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Bidding Strategy of Integrated Renewable-Thermal Energy Bases Considering the Precise Dynamic Carbon Emission Characteristics of Thermal Power Units#

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ABSTRACT

The continuous expansion of renewable energy installations has resulted in the emergence of integrated energy bases, which couple renewable power generation with conventional thermal units. These bases have experienced rapid development and have gradually become key participants in electricity and carbon markets. The behavior of these entities in terms of decision-making exerts a simultaneous influence on the clearing results of both markets. In this context, an analysis of actual operating conditions at integrated energy bases reveals that the carbon emission intensity of thermal units exhibits fluctuations tied to unit load factors. The carbon emission fluctuation characteristics of thermal power units exhibit distinct differences across different stages of power generation. This characteristic exerts a significant influence on the decision-making behavior of thermal power units engaged in the electricity and carbon markets. It is evident that a carbon-electricity coordinated decision-making model for integrated energy bases with combined renewable-thermal operation, considering the dynamic carbon emission characteristics of thermal power units, has been established. Utilizing an enhanced IEEE-5 node as a test case, the efficacy of the proposed method is substantiated.

Keywords: integrated energy bases, electric market, carbon market

NONMENCLATURE

Abbreviations	
IEB	Integrated Energy Bases
Genco	Generation Company
CEA	Carbon Emission Allowance
CEI	Carbon Emission Intensity

1. INTRODUCTION

Within the overarching framework guided by the dual carbon goals and accelerated development of new power systems [1], the share of renewable energy sources such as wind and solar power in China's electricity mix continues to rise. Large-scale wind farms and solar power stations are typically complemented by regulating power sources such as thermal power. Collectively, these elements constitute multi-energy, complementary IEB. Through coordinated operation, these bases mitigate output fluctuations, achieve stable power delivery, and enhance economic efficiency. As China's electricity spot market mechanisms continue to evolve and mature [2], there has been an increase in the number of market participants engaged in trading, thereby creating conditions that allow integrated energy bases to participate in spot markets. In this context, the electricity spot market is poised to become a significant revenue source for integrated energy bases.

In certain studies, multi-market strategic behavior considering both electricity and carbon markets has been the subject of investigation. In [3], the flexible operation of carbon-capturing power plants in both electricity and carbon markets was optimized under a given long-term average CEA price. The equilibrium achieved when electricity producers participate simultaneously in electricity, natural gas, and carbon emission markets was examined by [4].

Research on the interactions between electricity and carbon markets is based on the assumption that the CEI of generators is static [5]. However, an analysis of key performance indicators in [6] reveals that the CEI is inversely proportional to output power, due to a decrease in the net coal consumption rate. Conversely, the decline in CEI observed in studies [7] and [8] can be explained by thermal efficiency. However, extant studies have not accounted for the dynamic carbon emission factors of power units. This has resulted in an overly

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simplistic characterization of coal-fired power plants' carbon emission behavior within electricity carbon markets. This phenomenon results in the operational costs of coal-fired power plants being reduced, consequently weakening the regulatory influence of the carbon market price on the generation sector.

This paper constructs a model for integrated energy bases participating in electricity-carbon markets, incorporating the dynamic CEI into the analysis. The dynamic relationship between CEI and power output is achieved through theoretical modelling and field monitoring data fitting. This correlation was subsequently incorporated into the electricity and carbon market bidding strategy of the Genco.

2. DYNAMIC CARBON EMISSION INTENSITY MODELING FOR THERMAL POWER PLANTS

During the operational phase, thermal power plants must frequently adjust power output through the integration of renewable energy sources. In practice, as the power plant's output approaches its design capacity, its efficiency increases. In consideration of the aforementioned factors, the CEI model is hereby proposed as a means to establish a correlation between power output and the carbon emission intensity of the thermal power plant [9].

In the relationship curve between carbon emission intensity and output power for thermal power units, a inflection point exists. To the left of this inflection point, there is an inverse relationship between carbon emission intensity and output power. To the right of the inflection point, an approximately linear relationship is exhibited between carbon emission intensity and power output.

In the region to the right of the inflection point, efficiency is generally proportional to power output. Therefore, the following approximation can be made:

$$e_g\left(P_g^t\right)=aP_g^t+b,(a<0) \tag{1}$$

where, P_g^t indicates unit output power, $e_g\left(P_g^t\right)$ indicates carbon emissions corresponding to the unit's output power.

On the left side of the inflection point, the power output of a thermal power plant will typically decline to the fuel combustion threshold. In such instances, the thermal power plant will transition to oil combustion in order to satisfy the low-output requirements for reserve supply or peak shaving. Consequently, the carbon emission intensity at this point will increase significantly in inverse proportion to power output, and can be modelled as follows:

$$e_g\left(P_g^t\right)=c/P_g^t+d \tag{2}$$

However, the aforementioned formula introduces nonlinear terms into the final objective function, thereby complicating the problem's solution. Consequently, this paper further linearizes the carbon emission function in order to simplify the computational complexity of the associated optimization problem.

$$E_{i,v}=\int_{P_{i,v}}^{P_{i,v+1}} e_g\left(P_g^t\right)\cdot dP_g^t \tag{3}$$

$$I_{i,v}^{\mathrm{R}}=E_{i,v}/\left(P_{i,v+1}-P_{i,v}\right) \tag{4}$$

where, $E_{i,v}$ represents the carbon emission credit value for segment v, $P_{i,v}$ denotes the starting value of segment v, $I_{i,v}^{\mathrm{R}}$ denotes the linearized carbon emission intensity for segment v.

The curve in Fig.1 illustrates the relationship between the actual power generation of the generating units and carbon emissions [9]. The transparent blocks represent the linear relationship between carbon emissions and power generation.

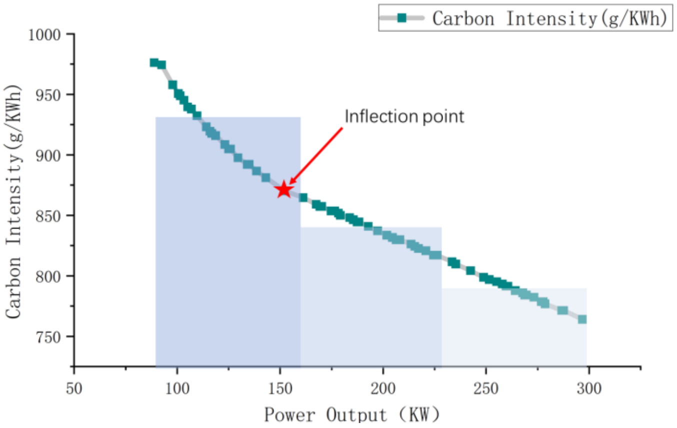

Fig. 1 Relationship Between Carbon Emission Intensity and Power Output [9]

3. A DUAL-LAYER OPTIMIZATION MODEL FOR INTEGRATED ENERGY BASES PARTICIPATING IN ELECTRICITY-CARBON SPOT MARKETS

3.1 Optimization Model for IEB

The strategic decisions made by integrated energy bases in regard to electricity-carbon coupling trading strategies within the context of spot electricity and carbon markets are driven by the objective of optimizing their financial returns. In consideration of the transferability of CEA across temporal domains, the establishment of carbon markets has resulted in the liberation of power generators' strategies from the confines of a single temporal period and the restriction to quantity coupling alone. Instead, they necessitate coordination across temporal domains.

$$\max \pi_i = R^{\mathrm{E}}_{i,t} + C^{\mathrm{C}}_{i,t} \tag{5}$$

$$\begin{aligned} R^{\mathrm{E}}_{i,t} = & \sum_{j\in\Omega_i}\left[Q^{\mathrm{E}}_{j,t}\lambda^{\mathrm{E}}_{(n:j\in\Psi_n),t} - c^o_j P^{\mathrm{E}}_{j,t}\right] \\ & + \sum_{r\in\Omega_i}\left[Q^{\mathrm{E}}_{r,t}\lambda^{\mathrm{E}}_{(n:r\in\Psi_n),t} - c^o_r P^{\mathrm{E}}_{r,t}\right] \end{aligned} \tag{6}$$

$$C^{\mathrm{C}}_{i,t} = Q^{\mathrm{C}}_{i,t}\mu^{\mathrm{C}}_t \tag{7}$$

where, $R^{\mathrm{E}}_{i,t}$ indicates revenue from the electricity market, $C^{\mathrm{C}}_{i,t}$ indicates revenue from the carbon market, $Q^{\mathrm{E}}_{j,t}$ indicates the cleared quantity in the electricity market, $\lambda^{\mathrm{E}}_{(n:j\in\Psi_n),t}$ indicates the node electricity price at time t for node n, c^o_j indicates the unit's power generation cost, $P^{\mathrm{E}}_{j,t}$ indicates the unit's power generation output, $Q^{\mathrm{E}}_{r,t}$ indicates the cleared electricity output of renewable energy units, c^o_r indicates the power generation cost of renewable energy units, $P^{\mathrm{E}}_{r,t}$ indicates the power generation output of renewable energy units.

$$\alpha^{\mathrm{E,min}}_{j,t,s} \le \alpha^{\mathrm{E}}_{j,t,s} \le \alpha^{\mathrm{E,max}}_{j,t,s} \tag{8}$$

$$\alpha^{\mathrm{E,min}}_{r,t,s} \le \alpha^{\mathrm{E}}_{r,t,s} \le \alpha^{\mathrm{E,max}}_{r,t,s} \tag{9}$$

$$u^{\mathrm{C,B,min}}_{i,t,s} \le u^{\mathrm{C,B}}_{i,t,s} \le u^{\mathrm{C,B,max}}_{i,t,s} \tag{10}$$

$$u^{\mathrm{C,S,min}}_{i,t,s} \le u^{\mathrm{C,S}}_{i,t,s} \le u^{\mathrm{C,S,max}}_{i,t,s} \tag{11}$$

where, $\alpha^{\mathrm{E,min}}_{j,t,s}$ and $\alpha^{\mathrm{E,max}}_{j,t,s}$ indicates the highest and lowest bids for thermal power units, $\alpha^{\mathrm{E,min}}_{r,t,s}$ and $\alpha^{\mathrm{E,max}}_{r,t,s}$ indicates the highest and lowest bids for renewable energy units, $u^{\mathrm{C,B,min}}_{i,t,s}$ and $u^{\mathrm{C,B,max}}_{i,t,s}$ indicates maximum and minimum prices for purchasing CEA, $u^{\mathrm{C,S,min}}_{i,t,s}$ and $u^{\mathrm{C,S,max}}_{i,t,s}$ indicates the maximum and minimum prices for CEA sales.

$$Q^{\mathrm{C}}_{i,t,s} = Q^{\mathrm{C,B}}_{i,t,s} - Q^{\mathrm{C,S}}_{i,t,s} \tag{12}$$

$$\sum_t Q^{\mathrm{c,dis}}_{i,t} = Q^{\mathrm{cap}}_i \tag{13}$$

$$\sum_t\left(\sum_{j\in\Omega_i} P^{\mathrm{E}}_{j,t}e^o_j\right) \le Q^{\mathrm{cap}}_i + \sum_t Q^{\mathrm{C}}_{i,t} \tag{14}$$

where, Q^{cap}_i indicates the CEA for power generators, $Q^{\mathrm{c,dis}}_{i,t}$ indicates allocation of CEA for IEB, e^o_j indicates the carbon emission factor for thermal power units, $Q^{C,B}_{i,t,s}$ indicates the volume of carbon credits purchased, $Q^{\mathrm{C,S}}_{i,t,s}$ indicates the quantity of CEA sold.

3.2 Electricity Market Model

The electricity spot market is centrally cleared by the power exchange under a power-pool model, with the optimization objective of maximizing social welfare in the electricity spot market [10]. The objective function comprises the utility of electricity load minus the bidding costs of generating units.

$$f_e = \max\sum_t\left(\sum_d \lambda^{\mathrm{E}}_{d,t}P^{\mathrm{E}}_{d,t} - \sum_j \alpha^{\mathrm{E}}_{j,t}P^{\mathrm{E}}_{j,t} - \sum_r \alpha^{\mathrm{E}}_{r,t}P^{\mathrm{E}}_{r,t}\right) \tag{15}$$

where, $\lambda^{\mathrm{E}}_{d,t}$ indicates the quotation for load, $P^{\mathrm{E}}_{d,t}$ indicates total load, e^o_j indicates the carbon emission factor for thermal power units, $\alpha^{\mathrm{E}}_{j,t}$ indicates quotation for thermal units, $\alpha^{\mathrm{E}}_{r,t}$ indicates quotation for renewable energy units.

$$\begin{aligned} \sum_{d\in\Omega_n} P^{\mathrm{E}}_{d,t} = & \sum_{j\in\Omega_n} P^{\mathrm{E}}_{j,t} + \sum_{r\in\Omega_n} P^{\mathrm{E}}_{r,t} \\ & - \sum_{m\in\Theta_n} B_{nm}\left(\delta^{\mathrm{E}}_{n,t} - \delta^{\mathrm{E}}_{m,t}\right) : \lambda^{\mathrm{E}}_{n,t} \end{aligned} \tag{16}$$

$$\left|B_{nm}\left(\delta^{\mathrm{E}}_{n,t} - \delta^{\mathrm{E}}_{m,t}\right)\right| \le Pf^{\max}_{nm,t} : v^{L\min}_{nm,t}, v^{L\max}_{nm,t} \tag{17}$$

$$0 \le P^{\mathrm{E}}_t \le P^{\mathrm{E,max}}_t : \mu^{\mathrm{E,min}}_t, \mu^{\mathrm{E,max}}_t \tag{18}$$

$$\delta^{\mathrm{E}}_{1,t} = 0 : \xi^{\mathrm{E}}_{1,t} \tag{19}$$

$$-\delta^{\mathrm{E,max}}_{n,t} \le \delta^{\mathrm{E}}_{n,t} \le \delta^{\mathrm{E,max}}_{n,t} : \xi^{\mathrm{E,min}}_{n,t}, \xi^{\mathrm{E,max}}_{n,t} \tag{20}$$

where, B_{nm} denotes the admittance of line n-m, $\delta^{\mathrm{E}}_{n,t}$ indicates the phase angle of node n, $Pf^{\max}_{nm,t}$ indicates the maximum transmission capacity of line n-m, $P^{\mathrm{E,max}}_t$ indicates the maximum power output of the generator set, $\delta^{\mathrm{E,max}}_{n,t}$ indicates the maximum phase angle， $\delta^{\mathrm{E}}_{1,t}$ represents the phase angle value of the balanced node.

3.3 Carbon Market Model

The carbon spot market is centrally cleared by carbon market exchanges [11]. The clearing of the carbon spot market aims to maximize social welfare within the carbon spot market. The objective function includes the utility of carbon quota buyers minus the costs of carbon quota sellers.

$$f_c = \max\sum_t\left(\sum_i\left(u^{\mathrm{C,B}}_{i,t}Q^{\mathrm{C,B}}_{i,t} - u^{\mathrm{C,S}}_{i,t}Q^{\mathrm{C,S}}_{i,t}\right)\right) \tag{21}$$

where, $u_{i,t}^{\mathrm{C,B}}$ and $u_{i,t}^{\mathrm{C,S}}$ denote the buying price and selling price of CEA, $Q_{i,t}^{\mathrm{C,B}}$ and $Q_{i,t}^{\mathrm{C,S}}$ represent the purchase volume and sale volume of CEA.

$$\sum_{i} Q_{i,t}^{\mathrm{C,B}} = \sum_{i} Q_{i,t}^{\mathrm{C,S}} \tag{22}$$

$$0 \le Q_{i,t,s}^{\mathrm{C,B}} \le Q_{i,t,s}^{\mathrm{C,B,max}} : \varepsilon_{i,t,s}^{\mathrm{C,B,min}}, \varepsilon_{i,t,s}^{\mathrm{C,B,max}} \tag{23}$$

$$0 \le Q_{i,t,s}^{\mathrm{C,S}} \le Q_{i,t,s}^{\mathrm{C,S,max}} : \varepsilon_{i,t,s}^{\mathrm{C,S,min}}, \varepsilon_{i,t,s}^{\mathrm{C,S,max}} \tag{24}$$

where, $Q_{i,t,s}^{\mathrm{C,B,max}}$ represents the maximum purchase quantity of CEA, $Q_{i,t,s}^{\mathrm{C,S,max}}$ represents the maximum quantity of CEA that may be sold.

4. CASE STUDIES

4.1 Basic Data

This system uses an enhanced IEEE 5-node model as a case study. Analogous to the format of [11], modify the IEEE 5-node model. This model comprises three thermal power units (1,500 MW) and two renewable energy unit (600 MW), giving a total generating capacity of 2,100 MW. Each unit is allocated an initial carbon quota. All generating units are divided into three Gencos: one for the integrated energy base, one for all other thermal power units, and the last one for a single renewable energy unit.

Genco	Unit	Capacity (MW)
Integrated energy base	Gen_1	600
	Renew_1	300
Conventional units Genco	Gen_2	600
	Gen_3	300
renewable energy unit Genco	Renew_2	300

4.2 Genco Revenue Comparison Analysis

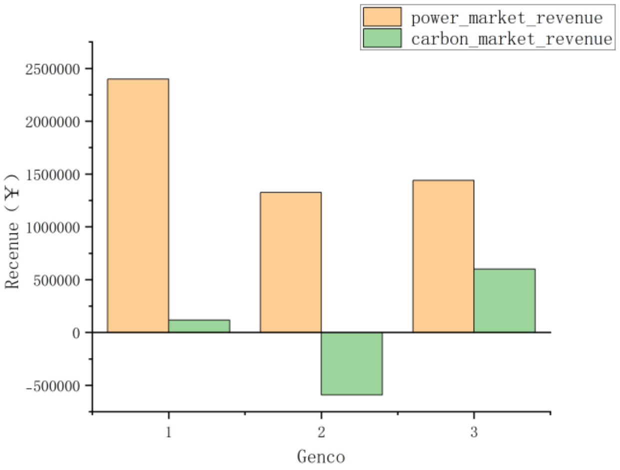

Fig. 2 Electricity-Carbon Market Revenues for Different Power Generators Considering Dynamic *Carbon Emission Intensity*

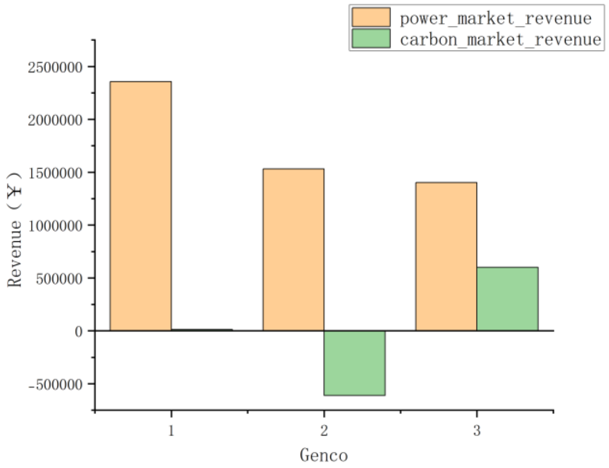

Fig. 3 Electricity-Carbon Market Revenues for Different Power Generators without Considering Dynamic *Carbon Emission Intensity*

Clearly, refining the carbon intensity assessment for thermal power units has a significant impact on the profitability of different types of power generators across various markets. Since some units primarily operate at lower power generation levels, their carbon emissions during these phases are substantially higher than average. Consequently, if these units were not to account for refined carbon intensity measurements, they would pay lower carbon emission costs, thereby undermining overall societal benefits.

5. CONCLUSION

This paper models the strategic behavior of Genco jointly considering electricity and carbon markets using a two-layer framework. The upper-layer strategy of Genco aims to maximize profits by determining multi-market bidding curves. The lower layer incorporates an electricity market clearing model and carbon market clearing model.

Dynamic CEI plays a crucial role in Gencos' multi-market bidding strategy by determining the volume and direction of CEA transactions in the carbon market. Ignorance of dynamic CEI leads to miscalculations of carbon emissions and misguided strategic decisions.

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