Electricity price decision-making method of electricity selling company based on multi-objective optimization and Min-Max Regret Theory

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Abstract. In the electricity selling market, the long-term goal of electricity selling companies is to maximize the revenue, but the strategies adopted in the short term have been different. Some electricity selling companies pay more attention to the revenue, while some electricity selling companies tend to reduce the sales price so as to agent more electricity. Based on the mixed integer programming (MIP) formula, this paper proposes a multi-objective mathematical programming (MMP) model, which considers maximizing the retailer's profit and minimizing the sales price to customers. The Pareto optimal solution is generated by the normal boundary intersection method. At the same time, considering the risk of electricity selling market faced by electricity selling companies, we use the theory of maximum and minimum regret to evaluate the risk of electricity selling companies in the decision-making of volume and price, and find the optimal solution of risk. Finally, through case analysis, it is proved that through reasonable electricity quantity and price decision, the seller can find the optimal decision to balance the two risks of market price fluctuation and user load fluctuation.

1. Introduction

In March 2015, China put forward the electric power system reform opinion of "opening both ends and supervising the middle". The focus of this electric power reform is to orderly open the power distribution business for social capital. The deregulation of the electricity market refers to the introduction of competition in the electricity market, giving users the right to choose freely. When the power selling side is liberalized, each power selling company, as an independent power selling entity, will participate in the market. It will not only face peer competition pressure, but also face uncertain spot price and customer demand. If the sales price provided by the power selling company is not competitive enough, customers may choose other suppliers. After determining the future market participation and selecting the sales price, the power selling company must determine its strategy in each market [1].

In the previous research, the goal of power selling companies is to maximize profits. It is assumed that within the framework of electricity market, competitors compete for price in order to obtain as many customers as possible. The reasonable selection standard of the electricity selling company is to choose a solution that can reach the minimum selling price on the premise of satisfying the constraints. Therefore, this paper proposes a multi-objective mathematical programming (MMP) model, which is
composed of profit and selling price of electricity selling company, including spot market and forward contract. At the same time, this paper also considers the financial risk faced by the power selling company, which is related to the sales price provided by the power selling company to different customer groups. In this paper, based on the mixed integer programming (MIP) formula, the Pareto frontier solution set for multi-objective decision-making of electricity selling company is found. Finally, the Max-Min regret theory is employed to evaluate the risk of electricity selling companies in the pricing decision-making and find the optimal risk solution.

2. Literature Reviewed
In view of the transaction strategy of the electricity market, several papers have discussed and put forward some different methods. In [2], the optimal price calculation under different price strategies is discussed, and the influence of customer demand elasticity is considered. Reference [3] provides a method for the seller to determine the optimal selling price and purchasing strategy, and establishes the customer behavior function in this paper. References [4,5] all put forward a stochastic programming method to determine the optimal price and electricity strategy of the electricity selling company under the conditions of purchasing electricity from the spot market and the forward contract market respectively. In reference [6], the idea proposed in [4] is developed, in which the response of customers to retailer price and the competition between competitors are explicitly considered through the two-level programming model.

In the power system literature, multi-objective optimization technology is widely used in many problems. Various multi-objective optimization methods are used, such as weighted sum method, objective realization method [7], ε-constraint method [8] and game theory [9]. In this paper, the normal boundary intersection (NBI) method is applied to the multi-objective optimization problem. Compared with the most commonly used multi-objective method, it has advantages [10]. In addition to the above problems, some work of NBI method has been reported so far. In reference [11], the NBI method of Pareto surface for multi-objective optimization of power system is proposed. Reference [12] uses NBI method to generate Pareto optimal set to make optimal bidding strategy. In the process of participating in the electricity market, electricity selling companies are faced with many risks, such as market uncertainty caused by spot market price and user load [13].

The risk assessment in the power market is generally completed through the measurement and assessment of various risk indicators. Modern portfolio theory (MPT) is realized by mean variance. In addition, VaR and CVaR are widely used at the same time. Reference [14,15] is a case study of VaR and CVaR methods applied to power market at home and abroad. Reference [16] has developed a multi-level stochastic optimization method, which considers the uncertainty of electricity price and load, and allows to specify conditional var requirements to optimize the hedging in each intermediate stage of the planning period. In this paper, the Min-Max regret method group is employed as the risk assessment method of the electricity selling company. The Min-Max regret method is widely used in Econometrics [17,18]. In the power system literature, it is applied to reduce the risk of intentional transmission interruption and control strategy bidding in network expansion planning [20].

3. Contributions of the Paper
Although the long-term goal is still to maximize the total revenue and minimize the risk, the strategies adopted in the short term have been different. Some power selling companies pay more attention to the net revenue, while some power selling companies need to agent more electricity for the long-term development of differentiated services, which requires the study of power selling companies to obtain an optimal revenue Benefit electricity match strategy. In order to meet the needs of customers, the power selling company needs to sign bilateral contracts with the power generation company and make a power purchase plan. The insufficient electricity needs to be traded in the spot market. However, many of its customers have certain uncertainty about the demand for electricity, so its power selling income is not always sensitive to the change of electricity price. Therefore, the purchase and sale of electricity companies are faced with two aspects: price risk of two markets and uncertainty of power load demand.
It is of great significance for the risk management of a power selling company how to make the optimal power purchasing strategy based on the two objectives of electricity quantity and revenue, and how to carry out effective risk assessment to maximize the total revenue and minimize the risk. The main contributions of this paper can be summarized as follows:

1. A new stochastic medium-term multi-objective framework is proposed, which includes profit expectation and sales price. The framework is implemented with MMP method based on NBI method.

2. Scene tree and Monte Carlo simulation are used to generate random scenes. In order to quantify the risk, the stochastic multi-objective problem with uncertainties is transformed into the corresponding deterministic problem. According to the Min-Max regret method, the optimal solution of risk aversion for electricity selling company is obtained from the Pareto solution set generated by NBI method.

4. Problem Description and Formulation

The main idea of this paper is to deduce the three decision-making objectives of the power selling company, i.e. medium and long-term contract purchase, spot market purchase and sales price. In addition, the planning scope includes multiple time periods based on decision-making time. Because some decisions are based on the hour level, this paper adopts the hour framework.

4.1. Uncertainty characterization

In this paper, the price and load forecasting errors are used to model the uncertainty of the spot market price and load corresponding to each planning period (1h). Scenario tree is a group of nodes and branches used in the uncertainty decision model. Nodes represent decision points, while branches are different realizations of random variables. The first node is called root node. In this paper, the branch leaving the root node is based on the existing historical data, using Monte Carlo simulation of random variables in different scenes, each scene has a relevant probability of occurrence. In order to make the problem easy to deal with, the size of scene tree can be reduced easily. Scene tree pruning refers to finding a new tree composed of a subset of scenes belonging to the original tree according to a specific probability distance, which is close to the original tree. Scene simplification technology provides an effective method to select the representative subsets of scenes and give them corresponding probability, covering most scene implementations, possible and extreme.

4.2. Supply of Energy Resources for the Retailer

4.2.1. Forward Contract: the power selling company can obtain the agreed amount of power or electric energy on time according to the fixed price agreed in the contract. Once the price and quantity of such contracts are signed, the power purchase business is carried out prior to the spot market, which can be used to avoid the risk of spot price volatility and volatility. A power selling company can usually sign a variety of medium and long-term contracts to meet the long-term power demand of its customers. As mentioned in [4], the medium and long-term market price should rise with the change of transaction volume, which reflects the law of general market transaction. Since the medium and long-term contract volume is the decision variable of the power selling company, the power selling company needs to determine the purchase volume of each medium and long-term contract. The cost of energy purchased by the power selling company through the medium and long-term contract is as follows:

$$C_F(t) = \sum_{f=1}^{F} p_F(f) \cdot P_F(f,t) \quad \forall t \in T$$  \hspace{1cm} (1)

$$0 \leq P_F(f,t) \leq \bar{P}_F(f,t) \quad \forall t \in T; \forall f \in F$$  \hspace{1cm} (2)

$$|P_F(f,t-1) - P_F(f,t)| \leq P_{Fc} \quad \forall t \in T; \forall f \in F$$  \hspace{1cm} (3)
Equation (1) shows the cost of procurement based on medium- and long-term contracts. This cost depends on the power and price entered into in each contract. The non-negativity and upper bound of the purchased power in each block are declared by constraint (2). Constraint (3) indicates the climbing constraint of the unit when the power plant signs the power purchase contract.

4.2.2. Spot Market: It is assumed that the electricity selling company is the price receiver of the spot market, and it will buy the electricity in the spot market at the spot price according to its own demand. Therefore, the transaction costs of electricity selling companies in the spot market are as follows:

\[ C_p(t, w) = p_p(t, s) \cdot E_p(t, w) \quad \forall t \in T; \forall w \in W \]  \hspace{1cm} (4)

4.3. Demand Supplied by Electricity Selling Companies

Generally speaking, there are many kinds of loads in the electricity market. In this paper, only three kinds of users are considered: residential, commercial and industrial users, so the number of user categories \( N_I = 3 \). According to the type of electricity sales contract, all kinds of users are divided into different user groups. The actual electricity purchased by the user group from the electricity sales company is a function of the electricity sales price. The function relationship can be expressed by the price quota curve, which reflects the demand price elasticity of each user group. The amount of electricity that customers tend to buy at a given price is based on a price quota curve. The precise derivation of price quota curve is a complex econometric problem beyond the scope of this paper.

\[ E_R(e, t, w) = E_R(i, e, t, w) \cdot \nu(i, e) \quad \forall e \in NI; \forall i \in I; \forall t \in T; \forall w \in W \]  \hspace{1cm} (5)

\[ \bar{p}_R(e, i - 1) \cdot \nu(e, i) \leq p_R(e, i) \leq \bar{p}_R(e, i) \cdot \nu(e, i) \quad \forall e \in NI; \forall i \in I \]  \hspace{1cm} (6)

\[ \sum_{i=1}^{I} \nu(e, i) = 1 \quad \forall i \in I \]  \hspace{1cm} (7)

\[ R(t, w) = \sum_{e=1}^{N_I} E_R(e, t, w) \cdot p_R(i, e) \quad \forall e \in NI; \forall i \in I; \forall t \in T; \forall w \in W \]  \hspace{1cm} (8)

Equation (5) and (7) shows that the purchasing power of the customers \( E_R(e, t, w) \) represented by the electricity selling company is a function of the price \( p_R(e, i) \), and the section of the price quota curve is determined by zero one variable \( \nu(e, i) \). Equation (8) is the income of the sale of electricity.

4.4. Energy Balance

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\[ \sum_{e=1}^{N_I} E_R(t, w) = E_p(t, w) + \varepsilon(t, w) + \sum_{i=1}^{F} P_f(f, t) \quad \forall t \in T; \forall w \in W \]  \hspace{1cm} (9)
Equation (10) - (11) refers to the deviation assessment quantity of the electricity selling company. Here we only consider the negative deviation assessment

\[ C_d(t, w) = \left| e(t, w) \right| \cdot p_d \quad \forall t \in T; \forall w \in W \]  

(10)

\[ e(t, w) \leq 0 \]  

(11)

5. Proposed Multi-Objective Problem

5.1. Proposed Optimization Formulation

In the medium-term planning, the multi-objective framework considers two objective functions: one is to maximize the retailer's profit, the other is to minimize the sales price, so as to achieve the maximum possible number of customers. Equations (12) and (13) represent the first and second objective functions, respectively.

1) Maximize \( f_1 \): profit

\[ \sum_{w=1}^{W} \pi(w) \cdot \sum_{t=1}^{T} (R(t, w) - C_d(t, w) - C_p(t, w) - C_f(t)) \]  

(12)

2) Minimize \( f_2 \): the sum of sales prices

\[ \sum_{\epsilon=1}^{NI} \sum_{i=1}^{l} p_{R}(\epsilon, i) \]  

(13)

The expected profit of the electricity selling company is equal to the expected revenue from the sale of electricity to the end user minus the expected purchase cost of the spot market and forward contracts, such as (11). The sum of the sales prices provided by the retailer to each group of customers is shown in (13). In addition, as mentioned above, the MMP issues raised are subject to a number of constraints.

5.2. Method of NBI

In mathematical notation, the general form of a multi-objective optimization problem can be loosely expressed as follow:

\[ \text{Min/Max} \quad F(x) = \{ f_1(x), f_2(x), ..., f_n(x) \} \]

subject to \( g(x) \leq 0, \quad h(x) = 0, \quad x \in C \)  

(14)

Since there is no \( x^* \), each \( \hat{f}_i \) is usually minimized at the same time, so the useful concept of optimality in multi-objective framework is Pareto optimality. The calculation method of general nonlinear multi criteria optimization problem can only guarantee the local Pareto optimality of the obtained solution at best. Local Pareto optimality is defined as: a point \( x^* \in C \) is said to be Pareto optimal or a locally efficient point for Multi-objective optimization problem (MOP) if and only if there exists an open neighborhood of \( x^* \), \( B(x^*) \), such that there does not exist \( x \in B(x^*) \cap C \) satisfying \( F(x) < F(x^*) \).

The shadow minimum or utopia point, \( F^- \), is defined as the vector containing the individual global minima, \( f^-_i \), of the objectives,

\[ F^- = \left[ f^-_1, f^-_2, ..., f^-_n \right] \]  

(15)
We assume that there is a minimum for each of our targets here. Therefore, shadow minimization is possible only when a single $x$ minimizes all objective functions. However, in practice, the best way we can hope for is to approach the shadow minimum and ensure a satisfactory trade-off between multiple objectives.

Convex hull of individual minima (CHIM). Let $x_i$ be the respective global minimum of the $f_i(x)$, over $x \in X$. Let $F^*_i = F(x_i)$. Let $\Phi$ be the $n \times n$ matrix whose $i$th column is $F^*_i - F^*$, sometimes called payoff matrix. Then the set of points in $R^n$ that are convex combinations of $F^*_1 - F^*$, is referred to as the CHIM.

The attainable set of target vectors is represented by $F$, and the space containing $F$ is usually called target space. We use $\partial F$ to express the boundary of $F$. All Pareto's best set is usually represented by $P$. Then, it should be assumed that the objective function is defined and the shadow minimum moves to the origin at least so that all objective functions are nonnegative, that $F(x)$ is redefined as:

$$F(x) - F^* \rightarrow F(x)$$ (16)

We observe that in Fig1, which shows the set $F$ in the objective space, the point A is $F_1^*$, B is $F_2^*$, O is the shadow minimum (and the origin), the broken line segment AB is the CHIM, while the arc ACB is the set of all Pareto minima in the objective space, or the trade-off curve.

![Figure 1. Map of Pareto schematic.](image)

Normal boundary intersection (NBI) is a method to find the best of Pareto in $\partial F$. The intersection of the boundary $F$ and the normal to the origin from any point in the CHIM is a point on the $F$ part that contains the valid points. This is also Pareto's best. Now let's use algebra to show how to find any such boundary point by solving an optimization problem. Given the center of gravity coordinate $\hat{\beta}, \beta \Phi$ represents a point in the CHIM. Let $\hat{n}$ denote the unit normal to the CHIM simplex pointing toward the origin, then $\beta \Phi + \hat{n}$, represents the set points on that normal. The intersection of the normal direction and the boundary of F closest to the origin is the global solution of the following sub problems;

$$\text{Max} t$$

subject to $\quad \Phi \beta + \hat{n} = F(x)$

$g(x) \leq 0, \quad h(x) = 0, \quad x \in C$

(17)
Vector constraints \( \Phi \beta + \tilde{t} = F(x) \) ensure that point \( x \) is actually mapped from \( F \) to a normal point, while the remaining constraints ensure that \( x \) is feasible relative to the original problem. If the origin is not moved to \( F^* \), the first set of constraints should be

\[
\Phi \beta + \tilde{t} = F(x) - F^*
\]

5.3. Min-Max Regret Stochastic Optimization Model

As mentioned above, it is inevitable for the power selling company to face the uncertainty in the power selling market, and the decision-making of the power selling company under different scenarios will bring different risks. The biggest challenge is that decision makers don't know which scenario to choose for future decisions. If the future realization of uncertainty is consistent with the decision-maker's choice, the decision they make is the best solution. Otherwise, the decision they make is not the optimal solution, and the decision makers will regret it. In order to consider the risk state in the decision-making of the electricity selling company, this paper uses the minimum maximum regret stochastic optimization method to help the electricity selling company understand the risk situation caused by the uncertainty under different decisions and find the optimal solution of the risk in the electricity price decision. In this method, we generate a given number of scenarios to describe the nature of uncertainty, and the model expects to find the optimal solution from a scenario, which can minimize the worst-case regret (or maximum regret) in all possible scenarios.

We think that the difference between the decision and the optimal solution is the regret value of the decision maker. In this paper, regret value can be defined as

\[
\text{Regret}_{i,j} = f_{max}(x_i) - f_j(x_j)
\]

\[
f_j(x_j) = U_j(x_j) - \overline{U}(x_j)
\]

The purpose of the min-max regret method is to find a decision that can minimize the sum of the worst-case regret values, as follows

\[
\min_{i,j} \text{Max}_{Regret_{i,j}}
\]

It is worth noting that for a given number of scenarios, we can enumerate all scenarios and calculate the regret between any two scenarios. Then, we can get a regret matrix, from which we can calculate the maximum regret of each column corresponding to the optimal solution in a particular case. Finally, the optimal solution is chosen as the choice with the least maximum regret.

6. Case Study

Based on the transaction data of some power markets in Jiangsu Province, this paper takes one week as an example to implement the model.

A stepwise price-quota curve consisting of 100 steps is used similar to [4] to simulate the relationship between the sales price provided by retailers and customer demand. In addition, three types of customers are considered, i.e. residential, commercial and industrial customers. Their demands are divided into three load levels, as shown in Fig2. There are 50 kinds of contracts in the medium and long-term market, and the distribution is shown in Fig3. 1000 scenarios are generated by Monte Carlo simulation to realize the proposed stochastic framework. Scenario reduction technology is applied to reduce the number of generated scenarios. At last, 50 scenarios are reserved for calculation.
In order to solve the multi-objective problem, firstly, the pay-off matrix $\Phi$ is obtained, and the maximum value of revenue and agent power are calculated respectively, as shown in Table 1. Then 20 Pareto sets are generated by NBI method. The Pareto set is shown in Fig 4, which shows the relationship between retailer's profit and agent's electricity in Pareto.

### Table 1. Information of pay-off matrix.

| Objection function | Profit | Sum of Sales Price | Residential Sales Price | Commercial Sales Price | Industrial Sales Price |
|--------------------|--------|--------------------|-------------------------|------------------------|------------------------|
| Profit(¥) Max $f_1$ | 755440 | 1190.5             | 390.8                   | 403.3                  | 396.4                  |
| Sum of Sales Price (¥) Min $f_2$ | -2583280 | 1080               | 360                     | 360                    | 360                    |

**Figure 2.** Price-quota curve of three types customer.

**Figure 3.** Forward Contract Price.
Figure 4. Pareto Curve of Objection function.

As shown in Fig4, the two goals are conflicting, i.e. the increase of each goal leads to the decrease of the other, and vice versa. The electricity selling company’s maximum profit in a week is 755440, but the agent's power is the lowest. In this state, retailers supply 50.2% of residential customers, 15.4% of industrial customers and 22.4% of commercial customers. As mentioned before, retailers can choose the cost strategy of maximizing their market share, and one of the most important tools to achieve this goal is to reduce the energy sales price. The lowest electricity selling price of the electricity selling company can obtain the whole market share, but reducing the energy selling price reduces the income, the cost of purchasing more electricity in the forward contract market and the spot market is higher, and the electricity selling company is in a state of loss.

Considering the risk factors, we use the minimax regret planning method to find the optimal risk solution. First, we generate regret matrix. We take the average value of every 10% scenario in the electricity market model as a risk scenario. Because we want to minimize the regret value of the worst scenario, we only extract the last 10% scenario with the largest risk loss and the first 10% scenario with the largest risk return. In Pareto solution set, several points with little profit difference are selected as alternative decision-making schemes. Regret value is shown in Table 2.

| Decision number | Profit (¥) | Risk loss regret | Risk benefit regret |
|-----------------|------------|------------------|---------------------|
| 1               | 292652.4   | 25443.7          | 0                   |
| 2               | 435654.8   | 16849.5          | 6380.4              |
| 3               | 556024.5   | 5510.5           | 10139.1             |
| 4               | 649931.0   | 0                | 13205.0             |
| 5               | 712013.7   | 4327.7           | 19500.3             |
| 6               | 746323.1   | 17742.1          | 21329.8             |
| 7               | 755440.0   | 24927.9          | 26050.8             |

As shown in the table, the risk of 4 in Pareto concentration decision is the least. In the electricity sale market, the risk degree of spot market price in pursuit of profit maximization is deepened, and the risk
degree of customers in pursuit of agent electricity maximization is deepened. This shows that the electricity sale company can find the optimal decision to balance the two risks through reasonable electricity price decision.

7. Conclusion
In this paper, a decision-making method of electricity selling companies is proposed. Under the framework of stochastic multi-objective MIP, retailers can avoid market risks and achieve business objectives by setting reasonable electricity selling prices, medium and long-term market and spot market purchase plans. In this method, the competition objective function includes profit and sales price as a multi-objective optimization problem. The Pareto set is generated by NBI method, and the optimal solution of risk decision is selected by minimax regret decision. According to the simulation results and the discussion results, the stochastic multi-objective framework proposed in this paper has two main advantages: first, by proposing a flexible framework, the two conflicting objectives of the problem, namely profit maximization and sales price minimization, are compromised. Second, we can find the market decision-making of the electricity selling company to balance the market price risk and the user load risk.

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