Research on Power Investment and Expansion Planning Considering Coal-fired Power Capacity and Electricity Price in Market-Driven Environment

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Abstract. The market-oriented environment and the shift away from the coal-fired power are inevitable trends in the future development of electric power energy. Based on this, this article establishes a dual-level model for power investment expansion planning with wind power system in an oligopoly competitive electricity market. In the upper-level model, power generation companies make investment decisions and formulate their bidding strategies in market transactions, while the lower-level model simulates the day-ahead market clearing process under the centralized bidding and trading mode. To encourage the transition from coal-fired power plants, a model for expected annual operating revenue of coal-fired power companies under a dual pricing system is proposed, and the conditional value-at-risk (CVaR) is used to measure the investment risk brought by the uncertainty of competitors in the investment planning game for power generation companies. The numerical results verify the effectiveness of the proposed model and method.

1 Introduction

With the release of the Central Committee of the Communist Party of China and the State Council's Opinions on Further Deepening the Reform of the Power System, China's power system reform is steadily advancing. The lastest power reform follows the institutional framework of "controlling the middle and opening up both ends", and implements "three opening up, one independence, and three strengthening", which has a profound impact on various aspects including generation, transmission, and sales. In generation, power generation groups have emerged as independent market entities, and the investment expansion planning of power sources has shifted from unified planning under regulatory system to an interest game, with each power generation group as the planning subject; in transmission, market-oriented power trading brings greater uncertainty in system flow; in sales, the granting of user choice rights makes the load more proactive.

Regarding the investment expansion planning of power sources in the power market-oriented environment, most existing research methods adopt a dual-level planning model to hierarchically model the investment behavior of power generation companies and the transaction processes of the power market [1-8]. Reference [1] proposes a power source investment expansion planning method that takes into account different power market structures by characterizing the power generation equilibrium models of various power generation companies under different degrees of competition, such as perfect competition and Cournot monopoly competition. References [2-3] use a multi-scenario approach to describe the uncertainty of competitors' investment and bidding strategies in the power generation market, simulating the trading process of the spot market through centralized bidding and establish a power source investment expansion planning model for a single power generation company. Building upon the work in references [2-3], reference [4] simultaneously takes into account the spot market trading and futures market trading, analyzing the impact of trading volume and arbitrage behavior in the futures market on the investment decision of power generation companies. References [6-8] study the game equilibrium problem when multiple power generation companies simultaneously invest in power generation capacity. In a market-oriented environment, power generation companies need to manage risks while pursuing maximum profits. However, the abovementioned literature does not include the investment risks brought to power generation companies by various uncertain factors.

This article considers the coal-electricity capacity pricing mechanism and market trading mechanism, and proposes a two-part electricity price model for coal-fired power enterprises. Based on this, a dual-level model for power investment expansion planning is established, with power generation companies as the investment entity, considering both investment returns and risks. By characterizing the uncertainty of competitor strategies in the investment planning game process using multiple scenario sets, the conditional value at risk (CVaR) is used to measure the investment risk brought to power generation companies by uncertainty factors. Case analysis proves the correctness and effectiveness of the method proposed in this article.

2 Issues Related to Power Investment Expansion Planning in a Market-Oriented Environment

2.1 Power Market Mechanism

In a market-oriented environment, the power market mechanism is a key factor determining the revenue of power generation companies, and thus has a significant impact on their investment decisions. Based on the long-term trends in power market development, the research work mainly focuses on the following power market models, trading methods, and rules:

1) The market model adopts the competitive power purchase model within the power joint operation market, with market participants including power generation companies and power users.

2) Currently, the power market transactions occur through a centralized bidding model. Power generation companies and electricity users submit segmented supply functions and segmented price information for each unit to the Power Exchange (PX), including the capacity values and prices for each segment.

3) The Power Exchange (PX) performs market clearing by considering the price information supplied by both power generation companies and electricity users. Settlements are carried out using the locational marginal price (LMP).

2.2 Model for expected annual operating revenue of coal-fired power enterprises under the two-part electricity price system

Inovember 2023, the National Development and Reform Commission and the National Energy Administration jointly issued the Notice on Establishing a Coal-fired Power Capacity Pricing Mechanism (hereinafter referred to as the Notice), which specifies that the nationwide fixed cost for coal-fired power is 330 yuan per kilowatt per year, and in the majority of locations betweenIn the majority of locations between 2024 and 2025, around 30% of the fixed costs will be recovered through capacity pricing. The issuance of the Notice indicates that the two-part electricity price system, which reflects the value of coal-fired power in terms of electricity quantity and capacity, is gradually taking shape. The electricity quantity price is determined through market-oriented means, responsively reflecting the supply and demand of the electricity market, fuel cost changes, and other factors. The level of capacity pricing is reasonably determined and gradually adjusted based on the progress of transformation, fully reflecting the supporting and regulating value of coal-fired power to the power system, and ensuring the sustainable and healthy operation of the coal-fired power industry. According to the dual pricing mechanism of coal-fired power generation, a model for the expected annual operating revenue of coal-fired power enterprises is established, represented by the sum of electricity revenue and capacity revenue minus fuel costs and environmental costs, as shown in equation (1).

$$F_{ope}^{C} = \sum_{n}\sum_{\omega} p(\omega) \sum_{l} T_l \sum_{k} [\lambda_{n\omega l} P_{n\omega lk}^{C} + A\overline{P}_{n\omega l}^{C} - P_{n\omega lk}^{C}(F_{f,n}^{C} + F_{e,n}^{C})] \tag{1}$$

In the equation, *n* represents the system node; *w* represents the scenario; *l* represents the operating state *l*; *k* represents the capacity segment *k* of the unit's segmented offer; *p(w)* represents the probability of the scenario *w* occurring; T_l represents the duration of the operating state *l*; $\lambda_{n\omega l}$ represents the marginal electricity price of the node *n* under the scenario *w* and operating state *l*; $P_{n\omega lk}^{\mathrm{C}}$ represents the active power output of the capacity segment *k* of the planned coal-fired power generation at the node *n* under the scenario w and operating state *l*; $\overline{P}_{n\omega l}^{C}$ represents the maximum declared output of the planned coal-fired power generation at the node *n* under the scenario w and operating state *l*; A represents the local coal-fired capacity price; $F_{f,n}^{\mathrm{C}}$ and $F_{e,n}^{\mathrm{C}}$ represent the unit fuel cost and unit environmental cost of the planned coal-fired power generation at the node *n*.

3 Power Generation Company's Dual-Layer Model for Power Investment and Expansion Planning

3.1 Dual-level planning

The power investment and expansion planning problem considering electricity market transactions has a dual-level structure. The upper-level model takes the power generation company as the decision-making entity, and optimizes the investment portfolio of power generation capacity and formulates pricing strategies based on the comprehensive consideration of benefits and risks. The lower-level model takes PX as the decision-making entity and conducts day-ahead market clearing under the centralized bidding trading mode based on the bidding information of various units and loads.

3.2 Upper-level model

1) Objective function

In the market-oriented environment, the power generation company, as a rational investor, needs to consider the investment profit and risk comprehensively when making investment decisions. The expected annual profit of power generation investment is determined by the equal annual value of investment and the expected annual operating income. In order to quantitatively describe the risk of power generation investment, this article selects CVaR as the risk measurement index to estimate the uncertainty of profits under different scenarios. In summary, the objective function can be described as:

$$\begin{aligned}\mathrm{Max.}\ F&=F_{pro}+\beta\mathrm{CVaR}\\ &=F_{ope}-F_{inv}+\beta\mathrm{CVaR}\end{aligned} \tag{2}$$

Where F represents the upper-level objective function; F_{pro} represents the expected annual profit of power investment expansion planning; F_{ope} represents the expected annual operating income; F_{inv} represents the investment equivalent annual value; CVaR is the conditional value at risk; β is the risk aversion coefficient, and the larger the β, the deeper the power generation company's aversion to risk, and its value can be appropriately adjusted according to the research purpose and the decision maker's preferences.

The expected annual operating income of wind power, and the investment equivalent annual value of coal power and wind power are shown respectively:

$$F_{ope}^{E}=\sum_{n}\sum_{\omega}p(\omega)\sum_{l}T_l\sum_{k}\lambda_{n\omega l}P_{n\omega lk}^{W} \tag{3}$$

$$F_{inv}=\sum_{n}(K^{\mathrm{C}}C_n^{\mathrm{C}}+K^{\mathrm{W}}C_n^{\mathrm{W}}) \tag{4}$$

Where $P_{n\omega lk}^{\mathrm{W}}$ represents the active power output of the planned wind farms at the node n in capacity segment k under the scenario w and operating state l; K^{C} and K^{W} respectively represent the annual value of unit capacity investment for planned coal-fired and wind farms; C_n^{C} and C_n^{W} respectively represent the installed capacity of planned coal-fired and wind farms at the node n.

Risk measurement tools widely used in the financial field include Value at Risk (VaR) and CVaR. VaR can be defined as: if there is a confidence level $\alpha\%$ that the profit is not less than y, then the maximum value of y that can be obtained is the VaR of the profit value under that investment decision. CVaR refers to the average size of the value under the condition that the profit is less than VaR, reflecting the average shortfall of investment profit at the confidence level α, which can better measure the potential risk size compared to VaR. The smaller the CVaR, the more severe the potential profit shortfall that the power generation company may bear, indicating a greater investment risk faced by the company. The optimization problem of CVaR can be transformed into an equivalent problem as shown in equation (7) for solving [9]:

$$\begin{cases}\mathrm{Max.\ CVaR}=\underset{\eta,s_\omega}{\mathrm{Max.}}\ \eta-\dfrac{1}{1-\alpha}\sum\limits_{\omega}p(\omega)s_\omega\\ \mathrm{s.t.}\ \eta-\sum\limits_{n}\{\sum\limits_{l}T_l\sum\limits_{k}[\lambda_{n\omega l}(P_{n\omega lk}^{\mathrm{C}}+P_{n\omega lk}^{\mathrm{W}}+P_{n\omega lk}^{\mathrm{E}})\\ \quad -P_{n\omega lk}^{\mathrm{C}}(F_{f,n}^{\mathrm{C}}+F_{e,n}^{\mathrm{C}})-p_{n\omega lk}^{\mathrm{E}}(F_{f,n}^{\mathrm{E}}+F_{e,n}^{\mathrm{E}})]\\ \quad -K^{\mathrm{C}}C_n^{\mathrm{C}}-K^{\mathrm{W}}C_n^{\mathrm{W}}\}\le s_\omega\\ \quad s_\omega\ge 0\end{cases} \tag{5}$$

Where η is the risk value of annual profit for power generation investment and expansion planning at the confidence level α ; s_ω is the difference between the scenario profit $(1-\alpha)\%$ below VaR and VaR.

2) Constraint conditions

a) Investment budget constraint.

$$\sum_{n}\left(K^{\mathrm{C}}C_n^{\mathrm{C}}+K^{\mathrm{W}}C_n^{\mathrm{W}}\right)\le K^{\max} \tag{6}$$

Where $K^{\max}$ is the available investment budget for the power generation company.

b) Unit segment quotation constraint. including new coal-fired power generation units and existing units of the power generation company.

$$O_{n\omega lk}^{\mathrm{C}}\ge O_{n\omega l(k-1)}^{\mathrm{C}}\ge 0\ \forall n,\forall\omega,\forall l,\forall k\ge 2 \tag{7}$$

$$O_{n\omega lk}^{\mathrm{E}}\ge O_{n\omega l(k-1)}^{\mathrm{E}}\ge 0\ \forall n,\forall\omega,\forall l,\forall k\ge 2 \tag{8}$$

In the formula, $O_{n\omega lk}^{\mathrm{C}}$ and $O_{n\omega lk}^{\mathrm{E}}$ represent the bids for the traditional power supply to be built at the node n and the existing unit in the scenario w and operating state l in the capacity segment k.

3.3 Lower-level model

The trading volume and price that determine the revenue of the power generation company are determined by the power market clearing process managed by PX. Therefore, this article simulates the trading process of the power market through the lower-level model to assist power generation companies in making investment decisions. In the lower-level model, PX determines the nodal marginal electricity price, the output of all generating units in each capacity segment, and the load size of each node in the day-ahead electricity market clearing under the centralized bidding trading mode for various operating states in each scenario.

1) Objective Function

The decision-making entity PX in the lower-level model collects the bidding information of all generating units and loads in the system and aims to maximize social welfare in the market clearing, as shown in Equation (11):

$$\text{Max.} \sum_{n}[\sum_{h} O^{\mathrm{D}}_{nlh} P^{\mathrm{D}}_{nlh} - \sum_{k}(O^{\mathrm{C}}_{n\omega lk} P^{\mathrm{C}}_{n\omega lk} + O^{\mathrm{W}}_{n\omega lk} P^{\mathrm{W}}_{n\omega lk} + O^{\mathrm{E}}_{n\omega lk} P^{\mathrm{E}}_{n\omega lk} + O^{\mathrm{R}}_{n\omega lk} P^{\mathrm{R}}_{n\omega lk})] \quad \forall \omega, \forall l \tag{9}$$

In the formula, the subscript h represents the capacity segment of the segmented pricing for power users; O^{D}_{nlh} and P^{D}_{nlh} represent the price and load size of the capacity segment *h* of the load at the node *n* in the operating state *l*; represents the price of the capacity segment *k* of the wind farm at the node *n* in the scenario *w* and operating state *l*; $O^{\mathrm{W}}_{n\omega lk}$ and $P^{\mathrm{R}}_{n\omega lk}$ represent the price and active power output of the opponent's power generation unit at the node *n* in the scenario *w* and operating state *l* at power segment *k*.

2) *Constraints*

The constraints include node power balance constraints, unit output constraints, load constraints, transmission capacity constraints, and voltage phase angle constraints, etc. For details, please refer to reference [10].

4 Case Study and Analysis

The model's effectiveness in this article is validated using the basic data from a provincial power grid. The maximum load of the power grid is 25950MW, the installed capacity of conventional units is 31929MW, and the installed capacity of new renewable energy is 9049MW. The basic data such as unit coal consumption and power grid structure are known. The research focuses on a significant power generation company with 6,070 MW installed capacity for conventional units and 563 MW for new renewable energy. Other units are considered as competing power generation companies, and their mixed strategy space are shown in Table 3, Appendix B. The user side provide market quotations based on historical price information. The parameters of the selected conventional units and new renewable energy generation for the power generation company are shown in Table 5. The solution method used aligns with the approach outlined in reference [10].

Table 1 Data for the candidate conventional and renewable generators

Unit Type	**Optional Capacity/MW**	**Unit Capacity Investment Equivalent Annual Value/$•(MW)-1**	**Fuel Cost/ $•(MWh)-1**
Conventional Power	100,200	35000	54.19
Conventional Power	300,350	35000	48.02
Conventional Power	600,660	35000	44.28
New renewable energy	10,20,30,40,50	75000	---

Without considering CVaR (β=0) and adopting the model in this article (β=1), the results of power investment expansion planning are shown in Table 6. From Table 6, it can be seen that the conventional power investment decision is 300MW; the factors are that although high-capacity units have lower fuel costs, they are limited by the power market space of the provincial grid, so the conventional power source, a 300MW unit with moderate capacity and lower generation costs is employed. Compared with the results when β=0, the total capacity of power investment is smaller when β=1, especially the renewable energy generation capacity with low reliability capacity has a significant decrease. This leads to a decrease in expected annual profit and an increase in conditional risk value, signifying a decrease in the overall risk level. This indicates that the risk aversion level of power generation companies plays a role in influencing the results of their power investment expansion planning. The model in this article provides decision support for power generation companies in China's electricity market-oriented environment, allowing them to carry out power investment expansion planning based on their own risk preferences.

An analysis was conducted, when selecting β=1, to determine whether to consider the impact of coal-fired capacity electricity price on the results of power investment expansion planning, as shown in Table X. The table indicates that factoring in the coal-fired capacity electricity price enhances the profitability of investments in coal-fired power generation, thereby increasing the motivation for investing in coal-fired power generation. Power generation companies tend to invest in larger coal-fired units, suggesting that implementing a coal-fired capacity electricity price mechanism is beneficial to increasing the capacity of the power system and ensure a reliable power supply.

Table 2 Generation investment expansion planning results in the provincial power grid

β	**Renewable Energy Investment Decision/MW**	**Conventional Power Investment Decision/MW**	**Total Power Investment Capacity/MW**	**Investment Equivalent Annual Value/ M$**	**Expected Annual Profit/ M$**	**CVaR/ M$**
0	70	300	370	15.75	494.26	291.49
1	50	300	350	14.25	493.32	292.33

Table 3 Analysis of the impact of coal-fired capacity and electricity price on power investment expansion planning results (β = 1)

Without considering coal-fired capacity and electricity price			**Considering coal-fired capacity and electricity price**		
Renewable Energy Investment	Conventional Power Investment	Total Power Investment	Renewable Energy Investment	Conventional Power Investment	Total Power Investment

Decision/ MW	Decision/ MW	Capacity/ MW	Decision/ MW	Decision/ MW	Capacity/ MW
50	300	350	50	350	400

5 Conclusion

In order to align with the evolving trends of the power industry, characterized by the marketization of the power system and the transformation of coal-fired power generation to supportive and adjustable sources, this article establishes a two-layer model for power investment expansion planning considering coal-fired capacity and electricity price in a market-oriented environment, and conducts case simulation analysis. The main conclusions are as follows.

1) A model for expected annual operating income of coal-fired power enterprises is established under the dual pricing system, in which coal-fired power generation canot only obtain electricity income but also capacity income, motivating the transformation of coal-fired power generation.

2) In the power investment expansion planning model proposed in this article, the objective function for investment decision-making is constructed based on both investment income and risk. This approach takes into account the impact of uncertainties such as market operation on power investment expansion planning decisions.

3) In response to the uncertainty of future market-oriented environment, the CVaR measure is used to assess the investment risk caused by changes in factors such as competitor's investment and bidding strategies, and the utility of investment income and risk in the decision function is harmonized through a risk aversion coefficient. The research method of this article provides a theoretical and methodological support for the investment decision-making of power generation companies in the future.

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