Design of a Two-Stage Pricing Mechanism for Renewable Energy Participation in the Electricity Market

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Abstract. Due to Chinese strong support for the development of renewable energy, the consumption of renewable energy power in current policy of most provinces is "guaranteed consumption". Renewable energy enterprises take advantage of this rule to adopt high quotation behavior in the electricity market competition, and their consumption prices are basically similar to those of coal-fired power generation enterprises. The existing consumption policy does not reflect either the cost which incurred by the high proportion of clean energy consumption for the power system or the adjustment of the value which produced by surplus electricity use. In this paper, we propose a two-stage trading mechanism for renewable energy participation in the power market. The idea is that in the first stage of trading, the "quantity preservation" constraint is not considered, and all units are calculated with the system power supply cost as the target for optimal clearing. In the second stage of trading, the consumption price of surplus power is used as the variable to calculate the optimal trading result that satisfies the renewable energy consumption constraint. Through the simulation analysis, we can see that this mechanism can guarantee the consumption of renewable energy power, meanwhile, it can play an important role in reducing the energy cost of customers and guiding the benign development of renewable energy power.

Keywords: renewable energy generaion; electricity market; second-stage trading; generation cost

1 Introduction

At present, China's renewable energy power consumption policy is based on full consumption, although it also participates in the market bidding, but adopts the mode of guaranteed consumption to start the transaction, renewable energy power plants tend to raise their offers in the quotation process to obtain excess revenue. In Hunan Province, for example, since May 2021, the trading price of renewable energy participation in the monthly market has been maintained at about 0.445-0.447 yuan/kWh, basically in line with the benchmark price of thermal power in Hunan Province. Some power plants even expect to keep in line with the thermal power trading price, quoting at a level of 20% up from the benchmark price. Although this model can guarantee the priority of renewable energy consumption, but in the reality of the scenario of a significant increase in coal prices on thermal power revenue caused a large impact,

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and large-scale scenery to the grid brought about by the various auxiliary service costs are also difficult to recover.

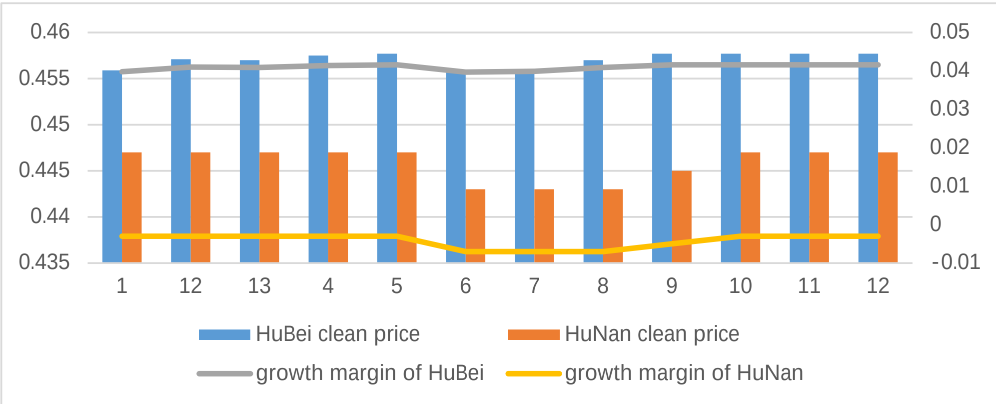

Fig.1. Change in Clearance Price of Renewable Energy Participation in the Monthly Market in Central China

2 Analysis of high renewable energy offers and the impact on electricity market prices

The reasons for the high offer of renewable energy generation in China are related to many aspects: firstly, the technical cost of renewable energy is high. However, in recent years, technologies such as solar and wind power are progressing, and the cost of renewable energy generation has significantly reduced and enjoys national subsidies for power generation[1] . Second, the construction of renewable energy generation is difficult. Due to the scattered distribution of renewable energy, factors such as geographic location and regional environment need to be considered when building renewable energy power generation, as well as making complex assessments and risk control. All these factors will lead to the difficulty of constructing renewable energy power generation[2]. Third, renewable energy is still in the period of market exploration. As the development of renewable energy is relatively new, the electricity market has not really formed a level playing field compared with traditional thermal power generation enterprises, which also affects the price level of renewable energy power generation[3].

Grid-connected power generation from renewable energy sources will have an impact on power market prices and regional power supply costs. First, renewable energy access will likely cause a change in the electricity market price system. The total cost of electricity generation in traditional electricity markets is determined by the marginal cost of the most expensive fuel (usually natural gas or coal)[4] . However, as renewables are gradually connected to the grid, their low marginal cost will pull down the market exit price. Second, renewable energy participation in the market will also affect the cost and profit structure of electricity prices[5]. Third, the storage technology and equipment of renewable energy is relatively backward[6] . Especially in the field of battery energy storage, the gap between China and developed countries is large, which makes it difficult for renewable energy to achieve stable grid-connected power generation and requires more auxiliary service costs to achieve reliable power supply, increasing the reliability cost of the system[7].Finally, the docking cost of renewable energy generation is higher. Since renewable energy sources are scattered, more transmission lines and substations and other facilities need to be built, which increases the cost of grid construction.

3 literature review and contribution of this paper

With the global energy crisis and climate problems becoming more and more serious, promoting the development of renewable energy and promoting the participation of renewable energy in the electricity market has become an international consensus[8]. Some foreign countries firstly formulate relevant laws and regulations to stimulate the development of renewable energy, and then establish relatively mature electricity market mechanism and corresponding management rules to implement the participation of renewable energy in electricity market transactions, and the development of renewable energy has achieved good results[9].

Germany adopted a fixed tariff policy in the early days, and when the development of renewable energy reached a certain level, a bidding system was introduced to stipulate the annual bidding volume for each type of installed renewable energy generation capacity. The literature [10] introduces the former means that the successful bidder receives the contracted feed-in tariff; the latter means that the successful bidder receives a premium subsidy, and the tariff settlement is composed of "market price + premium of the successful bid". The literature [11] introduces the implementation of the CFD mechanism in the UK since 2014, in which renewable energy sources participate in the electricity market through competitive bidding, and renewable energy generators sign CFD contracts with government-appointed CFD contractors and set the execution tariffs. In regions with relatively mature renewable energy development, such as Northern Europe and the United States, most of them implement day-ahead spot market trading or a combination of green certificates and renewable energy. For example, literature [12] proposes an energy sales/buyback pricing framework that uses time-dependent dynamic pricing strategies to provide benefits to power companies and their customers to maximize total social welfare.

Existing studies focus on the main instruments to promote renewable energy development, focusing on areas such as cost recovery and subsidies for renewable energy in electricity trading. However, renewable energy enterprises, as interest subjects, also have the possibility of using market rules to gain excess profits. The contribution of this paper is to explore the current problems of renewable energy consumption pricing based on the existing renewable energy consumption policies in China and propose specific mechanisms to solve the problems, which are highly current and practical. Secondly, the two-stage trading idea and arithmetic simulation proposed in this paper have an important role in promoting the reduction of energy cost for users and guiding the benign development of renewable energy power while ensuring the amount of renewable energy power consumption.

4 Design ideas of renewable energy participation in the second stage of electricity market trading

This paper draws on the trading idea of spot market, divides the power market trading into two parts: financial trading and actual delivery, and carries out two stages of power trading, the first stage is the clearing trading of the normal offer of renewable energy units and the same bidding with thermal power, but the power is not guaranteed to be fully cleared; the second stage is the replacement trading of the remaining renewable energy power and thermal power units, at which time the maximum amount of renewable energy power is cleared For the goal, but does not guarantee its consumption price.

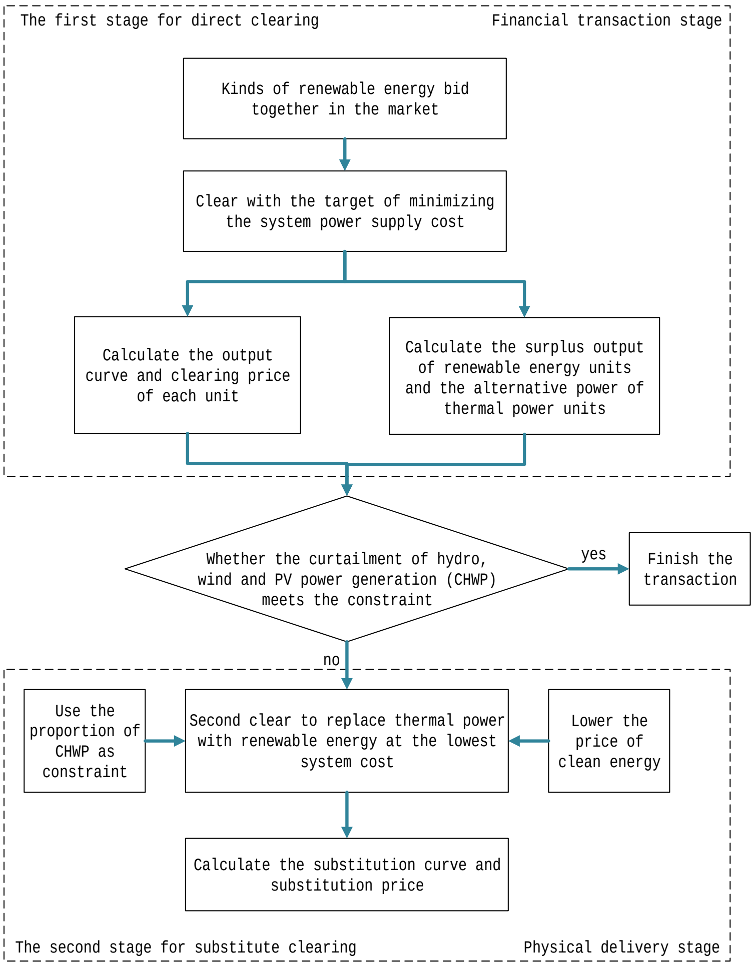

Fig.2. Trading Ideas for Renewable Energy Alternatives to Thermal Power

5 Two-stage pricing model construction for renewable energy and thermal power

With the objective of minimizing the total power supply cost in the power market, the optimal clearing model of the power market under the combination of multiple power sources is constructed by considering the resource and environmental benefits of different power supply units and using carbon emission cost and green certificate price as the metric. The objective function is function(1).

$$\min C = C_1 + C_2 + C_3 + C_4 + C_5 + C_6 - R_7 \tag{1}$$

In the model, C is the total cost of electricity supply for the whole inter-provincial transaction, and C_1 to C_4 are the generation cost models for thermal, hydro, wind and PV units respectively. At the same time, the backup cost of C_5 system is included in the measurement, considering the backup pressure brought by the large scale of wind and solar power consumption in the provincial power system. Finally, according to the impact of different power sources on resources and environment, carbon emission cost C_6 and green power certificate benefit are included R_7 .

Model construction of thermal power operation cost: Let the marginal generation coal cost function of thermal units be C_1 , the general function of thermal unit coal cost can be obtained from function(2):

$$C_1(P_{git}) = \sum_{t=1}^{T}\sum_{i=1}^{M}(a_i P_{git}^{2} + b_i P_{git} + c_i)S_{\mathrm{coal}} + C_{\mathrm{loss}}(P_{git}) + C_{oil}(P_{git}) \tag{2}$$

where P_{git} is the output power of the ith thermal unit; a_i, b_i, c_i is the thermal unit coal cost parameter; S_{coal} is the thermal unit coal price for electricity generation.

As the generation capacity of the unit increases, its life loss will also be affected and should be taken into consideration. The life loss of the unit with load curtailment to 40% is 0.005%, the life loss of hot start is 0.01% and the life loss of cold start is 0.05%. The unit loss cost under variable load peaking can be obtained as follows: $C_{\mathrm{loss}}(P_{git}) = \frac{\beta C_B}{2N_f(P_{git})}$ .Where: β is the operating influence coefficient of thermal power unit, indicating the degree of loss in different operating conditions; $N_f(P_{git})$ is the rotor cracking cycle cycle; C_B is the purchase cost of thermal power unit.

According to the steady combustion state of the unit and the combustion medium, during the oil feeding stage, usually the unit also needs to be fed with oil to maintain a minimum level of stable operation of the boiler and water circulation system, i.e. the cost of oil feeding is $C_{\mathrm{oil}} = \eta_{\mathrm{oil}} Q_{\mathrm{oil}}$ .Where: Q_{oil} is the oil consumption when the unit is put into oil stabilization:

η_{oil} is the oil price of the season, Yuan/t.

In summary, the components of the operating costs of thermal power units are different under different operating conditions, and the marginal costs of thermal power units are expressed here as the following segmentation functions,as function(3).

$$C_1(P_{git}) = \begin{cases} C(P_{git}) + C_{\text{loss}}(P_{git}) & , P_{\min} \le P_{git} < P_{\max} \\ C(P_{git}) + C_{\text{loss}}(P_{git}) & , P_{\text{n}} \le P_{git} < P_{\min} \\ C(P_{git}) + C_{\text{loss}}(P_{git}) + C_{\text{oil}} & , P_{\text{m}} \le P_{git} < P_{\text{n}} \end{cases} \tag{3}$$

Hydropower transaction costs: The cost of consuming hydropower is its price of consumption multiplied by the amount of electricity, as function(4).

$$C_2(P_{hit}) = \sum_{t=1}^{T} \sum_{i=1}^{N} \eta_h P_{\text{hit}} \tag{4}$$

Wind power transaction costs: Due to the large uncertainty of incoming wind conditions, there is a certain error between the predicted output and the actual output capacity, and the project uses a normal distribution to describe the uncertainty of the prediction error, as function(5).

$$\varepsilon_t \sim N(0, \frac{1}{5} P'_{wit} + \frac{1}{50} U_w) \tag{5}$$

Where: ε_t is the wind power prediction error at time t; P'_{wit} is the wind power prediction output at time t; U_w is the installed capacity of the wind farm. The actual capacity of the wind farm is the sum of the predicted wind power output and the prediction error, and the actual capacity of the wind farm should not exceed its installed capacity as function(6).

$$P_{wit}^{real} = \min(P'_{wit} + \varepsilon_t, U_w) \tag{6}$$

The cost model for wind power generation at this point is as as function(7).

$$C_3(P_{wit}) = \sum_{t=1}^{T} \sum_{i=1}^{Z} (1-\theta_{wit}) P'_{wit} \eta_w \tag{7}$$

θ_{wit} is the wind abandonment rate of the ith wind turbine.

PV power consumption costs: The sunshine situation also has a large uncertainty, and there is a certain error between the predicted output and the actual output capacity, and a normal distribution is used to describe the uncertainty of the prediction error, as function(8).

$$\varepsilon'_t \sim N(0, \frac{1}{5} P'_{sit} + \frac{1}{50} U_s) \tag{8}$$

Where: ε'_t is the forecast error of PV power generation at moment t; P'_{sut} is the forecast output of PV power generation at moment t; U_s is the installed capacity of PV farm, as function(9).

$$P_{sut}^{real} = \min(P'_{sut} + \varepsilon'_t, U_s) \tag{9}$$

At this point the cost model for PV power generation is as as function(10).

$$C_4\left(P_{sut}\right) = \sum_{t=1}^{T}\sum_{i=1}^{Z}(1-\theta_{sut})P'_{sut}\eta_{su} \tag{10}$$

Unit carbon emission cost: $E_{\mathrm{T}} = \delta_T \sum_{t=1}^{T}\sum_{i=1}^{M} P_{git}$ .Where E_{T} is the total carbon emission in one cycle, and δ_T is the carbon emission intensity of conventional thermal power units. In order to better control the carbon emissions of the system, this paper adopts a stepped carbon emission cost model and divides the carbon emissions into 3 segments. Specifically, it as function(11).

$$C_5(E_{\mathrm{T}})\begin{cases} \eta_T\left(E_T - E_L\right) & E_T \le E_L + \Delta E \\ \eta_T\Delta E + (1+\theta_E)\eta_T\left(E_T - E_L - \Delta E\right) & E_L + \Delta E \le E_T \le E_L + 2\Delta E \\ (2+\theta_E)\eta_T\Delta E + (1+2\theta_E)\eta_T\left(E_T - E_L - 2\Delta E\right) & E_T \ge E_L + 2\Delta E \end{cases} \tag{11}$$

$C_5(E_{\mathrm{T}})$ is the system carbon emission cost; η_T is the carbon trading price; ΔE is the length of the carbon emission interval; θ_T is the increase of carbon emission per 1 step up the carbon trading price. When $E_T \le E_L + \Delta E$ is negative, $C_4(E_{\mathrm{T}})$ indicates that the actual carbon emission of the system is less than the system's allowance, and the excess carbon emission allowance can be traded in the carbon trading market at the initial carbon emission price, so that the system can gain carbon revenue.

Spare cost for the province: Considering the forecast error of load and wind power output, the unit in this province needs to provide a certain capacity of additional rotating standby. The cost of rotating standby provided by thermal units can be calculated by the function(12).

$$C_6 = \sum_{t=1}^{T} \rho_{\mathrm{res}}(e_{\mathrm{D}}P_t + e_{\mathrm{w}}P_{wt} + e_v P_v) \tag{12}$$

Where: ρ_{res} is the system rotation backup cost factor; e_D, e_w, e_v is the forecast error rate of system load, wind power output and PV unit output, respectively.

Measurement of the environmental benefits of renewable energy consumption as function(13).

$$R_7 = \eta_{GCT}\left[\frac{\sum_{t=1}^{T}\left(\sum_{i=1}^{N} P_{hit} + \sum_{i=1}^{S} P_{wit} + \sum_{i=1}^{J} P_{vit}\right)}{1000} - N_{GCT}\right] \tag{13}$$

η_{GCT} is the price of green certificates, and N_{GCT} is the amount of green certificates required for the whole system to meet the renewable energy consumption responsibility.

Constraints to be satisfied by the system as function(14)~function(19):

Power balance constraints:

$$\sum_{i=1}^{M} P_{git} + \sum_{i=1}^{N} P_{hit} + \sum_{i=1}^{S} P_{wit} + \sum_{i=1}^{J} P_{vit} = P_D \tag{14}$$

Hydroelectric units:

$$P_{\mathrm{h}i\min} \le P_{\mathrm{h}it} \le P_{\mathrm{h}i\max} \tag{15}$$

Wind turbines:

$$P_{\mathrm{w}i\min} \le P_{wit} \le P_{\mathrm{w}i\max} \tag{16}$$

Photovoltaic units:

$$P_{su\min} \le P_{sut} \le P_{su\max} \tag{17}$$

Climbing restraint:

$$\begin{cases} u_{\mathrm{g}it} P_{\mathrm{g}it} - u_{\mathrm{g}i(t-1)} P_{\mathrm{g}i(t-1)} \le r_{\mathrm{g}i,\mathrm{up}} \\ u_{\mathrm{g}i(t-1)} P_{\mathrm{g}i(t-1)} - u_{\mathrm{g}it} P_{\mathrm{g}it} \le r_{\mathrm{g}i,\mathrm{down}} \end{cases} \tag{18}$$

Start/stop time constraint:

$$\begin{cases} \sum_{k=t}^{t+T_{\mathrm{on}}-1} u_{\mathrm{g}ik} \ge T_{\mathrm{on}} [u_{\mathrm{g}it} - u_{\mathrm{g}i(t-1)}] \\ \sum_{k=t}^{t+T_{\mathrm{off}}-1} (1 - u_{\mathrm{g}ik}) \ge T_{\mathrm{off}} [u_{\mathrm{g}i(t-1)} - u_{\mathrm{g}it}] \end{cases} \tag{19}$$

It can be obtained that the cost-optimal water, fire, and scenery power trading power and system cost can satisfy the transmission capacity constraint, and the comprehensive consideration of the resource and environmental benefits.

The second stage: the first stage of clearing result, is the least cost clearing result, but at this time the scenery consumption price for the conventional offer, higher prices may lead to higher abandoned wind and light rate, so to carry out the second clearing, still to minimize the cost as the goal, but to meet the renewable energy consumption responsibility weight, or abandoned wind and light rate as a constraint, the alternative price of scenery as a variable for clearing, clearing price that The clearing price is the mandatory trading price of renewable energy instead of thermal power, and the trading volume is the boundary volume to meet the responsibility weight of renewable energy consumption.

6 Simulation analysis of calculation cases

6.1 Data sources

Take the electricity market of province A as an example, the total installed capacity of power plants in province A: 56.2 million kilowatts, of which 13.732.3 million kilowatts or 24.4% is wind power; 9.815.5 million kilowatts or 17.5% is photovoltaic; 9.610.2 million kilowatts or 17.1% is hydropower; and 23.042 million kilowatts or 41% is thermal power. The province's maximum load is 17.14 million kilowatts, and the outgoing load is 10 million kilowatts. Then the calculation example is constructed as follows: three 600mw thermal power units, two 300mw, one 900mw hydropower, one 1300mw wind power and one 1000mw photovoltaic. coal price is 1000RMB/t, assuming that 200MW and 300MW units are only engaged in regular peaking.

The load standby factor, wind power standby factor and PV standby factor are 10%, 5% and 5% respectively; the error rate of load forecast, wind power output forecast error rate and PV output forecast error rate are 10%, 5% and 5% respectively; the price of hydropower is 300 yuan/MWh; the maximum and minimum values of purchased hydropower are 1600MW and 800MW respectively; the base price of carbon trading is 50 yuan/t; the length of carbon emission interval length is 100t; carbon trading price increase is 25%; green certificate price for wind power and PV consumption is 58.5 yuan/book and 43.1 yuan/book respectively; system rotation standby price is 112 yuan/MWh; wind turbine operation and maintenance cost coefficient and PV operation and maintenance cost coefficient are 380 yuan/MW.

6.2 Analysis of Phase I Transaction Results

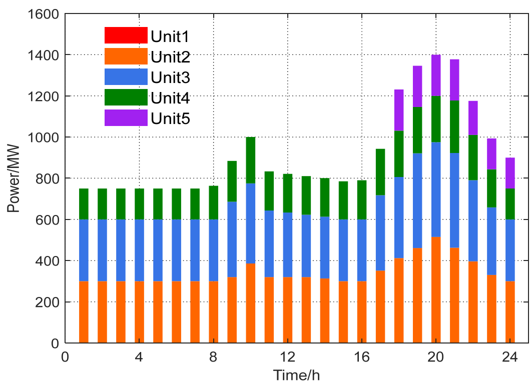

Fig.3. Thermal power output curve after one phase of trading

As shown in Figure 3, after the completion of one phase of trading, the total output of thermal units under the lowest system power supply cost condition is between 800 MW and 1400 MW. This indicates that the overall installed capacity of thermal power units is excessive, especially under the scenario of renewable energy participation in the power market, and some units need to be maintained in a shutdown state. However, the units that remain on have output levels that exceed 30% of their own capacity.

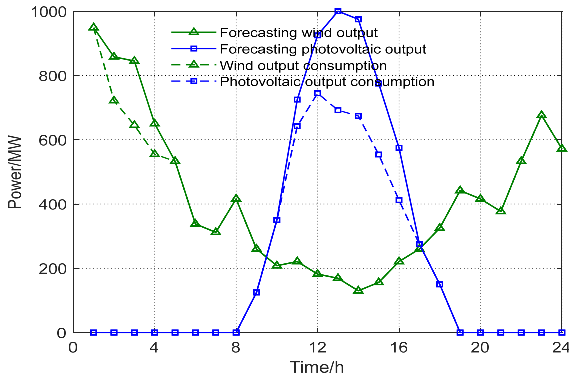

Fig.4. Scenery output curve after one stage of clearing

Figure 4 shows the predicted output and actual output of wind and PV generating units after one phase of trading. It can be seen that PV units have significant abandonment between 11:00 and 16:00, with the highest abandonment ratio between 12:00 and 14:00. The wind turbines, on the other hand, have a significant abandonment of wind during the low hours of the night, from 1:00 to 4:00. Therefore, the ratio of wind and light abandonment of the two power sources needs to be measured and the excess abandoned power needs to be dissipated.

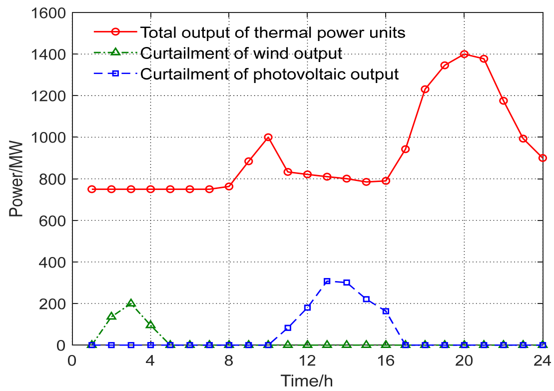

Fig.5. Wind and light abandonment after the first phase of clearing out power

From Figure 5 statistics can be seen, the maximum abandoned wind power of wind turbine is 200MW, photovoltaic unit is 320MW. Statistics at this time renewable energy generation accounted for the proportion of the total system power: wind power accounted for 18.45%, photovoltaic accounted for 8.86%, hydropower accounted for 30.29%. The proportion of renewable energy generation has exceeded 50%, playing an important role in China's low-carbon energy transition.

6.3 Analysis of Phase II Transaction Results

In order to ensure that renewable energy power can be fully consumed, the simulation of the second stage of trading is carried out by adjusting the quotation, aiming to guarantee the proportion of consumption while reducing the consumption price of renewable energy units and lowering the cost of system power supply. If the consumption price of renewable energy units is 0.2 yuan/kwh, the results of the consumption of abandoned wind and electricity are

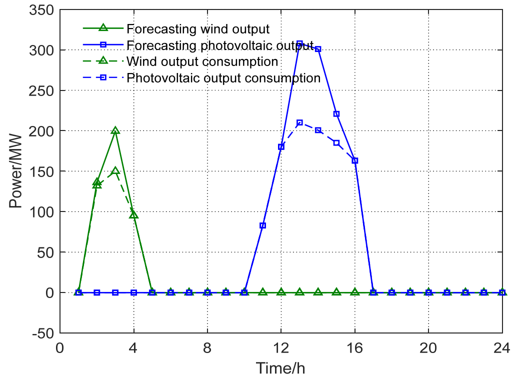

Fig. 6. Consumption results of surplus scenic power after price reduction

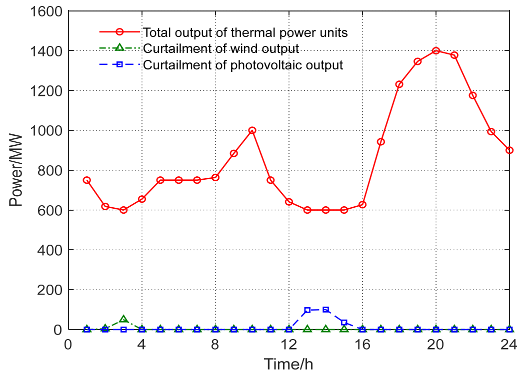

Fig. 7. Remaining size of surplus scenic power after tariff reduction

As can be seen from Figure 6 and Figure 7, the total wind abandonment rate at this point is 2.58% and the total light abandonment rate is 3.98%. After the second price reduction, the additional power consumption of wind power is 1.71% of the total power of wind turbines, and the additional power consumption of photovoltaic units is 4.62% of the total power generation. At this time, both renewable energy units have significantly increased their consumption, and the scenery units have gained reasonable power generation revenue.

7 Conclusions and Recommendations

This paper proposes a two-stage power trading mechanism which can meet the renewable energy consumption ratio constraint and ensure that the overall power supply cost of the system does not increase.The mechanism avoids the renewable energy enterprises to gain excessive profits, and at the same time guarantees the consumption ratio at a high scale by lower the price of surplus power consumption, which reflects the use value of different types of power from the economic point of view. This paper finds that:

(1) China's strong support for renewable energy development has led to the current policy of "guaranteed consumption" in most provinces for renewable energy power consumption. Renewable energy enterprises take advantage of this rule to adopt high quotation behavior in the electricity market competition, resulting in their consumption prices are basically similar to those of coal-fired power generation enterprises. However, with the progress of technology and the support of government subsidy policy, the cost of renewable energy generation has been gradually reduced, and the existing consumption policy does not reflect either the cost which incurred by high proportion of clean energy consumption for the power system or the adjustment of the value which produced by surplus electricity use.

(2) The two-stage trading mechanism of renewable energy participation in the power market can be one of the directions that mechanism reform for future power market development lead to. The idea is that, in the first stage of clearing, no consideration will be given to the "guaranteed quantity" constraint, and all units will be calculated on the basis of their real cost, with the system power supply cost as the goal of optimal clearing.This mechanism has an important role in promoting the reduction of energy costs for users and guiding the benign development of renewable energy power.

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