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Companies' Operation and Trading Strategies under the Triple Trading and Gaming of Electricity, Carbon Quota and Commodities: A Game Theory Optimization Modeling

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ABSTRACT

Electricity and carbon trading towards carbon reduction are highly coupled. The research on joint trading is essential for helping companies identify optimal strategies and enabling policymakers to detect potential policy loopholes. This study presents a novel game theory optimization model involving both power generation companies (GenCos) and factories to explore optimal operation strategies under electricity-carbon joint trading. By fully capturing the operational characteristics of power generation units and the technical energy consumption of electricity-consuming enterprises, it describes the relationship between renewable energy, fossil fuels, electricity, and carbon emissions detailedly. Considering the correlation between production volume and price of the same product, the case actually encompasses three trading systems: electricity, carbon, and commodities. Transforming this nonlinear model into a mixed-integer linear form through piecewise linearization and discretization, this study examines, through a virtual case with three GenCos and four factories, the impact of various emission reduction targets, comparisons of different carbon allocation mechanisms, and the influence of allowing zero-emission companies into carbon trading. Results reveal that since consumers may cut production rather than implement low-carbon technologies to lower emissions, driving up product prices to maintain profits, high electricity, and carbon prices become unsustainable for GenCos due to reduced electricity demand. Moreover, while intensity mechanisms can incentivize production, overall system profits decrease, which is undesirable for policymakers. Lastly, under strict carbon reduction targets, zero-emission companies may transform the carbon market into a seller's market by purchasing carbon to raise carbon prices, thereby reducing electricity prices and lowering their operating costs.

Keywords: electricity-carbon joint trading, game theory optimization, Nash equilibrium, decarbonization strategy, electricity-consuming factories

INTRODUCTION

It is a consensus that trading is the most effective way to achieve carbon emission reductions [1]. Currently, in most parts of the world, both electricity and carbon trading exist, which are both capable of decreasing carbon emissions. The high overlap in the range of trading participants and the high correlation of traded items make electricity and carbon trading deeply coupled [2]. The transaction behavior and equilibrium of joint trading must be emphasized. Corporations can acknowledge their reasonable and optimal decisions for higher profits in advance and policymakers can both verify the validity and detect potential policy loopholes.

Previous studies about the electricity-carbon joint transaction mostly focus on power generation companies (GenCos) [3, 4], while a large number of electricity consumers directly emitting CO_2, such as steel producers, participate in carbon trading. Although a few studies included electricity consumers before, their descriptions were quite simplified. Studies provided relatively detailed descriptions of end-users only primarily relied on the inverse function relationship between electricity price and demand [5], load curves and utility functions [6, 7]. The relationship between the consumption of electricity and fossil fuels in electricity consumption companies is seldom depicted. Thus, the transaction behavior of this class of firms participating in the electricity-carbon coupled market is always simplified. In addition, the competitive market for products between similar firms is naturally present and indispensable. Due to its prevalence and importance, the product market is one of the most vital factors for companies to make decisions [8], while it is hardly taken into consideration in previous electricity-carbon joint trading studies.

Therefore, this study proposes a novel game theory-based optimization model that includes both GenCos and electricity-consuming factories. Considering both the electricity-carbon joint trading and the competitive trading for substitution of similar products, this model detailedly depicts the correlations between the consumption of fossil energy, renewable energy, generation and consumption of electricity, as well as carbon emissions, through technologies and infrastructure, thereby obtain the Nash equilibrium for triple trading that is closer to the real trading situation. Moreover, this model is implemented on a virtual case with 3 GenCos and 4 electricity-consuming companies to discuss three problems: the enterprises' operational strategies under varying emission reduction requirements, the pros and cons of cap and intensity carbon quota allocation mechanisms, and the impact of integrating zero-emission enterprises into carbon trading.

METHODOLOGY

Modeling of power generation companies

The total power supply of each GenCo in each time slice s in one day can be written as Eq.(1), where η denotes the efficiency of batteries and the duration of each time slice is one hour, indicating that it is the sum of all kinds of generation gi and the net discharge of battery. This day is assumed to be the only representative day in a year. The power generation of each technology, $pg_{GenCo,s,gi}$, is restricted by its installed capacity and maximum operation hours. Additionally, for simplicity, the fuel consumption and carbon emissions of GenCos are directly proportional to the corresponding fossil fuel power generation. The longest continuous charging and discharging time is limited to 2 hours.

$$pg.sum_{GenCo,s} = \sum_{gi} pg_{GenCo,s,gi} + pw.discharge_{GenCo,s} * \eta - pw.charge_{GenCo,s}/\eta \quad (1)$$

The operational goal of power generation companies is to maximize their positive profit, which can be expressed as Eq.(2), where the income equals the product of power supply and electricity price, $fix.cost_{GenCo}$ denotes the average annual investment and operating costs of generation units, $pg.grid.cost_{GenCo}$ is considered as the electricity grid connection cost that enterprises need to undertake, $ramp.cost_{GenCo}$ refers to the additional costs caused by changes in the output of fossil energy units.

$$\begin{aligned} pg.profit_{GenCo} = & \sum_s pg.sum_{GenCo,s} * ep_s * 365 \\ & - fix.cost_{GenCo} - grid.cost_{GenCo} \\ & - fuel.cost_{GenCo} - ramp.cost_{GenCo} \\ & - \sum_s pg.tradecarbon_{GenCo,s} * cp_s * 365 \end{aligned} \quad (2)$$

Obviously, due to the product of two variables, both from electricity and carbon trading, our model becomes nonlinear, as summarized in Eq.(3). To linearize it, we discretize the variable y to $\{Y_i\}$ and introduce binary variables b_i, transforming the problem into Eq.(4), where M is a positive big number. In our model, the price is discretized.

$$z = xy, x \text{ and } y \text{ are all constant variables} \quad (3)$$

$$\begin{cases} z = \sum_i \gamma_i Y_i \\ y = \sum_i b_i Y_i, \ \sum_i b_i = 1 \\ \gamma_i \le x, \ \gamma_i \ge x - M(1-b_i), \ \gamma_i \le M b_i, \ \gamma_i \ge -M b_i \end{cases} \quad (4)$$

Modeling of electricity-consuming companies

In our case study, there are four factories A~D and only their direct carbon emissions are recognized to avoid duplicate accounting. Factory A and Factory B are both equipped with the same two technologies, but in different proportions, producing identical products P. Factory C does not emit CO_2, and only meets known electricity needs through purchased electricity and self-provided energy storage batteries. Factory D needs to complete the signed orders through two technologies. The operational goal of the four factories is the maximization of their positive profit. The revenue of Factory A and B is the product of their output and commodity prices, while the revenue and output of Factory C and Factory D have been determined through contracts. In order to describe the competition market for similar products P, we use the Cournor model to describe the negative correlation between production and price, as shown in Eq.(5), where $fac \in \{A, B\}$, pi stands for two production technologies and a, b are given parameters. This relationship is linearized by Eq.(6), where K is given.

$$P.price = a - b * \sum_{fac,pi,s} P.produce_{fac,pi,s} \quad (5)$$

$$P.price = a - \frac{Kb(i-1)}{n}, \frac{K(i-1)}{n} \le x < \frac{Ki}{n}, i = 1,2,\dots,n \quad (6)$$

The costs of all four factories consist of fixed costs, production costs, fuel costs, electricity purchase costs, and carbon trading costs. Production costs are positively proportional to production volume, which is strictly limited by installed infrastructure. In addition, for Factories

A, B and D, due to the different demands for fuels and electricity required by various technologies, and the consumption of fossil fuels often accompanied by carbon emissions, this model can reflect the negative correlation between the average electricity demand and direct carbon emissions per unit production of factories.

Modeling of electricity-carbon joint trading and calculation of Nash equilibrium

Not considering the transaction center, our model assumes equal buying and selling prices for electricity and carbon, with prices stable throughout the day. Electricity trading should be in real-time and meet supply and demand balance. Carbon trading also needs to meet the supply and demand balance requirement. Unlike electricity trading, carbon trading only requires companies to fulfill their emission obligations at the final moment.

This model directly uses the results of Nash equilibrium to solve the equilibrium in the joint transactions, as shown in Eq.(7a), which equals Eq.(7b). Obviously, this introduces significant nonlinearity to the model. Therefore, special ordered sets of type 2 (SOS2) variables, λ_i, are introduced to make our model linear, as shown in Eq.(8).

$$\max obj = \prod_{GenCo} profit_{GenCo} \prod_{factory_i} profit_{factory_i} \tag{7a}$$

$$\max obj = \sum_{GenCo} LN(profit_{GenCo}) + \sum_{factory_i} LN(profit_{factory_i}) \tag{7b}$$

$$\begin{cases} profit = \sum_i \lambda_i * i \\ LN(profit) = \sum_i \lambda_i * LN(i) \\ \sum_i \lambda_i = 1 \end{cases} \tag{8}$$

In conclusion, this research set up a nonlinear problem(NLP) and transform it into a mixed-integer linear programming(MILP) problem through methods including discretization and piecewise linearization to describe the triple trading of electricity, carbon, and commodities involving both power generation and consumption companies.

CASE STUDY

A diagram of our case study, including fundamental settings, is illustrated in Figure 1. Battery charging and discharging efficiencies are set at 90%, and the price for discharging photovoltaic and energy storage batteries into the grid is 0.1 yuan/kWh. The costs of coal-fired and gas-fired power due to changes in output are 0.05 yuan/kWh and 0.01 yuan/kWh, respectively. Electricity prices range from 0.5 to 1.5 yuan/kWh, while carbon prices range from 0.2 to 4.5 yuan/kg.

Factory A and Factory B both produce product P using two technologies, PT1 and PT2, with details provided in Table 1. The parameters in Eq.(5), a and b, are set as

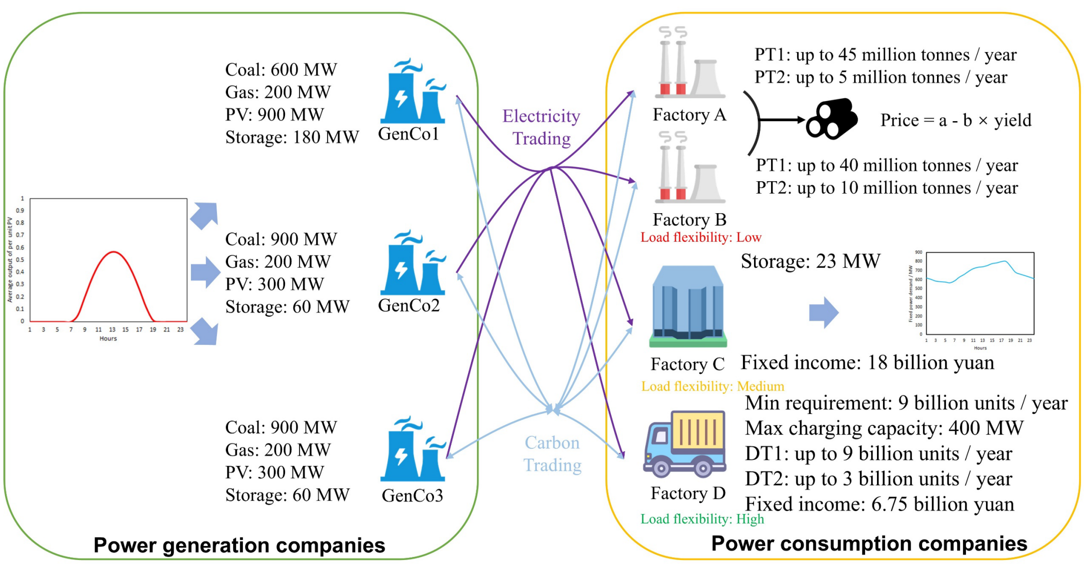

Figure 1: The diagram of the case study

Table 1: Detailed information of PT1 and PT2

Name	Fixed price (¥ / tonne)	Produce price (¥ / tonne)	Electricity demand (kWh / tonne)	CO_2 (kg / kg)	Ramp price (¥ / tonne)
PT1	160	3300	200	2.42	400
PT2	160	3800	600	1.9	200

Table 2: Detailed information of DT1 and DT2

Name	Fixed price (¥ / unit)	Fuel demand (kg or kWh / unit)	Fuel price (¥ / kg)	CO_2 (kg / unit)
DT1	0.012	Fossil fuel: 0.0245 kg	9.3	0.07791
DT2	0.08	Electricity: 0.66 kWh	Variable	0

45 and 10. For Factory D, the specifics of its two technologies, DT1 and DT2, are given in Table 2.

RESULTS AND DISCUSSION

Enterprises' operational strategies under varying emission reduction requirements

Eight scenarios are established to analyze operational strategies and identify patterns. In the Base and the EM only scenario, carbon trading is not allowed, and the electricity price is designated as 0.75 yuan/kWh in the Base scenario. For the scenarios JM0.9 to JM0.4, both carbon trading and electricity trading are allowed, with prices negotiated among participants. Initial carbon quotas are set based on emissions from the EM only scenario; for instance, JM0.9 provides 90% of that carbon quota. Factory C is restricted from participating in carbon trading. Significant results are summarized in Table 3.

Different from previous studies which found that more stringent carbon reduction targets drive up both carbon and electricity prices simultaneously [9], our findings show that when emission reduction targets are exceptionally strict, carbon prices increase while electricity prices decrease. This phenomenon needs to be explained by combining the competition of similar products P and the carbon trading willingness of each enterprise shown in Figure 2(a-f).

Table 3: Trading prices, yield and generation structure under different reduction targets (MT is the abbreviation of million tonnes)

Scenario	Electricity price (¥ / kWh)	Carbon price (¥ / kg)	Total yield of P (MT)	Price of P (¥ / tonne)
Base	0.75	/	65	3900
EM only	1.1	/	60	3950
JM0.9	1.2	0.2(min)	50	4050
JM0.8	1.25	0.2(min)	45	4100
JM0.7	1.25	0.2(min)	40	4150
JM0.6	1.25	0.8	35	4200
JM0.5	1.2	2.0	30	4250
JM0.4	1.0	3.75	24	4300

GenCos generally act as carbon sellers, profiting from both electricity and carbon sales, while factories tend to be buyers in both markets. GenCos can only sell electricity and carbon when consumers continue production, as reduced production means decreased demand for both electricity and carbon allowances. If both prices rise incredibly, consumers will choose to cut production to maintain their profit through raising unit prices, which can be seen from Table 3, then GenCos cannot sell so much. Therefore, electricity prices and carbon prices cannot both increase much. In addition, electricity price contributes more to electricity consumers' total costs

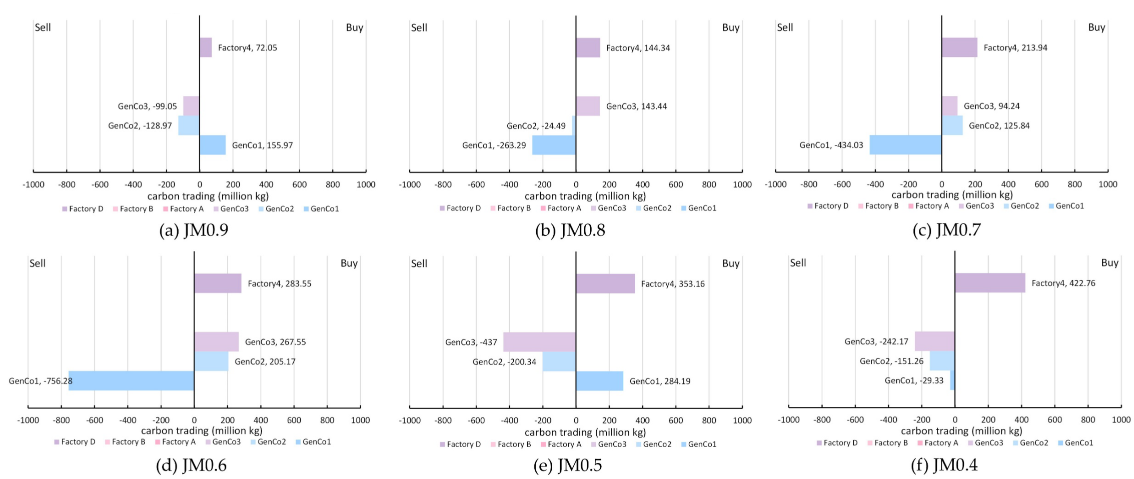

Figure 2: Carbon trading results under different reduction target

Table 4: Trading prices, yield and profit under different quota allocation mechanisms

Scenario	Electricity price (¥ / kWh)	Carbon price (¥ / kg)	Total yield of P (MT)	Profit of each enterprise (Billion yuan) (GenCo1~3; factory A~D)
JM0.9	1.2	0.2(min)	50	5.10, 5.16, 5.10; 4.80, 4.70, 5.87, 4.30
JM0.8	1.25	0.2(min)	45	5.00, 4.92, 5.00; 4.40, 4.35, 5.61, 4.31
Int-JM0.9	0.9	0.8	55	3.87, 4.30, 4.60; 3.70, 3.77, 7.44, 3.90
Int-JM0.8	0.8	0.8	45	1.97, 3.04, 4.34; 2.39, 2.40, 8.27, 4.21

compared with carbon cost; therefore, only when the electricity price is lower would they like to maintain a relatively high production volume. Previous studies were unable to reach these results because they often overlooked the probability of factories' reducing production and price yield relationship in commodity trading. The difference in conclusions also proves the necessity of considering the behavior of electricity-consuming factories more carefully in the electricity-carbon joint trading.

Although there is currently no empirical evidence to support the idea that electricity prices will drop as carbon prices rise due to end-use firms drastically reducing production to meet stricter emission targets, prior studies have observed similar patterns. When the cost of reducing carbon emissions becomes prohibitively high, end-use companies may opt to cut production and increase prices [10]. We speculate that this has not led to a reduction in electricity prices, possibly because these firms are not major electricity consumers within their regions, limiting their tariff negotiation power. However, this hypothesis requires further validation.

In addition, the results also state that factories are not willing to either use any expensive low-carbon technologies to reduce their emissions or purchase costly carbon quotas. This means that if there are no restrictions, the emission reduction of the system will mainly be achieved through the decarbonization of the power system and the reduction of factory production. However, the reduction of yield and the soaring of the price might not align with the goals of market regulators. Therefore, regulators must strictly limit the factories participating in the electricity-carbon joint market to prevent them from maliciously reducing production to maintain profits under the carbon target.

Pros and cons of cap and intensity carbon quota management mechanisms

In order to quantitatively acknowledge the pros and cons of the cap and intensity quota management mechanisms, the two most widely implemented in carbon trading in reality, this study proposes two additional scenarios: Int–JM0.9 and Int-JM0.8. In the two intensity scenarios, the sum of each enterprise's carbon emissions and carbon trading volume does not exceed the fixed percentage of the product of its production and emission intensity under the EM only scenario. Key findings are shown in Table 4.

Results show that under the intensity mechanism, factories' production enthusiasm can be improved, which is consistent with official cognition, confirming the reliability of our study. The electricity price decreases and the carbon price rises, which seems to be beneficial to both the production and carbon reduction. However, the profits of enterprises involved in carbon trading are all vulnerable under the intensity mechanism, making the total market profit decline violently. Although all the firms in the system are 'selfish' and want to maximize their own profit, the governor of the system always wishes that the total profit would be as high as possible from an economic development perspective. From this point of view, the cap mechanism is much better.

The impact of integrating zero-emission enterprises into carbon trading

Although some enterprises, such as Factory C in our case study, do not emit CO_2 directly, we still try to let them participate in carbon trading, exploring the impact of integrating zero-emission enterprises into carbon trading. Because that they do not own the initial carbon quota, leading to their non-negative net carbon purchases, thereby further promoting the system's carbon mitigation. The difference of involving Factory C into carbon trading is exhibited in Table 5.

Table 5: Trading prices, yield and profit under different quota allocation mechanisms

Scenario	Electricity price (¥ / kWh)	Carbon price (¥ / kg)	Total yield of P (MT)
JM0.5-exclude	1.2	2.0	30
JM0.4-exclude	1.0	3.75	24
JM0.5-include	1.0	4.5(max)	30
JM0.4-include	0.95	4.5(max)	24

First and foremost, the yield is not likely to be influenced. It can be also found that the inclusion of carbon-free enterprises in carbon trading will lead to a drop in electricity prices and an increase in carbon prices. These enterprises attempt to increase the scarcity of tradable quotas by increasing carbon trading volume, thereby raising carbon prices. Due to the fact that the electricity and carbon price cannot increase violently simutanesoulу, thus they can pay a smaller cost in exchange for a drop in electricity prices, thereby minimizing their total costs.

CONCLUSION

This study proposes a non-linear program to describe the triple gaming and trading of electricity, carbon and commodity between both power generation and consumption companies. Transforming it into a MILP problem and using a case with 3 GenCos and 4 factories in 3 types, this study discusses the optimal operation mode of enterprises under coupled transactions. Results state that power consumers are more likely to achieve reduction targets through reducing yield instead of implementing low-carbon technologies or trading quotas, which also leads to the inability of electricity and carbon prices in the electricity-carbon joint trading to be high at the same time. Meanwhile, if zero-emitting enterprises participate in the carbon market, they can increase the scarcity of carbon in the market by purchasing carbon, thereby reducing electricity prices and ensuring their own profits. This study also provides ideas for market managers. It is necessary to strictly control the output of electricity consuming enterprises and prioritize the use of Cap carbon management mechanisms when considering the total profit of the system.

However, our study has certain limitations. Future research should incorporate more detailed considerations, such as real-time electricity prices, policy analyses based on our proposed model, and discussions on parameter sensitivity, to better support the ongoing development of the electricity-carbon joint market.

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