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Information gap decision theory-based optimization of joint decision making for power producers participating in carbon and electricity markets

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Abstract

Carbon markets have been established in many countries and regions with the goal of promoting global carbon neutrality. The position of power producers as the dominant carbon emitters necessitates that they engage in both electricity and carbon markets. However, most studies have considered only short-term electricity markets and unrealistically static carbon markets, and the speculative behavior of power producers in the carbon market remains poorly considered. The present study addresses these issues by proposing an optimized joint decision model based on information gap decision theory to facilitate the participation of power producers in annual and monthly electricity markets, and monthly carbon markets, where uncertainties in the prices of electricity and carbon quotas, and the speculative behavior of power producers in the carbon market are explicitly considered to ensure that the revenues of market participants do not fall below a predetermined minimum acceptable value. The results of simulations based on the rules and actual market data obtained for electricity and carbon markets in a specific province of China demonstrate that the proposed model provides power producers with trading solutions to meet different expected revenue targets, and thereby assists them as much as possible in counteracting the risks to profit associated with fluctuations in electricity and carbon market prices.

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Keywords: Electricity market; Carbon market; Power producers; Information gap decision theory; Trading decision

1. Introduction

The consensus of most countries in the world today has moved toward protecting the global environment by implementing measures to reduce carbon emissions. Current carbon emission reduction measures mainly include

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the implementation of carbon taxes [1–3] and cap-and-trade programs [4–6]. However, the latter approach has become increasingly favored in recent years owing to its market-based solution for achieving the optimal reduction in carbon emissions. To this end, China launched a national unified carbon market in July 2021, and members of the power generation industry, which is the sector with the largest carbon emissions [7], were the first market participants. However, this new context requires power producers to make trading decisions in both the electricity and carbon markets, and complex interactions between these markets will have an important impact on the business decisions and interests of power producers [8].

A number of studies have sought to maximize the economical operations of power producers by optimizing their trading activities in both the electricity and carbon markets. For example, a two-tier optimization model with the objective of maximizing the annual expected return of power producers was developed based on the UK carbon reduction plan; the model assumes that the price of carbon quotas is fixed at the beginning and at the end of the year when power producers purchase these quotas [9]. The concept of conditional risk emissions was proposed in conjunction with an optimal day-ahead market bidding model for power producers considering the risk constraint of carbon emissions overrun in the Iberian electricity market under the Spanish carbon reduction plan [10]. However, the model considered only the carbon emission constraint, and neglected the participation of power producers in the carbon market. Finally, a Cournot–Nash equilibrium model of the electricity spot market that conjointly considered the carbon market was developed to analyze the impact of carbon market trading on the competitive strategies of power producers in the electricity market [11].

However, the aforementioned efforts suffer from a number of obvious problems. First, few studies have considered the participation of power producers in medium- and long-term electricity markets. Nonetheless, the revenues of power producers in the electricity market are mainly affected by medium- and long-term markets. Therefore, the results tend to be less than optimal. Second, most studies have assumed a fixed price for carbon quotas in the carbon market. However, this assumption is not realistic. Finally, few studies have considered the speculative behavior of power producers in the carbon market, such as in the hoarding and selling of carbon quotas. Additionally, in the existing decision making strategies in electricity market, the risks of renewable energy productions [12], demands [13] or electricity prices [14] were usually managed by using stochastic optimization framework with accurate probabilistic forecast results, which might be difficult to obtain in practice [15]. By contrast, information gap decision theory (IGDT)-based optimization technique is a non-probabilistic risk management approach without considering the probability distribution of uncertain parameters, which is easy to be implemented [16].

The present study addresses the shortcomings of existing work by establishing an optimized joint trading decision model for power producers based on information gap decision theory (IGDT). The main contributions of the present work can be described as follows.

(1) The proposed joint decision model enables power producers to participate in both medium- and long-term electricity markets, including annual and monthly markets, and the monthly carbon market, where the uncertainties in electricity prices and carbon quota prices and the speculative behavior of power producers in the carbon market are considered explicitly. Accordingly, the market environment considered in this study is more accurate and realistic than those considered in previous studies.

(2) We apply IGDT to address the uncertainties of electricity prices and carbon quota prices; the established decision model can ensure that the revenues of market participants do not fall below a predetermined minimum acceptable value by providing power producers with trading options to meet different expected revenue targets, and help them accommodate price fluctuation risks in the electricity and carbon markets as much as possible.

(3) The impact of risk preference on the trading strategies of power producers is further analyzed, and this analysis provides more accurate and objective guidelines for assisting power producers to arrange their output plans and organize their carbon and electricity market trading activities.

The remainder of this paper is organized as follows. The proposed decision-making model for power producers is introduced in Section 2. The results of case studies are presented in Section 3, and the report is concluded in Section 4.

2. Joint decision model

The rules of China's national unified carbon market are adopted in this study. Accordingly, power producers are generally free to buy and sell carbon quotas in the carbon market. However, the carbon quota compliance requirements must be met at the end of the compliance period. The other rules of the carbon market are presented later as constraints of the joint decision model. In addition, the carbon market is assumed to be a monthly market.

The large sizes of the electricity and carbon markets coupled with the large number of market participants ensures that the decision-making behavior of individual power producers has little impact on market prices. Therefore, power producers are considered to be price takers in both markets. The joint decision model proposed in the present work assumes that the price of electricity in the annual market is a known quantity, and power producers make business decisions based on forecasts of the electricity and carbon quota prices in the monthly markets obtained over the following 12 months using any of the many relatively mature methods for price forecasting. Therefore, power producers must make trading decisions in the annual electricity market, the monthly electricity market for each month of the following year, and the carbon quota trading volume for each month of the following year.

According to the preceding description, the annual revenue R of a power producer in the following year can be expressed as

$$R = \sum_{i=1}^{12} (p_{\mathrm{y}} q_{\mathrm{y},i} + p_{\mathrm{m},i} q_{\mathrm{m},i} - p_{\mathrm{c},i} q_{\mathrm{c},i} - C_i), \tag{1}$$

where p_{y} is the price of electricity in the annual market, and, for month i, $q_{\mathrm{y,i}}$ is the monthly electricity produced, which is obtained by decomposing the annual electricity market trading power; $p_{\mathrm{m,i}}$ is the monthly electricity price forecasted by the power producer; $q_{\mathrm{m,i}}$ is the monthly amount of electricity traded by the power producer; $p_{\mathrm{c,i}}$ is the monthly carbon quota price forecasted by the power producer; $q_{\mathrm{c,i}}$ is the monthly amount of carbon quota volume traded by the power producer; and C_i is the monthly cost of electricity generated by the power producer. Assuming that the production cost k of the power producer per unit of electricity is a constant, C_i can be expressed as

$$C_i = k(q_{\mathrm{y},i} + q_{\mathrm{m},i}). \tag{2}$$

However, the prices p forecasted by a power producer in the monthly electricity and carbon markets inevitably deviate from their actual values p^{r}. Therefore, the actual market price p^{r} can be expressed as follows:

$$\begin{cases} p^{\mathrm{r}} \in U(\alpha, p) \\ U(\alpha, p^{\mathrm{r}}) = \left\{ p^{\mathrm{r}} \,\|\, \frac{p^{\mathrm{r}}-p}{p} | \le \alpha \right\} \end{cases} . \tag{3}$$

Here, α is the volatility of p^{r} and $U(\alpha,\mathrm{p}^{\mathrm{r}})$ is the range of fluctuations in p^{r}.

Under monthly market price uncertainty, power producers generally seek to ensure that an expected target revenue can be achieved according to their degree of risk aversion, and then accordingly pursue a trading strategy that maximizes the range of market price fluctuations they can tolerate while meeting their expected minimum target revenue.

Based on the preceding discussion and IGDT, the following joint decision model can be developed for power producers to participate in the annual electricity market and the monthly electricity and carbon markets:

$$\max \quad \alpha_{\mathrm{e}} + \alpha_{\mathrm{c}}, \tag{4}$$

$$s.t. \quad R \ge (1-w)R_0, \tag{5}$$

$$\left| \frac{p^{\mathrm{r}}_{\mathrm{m},i} - p_{\mathrm{m},i}}{p_{\mathrm{m},i}} \right| \le \alpha_{\mathrm{e}}, \tag{6}$$

$$\left| \frac{p^{\mathrm{r}}_{\mathrm{c},i} - p_{\mathrm{c},i}}{p_{\mathrm{c},i}} \right| \le \alpha_{\mathrm{c}}, \qquad i = 1, 2, \ldots, 12; \tag{7}$$

where α_{e} is the volatility of the electricity price, α_{c} is the volatility of the carbon quota price, R_0 is the maximum revenue of the power producer when the market price equals the forecasted value, w is a deviation factor that represents the degree of deviation of the expected revenue R below R_0,$p^r_{m,i}$ is the actual electricity price, and $p^r_{c,i}$ is the actual carbon quota price in month i. Here, the value of w represents the degree of risk aversion of the power producer, which increases with increasing w. In addition, the following constraints must be considered.

(1) Carbon quota allocation

According to the rules of China's national unified carbon market, the initial carbon quota allocation for power producers is divided into two stages, including pre-allocation and final approval stages. First, the carbon quota Q_{C}

of a power producer is pre-allocated at the beginning of the year based on 70% of the power Q_{h} generated by that producer in the previous year as follows:

$$Q_{\mathrm{C}} = 70\% Q_{\mathrm{h}} K^*, \tag{8}$$

where K^* is the baseline value of carbon emissions approved by the government. The final approval of quotas is then made at the end of the year based on the actual power Q_{real} generated by the provider after completion of annual carbon emission data verification. Therefore, the final approved carbon quota $Q_{\mathrm{C,final}}$ allocated to the power producer at the end of the year is

$$Q_{\mathrm{C,final}} = Q_{\mathrm{real}} K^*. \tag{9}$$

(2) Carbon quota buying and selling constraint

The monthly purchase of carbon quotas by power producers cannot exceed a specified percentage of the free quotas allocated by the government, and the sale of carbon quotas cannot exceed the total amount of carbon quotas currently held. This constraint is defined as follows:

$$\begin{cases} q_{\mathrm{c},i} \le \mu Q_{\mathrm{C}} & q_{\mathrm{c},i} \ge 0 \\ -q_{\mathrm{c},i} \le Q_{\mathrm{C}} + \sum_{t=1}^{i-1} q_{\mathrm{c},t} & q_{\mathrm{c},i} < 0 \end{cases}. \tag{10}$$

Here, μ is the monthly carbon quota buy-in cap factor, which is determined by the regulator, and $\sum_{t=1}^{i-1} q_{c,t} = 0$ when $i = 1$.

(3) Carbon quota holding bound

The market imposes a limit on the maximum amount of carbon quotas that can be held by a power producer to prevent excessive speculation. This limit is specified as

$$Q_{\mathrm{C}} + \sum_{t=1}^{i} q_{\mathrm{c},t} \le g Q_{\mathrm{h}} K^*, \tag{11}$$

where g is the maximum carbon quota holding factor set by the regulator.

(4) Carbon quota minimum trading volume constraint

Carbon quota trading institutions usually specify that $q_{\mathrm{c,i}}$ meet a minimum amount of carbon quota trading volume, which is defined as follows:

$$\left| q_{\mathrm{c},i} \right| \ge r, \tag{12}$$

where r is the minimum carbon quota trading volume, which is usually 1 ton.

(5) Power producer capacity constraint

The amount of electricity that a power producer can generate each month is limited by their generation capacity q_{max}, and is defined as follows:

$$\begin{cases} q_{\mathrm{y},i} + q_{\mathrm{m},i} \le q_{\mathrm{max}} \\ q_{\mathrm{y},i} \ge 0, q_{\mathrm{m},i} \ge 0 \end{cases}. \tag{13}$$

Here, q_{max} is influenced by the amount of coal stocked by the power producer, unit maintenance schedules, and other factors.

(6) Annual market trading power constraint

The market encourages power producers to enter into long-cycle contracts. Therefore, a power producer must contract no less than a minimum proportional factor Z_{min} of their total electricity generated in the annual market, which is defined as follows:

$$Z_{\mathrm{min}} \sum_{i=1}^{12} (q_{\mathrm{y},i} + q_{\mathrm{m},i}) \le \sum_{i=1}^{12} q_{\mathrm{y},i}. \tag{14}$$

The value of Z_{min} is set by the regulator.

(7) Breakdown of annual contracted power supply of power producers by month

The annual contracted power supplied by a power producer is broken down by month according to a pre-determined ratio as follows:

$$L_i \sum_{i=1}^{12} q_{\mathrm{y},i} = q_{\mathrm{y},i}, \tag{15}$$

$$\sum_{i=1}^{12} L_i = 1. \tag{16}$$

Here, L_i is the percentage of annual contracts in month i, which can be determined based on the historical electricity consumption characteristics of market-wide customers.

(8) Carbon quota compliance constraint for power producers

At the end of the compliance period, the carbon quotas held by a power producer must be greater than the total amount of carbon emissions they generated. This yields the following constraint:

$$Q_{\mathrm{C,\ final}} + \sum_{i=1}^{12} q_{\mathrm{c},i} \geq K \sum_{i=1}^{12} (q_{\mathrm{y},i} + q_{\mathrm{m},i}), \tag{17}$$

where K is the carbon emission factor of the power producer.

3. Case studies

The case studies applied herein assume that the power producer has a coal-fired unit with an installed capacity of $q_{\max} = 640$ MW, an electricity generation cost of \$45/MWh, a carbon emission factor of $K = 0.9$ $\mathrm{tCO_2/MWh}$, and a carbon emission baseline value of $K^* = 0.85$ $\mathrm{tCO_2/MWh}$. According to the rules of the electricity and carbon markets, and the operational data of a specific province in China during the year 2021, it is assumed that $Z_{\min} = 70\%$, $\mu = 3$, $g = 1.2$, and the annual market price is $q_{\mathrm{y}} =$ \$63.27/MWh; the forecast values of electricity prices and carbon quota prices in monthly markets are presented in Fig. 1(a) and (b), respectively. In addition, a deviation factor of $w = 0.1$ is assumed unless otherwise specified when the volatilities in electricity and carbon quota prices are considered.

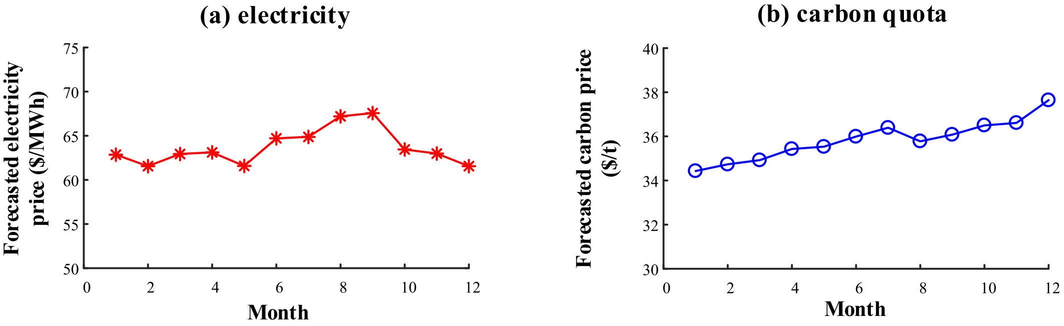

Fig. 1. Forecasted values of monthly market prices: (a) electricity; (b) carbon quota.

We first consider the condition where electricity and carbon quota price uncertainty are not accounted for, and the forecasted prices are taken as the accurate values. Under this condition, the power producer contracts a total of 2.28×10^6 MWh in the annual electricity market and 9.79×10^5 MWh in the monthly electricity market, for a total of 3.26×10^6 MWh for the year, and the revenue R_0 of the power producer is $\$5.98 \times 10^7$. In the absence of market price uncertainties, power producers will seek to generate more electricity in months with high electricity prices, buy more carbon quotas in months with low carbon quota prices, and sell more carbon quotas in months with high carbon quota prices to obtain higher revenues. At this point, the producer's trading strategy can resist the market price fluctuation with zero uncertainty, i.e., $a_{\mathrm{e}} = a_{\mathrm{c}} = 0$.

When considering both the uncertainty of the monthly electricity and carbon quota market prices, and optimizing the market decision of the producer based on IGDT, the power producer contracts a total of 2.80×10^6 MWh in the annual electricity market and 4.64×10^5 MWh in the monthly electricity market, for a total of 3.26×10^6 MWh for the year, which is equivalent to the total obtained under no market price uncertainties. This yields a minimum expected revenue of \$5.38 × 10^7 for the power producer, $\alpha_e = 0.1879$, and $\alpha_c = 0.0885$. The optimized trading decisions of the power producer in the electricity and carbon markets are presented in Fig. 2(a) and (b), respectively.

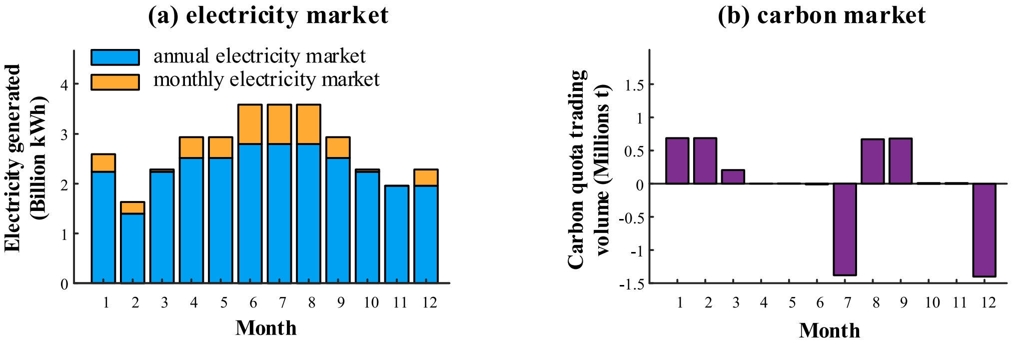

Fig. 2. Market decisions of power producers: (a) electricity market; (b) carbon market.

A comparison with the market decisions of the power producer when price uncertainties were ignored indicates that, while the total amount of electricity traded by the power producer is unchanged, the power producer decreased the total electricity contracted in the monthly market and increased the total electricity contracted in the annual market. In fact, the results in Fig. 2(a) indicate that trading in the monthly electricity market was zero or nearly so during several months of the year. The reason for this change in behavior is that monthly electricity market prices are uncertain, while annual electricity market prices are deterministic. Therefore, power producers increase trading in the annual electricity market to reduce risks to profit and improve the robustness of trading decisions.

It can be seen in Fig. 2(b) that the power producer buys carbon quotas in large quantities during some of the months at the beginning of the year when the carbon quota price is low, and then sells some of the quotas in June and July when the carbon quota price is relatively high. In addition, the power producer re-buys large quantities of carbon quotas later when the carbon quota price decreases again, and then sells some of them in December when the price is high. However, it is also noted that the power producer does not buy or sell all of its carbon quotas in any single month to avoid the excessive risk to profit arising from the price uncertainty.

In addition, we investigated the impact of different values of w on the decision making of a power producer, and the results are presented in Fig. 3. It can be seen that the maximum fluctuation ranges of electricity price and carbon quota price increase linearly with increasing w, and the expected minimum revenue of the power producer also decreases. This is because the expected revenue decreases as the degree of risk preventable to the power producer increases. Therefore, the decision model developed in this paper can provide power producers with different risk preferences with trading options that satisfy their minimum expected returns.

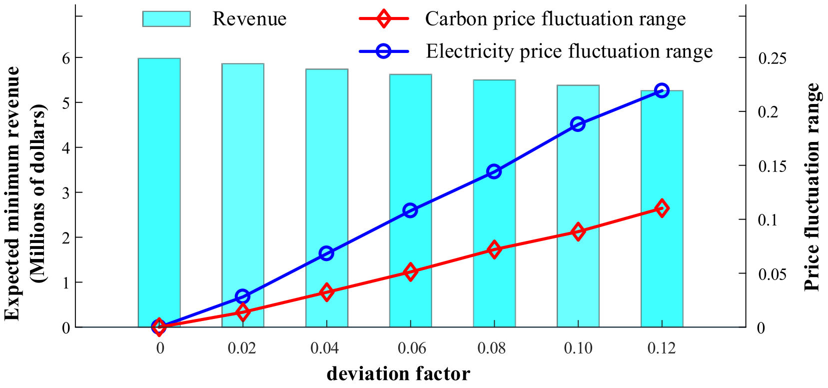

Fig. 3. Impact of the deviation factor on the revenue obtained and the price fluctuations experienced by a power producer.

It can also be noted from Fig. 3 that the volatility of the electricity price is always greater than that of the carbon quota price for a given value of $w > 0$. Therefore, power producers must take the volatility of the electricity price more into account than the carbon quota price when making trading decisions to reduce the risk to profit. Nonetheless, the superposition of price uncertainties in the electricity and carbon markets narrows the decision-making space of power producers, and exposes them to greater risks. Accordingly, considering the price uncertainties in the two markets jointly can provide a more reasonable assessment of the risks and benefits of various trading strategies, and thereby provide more accurate and objective suggestions for power producers to arrange their generation plans and organize their participation in various transactions.

4. Conclusion

The present study addressed the shortcomings of existing efforts to provide power providers with an optimized framework for jointly trading in both long-term annual and monthly electricity markets and monthly carbon markets by establishing an optimized IGDT-based joint trading decision model. The framework considers uncertainties in the prices of electricity and carbon quotas, and the speculative behavior of power producers in the carbon market explicitly to ensure that the revenues of market participants do not fall below a predetermined minimum acceptable value. The results of simulations demonstrated that the proposed model provides power producers with trading solutions to meet different expected revenue targets. Moreover, the impact of different risk appetites on the trading strategies adopted by power producers was investigated. The results demonstrated that power producers reduce the risks to profit and enhance the robustness of their trading decisions by electing to trade more in the annual electricity market than in the monthly electricity market, and they spread their carbon quota trading activities over different months of the year rather than buying or selling all of their carbon quotas at one time. In addition, the volatility of the electricity market price is greater than that of the carbon quota price at a given risk appetite. Therefore, power producers must focus more on the volatility of the electricity price when making trading decisions than the volatility of the carbon quota price to support their profits. The results collectively demonstrate that the proposed framework assists power producers as much as possible in counteracting the risks to profit associated with fluctuations in electricity and carbon market prices.

In the future research works, additional flexible resources or financial tools in power systems, such as energy storages [17] and virtual bidding in electricity markets [18], could be further utilized to decrease the risks for the power providers. Additionally, hybrid approached considering both IGDT-based and stochastic optimization techniques [19] could be also be developed for joint decision making in electricity and carbon markets with severe uncertainties.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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