
25. Sun, X.; Ding, Y.; Bao, M. Carbon-electricity Market Equilibrium Analysis Considering Multi-time Coupling Decisions of Power Producers. *Autom. Electr. Power Syst.* **2023**, *47*, 1–11. [CrossRef]
26. Guo, H.; Chen, Q.; Xia, Q.; Kang, C. Modeling Strategic Behaviors of Renewable Energy with Joint Consideration on Energy and Tradable Green Certificate Markets. *IEEE Trans. Power Syst.* **2020**, *35*, 1898–1910. [CrossRef]