Quotation and operation optimization of VPP in medium and long term market

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Abstract. Due to energy shortage and environmental pollution, distributed energy resource (DER) has been pouring into the grid, but its output is intermittent and fluctuant, which affects the operation of power grid. "Virtual power plant (VPP)" provides a channel to solve this problem. In this paper, VPP including distributed power supply (photovoltaic, wind power and gas turbine) and energy storage system (energy storage battery) is taken as the research object. Based on the uncertain factors such as season-of-use price, light intensity and wind speed, the VPP bidding strategy and operation scheduling strategy in the medium and long term contract market are studied, and the risk value model is applied to risk management. The example testing results show that, when quoting, the maximum loss caused by electricity price is generally within 5%, which is an acceptable risk; in operation, the gas turbine plays a major role in balancing the output deviation, and the VPP operation scheduling strategy has certain economic benefits.

1. Introduction

With the depletion of traditional primary energy such as petroleum and the increasingly serious problems of environmental pollution and climate change, renewable energy has become a new generation power in the energy army. The representative renewable energy power, wind power and photovoltaic power, has been connected to China's power grid on a large scale, bringing random and volatile impact to the power grid. The structure and control mode of traditional power system cannot be adapted to it, so the power system needs to be reformed urgently. VPPs can aggregate distributed energy resources in different regions, so that the units can coordinate organically, so as to more rationally and scientifically complete the allocation and utilization of energy to meet the requirements of the power market [1]. Nowadays, VPPs have attracted attention from all walks of life and have a bright future in the power market. With the concept and technology of VPPs becoming more and more mature, practical issues such as bidding strategies and uncertain operation optimization strategies under the power market model have become a research hotspot, in order to create higher power quality and economic benefits in the new power era.

For the bidding strategy of VPPs, scholars at home and abroad have done some research, and have proposed some different bidding strategies and models [2-6]. Reference [2] establishes a three-stage two-level stochastic optimization model for the day-ahead market. The upper level aims to maximize the benefits of VPP and the lower level is the day-ahead market liquidation problem of independent system operators. Reference [3] discusses the optimal bidding strategy in the combined market of
energy market and rotating reserve market. Reference [4] introduces the auction mechanism of VPPs, and establishes a stochastic programming model integrating the optimal bidding problem and bilateral contracts in power market. The bidding strategy in reference [5] is that wind power participates in the energy market bidding before the day, and electric vehicle participates in regulating the market bidding. A robust optimization model of cooperative bidding is constructed. Reference [6] studies the bidding model based on game theory, and establishes the supply function model with complete information and uncertain information.

For operation scheduling, scholars at home and abroad have also done a lot of research [7-11]. Reference [7] uses node pricing mechanism to study operation scheduling, but does not consider the uncertainty of distributed generation, so the model is simple. Reference [8] adopts stochastic programming method to study the medium-term optimal dispatching of VPPs. Reference [9] establishes an economic optimal dispatching model for wind storage system which can provide peak shaving and frequency modulation services. Reference [10] establishes an optimal dispatching model of VPPs based on time-sharing price of distribution network under the current market model. Reference [11] analyses the optimization model of demand response VPPs and traditional generators jointly participating in system dispatch considering uncertainties.

From the above analysis, it can be seen that there are few studies on bidding and operation optimization of VPPs under medium and long-term market model, and there are few specific risk assessment of bidding schemes. Based on this, this paper studies the bidding model of VPP in medium and long term market mode, and carries out operation optimization research on the basis of the optimal bidding scheme obtained by the calculation of the model. At the same time, risk value model is introduced to carry out risk assessment in both stages in order to maximize the overall economic benefits of VPP.

2. VPP quotation model in medium and long term contract market

2.1. Objective function

For the medium and long-term contract market model, the time span is large, with one year as the cycle and month as the basic unit of time. The analysis of each period is relatively independent.

The bidding model aims at maximizing net income in each period of VPP. The objective function is as follows

$$\max F = \sum_{t=1}^{12} \left( I_t - C_t \right)$$

(1)

Where

$$I_t = p_t \left[ 720P_{GT,t} + 360P_{PV,t} + 720P_{W,t} + \lambda_{ES_j} \mu_{ES_j} E_{max} \right]$$

(2)

$$C_t = 720C_{GT,t} + 360C_{PV,t} + 720C_{W,t} + \lambda_{ES_j} \mu_{ES_j} \frac{E_{max}}{P_{ES_j}} C_{ES_j}$$

(3)

Where, $I_t$ is the profit of VPP at month $t$, $C_t$ is the cost of VPP at month $t$, $p_t$ is the electricity price at month $t$, $P_{GT,t}$, $P_{PV,t}$, $P_{W,t}$, $P_{ES_j}$ and $C_{GT,t}$, $C_{PV,t}$, $C_{W,t}$, $C_{ES_j}$ are respectively the quoted output and operation cost of gas turbine, photovoltaic, wind turbine and energy storage battery at month $t$, $\lambda_{ES_j}$ is the charging/discharging number of energy storage battery at month $t$, $\mu_{ES_j}$ is the charging/discharging state variable of energy storage battery at month $t$, the value of which is -1 at charging state and 1 at discharging state, $E_{max}$ is the upper limit of storage capacity of energy storage battery. Moreover, $P_{ES_j}$ is treated as equal to the upper limit of charge/discharge rate, because the energy storage battery can only consider its comprehensive effect for a time span of up to one month.

Secondly, in the medium and long-term market model, the consideration of revenue and cost is
related to time, and should be analyzed on the basis of capacity rather than power. Consider that the number of days per month is 30 days, then, the number of hours per month is 720 hours. For photovoltaic modules, it is generally believed that effective solar radiation exists between 6 and 18 o'clock per day, so the working hours are 360 hours per month. What’s more, for photovoltaic and wind power, as new energy sources, VPP should give priority to their utilization, so it is considered that both of them are fully connected to the Internet.

For energy storage batteries, it is more complicated to analyze them in the medium and long term. Therefore, the physical characteristics of the single energy storage capacity limitation are blurred. It is abstracted as a "generator" that can generate positive or negative electricity and allows continuous charging or discharging, with the consideration of the upper and lower limits of charging and discharging times per month and the limitation of the total number of charging and discharging times per year. And when the unit power cost of this month's energy storage battery is lower than current month's electricity price, it is judged that the energy storage battery is discharged in that month, and if conversely, it is judged that the battery is charged.

The operating costs of the above-mentioned units are as follows:

- **Gas Turbine Generation Cost**
  \[ C_{GT,t} = a_{GT}^2 P_{GT,t}^2 + b_{GT} P_{GT,t} + c \]  
  Where, \( a, b, c \) are the consumption characteristic parameters of gas turbine.

- **Photovoltaic Power Generation Cost**
  \[ C_{PV,t} = k_{PV} P_{PV,t} \]  
  Where, \( k_{PV} \) is the consumption characteristic parameter of photovoltaic module.

- **Wind Power Generation Cost**
  \[ C_{W,t} = k_{W} P_{W,t} \]  
  Where, \( k_{W} \) is the consumption characteristic parameter of wind power.

- **Energy Storage Battery Operation Cost**
  Because the charging and discharging of energy storage battery can both be regarded as the loss of energy storage equipment, the independent variables in the cost function of energy storage should be calculated by absolute value first, and the power value should be negative when charging and positive when discharging.
  \[ C_{ES,t} = k_{ES} |P_{ES,t}| \]  
  Where, \( k_{ES} \) is the consumption characteristic parameter of energy storage battery.

### 2.2. Constraint conditions
- **Unit Power Constraint**
  \[ P_{GT,min} \leq P_{GT,t} \leq P_{GT,max} \]  
  \[ P_{PV,min} \leq P_{PV,t} \leq P_{PV,max} \]  
  \[ P_{W,min} \leq P_{W,t} \leq P_{W,max} \]  
  \[ P_{ES,min} \leq P_{ES,t} \leq P_{ES,max} \]  
  Where, \( P_{GT,max}, P_{PV,max}, P_{W,max}, P_{ES,max} and P_{GT,min}, P_{PV,min}, P_{W,min}, P_{ES,min} \) are respectively the upper and
lower power limits of gas turbine, photovoltaic, wind turbine and energy storage battery.

- Charge and Discharge Constraints of Energy Storage Equipment

\[
\begin{align*}
\lambda_{\text{charge}, \text{min}} & \leq \lambda_{\text{ES}, t} & \leq \lambda_{\text{charge}, \text{max}}, & \lambda_{\text{ES}, t} = -1 \\
\lambda_{\text{discharge}, \text{min}} & \leq \lambda_{\text{ES}, t} & \leq \lambda_{\text{discharge}, \text{max}}, & \lambda_{\text{ES}, t} = 1
\end{align*}
\]  
\hspace{1cm} (12)

\[
\begin{align*}
0 & \leq \sum_{\mu_{\text{ES}, t} = 1}^{\lambda_{\text{charge}, \text{max}}} \lambda_{\text{ES}, t} \\
0 & \leq \sum_{\mu_{\text{ES}, t} = 1}^{\lambda_{\text{discharge}, \text{max}}} \lambda_{\text{ES}, t}
\end{align*}
\]  
\hspace{1cm} (13)

\[
\sum_{t=1}^{12} \frac{\lambda_{\text{ES}, t} \lambda_{\text{ES}, t}}{\mu_{\text{ES}, t}} \leq \alpha \left( \lambda_{\text{charge}} + \lambda_{\text{discharge}} \right)
\]  
\hspace{1cm} (14)

\[
\left| \sum_{\mu_{\text{ES}, t} = 1}^{\lambda_{\text{charge}, \text{max}}} \lambda_{\text{ES}, t} \right| \geq \beta \lambda_{\text{charge}}
\]  
\hspace{1cm} (15)

Where, \( \lambda_{\text{charge}, \text{max}}, \lambda_{\text{discharge}, \text{max}} \) and \( \lambda_{\text{charge}, \text{min}}, \lambda_{\text{discharge}, \text{min}} \) are respectively the upper and lower limits of monthly charging and discharging times of energy storage battery, \( \lambda_{\text{charge}}, \lambda_{\text{discharge}} \) is the upper limit of annual charging and discharging times of energy storage battery, \( \alpha, \beta \) are the ratio coefficients.

Among them, formula (14) guarantees the balance of energy storage state of energy storage equipment, that is, the difference between the initial state and the end state of energy storage capacity after a cycle shall not exceed a certain proportion of the total energy storage capacity; formula (15) guarantees that the energy storage battery can maintain a certain utilization rate in VPP.

3. VPP scheduling model in medium and long term contract market

3.1. Objective function

The objective of dispatching model is to minimize the total cost in each period of VPP. The objective function is as follows

\[
\min C = 720C_{\text{GT}, t}^\prime + 360C_{\text{PV}, t}^\prime + 720C_{\text{W}, t}^\prime + 720C_{\Delta P, t}^\prime + \lambda_{\text{ES}, t} \left( \frac{E_{\text{ES}, t}^\max}{P_{\text{ES}, t}} \right)^{C_{\text{ES}, t}}
\]  
\hspace{1cm} (16)

In the model, \( C_{\text{GT}, t}^\prime, C_{\text{PV}, t}^\prime \) and \( C_{\text{W}, t}^\prime \) are the actual generation costs of gas turbine, photovoltaic and wind turbine in the \( t \) month, respectively, \( \lambda_{\text{ES}, t} \) is the actual charge/discharge times of energy storage battery in the \( t \) month, \( C_{\Delta P, t}^\prime \) is the difference penalty cost in the \( t \) month and the penalty coefficient is set to five times the current electricity price, and the penalty cost is set to be

\[
C_{\Delta P, t} = 5p_t \left| \Delta P_t \right|
\]  
\hspace{1cm} (17)

Among them, \( \Delta P_t \) is the VPP differential power in the \( t \) month, when the output deviation is greater than 0, it is the power purchased from the distribution network, and the value is positive; when the output deviation is less than 0, it is the excess idle power, and the value is negative.

The strategy of operation scheduling is as follows:
- Priority should be given to the utilization of wind power and photovoltaic power generation, with the policy of full access to the Internet.
If the output deviation is greater than 0, that is, the generation capacity of uncontrollable units is insufficient, combined with the market price, choose to supply power by energy storage battery or increase the output of gas turbine when the planned output of gas turbine is not up to the rated power value, and if it is not enough, then choose to purchase electricity from the distribution network to compensate for the output deviation.

If the deviation of output is less than 0, that is, excess generation of uncontrollable units, combined with market price, choose to use energy storage batteries to store excess power or reduce the output of gas turbines. If there is still surplus, a certain penalty will be paid for excess output.

Energy storage battery can be used to cut peak and fill valley appropriately, that is, charging and storing energy during the valley period of electricity price and discharging energy during the peak period of electricity price.

3.2. Constraint conditions
The constraints mentioned in Section 2.2 still need to be satisfied in the operation scheduling, just modify the corresponding quotation stage variable to the actual operation stage variable. In addition, the constraints of VPP's monthly output capacity balance should be met.

- Capacity Balance Constraint

\[
\begin{align*}
&\left[720P_{GT,t} + 360P_{PV,t} + 720P_{W,t} + \lambda_{ES,t}\mu_{ES,t}E_{\max}\right] \\
= &\left[720P_{GT,t}^+ + 360P_{PV,t}^+ + 720P_{W,t}^+ + 720\Delta P_t + \lambda_{ES,t}^+\mu_{ES,t}^+E_{\max}\right]
\end{align*}
\] (18)

4. Case study

4.1. Related data
VPP consists of two 100 MW A type and three 100 MW B type gas turbines, three 100 MW photoelectric fields (with the same parameters), five 220 MW wind farms (with the same parameters) and 50 MW energy storage batteries. The relevant parameters are listed in table A1 of Appendix A. It is considered that the upper and lower limits of charging and discharging rate of energy storage battery are the same, which can be simplified to the maximum and minimum output of the unit. The upper and lower limits of charging and discharging times per month and the upper limit of charging and discharging times per year for energy storage batteries are also treated as the same. The specific parameters of energy storage batteries are shown in table A2 of Appendix A.

The main influencing factors of photovoltaic power generation are illumination intensity and battery module temperature. The main influencing factor of wind power generation is wind speed. The corresponding influencing factors data are shown in table A3 of Appendix A. It is obvious that there are seasonal differences among the three factors.

According to the division of season-of-use price, June to October is divided into flood season and electricity price is lowered; January to April and December are divided into dry season and electricity price is raised; May and November are flat season and implemented according to the benchmark price [12]. The annual electricity price data are shown in table A3 of Appendix A.

For the photovoltaic module, according to its output characteristics, the photovoltaic power data can be obtained by substituting the above illumination intensity and the working temperature of the module. For wind turbines, the cut-in wind speed is 3 m/s, the cut-out wind speed is 24 m/s and the rated wind speed is 15 m/s [13]. According to the output characteristics of typical wind turbines, the wind power data can be obtained by substituting the wind speed data. The relevant data can be found in table A4 of Appendix A. Among them, the output characteristics of photovoltaic and wind power are shown in Appendix C.
4.2. Analysis of quotation scheme

4.2.1. Optimal quotation scheme. According to the quotation model, the optimal quotation scheme can be obtained. The specific scheme can be found in table A5 of Appendix A.

According to the bidding scheme, the bidding strategy under the medium-term and long-term contract market mode is relatively simple. The uncontrollable power supply (photoelectric field and wind farm) is fully connected to the Internet. Both types of gas turbines continue to work with maximum power output. The main factors that determine the different bidding scheme are the monthly charging and discharging status and specific times of energy storage battery under the influence of seasonal fluctuation of electricity price. The charging and discharging status of the energy storage battery is easy to determine. When the balance output deviation of the energy storage battery is not considered, it is only necessary to compare the monthly electricity price with the monthly unit power cost of the energy storage battery. When the former is higher, the energy storage battery operates in the discharge state, and when the former is lower, it operates in the charging state. Comparing with the electricity price data, it can be seen that from June to October, when the electricity price was lowered due to the flood season, the energy storage battery was also charged accordingly. The specific number of charges and discharges per month is determined by the five restrictions on the charging and discharging of energy storage batteries.

4.2.2. Risk analysis based on VaR method. The expression formula of Value at Risk Model, VaR [14] is as follows:

\[ \text{Prob} \left( \Delta P \leq \text{VaR} \right) = 1 - \alpha \] (19)

Among them, Prob denotes probability, specifically the probability that the expression in brackets holds; \( \Delta P \) denotes the loss of financial assets or portfolios; \( \alpha \) denotes confidence; VaR is the risk value needed under confidence \( \alpha \). At a given confidence level, VaR determines the maximum expected loss that may be incurred, and a \( 1 - \alpha \) probability guarantees that the expected loss of the financial asset or portfolio will not be greater than the VaR value. The confidence is 95%.

The average absolute error of electricity price forecast is not more than 10%, and the error is set as normal distribution. The risk analysis is divided into four cases: error rate of 10%, 5%, 2% and 1%.

| Error Rate of Electricity Price Prediction | VaR/USD | Percentage of maximum loss |
|------------------------------------------|---------|---------------------------|
| 1%                                       | 5080000 | 0.87%                     |
| 2%                                       | 9300000 | 1.60%                     |
| 5%                                       | 24640000| 4.24%                     |
| 10%                                      | 59540000| 10.25%                    |

When the maximum loss of net income in the whole year is not more than 5%, the risk is considered to be low and within acceptable range. As can be seen from table 1, the greater the error rate of electricity price prediction, the greater the maximum loss of net income. Because the electricity price is directly related to the net income value, the error rate of electricity price prediction and the percentage of maximum loss remain basically the same order of magnitude, and the difference between the values will not be too large. Specifically, when the error rate is 5%, 2% and 1%, the maximum loss percentage is slightly smaller than the corresponding error rate, while when the error rate is 10%, the maximum loss percentage is slightly more than 10%. Therefore, the functional relationship between the maximum loss percentage and the error rate of electricity price prediction is assumed to be linear and partly non-linear. Therefore, when the error rate of electricity price prediction is less than 5%, there is a 95% probability that the expected loss of net income for the whole year will not exceed 5%, which is an acceptable risk. Because VPP can forecast electricity price more
4.3. Analysis of operation dispatching results

According to the optimal quotation scheme in Section 4.2, the total planned output capacity of VPP in each period of the year can be obtained by accumulating the output capacity of each unit in different periods. The specific data are shown in table A6 of Appendix A.

Due to the errors in predicting the output of uncontrollable units, the actual output of each uncontrollable unit should be given beforehand before the example analysis. It is also assumed that the output prediction error of uncontrollable units is normal distribution. Among them, the average absolute error of photoelectric power prediction is between 5% and 8% [15]; the average absolute error of wind power prediction is between 10% and 15% [16], and the National Energy Administration stipulates that the prediction error of wind power curve should not exceed 25% [17]. Then the average absolute error of the two corresponding factors should be less than 10% and about 10%~25%.

Therefore, the data given by normal random distribution is chosen as the actual output of uncontrollable units. The error rate of illumination intensity is 10%, 5%, 2% and 1%. The error rate of wind speed is 25%, 20%, 15% and 10%, which can reflect the objective reality. In order to avoid tautology, the temperature of battery assembly is not taken into account.

4.3.1. Impact of prediction errors on scheduling schemes.

In order to clearly show the dispatching scheme, the optimization times are set as four times. Four dispatching schemes with specific error values are shown for each of the four groups of error rate combinations. The corresponding photoelectric and wind power curves are shown in Appendix B, figure B1. The larger the error rate is, the greater the fluctuation of the corresponding power curve is. Among them, the green “*” is the reference curve. These four groups of power curves can be used as actual output conditions to optimize the corresponding dispatching schemes, as shown in Appendix B, figure B2 to figure B5.

Because the research object is medium and long-term operation dispatching, the unit output in dispatching scheme is measured by capacity, and the differential power is converted into the corresponding differential capacity. Because VPP dispatching still needs to meet the policy of full access of photovoltaic and wind power, the photovoltaic and wind capacitance curves in Appendix B, figure B1 can find the corresponding power curves in figure B2 to figure B5. From each differential capacity curve, it can be seen that with the increase of error rate of error combination, the numerical range of differential capacity also tends to increase. Moreover, gas turbine and energy storage battery may not compensate for the output deviation completely in some time periods, resulting in the differential capacity of corresponding time periods not to be zero, but the differential capacity will never be negative, that is, VPP as a whole will not produce excess output. Comparing with the planned output curve of gas turbine, the output distribution of gas turbine in each period after dispatching begins to discrete and fluctuates, which is no longer identical.

Taking the scheduling scheme with 10% illumination intensity error and 25% wind speed error as example, the output scheduling of gas turbines and energy storage batteries is analyzed concretely, and the relationship between the two and the differential capacity is also discussed. The results are shown in figure 1.

Because there are some differences between the output capacity of gas turbine and energy storage battery and the number of units, the output capacity of gas turbine and energy storage battery are increased three times and ten times respectively for the convenience of observation, as shown in figure 1. In this figure, it can be seen more clearly that the difference capacity has been kept greater than or equal to 0, and the gas turbine plays a more critical role in balancing deviation, for the following reasons. According to the VPP operation scheduling strategy, when the uncontrollable generating units are short of power, the power supply of energy storage battery or the output of gas turbine will increase. However, in this example, all gas turbine units participate in the quotation with the greatest effort at all times, and no additional effort can be added in the dispatch. Therefore, it can only be
supplied by energy storage batteries, and then it can be purchased from the distribution network when
it is insufficient, thus the difference capacity is greater than zero. When uncontrollable units generate
excess power, the energy storage battery charging or gas turbine output decreases. Because the scale
of gas turbine units is equal to that of uncontrollable units, and it is dispatched in medium and long
term, and is not limited by the climbing rate, the excess deviation can be easily absorbed by reducing
the output of gas turbine units, thus the difference capacity equals zero. However, the energy storage
battery is limited by the initial and final capacity state and has to undertake its own output planning
tasks, so it can only play a moderate role of balance deviation.

4.3.2. Analysis of economic impact of forecasting error based on VaR. In section 4.3.1, the number
of optimizations is only 4 times, which cannot simulate the normal characteristics of errors. In this
section, the number of optimizations is reset to 200 times, and the difference situation is analyzed
more accurately, and the relationship between penalty cost and total cost risk value is obtained.
According to the optimal quotation scheme in Section 4.2, the total annual cost is calculated to be
$453940000, with this parameter as the basis for subsequent analysis.

The frequency histogram of the total penalty cost and the total annual cost under the four error
combinations is shown in Appendix B, figure B6. It can be seen from the graph that both distributions
have certain normal characteristics. Observing the range of abscissa of frequency histogram, we can
see that the larger the error rate is, the larger the fluctuation range of total penalty cost and total cost is,
and the trend of both is consistent.

The penalty cost of the four error combinations for operation scheduling and non-operation
scheduling is shown in tables 2 and 3. For the total penalty cost, table 2 is the fractional value at the
95% cumulative probability of the corresponding frequency histogram from small to large ranking;
table 3 is the penalty cost when the operation dispatch is not carried out without considering the
normal random distribution of error rate, that is, all output deviations of photovoltaic and wind power

\[ \text{Figure 1. Curve of output capacity change of gas turbine and energy storage battery and curve of}
\]

\[ \text{differential capacity.} \]
need to pay penalty cost. At this time, the total penalty cost is a single source of loss.

| Illumination intensity error rate | Wind speed error rate | Total penalty cost /USD | VaR of Total Cost /USD | Maximum loss percentage |
|----------------------------------|----------------------|-------------------------|------------------------|-------------------------|
| 1%                               | 10%                  | 222730000               | 202590000              | 44.63%                  |
| 2%                               | 15%                  | 355080000               | 320130000              | 70.52%                  |
| 5%                               | 20%                  | 493390000               | 447130000              | 98.50%                  |
| 10%                              | 25%                  | 620620000               | 563730000              | 124.19%                 |

Table 3. Penalty cost and percentage of loss when no operation is scheduled.

| Illumination intensity error rate | Wind speed error rate | Total penalty cost /USD | Percentage of loss |
|----------------------------------|----------------------|-------------------------|--------------------|
| 1%                               | 10%                  | 357390000               | 78.73%             |
| 2%                               | 15%                  | 538740000               | 118.68%            |
| 5%                               | 20%                  | 728930000               | 160.58%            |
| 10%                              | 25%                  | 927110000               | 204.24%            |

Comparing the columns 3 and 4 in table 2, we can see that the increased total annual cost mainly comes from the penalty cost which reflects the difference capacity deviating from the VPP output plan, but the total cost added value (VaR value of total cost) is always slightly smaller than the total penalty cost. The reason is that at this time, the output of gas turbine unit can be reduced in some period, but it will never increase the output, and the working cost of gas turbine unit increases with the increase of output power and decreases with the decrease of output power in the output range, so the unit work cost will be reduced in dispatch.

It can be seen from the table that the greater the error rate, the greater the maximum loss caused by the increase of the total cost, and the loss is astonishing, even exceeding the benchmark cost value. The benchmark net income value of output plan is $580640000. When the penalty coefficient is set high, the actual operating income may even be negative when the error rate is high. However, comparing the corresponding column data in the two tables, it can be seen that the application of operation scheduling strategy can greatly reduce the cost increase caused by uncontrollable unit output prediction errors in VPP, and the operation scheduling strategy has economic benefits.

5. Conclusions
The premise of this paper is that photovoltaic, wind power are fully connected to the Internet and VPP quotation are not limited by demand load and the electricity price is known, so there is no need to plan the transaction price. Based on uncertainties such as illumination intensity and wind speed, this paper studies VPP bidding strategy and operation scheduling strategy based on optimal bidding scheme in mid-long term contract market mode on the basis of season-of-use price, and uses risk value model to carry out risk assessment and management.

The analysis results of practical examples show that in the bidding stage, the maximum loss caused by electricity price is generally less than 5%, which is acceptable risk; in the operation stage, gas turbine plays a major role in the balance of output deviation under medium and long-term market mode. This deviation may not be fully compensated, resulting in penalty costs due to the difference capacity, but the value of the difference capacity must be greater than or equal to zero. Moreover, the operation dispatching strategy has certain economic benefits, and the unit operating cost is lower than the planned value in the quotation stage, which can reduce the cost increase caused by the output deviation of uncontrollable units.

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Appendix A

**Table A1.** Unit parameters of VPP.

| Unit type          | Consumption characteristic parameter $a$ \((\text{USD} \cdot \text{h}^{-1}/\text{MW}^2)\) | Consumption characteristic parameter $b$ \((\text{USD} \cdot \text{h}^{-1}/\text{MW})\) | Consumption characteristic parameter $c$ \((\text{USD} \cdot \text{h}^{-1})\) | Maximum output /MW | Minimum output /MW |
|--------------------|---------------------------------|---------------------------------|---------------------------------|-------------------|-------------------|
| A-type gas turbine | 0.25                            | 40                              | 0                               | 100               | 20                |
| B-type gas turbine | 0.2                             | 35                              | 0                               | 100               | 20                |
| Photoelectric field| 0                               | 50                              | 0                               | 100               | 0                 |
| Wind farm          | 0                               | 38                              | 0                               | ±50               | 0                 |
| Energy storage battery | 0                          | 112                             | 0                               | 0                 | 0                 |

**Table A2.** Specific parameters of energy storage batteries.

| Parameter name                                                                 | Parameter value |
|-------------------------------------------------------------------------------|-----------------|
| Upper limit of storage capacity of energy storage battery $E_{\text{max}}$     | 50MW·h          |
| Upper limit of monthly charge and discharge times                             | 200             |
| Lower limit of monthly charge and discharge times                             | 10              |
| Upper limit of annual charge and discharge times                              | 1000            |
| Proportionality coefficient $\alpha$                                         | 5\%             |
| Proportionality coefficient $\beta$                                          | 10\%            |

**Table A3.** Data of annual illumination intensity, battery module temperature, wind speed and corresponding monthly electricity price.

| Month | Illumination intensity \(/(\text{W/m}^2)\) | Battery module temperature \(^\circ\text{C}\) | Wind speed \(/(\text{m/s})\) | Electricity price \(/(\text{USD/MWh})\) |
|-------|---------------------------------|---------------------------------|-----------------|-----------------|
| 1     | 415                             | 1                               | 4.5             | 130             |
| 2     | 476                             | 2                               | 7.5             | 135             |
| 3     | 556                             | 9                               | 6.5             | 132             |
| 4     | 822                             | 15                              | 7.7             | 130             |
| 5     | 793                             | 20                              | 7.4             | 115             |
| 6     | 832                             | 24                              | 10              | 100             |
| 7     | 1000                            | 29                              | 12              | 98              |
| 8     | 947                             | 29                              | 11              | 102             |
| 9     | 730                             | 25                              | 8.5             | 103             |
| 10    | 614                             | 19                              | 8.5             | 100             |
| 11    | 538                             | 9                               | 6.2             | 115             |
| 12    | 431                             | 3                               | 5               | 128             |

**Table A4.** Data of annual photoelectric and wind power.

| Month | Photoelectric power /MW | Wind power /MW |
|-------|-------------------------|----------------|
| 1     | 46.0                    | 27.5           |
| 2     | 52.5                    | 82.5           |
| 3     | 59.6                    | 64.2           |
| 4     | 85.9                    | 86.2           |
| 5     | 81.1                    | 80.7           |
| 6     | 83.6                    | 128.3          |
| 7     | 98.2                    | 165.0          |
| 8     | 93.0                    | 146.7          |
### Table A5. Optimal quotation scheme.

| Month | A-type gas turbine /MW | B-type gas turbine /MW | Photoelectric field /MW | Wind farm /MW | Energy storage battery/times |
|-------|------------------------|------------------------|-------------------------|---------------|----------------------------|
| 1     | 100                    | 100                    | 46.0                    | 27.5          | 30 (discharge)              |
| 2     | 100                    | 100                    | 52.5                    | 82.5          | 200 (discharge)             |
| 3     | 100                    | 100                    | 59.6                    | 64.2          | 200 (discharge)             |
| 4     | 100                    | 100                    | 85.9                    | 86.2          | 140 (discharge)             |
| 5     | 100                    | 100                    | 81.1                    | 80.7          | 10 (discharge)              |
| 6     | 100                    | 100                    | 83.6                    | 128.3         | 200 (charge)                |
| 7     | 100                    | 100                    | 98.2                    | 165.0         | 200 (charge)                |
| 8     | 100                    | 100                    | 93.0                    | 146.7         | 10 (charge)                 |
| 9     | 100                    | 100                    | 73.0                    | 100.8         | 10 (charge)                 |
| 10    | 100                    | 100                    | 63.1                    | 100.8         | 80 (charge)                 |
| 11    | 100                    | 100                    | 57.7                    | 58.7          | 10 (discharge)              |
| 12    | 100                    | 100                    | 47.4                    | 36.7          | 10 (discharge)              |

### Table A6. Total capacity planned for each period of the year.

| Month | Planned total capacity /(MW·h) |
|-------|--------------------------------|
| 1     | 510180                         |
| 2     | 723700                         |
| 3     | 665488                         |
| 4     | 770092                         |
| 5     | 738608                         |
| 6     | 902168                         |
| 7     | 1050056                        |
| 8     | 988060                         |
| 9     | 801220                         |
| 10    | 787028                         |
| 11    | 634136                         |
| 12    | 543812                         |

Appendix B
Figure B1. Power curves of photoelectric and wind power under four error combinations.
Figure B2. Scheduling scheme with 1% illumination intensity error and 10% wind speed error.

Figure B3. Scheduling scheme with 2% illumination intensity error and 15% wind speed error.
Figure B4. Scheduling scheme with 5% illumination intensity error and 20% wind speed error.

Figure B5. Scheduling scheme with 10% illumination intensity error and 25% wind speed error.
Appendix C photoelectric and wind power output characteristics

- **Photovoltaic Generator Set**

  The influence factors of output characteristic function of photovoltaic generator set are solar radiation intensity and temperature of battery module.

  \[
  P_t = P_0 \left( \frac{I}{I_0} \right) \left[ 1 + \alpha_P \left( T_t - T_0 \right) \right]
  \]

  Where, \( P_t \) is the actual output power of photovoltaic cell module; \( P_0 \) is the rated output power; \( I \) is the actual solar radiation intensity; \( I_0 \) is the solar radiation intensity under the standard test conditions, taking the value of 1000 W/m²; \( \alpha_P \) is the power temperature coefficient of photovoltaic cell module, taking the value of -0.0045°C⁻¹; \( T_t \) is the actual temperature of photovoltaic cell module; \( T_0 \) is the temperature of battery module under standard test condition, and the value is 25°C [18].

- **Wind turbines**

  The output characteristic function of wind turbine is the function of wind power and wind speed.
\[ P(v) = \begin{cases} 
0, & 0 \leq v \leq v_{\text{in}} \\
Z(v)P_{W0}, & v_{\text{in}} \leq v \leq v_0 \\
P_{W0}, & v_0 \leq v \leq v_{\text{out}} \\
0, & v > v_{\text{out}} 
\end{cases} \] (C2)

\[ Z(v) = \frac{v - v_{\text{in}}}{v_0 - v_{\text{in}}} \] (C3)

Where, \( v_{\text{in}} \) is cut-in wind speed, \( v_{\text{out}} \) is cut-out wind speed, \( v_0 \) is rated power wind speed, referred to as rated wind speed, for different types of wind turbines, the values of these three parameters are also different. \( P(v) \) is the actual output power of wind turbine, and \( P_{W0} \) is the rated power.

The function \( Z(v) \) represents the ratio of actual output power to rated output power of wind turbine when wind speed is between cut-in wind speed and rated wind speed. Since the ratio varies with the change of wind speed, the real \( Z(v) \) function is a complex function related to wind speed, which is difficult to be expressed analytically. Therefore, some commonly used functions are usually used to approximate the ratio, such as linear function, quadratic function and cubic function [13]. Linear functions are used in this paper, as shown in formula (C.3).

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