Hindawi Publishing Corporation
Mathematical Problems in Engineering
Volume 2015, Article ID 493845, 11 pages
http://dx.doi.org/10.1155/2015/493845

Research Article

The Power Purchase Optimization Model in China considering the Renewable Energy Risks under Different Risk Preferences

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Received 8 January 2015; Revised 7 April 2015; Accepted 22 April 2015

Academic Editor: Zoran Gajic

To achieve the strategic target of energy conservation and emission reduction, China is vigorously developing its large-scale and distributed renewable energy power generation industry, dominated by wind power and photovoltaic power generation. In the new situation of renewable energy power interconnection, the grid company in China must fully consider the risks caused by renewable energy when making power purchase optimization decisions. This paper sets up a power purchasing model considering the risks of the renewable energy power interconnection and testifies to the effectiveness of the model through a case study. On this basis, this paper puts forward several reasonable suggestions to help the grid company make power purchase decisions under different risk preferences.

1. Introduction

In China's Twelfth Five-Year Plan, along with large-scale wind power and photovoltaic power generation interconnection, the situation of the power generation structure in China is experiencing significant changes. Large amounts of renewable energy power interconnection bring new risks to power purchasing of the grid company. Therefore, it is essential to consider fully the risks of the renewable energy power interconnection and set up a power purchase optimization model for the grid company against this background.

Many scholars have studied the optimization method of purchasing power. Reference [1] pointed out that, with the reforms of the power market, power industry will enter the retail competition phase from the monopoly phase. In the early stage, studies on the optimization of power purchasing did not fully consider the risks faced by the power purchasers [2]. With the reforms of the power market, the grid company should face the risks of power purchase. Research on the optimization of power purchasing is always conducted on the basis that the electricity prices obey normal distribution [3–5]; actually, however, the electricity prices, the power purchasing costs, and the power quantity are all random variables, and the grid company should consider them fully. References [6, 7] described the risks via the variances in the power purchasing costs. However, their premise is that the prices obey normal distribution.

The theory basis of power purchase optimization mainly includes risk measurements and the minimization of the power purchasing costs. Among them, the risk measurements theory mainly considers the risks of electricity price fluctuations and the uncertainty of the power quantity demand. The tools used to assess the power purchasing risks are mainly the value-at-risk indicators and the conditional value-at-risk indicators. As a risk measurement, VaR is currently widely used to assess the risks in the market. Reference [8] assessed the risks of power purchasing via the VaR indicators. Reference [9] considered both the probability and the extent of the expected risks in the future and confirmed the scale and the probability of the grid company's loss. The research revealed that the application of the VaR to portfolio optimization has some disadvantages. Reference [10] confirmed the power purchase allocation considering the adjustment of the ISO (independent system operator) market via mathematical analysis and simulated the power quantities of different power markets according to different demands.

The research results above provide feasible ways to solve the power purchase optimization problem under the condition of traditional risks. However, little of the existing research considers the risks of the renewable energy power interconnection, including wind power and photovoltaic power generation. Against this background, fully considering the risks that renewable energy power generation involves, we build up a linear programme model for electricity purchase optimization based on different risk preferences of the grid company. In accordance with the model and the results of the case study, we provide some practical methods and suggestions to the grid company for electricity purchasing.

2. The Operation Mode of the Power Market

According to the development of the power market, its operation modes can be categorized into four types: the vertical integration mode, the single-buyer mode, the wholesale competition mode, and the retail competition mode. China is currently in the second stage and will enter the third stage with the reforms of the power market. In the third stage, namely, the wholesale competition mode, the power market will include the contract market and the spot market. There will exist many power distributors and some large power users. The power distributors purchase the power from the independent power producers and sell the power to the common power users. The large power users purchase the power from the independent power producer directly.

3. The Analysis of the Renewable Energy Power Interconnection and Transaction Risks

With a large amount of renewable energy power interconnection, the power purchase risks of the grid company mainly consist of five aspects in the wholesale competition mode.

3.1. The Risks of Quantity Fluctuations in the Renewable Energy Power Generation. The first kind of risks for the grid company's purchasing power is the risk of quantity fluctuations in the renewable energy power generation, represented as γ_1. The output of wind power and photovoltaic power generation is volatile and difficult to predict accurately, and the fluctuations in the quantity of renewable energy power generation can affect the market profit of the grid company. The specific value can be calculated with the probability theory method.

3.2. The Risk of Fluctuations in the Pool Purchase Price. When one or several pool purchase prices of the power generation (including thermal power, wind power, hydropower, and photovoltaic power generation) change, the risk income and the fluctuation probability of the pool purchase price will affect the final profit of the grid company. Therefore, the second kind of risks is the risk of fluctuations in the pool purchase price, represented as γ_2. The specific value needs to be calculated according to the probability distribution of the pool purchase price.

3.3. The Risk of Fluctuations in the Sales Price and the Distribution Price. The sales price and the distribution price are important factors that affect the income of the grid company directly. When the sales price and the distribution price become volatile, the power selling income is bound to be affected. When the sales price of small users and large users fluctuates, the sales income of the grid company will change. Therefore, the third kind of risks is the risk of fluctuation in the sales price and the distribution price, represented as γ_3. The specific value needs to be calculated according to the probability distribution of the sales price and the distribution price.

3.4. The Risk of Quantity Fluctuations in the Power Sales. The accuracy of the load forecasting has a direct influence on the income of the grid company. The fourth kind of risks is the risk of fluctuations in the quantity of power sales, represented as γ_4. The specific value can be determined according to the actual situation.

3.5. The Risk of the Direct-Purchase Quantity of Large Users. The fifth kind of risks is the risk of the direct-purchase quantity of large users, represented as γ_5. The proportion of the direct-purchase quantity of large users will affect the grid company's market share and profitability. The specific value can be calculated according to the proportion of purchasing power of big users.

4. The Power Purchase Optimization Model of the Grid Company

In the wholesale competition mode, in which the power transmission and distribution are not separated, without considering the costs and profit which have nothing to do with the power trade, we can define the profit of the grid company as follows:

$$\begin{aligned}\Pi(Q) = (1-t_3)\Big\{&\Big[1-\frac{t_1}{1+t_1}\times(1+t_2)\Big]\\ &\cdot\{U[F,(1-k)Q]+U(f,kQ)\}-\Big[1-\frac{t_1}{1+t_1}\Big]\\ &\cdot C(p,Q)-C_0\Big\},\end{aligned} \tag{1}$$

where $\Pi(Q)$ represents the profit achieved by providing power services for the users; Q represents the total power demand; t_1 represents the value-added tax rate; t_2 represents the additional tax rate of the urban construction and education; t_3 represents the income tax rate; k represents the direct-purchase power proportion of the large users; F represents the sales price for the middle and small users; C_0 represents the fixed costs; p represents the power purchase price; f represents the transmission and distribution price which is charged to large users by the grid company; U represents the income function of the grid company; C represents the cost function of the grid company. $[1-t_1/(1+t_1)\times(1+t_2)]U[F,(1-k)Q]$ represents the sales income of the grid company by providing power to the middle and small users; $(1 - t_1/(1 + t_1))C[p, Q]$ represents the power purchase costs; $[1 - t_1/(1 + t_1) \times (1 + t_2)]U[f, kQ]$ represents the sales income by providing power to the large users.

Under certain power purchasing conditions, the profit of the grid company is mainly related to the power purchase channels, the power purchase prices, the power sales structure, the sales prices, the proportion of the direct-purchase power of the large users, and the transmission and distribution prices. However, the wholesale competition mode is different from the retail competition mode. In the wholesale competition mode, the government and the power supervision control the terminal sales price of residents and the small and medium industrial and commercial users who cannot carry out direct power purchases. The grid company cannot arbitrarily change the sales price. Therefore, trying to reduce the cost of purchasing power becomes the main strategy for the grid company to increase its profit.

Common optimization algorithms can obtain the optimal combination of the power purchase by solving the linear programming problem of maximizing the economic profit under the risk constraints or minimizing the risks under the constraints of maximizing the expected profit.

This paper mainly analyses the best power purchase portfolio strategy of the grid company in the wholesale competition mode. It also analyses some cases and verifies the applicability of the optimization methods. By comparing the profit of each strategy, we can seek the best combination of the power purchase.

Assume that $x^T = [x_1, x_2, \ldots, x_n] \in X$ is the power purchase portfolio ratio vector. X is a feasible set of the power purchase combination. In addition, x_i represents the power purchase proportion in the market i of the distribution company, and it meets the following equation constraint:

$$\begin{gathered} x_i \geq 0, \\ \sum_{i=1}^{n} x_i = 1, \\ x_i Q \leq Q_i. \end{gathered} \tag{2}$$

In formula (2), Q_i represents the maximal amount of the power purchase of the grid company in market i.

Assume that y_i is the power purchase price in market i and $y^T = [y_1, y_2, \ldots, y_n]$ $y_i \geq 0$.

y^T is the combination vector of the power purchase prices. Then, the cost of the power purchase combination is $\sum_{i=1}^{n} x_i y_i$.

In a certain period, the sales price is a fixed price F confirmed by the government for medium and small users. For the direct purchase for large users, the grid company can only charge the net costs of the large users. Assume that the price of the net costs is f and the total power demand is Q. The proportion k $(0 \leq k < 1)$ is the large users' net power quantity to Q. Then, the expected revenue function of the grid company is

$$\begin{aligned} &\max (1 - t_3) \\ &\quad \cdot \left[\frac{1 - t_1 t_2}{1 + t_1} F (1 - k) + \frac{1 - t_1 t_2}{1 + t_1} fk - \frac{1}{1 + t_1} x^T y \right] Q \\ &\quad - (1 - t_3) C_0. \end{aligned} \tag{3}$$

According to the risk theory, risks are usually defined as the product of the adverse events' probability and the possible disaster results.

The risks can be expressed by the following formula:

$$\gamma = \sum_{i=1}^{n} P_i \times I_i, \tag{4}$$

where γ is the scale of the risks; P_i represents the probability of risk event i; I_i is the loss of risk event i; and n is the number of risk events.

The grid company's power purchase price in the contract market is the benchmark price now, which is set by the government. However, the grid company cannot precisely predict the power purchase price of the spot market in advance, so it must purchase part of the power in the contract market first based on the assessment of the risks and then purchase the rest of the power in the spot market. The grid company can only predict the power purchase price of the power market by relying on its own information. According to the predicted values, it can determine the proportions of the power purchase in the contract market and in the spot market. Meanwhile, in the contract market and in the spot market, the distribution company also needs to consider various factors and determine the optimal proportions of intraprovincial and extraprovincial power purchase and the proportions of the power purchase from different intraprovincial power supplies, as shown in Figure 1.

As shown in the figure, the distribution company needs to determine the proportions of the power purchase under the risk situation of power purchase price fluctuations. According to the regulation, the distribution company must follow the full acquisition of wind power and photovoltaic generation. The power purchase prices y_1, y_2, y_3, y_4, and y_5 are determined by long-term contracts in the long-term contract market. They can be considered as fixed values. Meanwhile, the power purchase prices y_6, y_7, y_8, y_9, and y_{10} are variable in the spot market. Assume that the power purchase prices obey the triangular probability distribution and the power purchase optimization problem becomes how to optimize the power purchase proportions under the condition in which the price probability distribution is uncertain.

If the probability density of the random variables X is

$$f(x \mid a, b, c) = \begin{cases} \dfrac{2(x - a)}{(b - a)(c - a)} & a \leq x \leq c \\ \dfrac{2(b - x)}{(b - a)(b - c)} & c < x \leq b, \end{cases} \tag{5}$$

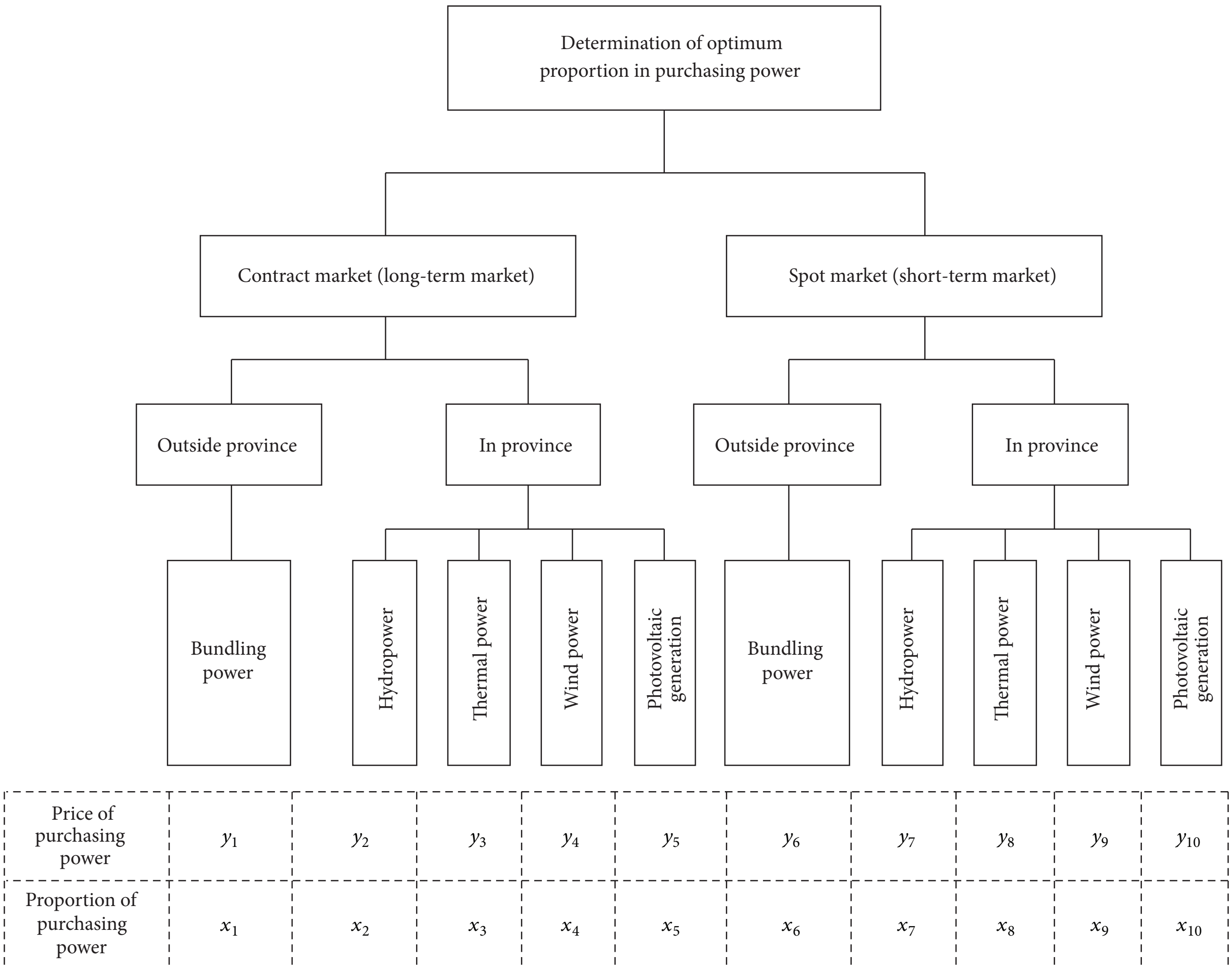

Figure 1: The power purchase optimization problem of the provincial grid company.

X obeys the triangular distribution. The lower limit and the upper limit of X are, respectively, a and b. The mode of X is c.

The probability distribution of the power purchase prices y_6, y_7, y_8, y_9, and y_{10} in the spot market can be expressed as follows:

$$f\left(y_i \mid y_{i\min}, \overline{y_i}, y_{i\max}\right) = \begin{cases} \dfrac{2\left(y_i - y_{i\min}\right)}{\left(\overline{y_i} - y_{i\min}\right)\left(y_{i\max} - y_{i\min}\right)} & y_{i\min} \le y_i \le \overline{y_i} \\ \dfrac{2\left(y_{i\max} - y_i\right)}{\left(y_{i\max} - \overline{y_i}\right)\left(y_{i\max} - y_{i\min}\right)} & \overline{y_i} \le y_i \le y_{i\max}, \end{cases} \quad (6)$$

where y_i represents the power price; $y_{i\min}$ is the minimum value of the power purchase prices; $\overline{y_i}$ is the most probable value of the power purchase price; and $y_{i\max}$ is the maximum value of the power purchase prices.

Based on the assumptions above, the risks of profit fluctuations brought about by the pool purchase price fluctuations are

$$\begin{aligned} \gamma &= x_i Q \times \int_{\overline{y_i}}^{y_{i\max}} \left(y_i - \overline{y_i}\right) f\left(y_i\right) dy_i \\ &= x_i Q \times \frac{\left(y_{i\max} - \overline{y_i}\right)^2}{3\left(y_{i\max} - y_{i\min}\right)}. \end{aligned} \quad (7)$$

In order to protect the interests of the grid company, the government implements a minimum price policy in the short term for the power purchase market:

$$y_i \ge y_{i0}. \quad (8)$$

In formula (8), $i = 6, 7, 8, 9, 10$. y_i is the power purchase price of the short-term market. y_{i0} is the minimum value of the power purchase price, which is set by the government.

To protect the interests of the renewable energy power generation companies and to promote the development of

Table 1: The probability distribution of the power purchase prices.

Type	Value	The extraprovincial market	The intraprovincial market			
			Hydropower	Thermal power	Wind power	Photovoltaic generation
Long-term contract	The most probable value	0.3047	0.22	0.32	0.31	0.31
	The minimal value	0.3047	0.22	0.32	0.31	0.31
	The maximal value	0.3047	0.22	0.32	0.31	0.31
Short-term contract	The most probable value	0.45	0.2443	0.3329	0.3249	0.3249
	The minimal value	0.448	0.2393	0.3279	0.3229	0.3229
	The maximal value	0.452	0.2493	0.3379	0.3269	0.3269

renewable energy power, we carry out full acquisition of renewable energy power:

$$x_4 + x_9 = x_{\text{wind}},$$
$$x_5 + x_{10} = x_{\text{solar}}. \tag{9}$$

In formula (9), $x_{\text{wind}}Q$ is the capacity of wind power. $x_{\text{solar}}Q$ is the capacity of photovoltaic power generation.

In addition, the extraprovincial power purchase must satisfy the physical constraints of the power transmission channel capacity. Assuming that the maximal allowable transmission power capacity is $Q_{\text{out max}}$, it needs to satisfy the following constraint:

$$\left(x_1 + x_6\right) Q \le Q_{\text{out max}}. \tag{10}$$

Based on the assumptions above and under the condition of the risk constraints, the distribution company's power purchase model for the profit optimization problem can be expressed as follows:

$$\begin{aligned} \max \quad & \left(1-t_3\right)\left[\frac{1-t_1t_2}{1+t_1}F\left(1-k\right)+\frac{1-t_1t_2}{1+t_1}fk-\frac{1}{1+t_1}x^T y\right]Q \\ & -\left(1-t_3\right)C_0 \\ \text{s.t.} \quad & \sum_{i=1}^{10} x_i = 1 \\ & x_i Q \le Q_i \\ & y_j \ge y_{j0} \\ & x_4 + x_9 = x_{\text{wind}} \\ & x_5 + x_{10} = x_{\text{solar}} \\ & \left(x_1 + x_6\right) Q \le Q_{\text{out max}} \\ & \gamma \le \gamma_{\max} \\ & x_i \ge 0 \\ & y_i \ge 0 \\ & i = 1, 2, \ldots, 10. \end{aligned} \tag{11}$$

In formula (11), $\gamma_{\max}$ represents the control value of the profit fluctuation risks. It is determined by the grid company according to its risk tolerance. In the case study, we carry out the analysis according to the tolerance capacity of three different kinds of risks.

Table 2: The probability distribution of electricity selling price and transmission prices.

Types of the power users	The sales prices of small- and medium-sized customers	Large users' electricity prices of transmission and distribution
The most possible values of the electricity prices (yuan/kWh)	0.505	0.132
The minimal value of the electricity price (yuan/kWh)	0.505	0.127
The maximal value of the electricity price (yuan/kWh)	0.505	0.137

5. The Case Study

5.1. The Basic Data. The basic data of the power purchase prices assumed in the model are shown in Table 1.

According to the price of the short-term contract subject to the triangular distribution hypothesis and the definition of the risks in the model, we can calculate the scale of the profit fluctuation risks generated by the fluctuations in the power purchase prices:

$$\gamma_2 = 0.00006\left(x_6 + x_9 + x_{10}\right)Q + 0.00083\left(x_7 + x_8\right)Q. \tag{12}$$

The basic data of the distribution company's sales price and distribution price assumed in the model are shown in Table 2.

The sales price of the medium and small users is determined by the long-term contract, so it is not variable. However, the transmission and distribution price that is paid to the grid company by the large users may change. If the price is approved by the government, it is not variable. Assuming that it obeys triangular distribution, we can calculate the scale of the profit fluctuation risks to the grid company. The risk influence of the grid company on the power sales side is mainly caused by the fluctuations in the transmission and distribution prices:

$$\gamma_3 = 0.00083kQ. \tag{13}$$

Table 3: The power quantity constraints of the grid company (unit: 100 GWh).

Type	Value	Power purchased from the extraprovincial market	Power purchased from the intraprovincial market			
			Hydropower	Thermal power	Wind power	Photovoltaic generation
Long-term contract	The most probable value	0.3047	0.22	0.32	0.31	0.31
	The minimal value	0.3047	0.22	0.32	0.31	0.31
	The maximal value	0.3047	0.22	0.32	0.31	0.31
Short-term contract	The most probable value	0.45	0.2443	0.3329	0.3249	0.3249
	The minimal value	0.448	0.2393	0.3279	0.3229	0.3229
	The maximal value	0.452	0.2493	0.3379	0.3269	0.3269

Table 4: The constraints of the minimal price in short-term contracts (unit: yuan/kWh).

Types of contract	Short-term contract				
Sources	Power purchased from the extraprovincial market	Power purchased from the intraprovincial market			
		Hydropower	Thermal power	Wind power	Photovoltaic generation
Lowest price	0.43	0.23	0.32	0.3	0.3

The basic data of the power purchase constraints assumed in the model are shown in Table 3.

According to the condition of the extraprovincial power transmission, we assume that the maximal capacity of the extraprovincial trade is 2 billion kWh and the fixed costs of the grid company are 15 billion yuan per year in this region.

Generally speaking, the load forecasting obeys normal distribution. We assume that the random variables of the total power demand obey normal distribution, the mean value is 115 billion kWh, and the standard deviation is 0.05 billion kWh.

Assume that in the super short term the power purchase price of the grid company, due to the lack of purchasing power, is 0.8 RMB per kWh. The power price is 0 because the power supply is too large to sell out. We can calculate the scale of the profit fluctuation risks brought about by the fluctuations in the power demand:

$$\gamma_4 = (0.6 - 0) \times 0.5 + (0.8 - 0.4) \times 0.5 = 0.5. \quad (14)$$

In the case analysis, we do not regard the proportion of large users in the power purchase as a risk source but as a hypothesis while analysing. For example, there is no direct power purchase for large users when $k = 0$. The power market model changes from the wholesale competition mode to the single-buyer mode. We take $k = 0$, $k = 5\%$, and $k = 10\%$ separately and three modes are analysed in the cases.

Under the condition of the given value k, the direct-purchase power for the large users no longer appears as a risk source. Then, $\gamma_5 = 0$.

Assume that, in accordance with the provisions, the lowest price constraints of the grid company in the short-term contract market are shown in Table 4.

The weather conditions have great influence on wind power and photovoltaic power generation. Furthermore, wind power and photovoltaic power generation are volatile. Therefore, the capacity of the wind power and photovoltaic power generation can be assumed to be a random variable. This paper assumes that the capacity of wind power and photovoltaic power generation obeys uniform distribution.

We assume that the capacity of wind power obeys the uniform distribution of 138 to 142 and the capacity of the photovoltaic power generation obeys the uniform distribution of 14 to 16. According to the probability theory, the random variable mean of wind power is 14 billion kWh and the standard deviation is 0.1155 billion kWh. The mean value of the photovoltaic power generation random variable is 1.5 billion kWh and the standard deviation is 0.0577 billion kWh.

According to the renewable energy power generation forecast, the power status of wind power or photovoltaic power generation can change. Assume that in the super short term the power purchase price due to the lack of power is 0.8 yuan/kWh. The power price is 0 because the power supply is too large to sell out. We can calculate the scale of the profit fluctuation risks that are produced by the change in the status of the wind power and photovoltaic power generation capacity:

$$\gamma_1 = (0.6 - 0) \times 1.732 + (0.8 - 0.4) \times 1.732 = 1.732. \quad (15)$$

According to the data above, the grid company's profit fluctuation risks of the total power purchase satisfy the following equation:

$$\begin{aligned} \gamma &= \gamma_1 + \gamma_2 + \gamma_3 + \gamma_4 + \gamma_5, \\ \gamma &= 0.00006 \left(x_6 + x_9 + x_{10}\right) Q \\ &\quad + 0.00083 \left(x_7 + x_8 + k\right) Q + 2.232. \end{aligned} \quad (16)$$

After adding the actual values to the equations above, the total profit of the distribution company is

$$\begin{aligned} R = {} & \left[0.84 \times 0.5 (1 - k) + 0.84 \times 0.2k - 0.86 \sum_{i=1}^{10} x_i y_i \right] \\ & \times 0.75Q - 112.5. \end{aligned} \quad (17)$$

The model can be expressed as

$$\begin{aligned}
\max \quad & R \\
& = \left[0.84\times 0.5\left(1-k\right)+0.84\times 0.2k-0.86\sum_{i=1}^{10}x_i y_i\right] \\
& \quad \times 0.75Q-112.5 \\
\text{s.t.} \quad & \sum_{i=1}^{10}x_i = 1 \\
& y_1 = 0.3047 \\
& y_2 = 0.22 \\
& y_3 = 0.32 \\
& y_4 = 0.31 \\
& y_5 = 0.31 \\
& y_6 = 0.45 \\
& y_7 = 0.2443 \\
& y_8 = 0.3329 \\
& y_9 = 0.3249 \\
& y_{10} = 0.3249 \\
& y_6 \geq 0.43 \\
& y_7 \geq 0.23 \\
& y_8 \geq 0.32 \\
& y_9 \geq 0.3 \\
& y_{10} \geq 0.3 \\
& x_4 = \frac{6}{115} \\
& x_5 = \frac{1}{115} \\
& x_9 = \frac{5}{115} \\
& x_{10} = \frac{5}{1150} \\
& 0 \leq x_1 \leq \frac{10}{1150} \\
& 0 \leq x_2 \leq \frac{240}{1150} \\
& 0 \leq x_3 \leq \frac{300}{1150} \\
& 0 \leq x_6 \leq \frac{5}{1150} \\
& 0 \leq x_7 \leq \frac{200}{1150} \\
& 0 \leq x_8 \leq \frac{800}{1150} \\
& x_1 + x_6 \leq \frac{20}{1150} \\
& \gamma \leq \gamma_{\max} \\
& i = 1, 2, \ldots, 10.
\end{aligned} \tag{18}$$

5.2. The Optimization Analysis. For the three different kinds of situations, we assume different proportion scenarios of the direct power purchase for large users in the calculation.

5.2.1. $k = 0$. This situation means that the proportion of the direct power purchase for large users is 0. There is no direct power purchase for large users. That is to say, the power market changes from the wholesale competition mode to the single-buyer mode. The distribution company's requirement and restrictions in relation to the power purchase risks are shown in Table 5.

The risks and profit in the model can be quantitative:

$$\begin{aligned}
\gamma &= 0.00006\left(x_6+x_9+x_{10}\right)Q \\
&\quad + 0.00083\left(x_7+x_8+k\right)Q + 2.232 \\
&= 0.0069\left(x_6+x_9+x_{10}\right) + 0.9545\left(x_7+x_8\right) \\
&\quad + 2.232, \\
R &= \left[0.84\times 0.5\left(1-k\right)+0.84\times 0.2k-0.86\sum_{i=1}^{10}x_i y_i\right] \\
&\quad \times 0.75Q-112.5 \\
&= \left(0.42-0.86\sum_{i=1}^{10}x_i y_i\right)\times 862.5-112.5.
\end{aligned} \tag{19}$$

When $\gamma_{\max} = 0.2505$ billion yuan, we calculate that the maximal profit is 2.8744 billion RMB. The optimal proportions of the power purchase are shown in Table 6.

When $\gamma_{\max} = 0.25$ billion yuan, we calculate that the maximal profit is 2.8632 billion yuan. The optimal proportion of the power purchase is shown in Table 7.

When $\gamma_{\max} = 0.2495$ billion yuan, we calculate that the maximal profit is 2.8033 billion yuan. The optimal proportion of the power purchase is shown in Table 8.

When $\gamma_{\max} = 0.249$ billion yuan, there is no feasible solution. In this case, the distribution company could not reduce the profit fluctuations of the power purchase to less than 0.249 billion yuan.

5.2.2. $k = 5\%$. This situation means that the proportion of the direct power purchase for the large users is 0.05. We assume that the distribution company's requirement and restrictions to the power purchase risks are shown in Table 9.

Table 5: The risk tolerance of the grid company when $k = 0$ (unit: 100 million yuan).

The endurance threshold of income fluctuation	High endurance	Medium endurance	Low endurance	Extremely low endurance
γ_{max}	2.505	2.5	2.495	2.49

Table 6: The optimal power purchase proportion of the grid company when $k = 0$ and $\gamma_{max} = 0.2505$ billion yuan.

Types of contract	The purchased quantity from the extraprovincial market (100 GWh)	The purchased quantity from the intraprovincial market (100 GWh)				The maximal profit (billion RMB)
		Hydropower	Thermal power	Wind power	Photovoltaic generation	
Long-term contract	10	240	300	60	10	2.8744
Short-term contract	0	200	275	50	5	

Table 7: The optimal power purchase proportion of the grid company when $k = 0$ and $\gamma_{max} = 0.25$ billion yuan.

Types of contract	The purchased quantity from the extraprovincial market (100 GWh)	The purchased quantity from the intraprovincial market (100 GWh)				The maximal profit (billion RMB)
		Hydropower	Thermal power	Wind power	Photovoltaic generation	
Long-term contract	10	240	300	60	10	2.8632
Short-term contract	3.06	200	271.94	50	5	

Table 8: The optimal power purchase proportion of the grid company when $k = 0$ and $\gamma_{max} = 0.2495$ billion yuan.

Types of contract	The purchased quantity from the extraprovincial market (100 GWh)	The purchased quantity from the intraprovincial market (100 GWh)				The maximal profit (billion RMB)
		Hydropower	Thermal power	Wind power	Photovoltaic generation	
Long-term contract	10	240	300	60	10	2.8033
Short-term contract	5.9	200	269.5	50	5	

Table 9: The risk tolerance of the grid company when $k = 5\%$ (unit: 100 million yuan).

The endurance threshold of income fluctuation	High endurance	Medium endurance	Low endurance	Extremely low endurance
γ_{max}	2.515	2.51	2.505	2.5

The risks and profit in the model can be quantitative:

$$\begin{aligned}\gamma &= 0.00006\left(x_6 + x_9 + x_{10}\right)Q \\ &\quad + 0.00083\left(x_7 + x_8 + k\right)Q + 2.232 \\ &= 0.0069\left(x_6 + x_9 + x_{10}\right) + 0.9545\left(x_7 + x_8\right) \\ &\quad + 2.32745, \\ R &= \left[0.84 \times 0.5\left(1 - k\right) + 0.84 \times 0.2k - 0.86\sum_{i=1}^{10} x_i y_i\right] \\ &\quad \times 0.75Q - 112.5 \\ &= \left(0.3998 - 0.86\sum_{i=1}^{10} x_i y_i\right) \times 862.5 - 112.5.\end{aligned} \tag{20}$$

When $\gamma_{max} = 0.2515$ billion yuan, we calculate that the maximal profit is 1.1355 billion yuan. The optimal proportion of the power purchase is shown in Table 10.

When $\gamma_{max} = 0.251$ billion yuan, we calculate that the maximal profit is 1.1244 billion yuan. The optimal proportion of the power purchase is shown in Table 11.

When $\gamma_{max} = 0.2505$ billion yuan, we calculate that the maximal profit is 1.0972 billion yuan. The optimal proportion of the power purchase is shown in Table 12.

When $\gamma_{max} = 0.25$ billion yuan, there is no feasible solution. In this case, the distribution company could not reduce the profit fluctuations of the power purchase to less than 250 million yuan.

5.2.3. $k = 10\%$. This situation means that the proportion of the direct power purchase for the large users is 0.1. We assume

Table 10: The optimal power purchase proportion of the grid company when $k = 5\%$ and $\gamma_{max} = 0.2515$ billion yuan.

Types of contract	The purchased quantity from the extraprovincial market (100 GWh)	The purchased quantity from the intraprovincial market (100 GWh)				The maximal profit (billion RMB)
		Hydropower	Thermal power	Wind power	Photovoltaic generation	
Long-term contract	10	240	300	60	10	1.1355
Short-term contract	0	200	275	50	5	

Table 11: The optimal power purchase proportion of the grid company when $k = 5\%$ and $\gamma_{max} = 0.251$ billion yuan.

Types of contract	The purchased quantity from the extraprovincial market (100 GWh)	The purchased quantity from the intraprovincial market (100 GWh)				The maximal profit (billion RMB)
		Hydropower	Thermal power	Wind power	Photovoltaic generation	
Long-term contract	10	240	300	60	10	1.1244
Short-term contract	2.46	200	272.54	50	5	

Table 12: The optimal power purchase proportion of the grid company when $k = 5\%$ and $\gamma_{max} = 0.2505$ billion yuan.

Types of contract	The purchased quantity from the extraprovincial market (100 GWh)	The purchased quantity from the intraprovincial market (100 GWh)				The maximal profit (billion RMB)
		Hydropower	Thermal power	Wind power	Photovoltaic generation	
Long-term contract	10	240	300	60	10	1.0972
Short-term contract	8.48	200	266.52	50	5	

Table 13: The risk tolerance of the grid company when $k = 10\%$ (unit: 100 million yuan).

The endurance threshold of income fluctuation	High endurance	Medium endurance	Low endurance	Extremely low endurance
γ_{max}	2.525	2.52	2.515	2.51

that the distribution company's requirement and restrictions to the power purchase risks are shown in Table 13.

The risks and profit in the model can be quantitative:

$$\begin{aligned}\gamma &= 0.00006\left(x_6 + x_9 + x_{10}\right)Q \\ &\quad + 0.00083\left(x_7 + x_8 + k\right)Q + 2.232 \\ &= 0.0069\left(x_6 + x_9 + x_{10}\right) + 0.9545\left(x_7 + x_8\right) \\ &\quad + 2.4229, \\ R &= \left[0.84 \times 0.5\left(1 - k\right) + 0.84 \times 0.2k - 0.86\sum_{i=1}^{10} x_i y_i\right] \\ &\quad \times 0.75Q - 112.5 \\ &= \left(0.3948 - 0.86\sum_{i=1}^{10} x_i y_i\right) \times 862.5 - 112.5.\end{aligned} \tag{21}$$

When $\gamma_{max} = 0.2525$ billion yuan, we calculate that the maximal profit is 485.2 million yuan. The optimal proportion of the power purchase is shown in Table 14.

When $\gamma_{max} = 0.252$ billion yuan, we calculate that the maximal profit is 476.3 million yuan. The optimal proportion of the power purchase is shown in Table 15.

When $\gamma_{max} = 0.2515$ billion yuan, we calculate that the maximal profit is 413.9 million yuan. The optimal proportion of the power purchase is shown in Table 16.

When $\gamma_{max} = 0.251$ billion yuan, there is no feasible solution. In this case, the distribution company could not reduce the profit fluctuations of the power purchase to less than 251 million yuan.

5.3. The Analysis of the Results. Based on the analysis results above, Figure 2 shows the relationship of the profit's volatility risk threshold and the expected profit under different ratios of direct power purchase for large users after considering the risks of renewable energy power interconnection.

From Figure 2, we can see that the maximum risk profit of the distribution company increases with an increase in the allowable profit's fluctuation risk threshold. It complies with the principle of "the greater the risks are, the greater the profit is." Besides, along with the increase in the ratio of direct power purchase for large users, the distribution company's risks will increase and the risk profit will decrease. Thus, the increase in

Table 14: The optimal power purchase proportion of the grid company when $k = 10\%$ and $\gamma_{max} = 0.2525$ billion yuan.

Types of contract	The purchased quantity from the extraprovincial market (100 GWh)	The purchased quantity from the intraprovincial market (100 GWh)				The maximal profit (billion RMB)
		Hydropower	Thermal power	Wind power	Photovoltaic generation	
Long-term contract	10	240	300	60	10	0.4852
Short-term contract	0	200	275	50	5	

Table 15: The optimal power purchase proportion of the grid company when $k = 10\%$ and $\gamma_{max} = 0.252$ billion yuan.

Types of contract	The purchased quantity from the extraprovincial market (100 GWh)	The purchased quantity from the intraprovincial market (100 GWh)				The maximal profit (billion RMB)
		Hydropower	Thermal power	Wind power	Photovoltaic generation	
Long-term contract	10	240	300	60	10	0.4763
Short-term contract	1.98	200	273.02	50	5	

Table 16: The optimal power purchase proportion of the grid company when $k = 10\%$ and $\gamma_{max} = 0.2515$ billion yuan.

Types of contract	The purchased quantity from the extraprovincial market (100 GWh)	The purchased quantity from the intraprovincial market (100 GWh)				The maximal profit (billion RMB)
		Hydropower	Thermal power	Wind power	Photovoltaic generation	
Long-term contract	10	240	300	60	10	0.4139
Short-term contract	8	200	267	50	5	

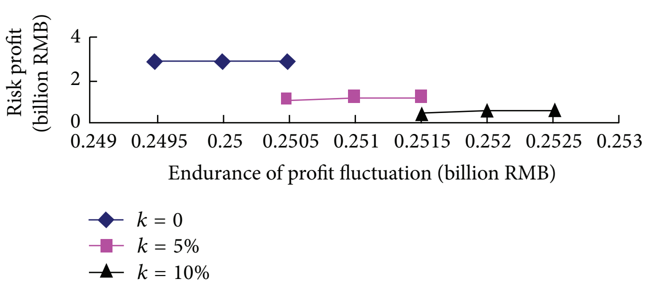

Figure 2: The risk profile of the grid company under different ratios of direct power purchase for large users.

the direct power purchase for large users will have an adverse impact on the grid company.

6. Conclusions

This paper considers in depth the background of China's large-scale renewable energy power interconnection. Fully considering the risks that renewable energy power generation brings, we build up a linear programme model for power purchase optimization based on different risk preferences on the power purchase side. The feasibility of the model is verified by the case study. Through the research, we reach the following conclusions:

(1) Since wind power and photovoltaic power generation and their output are not controllable, the amount of power generation cannot be predicted accurately. This brings new risks to the grid company's power purchase. Therefore, we need to conduct research constantly to improve the precision of the forecasting method of wind power and photovoltaic power generation to reduce the risks.

(2) Along with the increase in large users' direct-purchase power ratio, the distribution company's risks will increase and the risk profit will decrease. Thus, direct purchasing has adverse impacts on the grid company. With the background of the power market reform and large users' direct-purchase power increasing, the grid company must take action early and improve the service quality for large users to reduce the power system reforms' influence on the grid company.

(3) The risk profit of the grid company increases along with the increase in risk tolerance. This complies with the principle of "the greater the risks are, the greater the profit is." Therefore, in the process of purchasing power, the grid company should fully consider its risk tolerance and control the risks within a reasonable scope to seek the maximal profit.

(4) After using the linear programming optimization model recommended in this paper, the grid company's economic income level will experience a certain improvement. It means that the model reflects the power purchase risks well and solves the power purchase optimization problem of the grid company under these conditions.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

The work described in this paper was supported by the National Natural Science Foundation of China (Grant no. 71273089) and the National Social Science Foundation of China (Grant no. 14BJY063).

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