Bidding Strategy of a Flexible CHP Plant for Participating in the Day-Ahead Energy and Downregulation Service Market

HE CUI¹,², KUN SONG³, WENLEI DOU⁴, ZHE NAN⁵, ZHENG WANG⁴, AND NA ZHANG⁶,³

¹State Grid Liaoning Marketing Service Center, Shenyang 110000, China  
²Shenyang Institute of Engineering, Shenyang 110136, China  
³State Grid Liaoning Economic Research Institute, Shenyang 110015, China  
⁴State Grid Liaoning Electric Power Company Ltd., Shenyang 110006, China

Corresponding author: Na Zhang (260541055@qq.com)

ABSTRACT To integrate renewable energy generation from wind and solar radiation, most combined heat and power (CHP) plants in northern China are undergoing large-scale upgrades and retrofitting to improve operational flexibility. Simultaneously, the downregulation service (DRS) market is still retained in the day-ahead market in many provinces. Considering a flexible CHP plant with multiple types of coal-fired CHP units and heat storage as a price taker, this paper establishes a collaborative bidding strategy for the CHP plant to participate in both the day-ahead energy market and day-ahead DRS market. The bidding strategy includes the optimal output decision model, power output range model, capacity segmenting model, and bidding models for two markets determined by the marginal generation cost (MGC) and the marginal downregulation cost (MDRC), respectively. These models are validated based on realistic data from a CHP plant in Northeast China.

INDEX TERMS Bidding strategy, combined heat and power (CHP), day-ahead spot market, downregulation service (DRS) market.

ABBREVIATIONS
- CHP: Combined heat and power.
- FOR: Feasible operating region.
- MGC: Marginal generation cost.
- MDRC: Marginal downregulation cost.
- DRS: the downregulation service.
- CLPT: cutting-off low-pressure turbine.

I. INTRODUCTION

In China, to motivate thermal power plants to reduce their output of power to accumulate curtailed renewable power, such as wind power and PV power, the downregulation service (DRS) market [1] is designed to be a supplement to the benchmarking electricity price mechanism (BEPM). Under the BEPM, the price of power is fixed at all hours. Therefore, thermal power plants always attempt to increase their output of power or refuse to reduce it for many reasons to gain more profits. However, with the DRS market, thermal power plants can obtain more compensation than opportunity costs when they reduce their output rate to less than the baseline, such as 0.5.

Under the incentive of the DRS market, CHP plants have actively improved their operation flexibility in recent years [2], [3], mainly focusing on reducing the lower limit of power output of the whole plant while satisfying the demand for heat. Some traditional extraction condensing units have been retrofitted into extraction back-pressure units or new-type extraction condensing units that could operate in the cutting-off low-pressure turbine situation (CLPT) [4]. In addition, many CHP plants have or will be equipped with heat storage to decouple heat and power [3].

At the same time, the spot market is being actively promoted in China. Pilots have been built in 14 regions, such as Guangdong, Zhejiang, Shanxi, and Liaoning Provinces. Although the spot market can also motivate thermal power plants to improve their operational flexibility through time-of-use pricing, the DRS market is still supposed to be reserved at the early stage of the spot market in some northern provinces, such as Shanxi [5], Gansu, and Liaoning. In these provinces, nonflexible generation, such as wind, solar, and nuclear generation, has a very large share and continues to
increase rapidly. The annual hours of capacity utilization of the thermal power plants were significantly fewer than at the design level, indicating that most thermal power plants had a lower rate of profit than the design level and even suffered enormous losses. The lower prices in valley hours when renewable power is curtailed in the spot market will intensify the difficulty of operation for thermal power plants, so the DRS market is considered to be able to increase the income of thermal power plants and to motivate the thermal power plants to improve their operation flexibility more positively.

When the DRS market is reserved, the day-ahead market consists of the spot energy market and DRS market. The spot energy market is usually cleared first, and then the DRS market is cleared if there is wind or solar curtailment. The generation plan of each plant for the next day consists of the superposition of results cleared in two markets [5].

Therefore, the operation decisions for thermal power plants in the spot energy market will also affect the profits in the subsequent DRS market. Specifically, when a CHP plant is equipped with heat storage, the stored heat could either be released during the high price period of the energy market to improve the generating capacity of CHP units and obtain high profits or during the low-price period to improve the downregulation capacity of CHP units and to obtain high compensation by participating in the DRS market. Therefore, the bidding decision for a CHP plant should consider both the profit potential in the spot energy market and in the DRS market to maximize the overall profit.

However, there has been little research on collaborative bidding for CHP plants in the spot energy market and DRS market because the DRS market is a special auxiliary service market that only exists in China. The DRS market is essentially a generation right transfer trading market. In this market, thermal power plants are given a certain amount of generation rights by the authorized baseline of the output rate, such as 0.5, and they can sell the generation rights to the market by reducing their output under the baseline and obtain compensation if winning bids [1]. It is totally different from the balancing market, as in Germany [6] and other countries [7], so there is no similar research outside China. At the same time, the spot market in China is still in its early stage, and the existing literature inside China is more focused on the analysis of a single energy market [8], a single DRS market [9], [10], or both the energy and reserve markets [11].

Therefore, cooperative bidding in the energy and DRS markets for a CHP plant is still not well studied [12]. However, along with deepened reform of the electricity market in China, cooperative bidding in the two markets will become an urgent issue for CHP plants in northern China.

Based on previous research [8], this paper presents a collaborative bidding strategy for flexible CHP plants with multiple types of units and heat storage for participating in the day-ahead energy and DRS market in Northeast China. The bidding strategy is based on the predicted spot energy price and deep downregulation compensation price and considers the CHP plant as a price taker. The bidding strategy consists of an optimal output decision model, output power range model, capacity segmentation model, marginal generation cost (MGC) model, marginal downregulation cost (MDRC) model, and bidding models in the two markets.

II. ANALYSIS OF BIDDING DECISION IN TWO MARKETS FOR FLEXIBLE CHP PLANTS

A. THE OPERATION PRINCIPLE OF THE DAY-AHEAD ENERGY MARKET

The day-ahead energy market in most pilots in China is similar to the PJM electricity market. The power capacity of the thermal plant must bid into the market, and the bid-winning volume in each period will be the generation plan for the next day. The bid-winning volume is calculated by the market trading center to minimize the power generation cost or maximize the social benefit according to the bids of all power plants. Medium- and long-term transactions are financial contracts for the price difference, the generation curves and prices of which only affect the settlement and do not affect the day-ahead generation plan.

The thermal power plants must submit the bidding curve every hour on the next day and technical parameters, such as minimum start-off time and ramp rate. The bidding is generally a monotonously increasing stepwise curve. According to the bidding information, the market is cleared by running the safety constrained unit commitment (SCUC) and the safety constrained economic dispatch (SCED) programs to determine and arrange the startup and shutdown plan and power generation plan of units and the price in each period of the next day to minimize the purchase cost.

B. THE OPERATION PRINCIPLE OF THE DAY-AHEAD DRS MARKET

After the spot market is cleared, a downregulation market is needed if there is wind or solar energy curtailment. In this market, the thermal power plant reducing its minimum output to less than the baseline should be compensated. The compensation price is determined by the bidding price of all plants and the demand for downregulation.

Stepwise bidding curves and marginal price settlement are usually adopted by the downregulation market [1], [5]. Thermal power plants are required to quote their downregulation capacity and compensation price at different levels at the same time as the energy market quotation. Northeast China selects two levels of bidding [1], and Shanxi Province selects three levels of bidding [5]. The first level of downregulation capacity is cleared first. Then, the second level is further cleared if there is still renewable energy curtailment. Each level is settled at marginal price.

In the downregulation market of Northeast China, the downregulation capacity is divided into two sections: the first section is \((0.4 – 0.5)P_{e,N}\), and the second section is \((0 – 0.4)P_{e,N}\), where \(P_{e,N}\) is the unit capacity. For example, the unit can participate in the first level if its output rate is 0.45, and the downregulation capacity is \((0.5 – 0.45)P_{e,N}\).
The corresponding bidding price range is 0–0.4 ¥/kWh. If the load rate is 0.3, the downregulation capacity at the first level is \((0.5 - 0.4)\gamma e_p\), the bidding price range of which is 0–0.4 ¥/kWh, and the downregulation capacity at the second level is \((0.4 - 0.3)\gamma e_p\), the corresponding bidding price range of which is 0.4–1.0 ¥/kWh.

All power plants operating under the baseline will obtain payment at the market-clearing price, while the payment for the reimbursement will be allocated proportionally to those plants operating at greater than the baseline during the downregulation period, as well as the wind and solar power plants, indicating that these plants purchase DRS from the plants that have undergone downregulation. The allocated payment is according to the revised power quantities of power plants. The revised power quantity model of the power plant is as follows:

\[
q^{\text{e}}_{\text{plant}} = \gamma e_p \\left\{ \begin{array}{ll}
\gamma_1 L^{e}_{\text{plant}} & \text{if } L_{\text{sys}} < \gamma e_p \text{ and } L_{\text{sys}} \leq 70\% \\
70\% \gamma_1 + \gamma e_p - 70\% & \text{if } 70\% < L_{\text{sys}} \leq 80\% \\
70\% \gamma_1 + 10\% \gamma_2 + \left( L^{e}_{\text{plant}} - 80\% \right) \gamma_3 & \text{if } L^{e}_{\text{plant}} > 80\% 
\end{array} \right.
\]

(1)

where \(\gamma e_p\) is the total capacity of the thermal power plant, \(\gamma_1\) is the unit time length, \(L_{\text{sys}}\) is the baseline of downregulation, \(L^{e}_{\text{plant}} = P^{e}_{\text{plant}} / P^{e}_{\text{plant}}\) is the actual output rate of the plant, \(P^{e}_{\text{plant}}\) is the power output, and \(\gamma_1, \gamma_2\) and \(\gamma_3\) are related correction coefficients.

### C. BIDDING CURVE IN THE TWO MARKETS

As mentioned above, there are two markets in the day-ahead spot market in some pilot provinces in North China: the energy market and the downregulation market. A thermal power plant must submit the stepwise bidding curve of power generation in the energy market, as shown by the blue stepwise type curve in Figure 1. It is also necessary to submit the downregulation capacity and bidding of each segment in the downregulation market, as shown by the green stepwise curve in Figure 1, where \(L^{e}_{\text{plant}}\) and \(L^{e}_{\text{plant}}\) represent the minimum and maximum output rates of the thermal plant, respectively. \(L^{e}_{\text{plant}}\) represents the upper boundary output rate of the first level downregulation (50%), which is the baseline \(L_{\text{sys}}\). \(L^{e}_{\text{plant}}\) is the upper boundary output rate of the second segment (40%).

### D. ANALYSIS OF BIDDING DECISIONS IN THE TWO MARKETS FOR FLEXIBLE CHP PLANTS

1) THE NECESSITY OF COLLABORATIVE BIDDING

Because of the improvement of the operational flexibility, a CHP plant in northern China often contains multiple types of units, such as traditional extraction condensing units, extraction condensing units that could operate under CLPT conditions, and extraction back-pressure units. In particular, the plant could be equipped with heat storage for heat-power decoupling [3], [13]. The generation plan of the CHP plant in the energy market will therefore affect the capacity, cost, and profitability of the subsequent downregulation market. For example, the stored heat could be released to improve the generating capacity of CHP units and obtain high profits during the high price period of the energy market, while during the low-price period, it could also improve the downregulation capacity of CHP units by reducing the lower limit of output and obtain high compensation in the downregulation market. Therefore, the CHP plant should consider the energy market and the downregulation market to maximize the overall profits in both markets when making a day-ahead decision.

2) PRICE TAKER MODEL IS THE BASIC FOR DECISION

Regarding the CHP plant in the market, it will compete as a price taker or a price maker [14]. When acting as a price maker, the bidding strategy is based on the predictions of competitors and arranges the generation plan for the plant and bidding curve based on the electricity price by the game equilibrium analysis method. When acting as a price taker, the bidding strategy is based on the predicted prices and arranges the optimal generation plan and bidding curve based on the MGC. Considering the limited behavior information about competitors in the initial stage of the spot market, it is more realistic to predict prices. Therefore, aiming to maximize the overall expected revenue of the plant in the spot market and downregulation market, this paper presents a cooperative bidding strategy on the role of price takers for CHP plants with multiple types of units and heat storage.

3) SUGGESTED BIDDING DECISION-MAKING PROCESS

The keys to the decision-making process are the optimal generation plan and the corresponding bidding curve. Heat storage has a time coupling characteristic, and its state affects the power output range of the CHP plant. In this regard, this paper proposes a step-by-step decision-making strategy. First, the optimal generation plan of the CHP units and operation plan of heat storage are determined based on the predicted prices of both markets. Second, according to the operation plan of heat storage, the maximum and minimum power output at all times of the next day, determining the output power range, is calculated. Then, the capacity of the output is segmented. The MGC of each segment capacity and MDRC are calculated, providing the basis for bidding prices.

4) RISK AVERSION OF PRICE UNCERTAINTIES IN THE PRICE-TAKER MODEL

As a price taker, the optimal strategy of the CHP plant should submit marginal cost curves [14], [15]. At every possible price of the energy market and downregulation market, the clearing result will be optimal. If the price is lower than the marginal cost of the subsection on the bidding curve, the subsection will not be selected and reverse the risk, and if the price is higher than the marginal cost of the subsection...
on the bidding curve, the subsection will be selected by the market and earn profits. Therefore, the bidding strategy in which a price taker should submit the marginal cost curve for each market is risk averse due to price uncertainty, and no other measure must be considered to avoid the risk.

III. THE BIDDING MODELS IN THE TWO MARKETS

It is assumed that the flexible CHP plant includes heat storage and three types of CHP units: a typical extraction condensing unit, an extraction back-pressure unit, and an extraction condensing unit with an LP turbine that could be flexibly cut off. Generally, the latter two types of units are retrofitted from the first type of unit [4], [16]. This structure is typical in northeast China.

As mentioned above, the bidding decision models include the optimal output decision model, power output range model, capacity segmenting model, and bidding models based on marginal costs for the two markets.

A. THE OPTIMAL OUTPUT DECISION MODEL

Considering the role of the price taker, with the operation constraints of each piece of equipment, the objective function is to maximize the overall profit in the two markets, as follows:

\[
    \sum_{t=1}^{T} \lambda_0^i P_{\text{plant},t} - \rho \left( \sum_{t=1}^{T} F_{\text{plant},t} + \alpha_{\text{HA}}(S_{\text{HA}}^T - S_{\text{HA}}^0) \right) + \max \left\{ \sum_{t=1}^{T} I_{\text{DDR}} \left( \sum_{d=1}^{D} \lambda_d^i \Delta P_{d,t} \right) \right\}
\]

where \( \lambda_0^i \) is the predicted electricity clearing price during period \( t \) of the next day (\$/MWh), \( T \) is the decision-making cycle, and \( F_{\text{plant}} \) is the total coal consumption of the CHP plant during period \( t \), which depends on the power and heat generation. \( \rho \) is the standard coal price (\$/t). \( S_{\text{HA}}^0 \) and \( S_{\text{HA}}^T \) represent the heat storage in the first and last periods, respectively, \( \alpha_{\text{HA}} \) is the coal consumption rate of the heat storage, and \( \alpha_{\text{HA}}(S_{\text{HA}}^T - S_{\text{HA}}^0) \) represents the equivalent coal consumption of the heat storage. \( I_{\text{DDR}} \) is a Boolean variable reflecting the demand for downregulation in period \( t \) of the next day. \( I_{\text{DDR}} = 0 \) represents no demand. \( \lambda_d^i \) is the allocated payment for the reimbursement, and \( \Delta P_{d,t} \) is the power quantity to share the payment during period \( t \), given by Equation (1). \( \lambda_d^i \) is the clearing price of the different levels in the downregulation markets \( d = 1, 2 \), and \( \Delta P_{d,t} \) is the downregulation power capacity of level \( d \) at period \( t \), as shown in Equations (3) and (4).

\[
    \Delta P_{1,t} = \max \left\{ \min \left( (L_{d1} - L_{d2}) P_{\text{e},N}^{\text{plant}}, L_{d1} P_{\text{e},N}^{\text{plant}} - P_{\text{e},t}^{\text{plant}} \right), 0 \right\}
\]

\[
    \Delta P_{2,t} = \max \left( L_{d2} P_{\text{e},N}^{\text{plant}} - P_{\text{e},t}^{\text{plant}}, 0 \right)
\]

1) THE CONSTRAINTS OF CHP UNITS

The feasible operation regions (FORs) of the extraction condensing unit, the extraction condensing unit that could operate CLP T and the extraction back-pressure unit are shown in Figure 2. The mathematical expression is as follows. In addition, this paper does not consider the constraint of the minimum start-off time because the coal-fired CHP units do not shut down during the heating period.

a: THE EXTRACTION CONDENSING UNIT (EX UNIT FOR SHORT)

The mathematical model for the FOR of the extraction condensing unit is shown in inequality (5), where \( P_{\text{e},t}^{\text{Ex},i} \) and \( P_{\text{h},t}^{\text{Ex},i} \) are the power and heat output of the extraction condensing unit \( i \), respectively. \( c_{\text{v},i} \) is the ratio of the power loss to the heat output when heating, and \( c_{\text{m},i} \) is the electric-heat ratio when unit \( i \) operates in the maximum extraction condition. \( P_{0,i}^{\text{e}} \) is a constant, \( P_{\text{e},\text{max},i}^{\text{Con}} \) and \( P_{\text{e},\text{min},i}^{\text{Con}} \) are the maximum and minimum power outputs of unit \( i \) under condensing conditions, respectively, and \( P_{\text{h},\text{max},i}^{\text{Ex}} \) is the maximum heating output.

\[
    \begin{aligned}
    P_{\text{e},t}^{\text{Ex},i} &\leq P_{\text{e},\text{max},i}^{\text{Con}} - c_{\text{v},i} P_{\text{h},t}^{\text{Ex},i} \\
    P_{\text{e},t}^{\text{Ex},i} &\geq \max \left\{ P_{0,i}^{\text{e}} + c_{\text{m},i} P_{\text{h},t}^{\text{Ex},i}, P_{\text{e},\text{min},i}^{\text{Con}} - c_{\text{v},i} P_{\text{h},t}^{\text{Ex},i} \right\} \\
    0 &\leq P_{\text{h},t}^{\text{Ex},i} \leq P_{\text{h},\text{max},i}^{\text{Ex}}
    \end{aligned}
\]
The ramp rates constraint is:

\[
\begin{cases}
(P_{\text{Ex-LC},i}^{e,t} + c_{v,i}p_{\text{Ex-LC},i}^{h,t}) - (P_{\text{Ex-LC},i}^{e,t-1} + c_{v,i}p_{\text{Ex-LC},i}^{h,t-1}) \leq P_{\text{up},i}^{t-1} \\
(P_{\text{Ex-LC},i}^{e,t-1} + c_{v,i}p_{\text{Ex-LC},i}^{h,t-1}) - (P_{\text{Ex-LC},i}^{e,t} + c_{v,i}p_{\text{Ex-LC},i}^{h,t}) \leq P_{\text{dn},i}^{t-1}
\end{cases}
\]

where \( P_{\text{up},i}^{t} \) and \( P_{\text{dn},i}^{t} \) represent the up and down ramp rates of extraction condensing unit \( i \), respectively.

b: THE EXTRACTION CONDENSING UNIT COULD OPERATE BY CLPT (EX-LC UNIT FOR SHORT)

The mathematical model for the FOR of the new type of extraction condensing unit is shown in inequality (7):

\[
0 \leq p_{1,p}^{h,t} \leq (1 - \gamma_{\text{LP},i}^{t})p_{\text{Ex,p}}^{h,\text{max}}
\]

\[
P_{1,p}^{e,t} \leq \max\left\{ (1 - \gamma_{\text{LP},i}^{t})p_{\text{Con,p}}^{e,\text{min}} - c_{v,p}p_{1,p}^{h,t}, c_{m,p}p_{1,p}^{h,t} + (1 - \gamma_{\text{LP},i}^{t})p_{0,p}^{e,t}\right\}
\]

\[
p_{2,p}^{h,t} \leq \gamma_{\text{LP},i}^{t}(P_{\text{Ex,p}}^{h,\text{max}} + \Delta P_{\text{LC,p}}^{h,t})
\]

\[
p_{2,p}^{h,t} \geq \gamma_{\text{LP},i}^{t}\left[p_{0,p}^{e,t} - (1 + c_{m,p}c_{v,p})\Delta P_{\text{LC,p}}^{h,t}\right] + c_{m,p}p_{2,p}^{h,t}
\]

\[
(P_{\text{Ex-LC,p}}^{e,t} + c_{v,p}p_{\text{Ex-LC,p}}^{h,t}) - (P_{\text{Ex-LC,p}}^{e,t-1} + c_{v,p}p_{\text{Ex-LC,p}}^{h,t-1}) \leq P_{\text{up},p}^{t-1}
\]

\[
(P_{\text{Ex-LC,p}}^{e,t-1} + c_{v,p}p_{\text{Ex-LC,p}}^{h,t-1}) - (P_{\text{Ex-LC,p}}^{e,t} + c_{v,p}p_{\text{Ex-LC,p}}^{h,t}) \leq P_{\text{dn},p}^{t-1}
\]

where \( p_{1,p}^{h,t} \) and \( p_{2,p}^{h,t} \) are the power and heat output of the new type of extraction condensing unit \( p \) at period \( t \), respectively. \( \gamma_{\text{LP},i}^{t} \) represents the state of the LP turbine of unit \( p \); “1” indicates cutting off mode, and “0” indicates cutting off mode. Considering that the manipulation of CLPT is flexible, there is no constraint on the number of \( \gamma_{\text{LP},i}^{t} \). The number is guided by the objective function and calculated by the model. In addition, the dynamics of the switching process between the two modes are not considered because the switching process can be finished in minutes, which is less than the trade period, such as one hour or half an hour. \( p_{1,p}^{h,t} \), \( p_{2,p}^{h,t} \), \( p_{1,p}^{h,t} \), and \( p_{2,p}^{h,t} \) represent the power and heat output of the unit in extraction and back-pressure conditions, respectively. \( \Delta P_{\text{LC,p}}^{h,t} \) is the heat output increased by CLPT when the steam intake of the unit remains unchanged.

c: THE EXTRACTION BACK-PRESSURE UNIT (EX-B UNIT FOR SHORT)

The mathematical model for the FOR of the extraction back-pressure unit is shown in inequality (9):

\[
\begin{cases}
P_{\text{Ex-B,j}}^{e,t} \leq \min\{c_{m1,j}P_{\text{Ex-B,j}}^{h,t} + \frac{c_{m1,j} + 1}{c_{m1,j}}P_{\text{Ex-B,j}}^{e,\text{max}} - P_{\text{Ex-B,j}}^{h,t}\}
\\P_{\text{Ex-B,j}}^{e,t} \geq \max\{c_{m2,j}P_{\text{Ex-B,j}}^{h,t} + \frac{c_{m1,j} + 1}{c_{m1,j}}P_{\text{Ex-B,j}}^{e,\text{min}} - P_{\text{Ex-B,j}}^{h,t}\}
\\P_{\text{Ex-B,j}}^{e,\text{min}} \leq \frac{c_{m1,j}}{c_{m1,j} + 1}P_{\text{Ex-B,j}}^{h,\text{max}} \leq P_{\text{Ex-B,j}}^{h,\text{max}}
\end{cases}
\]

where \( P_{\text{Ex-B,j}}^{e,t} \) and \( P_{\text{Ex-B,j}}^{h,t} \) are the power and heat output of the extraction back-pressure unit \( j \) at period \( t \), respectively. \( c_{m1,j} \) and \( c_{m2,j} \) are the electric-heat ratios when the unit is operating under back-pressure conditions and maximum extraction conditions, respectively. \( P_{\text{Ex-B,j}}^{e,\text{max}} \) and \( P_{\text{Ex-B,j}}^{e,\text{min}} \) are the maximum and minimum outputs of unit \( j \) under backpressure conditions, respectively. \( P_{\text{Ex-B,j}}^{h,\text{max}} \) is the maximum heat output.

The ramp rate constraint is:

\[
\begin{cases}
\frac{c_{m1,j}}{c_{m1,j} + 1}P_{\text{Ex-B,j}}^{e,t-1} + P_{\text{Ex-B,j}}^{h,t-1} \leq P_{\text{up},j}^{t-1} \\
\frac{c_{m1,j}}{c_{m1,j} + 1}P_{\text{Ex-B,j}}^{e,t-1} + P_{\text{Ex-B,j}}^{h,t-1} \leq P_{\text{dn},j}^{t-1}
\end{cases}
\]

where \( c_{m1,j}P_{\text{Ex-B,j}}^{e,t-1} + P_{\text{Ex-B,j}}^{h,t-1} \) represents the power under back-pressure conditions with equal coal consumption. \( P_{\text{up},j}^{t} \) and \( P_{\text{dn},j}^{t} \) represent the up and down ramp rates of the new Ex-B unit \( j \), respectively.

2) THE COAL CONSUMPTION

The coal consumption of a typical Ex unit and the new Ex-LC unit can be expressed as:

\[
F_{\text{Ex},i}^{t} = a_{i}(P_{\text{Ex-LC},i}^{e,t} + c_{v,i}P_{\text{Ex-LC},i}^{h,t}) + b_{i}(P_{\text{Ex-LC},i}^{e,t} + c_{v,i}P_{\text{Ex-LC},i}^{h,t}) + c_{i}
\]

where \( a_{i} \), \( b_{i} \), and \( c_{i} \) are coal consumption coefficients of the unit under condensing conditions.

The coal consumption function of the Ex-B unit is Equation (12):

\[
F_{\text{Ex-B,j}}^{t} = d_{j}\left(\frac{c_{m1,j}P_{\text{Ex-B,j}}^{e,t} + P_{\text{Ex-B,j}}^{h,t}}{c_{m1,j} + 1}\right)^{2} + b_{j}\left(\frac{c_{m1,j}P_{\text{Ex-B,j}}^{e,t} + P_{\text{Ex-B,j}}^{h,t}}{c_{m1,j} + 1}\right) + c_{j}
\]
where \( a_j, b_j \) and \( c_j \) are coal consumption coefficients of the extraction back-pressure unit under the back-pressure condition.

The total coal consumption of the CHP plant is as follows:

\[
F_{\text{plant}}^t = \sum_{i=1}^{n_1} F_{\text{Ex},i}^t + \sum_{p=1}^{n_2} F_{\text{Ex-LC},p}^t + \sum_{j=1}^{n_3} F_{\text{Ex-B},j}^t
\]  
(13)

where \( n_1, n_2, \) and \( n_3 \) are the number of Ex units, Ex-LC units and Ex-B units, respectively, included in the thermal power plant.

3) THE CONSTRAINT OF THE HEAT STORAGE

\[
\begin{align*}
S_{\text{HA}}^t - \eta_{\text{HA}} S_{\text{HA}}^{t-1} & \leq P_{\text{HA},c}^t, \\
\eta_{\text{HA}} S_{\text{HA}}^{t-1} - S_{\text{HA}}^t & \leq P_{\text{HA},i}^t, \\
S_{\text{HA}}^t & \leq S_{\text{HA}}^{\max}
\end{align*}
\]
(14)

where \( S_{\text{HA}}^{\max} \) is the capacity of the heat storage, and \( S_{\text{HA}}^t \) represents the stored heat at period \( t \). \( P_{\text{HA},c}^t \) and \( P_{\text{HA},i}^t \) are the maximum charging and discharging heat output, respectively. \( \eta_{\text{HA}} \) is the heat storing efficiency. Considering that the operating cost of the heat storage is included in the objective function, there is no need to set the constraint at the ending state of the storage, which is determined by the optimized operation result of the model.

4) THE CONSTRAINT OF HEAT BALANCE

\[
P_{\text{HA}}^t = \rho_{LD} \sum_{i=1}^{n_1} P_{\text{Ex},i}^t + \sum_{p=1}^{n_2} P_{\text{Ex-LC},p}^t + \sum_{j=1}^{n_3} P_{\text{Ex-B},j}^t
\]

\[
+ \left( \eta_{\text{HA}} S_{\text{HA}}^{t-1} - S_{\text{HA}}^t \right)
\]
(15)

where \( \rho_{LD} \) refers to the heat load of the CHP plant at period \( t \).

5) THE CONSTRAINT OF POWER OUTPUT

\[
P_{\text{plant}}^t = \sum_{i=1}^{n_1} P_{\text{Ex},i}^t + \sum_{p=1}^{n_2} P_{\text{Ex-LC},p}^t + \sum_{j=1}^{n_3} P_{\text{Ex-B},j}^t
\]  
(16)

B. THE POWER OUTPUT RANGE MODEL

According to the model described in Section IIIA, the optimal generation plan of the next day can be obtained, and the heat load of all units in the plant can be obtained by deducting the storage (or releasing) heat. With the heat load of units and Equations (3)-(8), (13) and (14) as the constraints, the maximum and minimum output of the CHP plant represented by (16) are the objective functions, which can obtain the output range of the plant at period \( t \).

\[
P_{\text{plant}}^{\text{t, max}} = \max \left( \sum_{i=1}^{n_1} P_{\text{Ex},i}^t, \sum_{p=1}^{n_2} P_{\text{Ex-LC},p}^t, \sum_{j=1}^{n_3} P_{\text{Ex-B},j}^t \right)
\]  
(17)

Based on Equations (17) and (18), the power output range of the CHP plant the next day can be obtained. To provide the stepwise bidding curves in the day-ahead market and downregulation market, it is still necessary to segment the output capacity and to calculate the marginal cost for each segment.

C. THE CAPACITY SEGMENTING MODEL

If the minimum load rate \( P_{\text{plant}}^{\text{e, t, min}} \) of the CHP plant is greater than the baseline load rate \( L_{\text{sys}} \) of the downregulation market at a certain period, it means that the plant has the ability to participate in the energy market but no ability to participate in the downregulation market. It is the most likely to be the actual optimal generation close to the output \( P_{\text{plant}}^{\text{e, t, *}} \) determined by the model in Section 3.1. The capacity is first divided into two segments by \( P_{\text{plant}}^{\text{e, t, *}} \). Then, each segment before and after \( P_{\text{plant}}^{\text{e, t, *}} \) is further segmented averagely according to the capacity limit of the spot market rule. The segmental outputs quoted by the CHP plant are described as \( P_{\text{plant}}^{(1) e, t} \), \( P_{\text{plant}}^{(2) e, t} \), \( P_{\text{plant}}^{(3) e, t} \) and \( P_{\text{plant}}^{(4) e, t} \), and the corresponding prices are \( M_1, M_2, \ldots, M_N \).

If the minimum load rate \( P_{\text{plant}}^{\text{e, t, min}} \) of the CHP plant at a certain period is lower than the baseline \( L_{\text{sys}} \), it means that the plant has the ability to participate in the downregulation market with a capacity between \( L_{\text{plant}}^{\text{sys}} \) and \( L_{\text{sys}} \). The capacity at each level of downregulation can be determined according to \( P_{\text{plant}}^{\text{e, t, min}} \) and the rule mentioned in Section II.C, as shown in Figure 1.

D. THE BIDDING MODELS FOR ENERGY MARKET AND DOWNREGULATION MARKET

As a price taker, the CHP plant should submit the MGC of each capacity segment to participate in the energy market while submitting the MDRC of the capacity below \( L_{\text{d1}} \) to participate in the downregulation market.

1) THE MGC MODEL

\[
M_n = \frac{\rho \left( F_{\text{plant}}(P_{n-1}^{\text{e, t}}), P_{\text{plant}}^{\text{e, t}}, P_{\text{plant}}^{\text{h, t}} \right) - F_{\text{plant}}(P_{n-1}^{\text{e, t}}, P_{n-1}^{\text{h, t}})}{P_{n}^{\text{e, t}} - P_{n-1}^{\text{e, t}}}
\]  
(19)

where \( n \) is the number of capacity segments participating in the energy market, \( n \in [2, N] \).

2) THE MDRC MODEL

When the CHP plant reduces the load rate from baseline \( L_{\text{d1}} \) to a certain load rate \( L_{\text{d1}}^{\text{e, 1}} \) in the downregulation period, the total cost of downregulation is the lost profit due to reducing the generation output:

\[
H_{\text{d1}} = \frac{\lambda_0 (L_{\text{d1}} - L_{\text{d1}}^{\text{e, 1}}) P_{\text{plant}}^{\text{e, t, min}} - \rho \cdot \Delta F_{\text{plant}}}{\tau}
\]  
(20)
where $\Delta F_{\text{plant}}^S$ is the saved coal consumption because of reducing the generation for downregulation, which can be obtained using Equation (13).

During the downregulation period, the CHP plant can participate in a certain level of downregulation when its minimum output rate $L_{\text{plant}}$ meets the following conditions.

- First level of downregulation: $L_{d2} \leq L_{\text{plant}} < L_{d1}$

In this situation, the CHP plant has participated in the DRS, the power capacity reduction is $(L_{d1} - L_{\text{plant}}) \cdot P_{e,N} \tau$, and the MDRC is:

$$C_1(L_{\text{plant}}) = \frac{H_{d1-1}}{(L_{d1} - L_{\text{plant}}) \cdot P_{e,N} \tau}$$

(21)

If $C_1(L_{\text{plant}})$ is higher than the upper price limit at this level, the gained reimbursement from the downregulation market will not be able to cover the total cost due to the downregulation, and the CHP plant could not participate in the downregulation market. Otherwise, the CHP plant would like to participate in this market, and the bidding of the first-level downregulation should be:

$$B_1 = \max(e_l^\min, C_1(L_{\text{plant}}))$$

(22)

where $e_l^\min$ is the lower price limit of the first-level downregulation.

- Second level of downregulation: $n0 \leq L_{\text{plant}} < 40\%$

In this situation, the CHP plant has the capability to participate in two levels of downregulation. The power capacity reduction provided by the plant to the first level is $(L_{d1} - L_{d2}) \cdot P_{e,N} \tau$. The corresponding MDRC can be calculated using Equation (21).

The second level of the downregulation capacity of the CHP plant to the downregulation market is $(L_{d2} - L_{\text{plant}}) \cdot P_{e,N} \tau$. The corresponding MDRC can be calculated by:

$$C_2(L_{\text{plant}}) = \frac{H_{d1-1} - MCP_1 \times (L_{d1} - L_{d2})P_{e,N} \tau}{(L_{d2} - L_{\text{plant}}) \cdot P_{e,N} \tau}$$

(23)

where $MCP_1$ is the market-clearing price of the first level.

If $C_2(L_{\text{plant}})$ is higher than the price cap of the second level (namely 1000 ¥/MWh), the CHP plant will not participate in the second level of DRS. However, if $C_1(40\%)$ is less than 400 ¥/MWh, the CHP plant will participate in the first level of DRS.

If $C_2(L_{\text{plant}})$ is higher than the price cap, the bidding of the two levels of downregulation capacity (as shown in Fig. 1) should be:

$$\begin{align*}
B_1 &= \max(C_1^\min, C_1(L_{d2})) \\
B_2 &= \max(C_2^\min, C_2(L_{\text{plant}}))
\end{align*}$$

(24)

IV. CASE STUDY

Based on the existing pilot spot market rules and Northeast downregulation market rules, this paper uses the aforementioned models to build day-ahead bidding strategies of two markets for a CHP plant in Northeast China. The optimization model is solved using IBM ILOG CPLEX software.

A. BASIC DATA

1) THE CHP PLANT DATA

The real CHP plant has 4 CHP units of 350 MW. Unit #1 was retrofitted into an extraction back-pressure unit. Unit #2 was retrofitted into a new extraction condensing unit that could operate CLPT mode. The FOR and operating parameters of each unit are detailed in Table 1. The standard coal price is 800 ¥/t.

| TABLE 1. The FOR and operating parameters of units. |
|---------------------------------------------------|
| Unit No. | #1 | #2 | #3 | #4 |
|-----------|----|----|----|----|
| Type      | EX-B | EX-LC | EX | EX |
| $p_{e,max}$ /MW | 297 | 350 | 350 | 350 |
| $p_{e,min}$ /MW | 120 | 140 | 140 | 140 |
| $p_{b,max}$ /MW | 508 | 511 | 359 | 359 |
| $P_e$ /MW | 0 | 110 | 110 | 110 |
| $\Delta P_{M,C}$ /MW | 57 | / | / | / |
| $\Delta P_{e,b}$ /MW | / | 37.6 | / | / |
| $C_1$ | / | 0.248 | 0.248 | 0.248 |
| $C_2$ | / | 0.4196 | 0.4196 | 0.4196 |
| $C_3$ | 0.6574 | / | / | / |
| $C_4$ | 0.4715 | / | / | / |
| $a \times 10^4$ (¥/MW$^2$-h) | 9.841 | 7.942 | 7.7 | 7.7 |
| $b$ (¥/MW-h) | 0.2996 | 0.2418 | 0.2389 | 0.2389 |
| $C$ (t/h) | 11.807 | 11.807 | 11.616 | 11.616 |

The heat load of the CHP plant is 1386 MW, which is approximately 80% of the maximum heating capacity of the units in the plant. It is assumed that the heat load remains constant over the day because the actual heating load generally changes slightly. The output range of the CHP plant is small, namely approximately 20% of the rated capacity, because of the high heat load. In the long term, the plant will be equipped with heat storage to improve its operational flexibility. The capacity of heat storage is set to be 7200 MW-h. The maximum charging and discharging power is 900 MW, which can fill or empty the heat storage for 8 hours and can supply heat to meet the demand of the highest heat load when the units operate at the minimum power point. The single-period loss rate of heat storage is 0.1%. It is assumed that the initial heat storage is 3600 MW-h and that there is no constraint on the ending state, depending on the demand.

2) DATA FOR THE TWO MARKETS

In light of the large-scale integration of wind and solar generation, the supply capacity will fluctuate greatly, and the electricity prices in the energy market will fluctuate more. This article analyzes an actual provincial grid of China, in which electricity prices are used, as shown in Figure 3. Considering that the electricity price will inevitably be lower than the MGC of coal-fired units in the condition of renewable energy
curtailment, it is assumed that the system has the requirement of DRS when the price is less than 150 ¥/MWh (from 2 to 4 a.m.).

Based on the trading rules of Northeast China, the baseline of downregulation is 50%. The load rate range of the first level is 50% to 40%, and the price range is 0 to 400 ¥/MWh. The load rate range of the second level is 40% to 0%, and the price range is 400–1000 ¥/MWh. The modification factors of thermal power plants participating in the payment allocation for the reimbursement, $k_1$, $k_2$ and $k_3$, are 1, 1.5, and 2, respectively.

**B. OPTIMAL OUTPUT PLAN ANALYSIS OF THE CHP PLANT**

Assuming that the system has a large demand for downregulation in the scenario shown in Figure 1, there are two levels of downregulation. The clearing price of the first level is set at 400 ¥/MWh, and that of the second level is 600 ¥/MWh.

In Figure 4(a), the blue curve represents the optimal power output plan of the CHP plant only participating in the energy market. The red dotted line represents the optimal output plan when participating in both the energy market and the downregulation market. The downregulation capacity is shown as the difference in the red dotted line and the first level baseline from 2 to 4 a.m., which is approximately 254 MW.

Figure 4(b) shows the states of heat storage when the CHP plant only participates in the day-ahead energy market or both markets.

It can be seen that heat storage releases more heat during the renewable energy curtailment period when the plant participates in the two markets than only in the energy market. This difference leads to a reduction in the heat load of CHP units in the plant, thereby reducing the minimum output of the plant to participate in the downregulation market to obtain more compensation. It shows the obviously different optimal operation plans in different markets. The downregulation market causes the CHP plant to reduce output and to integrate renewable energy during the period of renewable energy curtailment.

During the peak periods of electricity prices (10 a.m., 11 a.m., 7–9 p.m.), the heat storage releases the heat stored during the off-peak period of electricity prices. It increases the output of CHP units and gained more profits.

This outcome shows that the output decision-making model in this paper can reasonably optimize the operation plan of the plant according to the prices in the energy market and the downregulation market to maximize profits.

**C. OUTPUT RANGE ANALYSIS OF THE CHP PLANT**

Based on the heat storage operation determined by the optimal output decision, the output range of the CHP plant determined by the adjustment performance of the CHP units is shown as the dotted line in Figure 5. The solid line in the figure represents the optimal output generation plan considering the two markets.

The power output ranges of the CHP plant at different periods are different, affected by the heat storage status (as shown in Figure 4(b)). The optimal power output is at the lower bound of the output range to minimize the loss of generation when the predicted electricity price is less than the MGC (1–5 a.m.). However, it is at the upper bound of the output range when the electricity price is greater than the MGC (6 a.m.–11 p.m.) to maximize the income from generation.

**D. ANALYSIS OF CAPACITY SEGMENTATION AND BIDDING DECISIONS**

1) OUTPUT SEGMENTATION AND BIDDING DECISION IN THE ENERGY MARKET

After obtaining the power output range in each period, the power generation capacity greater the baseline of downregulation (50%) can be segmented according to the capacity
FIGURE 6. (a) Segmentation and bidding during peak price periods; (b) segmentation and bidding during lower price periods.

The segmentation model built in Section III.C. The market rules require that the number of segments does not exceed 5 and that the capacity of each segment does not exceed 10% of the rated capacity of the plant. The segmentation of the plant participating in the energy market during the price peak and valley periods is shown in Figure 6.

The bidding in each period is the MGC of each capacity segment calculated by formula (19). Therefore, the bidding is a stepwise curve, as shown in Figure 6. The electricity prices at 10 a.m. and 4 p.m. are the price peak periods of the day, shown as the red dotted lines in Figure 6, and all of the bids are accepted, indicating that the trading capacities are 1338 MW and 1111 MW, respectively. During periods of electricity prices less than the MGC, the trading capacity is 700 MW (50% \(P_{e,N}^{\text{plant}}\)), that is, the minimum power generation allowed by the energy market.

2) SEGMENTATION AND BIDDING DECISION IN THE DOWNREGULATION MARKET

According to Figure 5, the minimum power generation of the CHP plant can be reduced to 446 MW (approximately 32% of \(P_{e,N}^{\text{plant}}\)) during the price valley period (2–4 a.m.). The plant can participate in the two levels of downregulation. According to the market rules, the capacity for the first-level downregulation is 140 MW (50% \(P_{e,N}^{\text{plant}}\)) and the second-level capacity is 112 MW (40% \(P_{e,N}^{\text{plant}}\)).

According to Equations (21) and (23), the MDRC of the two levels of downregulation can be calculated and shown in Table 2.

| Time  | The first level | The second level |
|-------|----------------|-----------------|
|       | MDRC | the bidding | MDRC | the bidding |
| 2 a.m. | -0.172 | 0 | -0.835 | 0.4 |
| 3 a.m. | -0.202 | 0 | -0.902 | 0.4 |
| 4 a.m. | -0.17 | 0 | -0.735 | 0.4 |

The reason for the MDRC being negative is that the electricity price in the day-ahead energy market is less than that in the MGC in these periods, and downregulation can compensate for the generation loss. This finding shows that the electricity price of the energy market can encourage the plant to conduct downregulation, while the compensation from the downregulation market enhances the encouragement.

V. CONCLUSION

This paper studied the bidding strategy of a flexible CHP plant with multiple types of CHP units and heat storage participating in a day-ahead market composed of the energy market and DRS market. Based on predicted energy prices and downregulation compensation prices, bidding decision models for the flexible CHP plant to participate in the two markets collaboratively were proposed as a price taker. These models are validated based on realistic data from the CHP plant in Northeast China. The conclusions are as follow.

Compared with only participating in the energy market, the optimal output decision results of the CHP plant participating in both the day-ahead energy market and downregulation market are significantly different. Compensation in the downregulation market greatly improves the enthusiasm of plants to provide downregulation. It also promotes the accommodation of renewable energy.

The state of heat storage will significantly affect the output range of the CHP plant in each period. The proposed models in this paper can optimize the coordinated operation of multiple types of units and heat storage and maximize the overall profit of the plant in both the energy market and the downregulation market.

The bidding models proposed can provide the bidding curves in the energy market and the bidding prices in the downregulation market for the flexible CHP plant. They could provide a decision-making tool for flexible CHP plants to formulate operating strategies under the combined energy and downregulation market.

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HE CUI was born in Liaoyang, Liaoning, in 1994. He received the bachelor’s degree in agricultural electrification and automation from Shenyang Institute of Engineering. Since 2016, he has been working with the State Grid Liaoning Electric Power Company Ltd. He was admitted to the School of Information and Electrical Engineering, Shenyang Agricultural University, majoring in power systems. Since 2019, he has been involved in the writing of a book and seven articles. His work content and research direction concern power system marketing.

KUN SONG received the master’s degree in power systems and automation from Northeast Electric Power University, in 2007. He obtained the Senior Engineer qualification, in 2013. His research interests included the technology of energy and electricity development and power system planning and design.

WENLEI DOU was born in Liaoyang, Liaoning, in 1979. He received the bachelor’s degree in electrical automation from Shenyang Agricultural University, in 2001. He currently works with State Grid Liaoning Electric Power Company Ltd. He is an Expert in distribution network planning, construction, and operation and photovoltaic power grid connection.

ZHE NAN was born in Shenyang, Liaoning, in 1984. He received the master’s degree in agricultural electrification and automation from Shenyang Agricultural University, in 2010.

Since 2010, he has been performing research work with the Planning Review Center and Technological Economic Center, Economic and Technical Research Institute, Liaoning Electric Power Company Ltd., State Grid Corporation of China. He is the author of three books, more than 20 articles, and more than ten inventions. His research interests include large-scale power grid transient and steady-state analysis, power grid planning, energy planning and other medium- and long-term planning research, engineering construction technology, and economic research.

ZHENG WANG was born in Linghai, Liaoning, in 1980. He received the bachelor’s degree in electrical automation from Shenyang Agricultural University, in 2001. He currently works with State Grid Liaoning Electric Power Company Ltd. He is an Expert in distribution network planning, construction, and operation and photovoltaic power grid connection.

NA ZHANG was born in Jinzhou, Liaoning, in 1986. She received the Ph.D. degree in electric power systems and their automation from Dalian University of Technology, Dalian, China, in 2014. She is currently working as a Senior Engineer and the Vice Director of the Strategic Development Research Center, Liaoning Electric Power Company Ltd., Economic Research Institute. Her research interests include integrated energy system planning, clean energy absorption and application technology, and the electric power market.

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HE CUI was born in Liaoyang, Liaoning, in 1994. He received the bachelor’s degree in agricultural electrification and automation from Shenyang Institute of Engineering. Since 2016, he has been working with the State Grid Liaoning Electric Power Company Ltd. He was admitted to the School of Information and Electrical Engineering, Shenyang Agricultural University, majoring in power systems. Since 2019, he has been involved in the writing of a book and seven articles. His work content and research direction concern power system marketing.

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