Joint Bidding Decision of Wind Farms and Energy Storage Based on Newsvendor Model

Xinyue SUN

*School of Economics and Management, Nanjing University of Science and Technology, Nanjing
210094, China*

E-mail: 119107010748@njust.edu.cn

Jian LIU*

*School of Economics and Management, Nanjing University of Science and Technology, Nanjing
210094, China*

E-mail: jianlau@njust.edu.cn

Meng OU

*School of Economics and Management, Nanjing University of Science and Technology, Nanjing
210094, China*

E-mail: meng@njust.edu.cn

Yanyan LIU

*School of Economics and Management, Nanjing University of Science and Technology, Nanjing
210094, China*

E-mail: liuyy@njust.edu.cn

Abstract Currently, renewable energy generation has received more and more attention. This article focuses on wind energy generation, one of the renewable energy sources. Aiming at the intermittent and unpredictable wind power problems, according to the day ahead bidding mechanism in the power market, this paper introduces the energy storage system to maximize wind power merchants profit based on the newsvendor model. First, this paper focuses on the wind farms combined with storage system to put forward the optimal bidding decision of selling or buying electricity to the market one day in advance and the optimal bidding amount. Then, we analyze the relationship between the optimal bid amount and the market penalty price coefficient, government subsidy, storage system charge and discharge efficiency, and other parameters. Based on the analysis of various parameters, power generation companies can make reasonable bidding decisions and amount to maximize profits.

Keywords wind farms; energy storage; optimization and scheduling; newsvendor model; power market

1 Introduction

Recently, wind power, based on its mature technology and the subsidy policy provided by the government^[1], will surely get faster development. However, wind power generation has

Received November 19, 2020, accepted February 9, 2021

Supported by the National Natural Science Foundation of China (71671092, 72071112)

*Corresponding author

great instability due to heavily dependence on weather^[2], thus it is very difficult for wind power plants to accurately predict the future power supply under the day-ahead bidding mechanism of the electricity market^[3, 4]. Besides, the electricity supply and demand must be matched in real time^[5], therefore how to deal with the deviation between their bidding volume and the actual power generation volume is particularly important.

In order to maintain stability of the electricity market, the power market manager will adopt a penalty mechanism: When the actual amount of electricity produced by the generator deviates from the bidding, the merchant will be punished^[6] by the market manager (i.e., Independent System Operator). Thus, wind power producers may face penalty risks when participating in market bidding due to the uncertainty of wind power generation, which will affect their revenue. For example, if the wind farm in the electricity market is a supplier, and its actual power generation does not reach the bid volume, they need to compensate for the power shortage by the method of purchasing additional electricity from the market at a price higher than the current electricity price, and this part of the purchase expenditure serves as a penalty. Instead, if the supplier provides the market with more electricity than the bid amount, a certain fee is also required to consume the excess electricity^[7]. In the power market, for each power supplier participating in the bidding, the ideal strategy is to maximize its own profits^[8], so it is very important to make accurate bidding decisions as well as volume.

In view of the unpredictability and uncertainty of wind power generation, in order to meet the requirements of real-time matching of power supply and demand, an effective strategy is to combine with power storage systems^[9]. One of the functions of the storage system is to smooth power supply fluctuations^[10]. When the power is insufficient to meet the market demand, the storage system discharges to meet the remaining demand, and when the power exceeds, the excess power is stored in the system for backup. The second function of the power storage system is to postpone the sale of electricity. When participating in the power market, merchants will firstly estimate future electricity prices. If the predicted price is higher, they may store the power generated and even buy additional electricity from the market to store at the current stage and sell it at a higher price in the future so as to obtain higher profits^[4]. In short, the use of power storage systems can help improve the utilization rate of the company's generation, reduce penalties, and increase revenue. Thus, merchants will not only bid to sell electricity, but also bid to purchase. Thus, how to make the bidding decision is the main problem for merchants with both wind farms and storage systems. This paper will use the newsvendor model to study the joint optimization bidding problem.

Concerning the joint optimization of the wind farm and energy storage system, most papers mainly study the dispatch strategy through different methods. For example, Castronuovo and Lopes proposed a discrete hourly optimization algorithm to maximize daily profits to determine the optimal daily operating strategy for wind turbines and hydroelectric power generation^[11]. Garcia-Gonzalez, et al. used two-stage stochastic programming to solve the optimal decision-making scheme of the joint operation of wind power generation and pumped storage^[12]. Richmond, et al. considered the wind storage model to slow power supply and solve it by Markov decision process to minimize the overall cost^[13]. Grillo, et al. modeled renewable energy as a Markov chain and design an optimal scheduling strategy for energy storage

devices to minimize energy cost and network loss^[14]. Kiedanski, et al. adopted a sequential stochastic decision-making process to develop a wind farm control scheme with combined battery storage^[15]. Hashmi, et al. used a convex relaxation method to optimize battery storage and renewable energy power generation based on the energy arbitrage problem^[16]. All follows the principle that merchants buy electricity from the market to store when the market electricity demand and the electricity price are low, and generate electricity to sell when they are high^[17]. Different from electricity dispatch strategy, we focus on the bidding problem of the merchants with a wind farm and storage systems.

Regarding power bidding, most papers focus on the bidding strategies of power generation merchants, including using Bayesian game models to study the bidding strategies of power companies under incomplete information^[18]; using artificial neural networks to predict the bidding behavior of other power suppliers, and propose the power supplier's bidding price after assessing the risk^[19]; adopting stochastic dual dynamic programming to deal with the uncertainty of wind power output and power spot market prices to solve power bidding and operation planning problems^[20], etc. This article mainly uses the newsvendor model to study the bidding decision and bidding volume problem.

The traditional newsvendor problem is mainly about how to make optimal decisions on product ordering and inventory in the face of the uncertainty of market demand, such as: A continuous time newsvendor model to determine the optimal inventory level for commodities in an established financial market^[21]; the newsvendor model used to study the optimal order quantity in the context of suppliers recovering the leftover products of retailers and selling them again afterwards^[22]; using distributional robust optimization (DRO) to model a general class of newsvendor problems with unknown demand distribution^[23], and so on. Based on the unpredictability of the wind power supplier, this paper uses the newsvendor model to study the optimal bidding decision and volume of merchants with wind plants and storage systems. The difference from the traditional classic model is that this article mainly considers the uncertainty of the supplier.

The novelty of this work is that the newsvendor model is from the perspective of the supplier, and we model the bidding problem from 3 perspectives. The contribution is that the optimal bidding decision and volume are given, and the properties of the relevant parameters of the bidding volume are analyzed respectively. The relationships between the optimal joint bidding amount and the market punishment mechanism, the transmission efficiency, the charging/discharging efficiency of energy storage system and the government subsidy amount under different circumstances are obtained. Based on the analysis results, management enlightenment is proposed for the joint operators of wind power generation and power storage.

The remainder of this paper is organized as follows. The situation classification and notation are expressed in Section 2. Section 3 introduces the model and solution analysis for joint bidding of selling electricity. Section 4 is the model and solution analysis for joint bidding of purchasing electricity when there is no additional electricity demand, while model and solution where there is additional electricity demand are in section 5. The corresponding management enlightenment and possible future developments of this work as well as the conclusion are outlined in Section 6.

2 Situation Classification and Notation

For the power market, since the power producers bid one day in advance, it is assumed that the electricity price for the next day is predicted to be p at the time of bidding for the wind farm, meanwhile, the selling price of electricity is predicted to be γ after the next day, and the line transmission efficiency is η . Let α and β represent the charging efficiency and discharging efficiency of storage facility, respectively. In the context of joint optimization of power plant and power storage system, in order to maximize profits, bidding decisions are classified based on the situation of future electricity prices:

1) Where $\gamma\alpha\beta \leq p$, i.e., (the profit from the sale of the electricity generated in the current period is greater than the profit from the system being stored for later sale), the bidding decision of the wind power producer is to sell the electricity to the market (i.e., sell the electricity). At the same time, taking into account the penalty in the electricity market, if the actual generating capacity is insufficient to meet the bidding quantity and thus causes deviation, the penalty coefficient of the power shortage is assumed to be $k(k > 1)$, that is, the additional purchase of the failing power at a price higher than the market price is required to achieve the real bidding power; When the bid quantity is less than the actual generating capacity and the excess capacity cannot be accommodated by the power storage system, resulting in a waste of power, the penalty factor for the surplus is l (Without loss of generality, $0 < l < k$), i.e., the penalty cost for the additional power.

2) Where $\gamma\alpha\beta > p$, i.e., (the wind power producer anticipates that the profit from storing the current generated electricity for later sale will be greater than the profit from direct sale), its bidding decision is to store the generated electricity into its own power storage system for later sale. And based on the size of the remaining capacity of energy storage, they will decide whether to buy part of the electricity for later sold at higher prices (i.e., buy electricity). At the same time, based on the question of whether the remaining space of the electricity storage system after the electricity has been stored in the current period can meet the bid to purchase electricity, considering the effect of the penalty, when the generator finds that the remaining space of the storage system is not enough to accommodate all bid purchase, the generator's actual purchase of electricity will be less than the bidding amount, and a penalty fee will be paid for the unpurchased part by the power shortage penalty coefficient $k(k > 1)$; If the amount of electricity left is sufficient for the bidding amount and there is still room, then there is a question of whether to continue the purchase. i.e., if the actual amount of electricity purchased exceeds the bidding amount, the penalty cost shall be paid by the power surplus penalty factor $l(0 < l < k)$. When the power generator bids to purchase insufficient power to fill the power storage system, it will compare the penalties that need to be paid for continuing the purchase $\frac{lp}{\alpha\beta\eta^2}$ with the predicted value of the later power price γ . When $\frac{p}{\alpha\beta} < \gamma < \frac{lp}{\alpha\beta\eta^2}$, that is, the sale of electricity at a later stage will not be enough to cover the current penalty payment for continuing to purchase the electricity. The generator will not continue to purchase the electricity, and purchase according to the bidding quantity; when $\gamma > \frac{lp}{\alpha\beta\eta^2}$, that is, the later price of electricity is enough to make up for the current penalty paid for continuing to purchase electricity, and the generator will buy additional power from the market to fill the system, even if a certain penalty is required. Thus, there are two different scenarios in which power producers

choose to buy electricity.

Thus, there are three different scenarios based on the magnitude of the relationship between the predicted price for the second day and the price for a certain time after the second day when bidding. Under the background of joint optimization of power plant and power storage system in this paper, it will take $X_{\bar{j}}$ as the joint bidding amount of wind power plant one day in advance, $i = 1, 2, 3$, that is, the joint bidding amount corresponding to three different situations, where: $X_{J_i} > 0$ means selling electricity, and $X_{J_i} < 0$ means buying electricity. Correspondingly, assuming that the power generation cost of wind power plant is $\mathcal{C}$, the actual power generation is y , and the probability density function of wind power is $f(y)$, this article follows the assumptions of Kim, Powell and Densing^[10, 24]: The wind output of the wind power plant follows a uniform distribution, that is, y obeys a uniform distribution:

$$f(y) = \begin{cases} \frac{1}{G_{\max} - 0}, & 0 \leq y \leq G_{\max}, \\ 0, & \text{otherwise,} \end{cases} \quad (1)$$

where $G_{\max}$ is the upper limit of wind power generation (constrained by the physical conditions of the wind power generation unit), and 0 is the lower limit which means that there exists no wind or wind turbines are not working.

For the power storage system combined with wind farms, its own properties during operation should be taken into account. Assuming the existing power of the power storage system is E at the initial state, the unit cost of the electric energy stored in the current system is m , and the upper limit of the capacity of the power storage system is $C_{\max}$. Based on the current national subsidy policies of new energy power generation, this article assumes that when wind power companies sell electricity, they will receive subsidies for the actual electricity sold on the market^[25, 26], that is, wind power companies can obtain unit subsidy costs S . However, if the wind power plant chooses to buy electricity and store it as a situation for re-selling electricity to obtain profit later, no subsidy will be get.

3 Model Construction and Solution Analysis for Selling Electricity Through Joint Bidding

3.1 Model Construction

When $\gamma\alpha\beta \leq p$, that is, when the power generation company chooses to store the current electricity in the system for later sales, the profit obtained is less than the profit obtained from the current sale, the power generation merchant will directly bid to sell the electricity generated.

1) When $X_{J1} > E\beta\eta + y\eta$, that is, $y < \frac{X_{J1}}{\eta} - E\beta$, the bidding amount is greater than the sum of the actual power generation and the complete discharge of the power storage system. Because the bidding amount X_{J1} cannot be completed, the actual electricity sent to the market is $y\eta + E\beta\eta$, the income obtained is $p \cdot (y\eta + E\beta\eta)$, and the corresponding government subsidy is $s \cdot (y\eta + E\beta\eta)$. At the same time, companies need to pay the cost of power generation, including the cost of wind power cy and the cost of the initial state energy of the power storage system mE . Since the delivery cannot be made according to the amount, the company must pay a

penalty for the shortage $kp(X_{J1} - E\beta\eta - y\eta)$. Therefore, the profit function is

$$\Pi_1 = \int_0^{\frac{X_{J1}}{\eta} - E\beta} [p(y\eta + E\beta\eta) - cy - mE - kp(X_{J1} - E\beta\eta - y\eta) + s(y\eta + E\beta\eta)] f(y) dy. \quad (2)$$

2) When $y\eta \leq X_{J1} \leq E\beta\eta + y\eta$, i.e., $\frac{X_{J1}}{\eta} - E\beta \leq y \leq \frac{X_{J1}}{\eta}$, the bidding amount is more than the actual power generation but less than the sum of the actual power generation and the complete discharge of the power storage system, that is, the power generation company can release part of the power in the power storage system to deliver the power order X_{J1} . Thus, the company's income is $p \cdot X_{J1}$, the corresponding government subsidy is $s \cdot X_{J1}$, the cost of wind power is cy , and the cost of energy in the initial state of the power storage system is mE . The remaining part of the electricity after the discharge of the power storage system can be used for future discharge to obtain income $\gamma\beta\eta \left(E - \frac{X_{J1} - y\eta}{\beta\eta}\right)$. This article assumes that the future discharge of income is part of the profit at this stage. Therefore, the profit function is:

$$\Pi_2 = \int_{\frac{X_{J1}}{\eta} - E\beta}^{\frac{X_{J1}}{\eta}} \left[pX_{J1} - cy - mE + \gamma\beta\eta \left(E - \frac{X_{J1} - y\eta}{\beta\eta} \right) + sX_{J1} \right] f(y) dy. \quad (3)$$

3) When $0 \leq y - \frac{X_{J1}}{\eta} \leq \frac{C_{MAX} - E}{\alpha}$, i.e., $\frac{X_{J1}}{\eta} \leq y \leq \frac{C_{MAX} - E}{\alpha} + \frac{X_{J1}}{\eta}$, at this time, the actual power generation of the wind power plant is more than the bidding amount, and there is a power surplus $y\eta - X_{J1}$. All the surplus power can be stored in the power storage system, so there is no penalty for excess electricity consumption. At this time, the excess power is stored in the power storage system for future discharge to obtain profits $\gamma\alpha\beta\eta \left(y - \frac{X_{J1}}{\eta}\right) + \gamma\beta\eta E$. Therefore, the profit function is:

$$\Pi_3 = \int_{\frac{X_{J1}}{\eta} - E\beta}^{\frac{X_{J1}}{\eta}} \left[pX_{J1} - cy - mE + \gamma\alpha\beta\eta \left(y - \frac{X_{J1}}{\eta} \right) + \gamma\beta\eta E + sX_{J1} \right] f(y) dy. \quad (4)$$

4) When $y - \frac{X_{J1}}{\eta} > \frac{C_{MAX} - E}{\alpha}$, i.e., $y > \frac{C_{MAX} - E}{\alpha} + \frac{X_{J1}}{\eta}$, the actual power generation is more than the bid-sale power, after the power market order is delivered according to the amount, there is a power surplus. The difference between this situation and [3] is that the surplus power cannot be completely stored by the power storage system, so you need to pay a penalty for this part of the electricity $lp\eta \left(y - \frac{X_{J1}}{\eta} - \frac{C_{MAX} - E}{\alpha}\right)$. The electricity stored in the power storage system is used for future discharge to obtain revenue $\gamma\beta\eta C_{MAX}$. Therefore, the profit function is:

$$\Pi_4 = \int_{\frac{C_{MAX} - E}{\alpha} + \frac{X_{J1}}{\eta}}^{G_{max}} \left[pX_{J1} - cy - mE + \gamma\beta\eta C_{MAX} - lp\eta \left(y - \frac{X_{J1}}{\eta} - \frac{C_{MAX} - E}{\alpha} \right) + sX_{J1} \right] f(y) dy. \quad (5)$$

Therefore, the total expected profit function of wind power plants is:

$$\begin{aligned}
& E_1(\Pi) \\
&= \Pi_1 + \Pi_2 + \Pi_3 + \Pi_4 \\
&= \int_0^{\frac{X_{J1}}{\eta} - E\beta} [p(y\eta + E\beta\eta) - cy - mE - kp(X_{J1} - E\beta\eta - y\eta) + s(y\eta + E\beta\eta)] f(y)dy \\
&\quad + \int_{\frac{X_{J1}}{\eta} - E\beta}^{\frac{X_{J1}}{\eta}} \left[pX_{J1} - cy - mE + \gamma\beta\eta \left(E - \frac{X_{J1} - y\eta}{\beta\eta} \right) + sX_{J1} \right] f(y)dy \\
&\quad + \int_{\frac{X_{J1}}{\eta}}^{\frac{C_{\max}}{\alpha} - E_L + \frac{X_{J1}}{\eta}} \left[pX_{J1} - cy - mE + \gamma\alpha\beta\eta \left(y - \frac{X_{J1}}{\eta} \right) + \gamma\beta\eta E + sX_{J1} \right] f(y)dy \\
&\quad + \int_{\frac{C_{\max}}{\alpha} - E + \frac{X_{J1}}{\eta}}^{G_{\max}} \left[pX_{J1} - cy - mE + \gamma\beta\eta C_{\max} \right. \\
&\quad \quad \left. - lp\eta \left(y - \frac{X_{J1}}{\eta} - \frac{C_{\max} - E}{\alpha} \right) + sX_{J1} \right] f(y)dy. \tag{6}
\end{aligned}$$

3.2 Optimal Solution and Property Analysis

The goal of the enterprise is to maximize the expected profit, so the optimization solution of Equation (5) (that is, the first-order partial derivative) can be obtained:

$$\begin{aligned}
\frac{\partial E_1(\Pi)}{\partial X_{J1}} &= -(kp + p + lp + s) \int_0^{\frac{X_{J1}}{\eta} - E\beta} f(y)dy - (\gamma + lp) \int_{\frac{X_{J1}}{\eta} - E\beta}^{\frac{X_{J1}}{\eta}} f(y)dy \\
&\quad - (\gamma\alpha\beta + lp) \int_{\frac{X_{J1}}{\eta}}^{\frac{C_{\max}}{\alpha} - E + \frac{X_{J1}}{\eta}} f(y)dy + (p + lp + s). \tag{7}
\end{aligned}$$

The second-order partial derivative of Equation (7) with respect to X_{J1} is

$$\begin{aligned}
\frac{\partial^2 E_1(\Pi)}{\partial^2 X_{J1}} &= -\frac{1}{\eta}(kp + p + s - \gamma)f\left(\frac{X_{J1}}{\eta} - E\beta\right) - \frac{1}{\eta}(\gamma - \gamma\alpha\beta)f\left(\frac{X_{J1}}{\eta}\right) \\
&\quad - \frac{\gamma\alpha\beta + lp}{\eta}f\left(\frac{C_{\max}}{\alpha} - E + \frac{X_{J1}}{\eta}\right). \tag{8}
\end{aligned}$$

Obviously, the second-order partial derivative is less than 0, so the original function has a maximum value X_{J1}^* that satisfies $\frac{\partial E_1(\Pi)}{\partial X_{J1}^*} = 0$, that is:

$$\begin{cases}
-(kp + p + lp + s) \int_0^{\frac{X_{J1}^*}{\eta} - E\beta} f(y)dy - (\gamma + lp) \int_{\frac{X_{J1}^*}{\eta} - E\beta}^{\frac{X_{J1}^*}{\eta}} f(y)dy, \\
-(\gamma\alpha\beta + lp) \int_{\frac{X_{J1}^*}{\eta}}^{\frac{C_{\max}}{\alpha} - E + \frac{X_{J1}^*}{\eta}} f(y)dy + (p + lp + s) = 0, \\
f(y) = \begin{cases} \frac{1}{G_{\max} - 0}, & 0 \leq y \leq G_{\max}, \\ 0, & \text{otherwise.} \end{cases}
\end{cases} \tag{9}$$

The optimal bidding amount is:

$$X_{J1}^* = \frac{\eta}{\alpha(kp + p + s + lp)} \cdot [E\alpha\beta(kp + p + s) + Elp - (\gamma\alpha\beta + lp)C_{\max} + (p + s + lp)\alpha G_{\max}]. \quad (10)$$

The results show that under the goal of profit maximization, the optimal joint bidding amount is related to the transmission efficiency of the power line, the penalty coefficient, the amount of government subsidies and the attributes of the power storage system. Therefore, according to equation (10), property analysis of each parameter can be obtained as follows:

$$\left\{ \begin{array}{l} \frac{\partial X_{J1}^*}{\partial k} = - \frac{-p \int_0^{\frac{X_{J1}^*}{\eta} - E\beta} f(y) dy}{-\frac{1}{\eta}(kp + p + s - \gamma)f\left(\frac{X_{J1}^*}{\eta} - E\beta\right) - \frac{1}{\eta}(\gamma - \gamma\alpha\beta)f\left(\frac{X_{J1}^*}{\eta}\right) - \frac{\gamma\alpha\beta + lp}{\eta}f\left(\frac{C_{\max} - E}{\alpha} + \frac{X_{J1}^*}{\eta}\right)} < 0, \\ \frac{\partial X_{J1}^*}{\partial l} = - \frac{p \int_{\frac{G_{\max} - E}{\alpha} + \frac{X_{J1}^*}{\eta}}^{G_{\max}} f(y) dy}{-\frac{1}{\eta}(kp + p + s - \gamma)f\left(\frac{X_{J1}^*}{\eta} - E\beta\right) - \frac{1}{\eta}(\gamma - \gamma\alpha\beta)f\left(\frac{X_{J1}^*}{\eta}\right) - \frac{\gamma\alpha\beta + lp}{\eta}f\left(\frac{C_{\max} - E}{\alpha} + \frac{X_{J1}^*}{\eta}\right)} < 0, \\ \frac{\partial X_{J1}^*}{\partial \eta} = - \frac{\frac{X_{J1}^*}{\eta^2}(kp + p + s + lp)f\left(\frac{X_{J1}^*}{\eta} - E\beta\right) + \frac{X_{J1}^*}{\eta^2}(\gamma + lp)[f\left(\frac{X_{J1}^*}{\eta}\right) - f\left(\frac{X_{J1}^*}{\eta} - E\beta\right)] + \frac{X_{J1}^*}{\eta^2}(\gamma\alpha\beta + lp)[f\left(\frac{C_{\max} - E}{\alpha} + \frac{X_{J1}^*}{\eta}\right) - f\left(\frac{X_{J1}^*}{\eta}\right)]}{-\frac{1}{\eta}(kp + p + s - \gamma)f\left(\frac{X_{J1}^*}{\eta} - E\beta\right) - \frac{1}{\eta}(\gamma - \gamma\alpha\beta)f\left(\frac{X_{J1}^*}{\eta}\right) - \frac{\gamma\alpha\beta + lp}{\eta}f\left(\frac{C_{\max} - E}{\alpha} + \frac{X_{J1}^*}{\eta}\right)} > 0, \\ \frac{\partial X_{J1}^*}{\partial k} = - \frac{p \int_{\frac{X_{J1}^*}{\eta} - E\beta}^{G_{\max}} f(y) dy}{-\frac{1}{\eta}(kp + p + s - \gamma)f\left(\frac{X_{J1}^*}{\eta} - E\beta\right) - \frac{1}{\eta}(\gamma - \gamma\alpha\beta)f\left(\frac{X_{J1}^*}{\eta}\right) - \frac{\gamma\alpha\beta + lp}{\eta}f\left(\frac{C_{\max} - E}{\alpha} + \frac{X_{J1}^*}{\eta}\right)} < 0. \end{array} \right. \quad (11)$$

The following properties can be obtained by formula (11).

Proposition 1 The optimal bidding amount X_{J1}^* decreases monotonically with the power shortage penalty price coefficient k . When k increases, the company will pay more penalties due to shortages, so the power generation company will reduce bids to ensure that electricity is provided in accordance with the bidding amount required by the market, reduce the probability of default, and maintain the stability of the power system; when k decreases, the bidding amount will increase, and companies will pay less penalties due to shortages. Therefore, power generation companies will increase their bids and strive for market share as much as possible, in order to obtain greater profits by selling more electricity.

Similarly, the optimal bidding amount X_{J1}^* increases monotonically with the power surplus penalty price coefficient l . When l increases, the company will pay more penalties for the surplus power actually issued. Therefore, the company will increase the bidding amount to reduce the power surplus that may occur the next day; when l decreases, the company will conservatively estimate their real-time power generation capacity the next day to provide a smaller bidding amount, as far as possible to ensure that the amount can be delivered.

Obviously, the optimal bidding amount X_{J1}^* increases monotonically with the line transmission efficiency η . When η increases, the transmission efficiency of the line increases, and the power plant can sell more power to the market with the same power generation. On the contrary, when η decreases, the power plant's bidding will decrease under the same power generation forecast. At the same time, the optimal bidding amount X_{J1}^* is positively correlated with the unit subsidy S provided by the government. When S increases, the amount of sub-

sidy increases, and the bidding of power plants will increase; conversely, when S decreases, the bidding of power plants will also decrease.

Therefore, to determine the optimal bidding amount to maximize profits, power generation companies need to consider the above parameters and adjust the bidding amount.

4 Model Construction and Solution Analysis When There Is No Additional Electricity Demand Under the Condition of Purchasing

4.1 Model Construction

When $\gamma\alpha\beta > p$, i.e., the power generation company predicts that the profit obtained by storing the current electricity in the system for later sales is greater than the profit obtained from the current sale, the generator will plan to store the current power generation, and continue to purchase part of the electricity from the market into the energy storage system for later sale at a higher price. When $\frac{p}{\alpha\beta} < \gamma < \frac{ip}{\alpha\beta\eta^2}$, that is, after purchasing electricity according to the bidding amount, there is still capacity remaining in the storage system. Because the additional purchased electricity needs to pay a part of the penalty, and the cost will be higher than the profit obtained from later selling. Therefore, the firm will not purchase electricity from the market even if the amount of electricity purchased is not fully charged.

1) When $C_{\max} - (E + y\alpha) > 0$, and $-X_{J2} \leq \frac{C_{\max} - (E + y\alpha)}{\alpha\eta}$, i.e., $y \leq \frac{C_{\max} - E + X_{J2}\alpha\eta}{\alpha}$, $X_{J2} < 0$, the power y generated by the plant is stored in the electricity storage, and there is still space $C_{\max} - (E + y\alpha)$ left, and the company's planning bid to purchase electricity X_{J2} is less than the remaining space of the electricity storage. At this time, the cost of the generator includes the cost of power generation cy , initial storage cost mE and power purchase cost pX_{J2} , so the expected benefit is $\gamma\beta\eta(-X_{J2}\alpha\eta + E + y\alpha)$, since no additional power is purchased, the profit function at this time is:

$$\Pi_1 = \int_0^{\frac{C_{\max} - E + X_{J2}\alpha\eta}{\alpha}} [\gamma\beta\eta(-X_{J2}\alpha\eta + E + y\alpha) - cy - mE + pX_{J2}] f(y) dy. \quad (12)$$

2) When $C_{\max} - (E + y\alpha) > 0$ and $-X_{J2} > \frac{C_{\max} - (E + y\alpha)}{\alpha\eta}$, that is, $\frac{C_{\max} - E + X_{J2}\alpha\eta}{\alpha} < y < \frac{C_{\max} - E}{\alpha}$. At this time, after all the power of the power plant is stored in the electricity storage, there is still space, but it is not enough to accommodate the amount of electricity the enterprise plans to bid for. The actual cost of power purchase is $p\left(\frac{C_{\max} - E - y\alpha}{\alpha\eta}\right)$. For a part of the electricity that will be purchased less than the bidding amount, the penalty $kp\left(-X_{J2} - \frac{C_{\max} - E - y\alpha}{\alpha\eta}\right)$ should be paid with the power shortage penalty coefficient k . The revenue function at this time is:

$$\Pi_2 = \int_{\frac{C_{\max} - E + X_{J2}\alpha\eta}{\alpha}}^{\frac{C_{\max} - E}{\alpha}} \left[\gamma C_{\max} \beta \eta - cy - mE - p\left(\frac{C_{\max} - E - y\alpha}{\alpha\eta}\right) - kp\left(-X_{J2} - \frac{C_{\max} - E - y\alpha}{\alpha\eta}\right) \right] f(y) dy. \quad (13)$$

3) When $C_{\max} - (E + y\alpha) \leq 0$ and $-X_{J2} > \frac{C_{\max} - (E + y\alpha)}{\alpha\eta}$, i.e., $y \geq \frac{C_{\max} - E}{\alpha}$. At this time, after storing all the power of the power plant in the storage system, there is no remaining space,

and there will be surplus power. Therefore, not only can the company not purchase electricity as planned, but also put the surplus power of the power plant in the market at this stage. So, the revenue function is:

$$\Pi_3 = \int_{\frac{C_{\max}-E}{\alpha}}^{G_{\max}} \left[\gamma C_{\max} \beta \eta - cy - mE - kp\eta \left(y - \frac{C_{\max}-E}{\alpha} \right) + kpX_{J2} \right] f(y) dy. \quad (14)$$

Thus, the total profit function of wind power generator is:

$$\begin{aligned} E_2(\Pi) &= \Pi_1 + \Pi_2 + \Pi_3 \\ &= \int_0^{\frac{C_{\max}-E+X_{J2}\alpha\eta}{\alpha}} [\gamma\beta\eta(-X_{J2}\alpha\eta + E + y\alpha) - cy - mE + pX_{J2}] f(y) dy \\ &\quad + \int_{\frac{C_{\max}-E}{\alpha}}^{\frac{C_{\max}-E+X_{J2}\alpha\eta}{\alpha}} \left[\gamma C_{\max} \beta \eta - cy - mE - p \left(\frac{C_{\max}-E-y\alpha}{\alpha\eta} \right) \right. \\ &\quad \left. - kp \left(-X_{J2} - \frac{C_{\max}-E-y\alpha}{\alpha\eta} \right) \right] f(y) dy \\ &\quad + \int_{\frac{C_{\max}-E}{\alpha}}^{G_{\max}} \left[\gamma C_{\max} \beta \eta - cy - mE - kp\eta \left(y - \frac{C_{\max}-E}{\alpha} \right) + kpX_{J2} \right] f(y) dy. \end{aligned} \quad (15)$$

4.2 Optimal Solution and Property Analysis

Similar to solving formula (7), the optimal solution of formula (15) can be obtained as follows:

$$X_{J2}^* = \frac{1}{\alpha\eta} \left(\frac{-kp\alpha G_{\max}}{-\gamma\alpha\beta\eta^2 + p - kp} + E - C_{\max} \right). \quad (16)$$

Similarly, when a generator chooses to purchase electricity from the power market for storage and future sales, the optimal purchase bidding amount of the joint system is also related to the line transmission efficiency of the electricity, the charging efficiency of the electricity storage system, and the two penalty coefficients. Analyzing the formula (16), we can get $\frac{\partial X_{J2}^*}{\partial k} > 0$ and $\frac{\partial X_{J2}^*}{\partial \eta} > 0$, and the following properties can be obtained.

Proposition 2 *The difference from Property 1 is that the optimal bidding amount X_{J2}^* increases monotonically with the power shortage penalty price coefficient k . When k increases, the power generation company will pay more penalties for not fulfilling the purchase order in accordance with the amount, because the decision of the power generation company at this time is to buy electricity, that is, $X_{J2}^* < 0$, the optimal bidding purchase amount X_{J2}^* increases, i.e., the company will reduce the bidding purchase amount. On the contrary, when k decreases, the power generation company will increase the bidding for electricity purchase to ensure that the electricity storage system can be fully charged. The similarity with property 1 is that the optimal bidding amount X_{J2}^* increases monotonically with the line transmission efficiency η . When η increases, the transmission efficiency increases. When the company estimates that the same amount of electricity purchased for storage, the amount of electricity that needs to be purchased will decrease, that is, X_{J2}^* increase; the same goes for the reverse.*

5 Model Construction and Solution Analysis When There Is Additional Electricity Demand Under the Condition of Purchasing

5.1 Model Construction

When $\gamma\alpha\beta > p$, and $\gamma > \frac{lp}{\alpha\beta\eta^2}$, it indicates that there is still capacity surplus in the storage system after purchasing electricity according to the bidding amount. At this time, if additional electricity is purchased, a certain penalty will be paid, and the cost can be made up by the profit obtained from the later sales. Therefore, when the bidding power is not enough to fill the battery, even if the penalty is needed, the generator will still purchase additional power from the market.

When $C_{\max} - (E + y\alpha) > 0$, and $-X_{J3} \leq \frac{C_{\max} - (E + y\alpha)}{\alpha\eta}$, i.e., $y \leq \frac{C_{\max} - E + X_{J3}\alpha\eta}{\alpha}$, all the power of the power plant is stored in the storage system, and there is still space left. Because the forecast of future electricity price is very high, even if the generator needs to pay penalty $lp \frac{C_{\max} - E - y\alpha + X_{J3}\alpha\eta}{\alpha\eta}$ for the extra purchased power with the power surplus penalty price coefficient l , they will still choose to continue to purchase so as to make the power storage system full. At this time, the revenue function is as follows:

$$\Pi_1 = \int_0^{\frac{C_{\max} - E + X_{J3}\alpha\eta}{\alpha}} \left[\gamma C_{\max}\beta\eta - cy - mE + pX_{J3} - lp \frac{C_{\max} - E - y\alpha + X_{J3}\alpha\eta}{\alpha\eta} \right] f(y) dy. \quad (17)$$

The revenue function of the other two cases is similar to (4.1.2) and (4.1.3), and the total profit function of wind power generator is shown as follows:

$$\begin{aligned} E_3(\Pi) &= \Pi_1 + \Pi_2 + \Pi_3 \\ &= \int_0^{\frac{C_{\max} - E + X_{J3}\alpha\eta}{\alpha}} \left[\gamma C_{\max}\beta\eta - cy - mE + pX_{J3} - lp \frac{C_{\max} - E - y\alpha + X_{J3}\alpha\eta}{\alpha\eta} \right] f(y) dy \\ &\quad + \int_{\frac{C_{\max} - E}{\alpha}}^{\frac{C_{\max} - E + X_{J3}\alpha\eta}{\alpha}} \left[\gamma C_{\max}\beta\eta - cy - mE - p \left(\frac{C_{\max} - E - y\alpha}{\alpha\eta} \right) \right. \\ &\quad \left. - kp \left(-X_{J3} - \frac{C_{\max} - E - y\alpha}{\alpha\eta} \right) \right] f(y) dy \\ &\quad + \int_{\frac{C_{\max} - E}{\alpha}}^{G_{\max}} \left[\gamma C_{\max}\beta\eta - cy - mE - lp\eta \left(y - \frac{C_{\max} - E}{\alpha} \right) + kpX_{J3} \right] f(y) dy. \end{aligned} \quad (18)$$

5.2 Model Solving and Property Analysis

Similar to the solution of formula (7), the solution of formula (18) is obtained, i.e., the optimal solution:

$$X_{J3}^* = \frac{1}{\alpha\eta} \left(\frac{-\alpha k G_{\max}}{1 - k - l} + E - C_{\max} \right). \quad (19)$$

Similarly, under the goal of profit maximization, the optimal bidding amount of the combined system is related to the transmission efficiency of the power line, the charging efficiency of the power storage system and the two penalty coefficients. Similarly, by analyzing formula (19), we can obtain $\frac{\partial X_{J3}^*}{\partial k} > 0$, $\frac{\partial X_{J3}^*}{\partial l} < 0$, $\frac{\partial X_{J3}^*}{\partial \eta} > 0$, and thus obtain the following properties:

Proposition 3 *Similar to property 2, the optimal bidding amount X_{j3}^* monotonically increases with penalty price coefficient k and transmission efficiency η , differing from property 2, the optimal bidding amount X_{j3}^* is also related to the power surplus penalty price coefficient l . The difference between this property and property 1 is that X_{j3}^* decreases monotonically with the penalty price coefficient l . When l increases, the enterprise will pay more penalty for purchasing electricity from the market. Because the bidding decision does not purchase electricity, i.e., $X_{j3}^* < 0$, so the decrease of X_{j3}^* means that the enterprise will increase the bidding purchase amount to minimize the probability of additional power purchase; However when l decreases, the enterprise will reduce the bidding purchase amount.*

6 Conclusion

From the perspective of wind power enterprises, concerning the uncertainty and unpredictable characteristics of wind power generation, in order to maximize the profits of power producers as the optimization goal, this paper introduces the power storage system to smooth the supply fluctuation of wind power generation and studies the joint optimization strategy of wind power plants and power storage systems and finally obtains the corresponding day-ahead bidding decision and amount.

According to the prediction of future electricity price, there are two kinds of decision for power producers: Selling or purchasing electricity, corresponding to three scenarios. The premise for power producers to decide whether to bid to sell or purchase electricity is based on the ability to accurately predict future electricity prices. When power producers decide to sell electricity, the decision on the joint bidding amount should be adjusted according to relevant parameters, such as the penalty coefficients of the market and the unit subsidy of the government. If the power shortage penalty price coefficient increases, the optimal bidding amount should be appropriately reduced, and when the power surplus penalty price coefficient increases, the optimal bidding amount should be appropriately increased; When the unit subsidy of the government increases, the optimal bidding amount should also be appropriately increased. When power producers decide to purchase electricity, the decision on the joint tender amount should also be adjusted according to the changes of relevant parameters: In the case of no additional electricity purchase, when the penalty price coefficient increases, the enterprise should appropriately reduce the bidding purchase amount. In this case, the optimal bidding amount is independent of the power surplus penalty price coefficient, while in the case of additional electricity purchase, when increases, the enterprise should reduce the bidding purchase amount appropriately; when the penalty price coefficient increases, the enterprise should increase the bidding purchase amount. Besides in the random case, the optimal bidding amount is also related to the prediction probability of the three scenarios. At the same time, power producers should also improve the transmission efficiency of power lines and reduce the loss cost. As for the power storage equipment, they should also pay attention to the impact of the charging and discharging efficiency of the storage system on the profits, and should find ways to improve the charging and discharging efficiency, reduce the charge and discharge loss, and increase the power utilization rate of enterprises.

In this paper, the newsvendor model is used to study the power dispatching and optimization problem, but this paper does not consider the multi-period optimization problem of power storage. In the future, we will use a multi-period newsvendor model or dynamic programming method to further analyze on the situation of multiple periods. Moreover, in the actual situation, there may be negative price in the electricity market which will affect the storage strategy of the power producers. Therefore, we will also study the case of negative price to optimize the solution. In this paper, enterprises only submit planned sales or planned purchases to the market. It is also our future research problem to study the combination strategy of submitting bidding amount and price at the same time.

References

- [1] Yang X, He L, Xia Y, et al. Effect of government subsidies on renewable energy investments: The threshold effect. *Energy Policy*, 2019, 132: 156–166.
- [2] Qi W, Liang Y, Shen Z J. Joint planning of energy storage and transmission for wind energy generation. *Operations Research*, 2015, 63(6): 1280–1293.
- [3] Hassler M. Heuristic decision rules for short-term trading of renewable energy with co-located energy storage. *Computers & Operations Research*, 2017, 83: 199–213.
- [4] Zhou Y, Scheller-Wolf A, Secomandi N, et al. Managing wind-based electricity generation in the presence of storage and transmission capacity. *Production and Operations Management*, 2019, 28(4): 970–989.
- [5] Machi B, Zanoni S, Pasetti M. Multi-period newsvendor problem for the management of battery energy storage systems in support of distributed generation. *Energies*, 2019, 12(23): 1–13.
- [6] Jiang D R, Powell W B. Optimal hour-ahead bidding in the real-time electricity market with battery storage using approximate dynamic programming. *INFORMS Journal on Computing*, 2015, 27(3): 525–543.
- [7] Cigdem E. A newsvendor approach to energy imbalance mechanism in a day ahead electricity market. Bilkent University, 2017.
- [8] Wang Q, Guan Y, Wang J. A chance-constrained two-stage stochastic program for unit commitment with uncertain wind power output. *IEEE Transactions on Power Systems*, 2012, 27(1): 206–215.
- [9] Eyer J, Corey G. Energy storage for the electricity grid: Benefits and market potential assessment guide: A study for the DOE energy storage systems program. Sandia: Sandia National Laboratories, 2010: 1–153.
- [10] Kim J H, Powell W B. Optimal energy commitments with storage and intermittent supply. *Operations Research*, 2011, 59(6): 1526–5463.
- [11] Castronuovo E D, Lopes J A P. On the optimization of the daily operation of a wind-hydro power plant. *IEEE Transactions on Power Systems*, 2004, 19(3): 1599–1606.
- [12] Garcia-Gonzalez J, Moraga R, Santos L M, et al. Stochastic joint optimization of wind generation and pumped-storage units in an electricity market. *IEEE Transactions on Power System*, 2008, 23(2): 460–468.
- [13] Richmond N, Jacko P, Makowski A M. Optimal planning of slow-ramping power production in energy systems with renewables forecasts and limited storage. 2014 International Conference on Probabilistic Methods Applied to Power Systems (PMAPS), Durham, 2014: 1–6.
- [14] Grillo S, Pievatolo A, Tironi E. Optimal storage scheduling using Markov decision processes. *IEEE Transactions on Sustainable Energy*, 2016, 7(2): 755–764.
- [15] Kiedanski D, Kofman D, Horta J, et al. Strategy-proof local energy market with sequential stochastic decision process for battery control. 2019 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT), 2019.
- [16] Hashmi M U, Deka D, Bušić A, et al. Arbitrage with power factor correction using energy storage. *IEEE Transactions on Power Systems*, 2020, 35(4): 2693–2703.
- [17] Bradbury K, Pratson L, Patino-Echeverri D. Economic viability of energy storage systems based on price arbitrage potential in real-time U.S. electricity markets. *Applied Energy*, 2014, 114: 512–519.
- [18] Heredia F, Rider M J, Corchero C. Optimal bidding strategies for thermal and generic programming units in the day-ahead electricity market. *IEEE Transactions on Power Systems*, 2010, 25(3): 1504–1518.
- [19] Abapour S, Mohammadi-Ivatloo B, Hagh M T. A Bayesian game theoretic based bidding strategy for

- demand response aggregators in electricity markets. *Sustainable Cities and Society*, 2020, 54.
<https://doi.org/10.1016/j.scs.2019.101787>.
- [20] Pinto T, Sousa T M, Praça I, et al. Support Vector Machines for decision support in electricity markets' strategic bidding. *Neurocomputing*, 2016, 172: 438–445.
 - [21] Wozabal D, Rameseder G. Optimal bidding of a virtual power plant on the Spanish day-ahead and intraday market for electricity. *European Journal of Operational Research*, 2020, 280(2): 639–655.
 - [22] Ding H, Pinson P, Hu Z, et al. Integrated bidding and operating strategies for wind-storage systems. *IEEE Transactions on Sustainable Energy*, 2016, 7(1): 163–172.
 - [23] Fard F A, He J, Ivanov D, et al. A utility adjusted newsvendor model with stochastic demand. *International Journal of Production Economics*, 2019, 211: 154–165.
 - [24] Densing M. Dispatch planning using newsvendor dual problems and occupation times: Application to hydropower. *European Journal of Operational Research*, 2013, 228(2): 321–330.
 - [25] Rahimian H, Bayraksan G, Homem-de-Mello T. Controlling risk and demand ambiguity in newsvendor models. *European Journal of Operational Research*, 2019, 279(3): 854–868.
 - [26] Mostard J, Teunter R. The newsboy problem with resalable returns: A single period model and case study. *European Journal of Operational Research*, 2006, 169(1): 81–96.