# Optimal trading decision of wind power supply chain based on insurance mechanism under uncertainty of supply and demand

## Wang Hui, Wang Junjie, Wang Tengfei

*Abstract* — **With the new round of power system reform, the participation in the power market competition is the only way to eliminate renewable energy such as wind power. Due to wind power output is affected by natural conditions such as wind speed, the output has strong uncertainty, which makes its actual output difficult to predict, which makes wind power suppliers face huge profit risks in participating in the power market. Reasonably transferring the market risk of wind power providers and introducing effective risk aversion mechanisms are of great significance to improving the stability of wind power providers' returns. Therefore, based on the power loss insurance mechanism, this paper establishes the Stackelberg game model of wind power suppliers, electricity sales companies and insurance companies, solves the Nash equilibrium by inverse recursive method, analyzes the relationship between insurance premium rate and market tripartite profit, and obtains the market subject wind power. Optimal trading decisions for commerce, electricity sales companies and insurance companies. Finally, through the analysis of specific examples, it is concluded that the introduction of the electricity insurance mechanism and the establishment of appropriate insurance rates will enable the interests of wind power suppliers, power sales companies and insurance companies to achieve a win-win situation.**

*Index Terms*—**wind power supplier, uncertainty, insurance mechanism, benefit win-win.**

## I. INTRODUCTION

In recent years, the global environmental and energy issues have become prominent, making intermittent renewable energy based on wind power and photovoltaics widely concerned and rapidly developed worldwide[1]. According to statistics from the World Wind Energy Association, as of the end of 2018, the cumulative installed global wind power capacity reached 596,556MW, of which China's installed wind power capacity was 216,870MW, ranking first in the world. On May 15, 2019, the National Development and Reform Commission and the National Energy Administration jointly issued the "Notice on Establishing and Perfecting a Renewable Energy Power Consumption Guarantee Mechanism" to accelerate the construction of a clean, low-carbon, safe and efficient energy system and promote the development of renewable energy.

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Use [3] to encourage the whole society to increase the development and utilization of renewable energy. In the future, the proportion of renewable energy consumption will continue to grow rapidly. However, as an important renewable energy power, wind power output is uncertain and the technology for predicting wind power output is not mature at this stage, which makes wind power companies participate in the power market and compete with traditional power generators to co-exist with great revenue risks. Therefore, it is of great practical significance to solve the problem of uncertainty risks faced by wind power suppliers participating in the power market.

Literature [4] proposed different models of wind power consumption schemes from the overall market structure, providing a reference and reference for large-scale wind power consumption nationwide. Reference [5-6] used the method of balanced market to solve the deviation of bidding output of wind power suppliers. Reference [7] introduced a demand response trading market to deal with the bidding deviation of wind power suppliers in the previous market, which improved the system's ability to absorb wind power. However, at present, it is technically impossible to accurately predict the output of wind power. These methods cannot completely eliminate the risk of uncertainty in the output of wind power companies participating in market competition. Therefore, wind power companies participating in the market competition urgently need to find a risk management tool to transfer and diversify the market risks they face. What can adapt to the randomness and uncertainty of risk is the insurance mechanism, and the existence of risk is the natural basis for the emergence and development of the insurance industry. The insurance mechanism accumulates the benefits of normal conditions to meet the need for compensation when losses occur, and distributes and transfers the losses from time and space. Therefore, the introduction of insurance mechanisms into the power sector came into being. Prior to this, many scholars have made corresponding research foundations. At the earliest stage of the reform of electricity marketization, reference [9] analyzed the feasibility of introducing income insurance for power generation enterprises. Through a specific example analysis of a province's electricity market, it was concluded that the operating income of power generators became more stable after the insurance was insured, and market price fluctuations were avoided. Risk of lost revenue. Reference [10] aimed at the uncertainty of water quantity of specific power producers' hydropower plants, and introduced independent insurance mechanisms to

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improve the market competitiveness of hydropower plants. The literatures [11-12] consider the introduction of insurance theory to manage risk on the demand side in the direct purchase of electricity by large users. In essence, the large users directly sign the electricity contract with the power grid company as the insurer to obtain the best reserve capacity. , Improve the reliability of power supply during the power purchase process, and reduce the power loss of large users. Documents [13-14] introduced reliability insurance and business interruption insurance from the aspects of power supply reliability and power quality, respectively. The insurance mechanism effectively dispersed the risk of electricity consumption by users, and achieved a win-win situation for both power supply and consumption.

The above scholars introduced the insurance mechanism into the traditional energy generation side and the electricity consumption side in the research of the electricity market, and they have obtained a win-win situation of supply and demand on both sides of the insurance mechanism. This paper draws on the successful experience of the above scholars, based on the method of introducing insurance mechanisms in the supply and demand uncertainty supply chain based on the literature [14-16], combining the uncertainty of the wind power supplier's output with the uncertainty of the demand faced by the electricity sales company, this paper studies wind power suppliers In the renewable energy supply chain consisting of electricity sales companies and users, insurance mechanisms are introduced to analyze the impact of insurance mechanisms on wind power companies and electricity sales companies participating in market decisions.

## II. MARKET STRUCTURE OF WIND POWER SUPPLY CHAIN UNDER THE ELECTRICITY INSURANCE MECHANISM

The output of wind turbines is affected by factors such as climate and has large fluctuations, which leads to uncertainty in wind power output. This makes the bidding power of wind power companies in the medium- and long-term contract market different from the actual power delivered, which allows wind power companies to participate. The electricity market has brought risks, and thus introduced insurance mechanisms, making insurance companies a risk sharer for wind power providers. Taking into account the characteristics of wind power providers, this paper proposes an independent type of insurance suitable for wind power providers-power loss insurance. The so-called power loss insurance is that the wind power company through the insurance company to guarantee their power after participating in the power market bidding. The insurer and the insurance company agree on an amount of electricity in the power loss insurance contract. When the amount of electricity generated is less than this amount, the insurance company will give the insurer corresponding compensation[10].

It is assumed that the information of the wind power supplier and the electricity supplier is symmetrical. They are both risk-neutral, and each of them seeks to maximize their expected profits. The transaction structure of the entire wind power supply chain under the power

insurance mechanism is shown in Figure 1. Wind power companies participate in bidding for the medium and long-term contract market, and under the PPA model, they sign bilateral contracts with electricity sales companies in the medium and long-term contract market. Wind power companies first estimate their power generation capacity based on natural conditions such as climate and wind speed, and then bid for electricity $q$ in mid-to-long-term contracts. However, the instability of wind power output results in only $\eta q$ amount of electricity can be realized, and the electricity sales company purchases all the electricity that the wind power company finally realizes according to the contract price $\lambda$ signed by the wholesale market. This article assumes that $\eta(0 \leq \eta \leq 1)$ is a non-negative continuous random variable, whose probability density function is $g(\cdot)$, the cumulative distribution function is $G(\cdot)$, the mean is $u$, and the variance is $\sigma^2$.
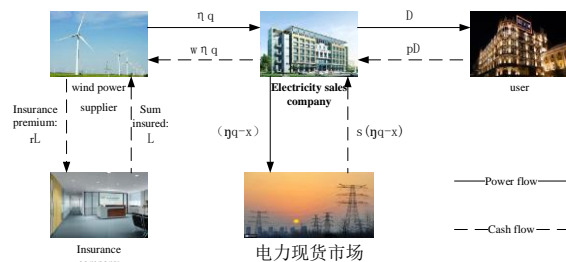


Fig.1 Wind power supply chain under uncertainty of supply and demand based on insurance mechanism

## III. PROFIT MODELS OF MARKET ENTITIES UNDER THE ELECTRICITY INSURANCE MECHANISM

### A. Profit model of electricity retail companies

The power sales company and the wind power supplier signed a wholesale contract in the medium- and long-term contract market. The contract confirmed that the power sales company purchased the actual power of the wind power supplier at the wholesale electricity price $\lambda$. The market demand for renewable energy electricity for electricity sales companies is $x$, which obeys the distribution $D$ (the probability density is $f(x)$, cumulative distribution function is $F(x)$). The electricity sales company determines the price $(p元/MW \cdot h)$ of renewable energy power.

If $\eta q > x$, then the electricity sales company can sell the excess electricity on the spot market at a price $(s元/MW \cdot h)$ to obtain additional profits; if $\eta q \leq x$, the electricity sales company has a loss of power shortage, and the total power loss is $s(x - \eta q)$. After determining the distribution function of the wholesale price and market demand, whether the wind power supplier is insured or not, the expected profit function of the electricity sales company remains unchanged. Then the profit function and expected profit function of the electricity sales company are as follows:

$$\pi_D(q) = \begin{cases} px + s(\eta q - x) - \lambda \eta q, \eta q > x \\ p\eta q - s(x - \eta q) - \lambda \eta q, \eta q < x \end{cases} \quad (1)$$

$$E[\pi_D(q)] = \int_0^1 \{ p[\int_0^{yq} xf(x)dx + \int_{yq}^1 yqf(x)dx]$$
$$+ syq - \lambda yq - s\int_0^{+\infty} xf(x)dx\}dG(y) \quad (2)$$
$$= puq + suq - \omega uq - sE(x)$$
$$- p\int_0^1 [\int_0^{yq} F(x)dx]dG(y)$$

### B. Wind power supplier profit model

The wind power supplier bids for electricity $q$, the electricity $\eta q$ actually sold to the electricity company, and the fuel cost of wind power is 0, that is, there is no marginal cost. The investment cost of the wind power plant construction process and the operating cost of the operation period are converted into parameters $c$ ($c$ =0.5 ~ 0.6). the cost of power generation is $cq$.

The profit function of a wind power supplier before insurance and without considering the risk of output uncertainty is:

$$\pi_{s1}(\lambda) = \lambda q - cq \quad (3)$$

The actual profit function and expected profit function of the wind power supplier before taking out the insurance and considering the output uncertainty risk are:

$$\pi_{s2}(\lambda) = \lambda \eta q - cq \quad (4)$$
$$E[\pi_{s2}(\lambda)] = \lambda uq - cq \quad (5)$$

Therefore, subtracting formula (4) from formula (3) to obtain the profit loss of wind power companies before insurance is:

$$L = (1-\eta)\lambda q \quad (6)$$

In order to stabilize the revenue and reduce losses in participating in the electricity market competition, wind power companies consider signing power loss insurance with insurance companies to reduce their own market risks. Wind power companies deliver insurance premiums to insurance companies, among which insurance companies weigh the various factors for insurance premium rates. This is the maximum amount of compensation that a wind power company may receive after the electricity loss agreed between the wind power company and the insurance company, so the insurance company's insurance compensation amount is.
Then the actual profit function and expected profit function of the wind power supplier after insurance is as follows:

$$\pi_s(\lambda, I) = \lambda \eta q - cq - rI + \min\{L, I\},$$
$$0 \le r \le 1, 0 \le I \le \omega q \quad (7)$$

$$E[\pi_s(\lambda, I)] = \lambda uq - cq - rI + \int_0^{1-I/\lambda q} IdG(y)$$
$$+ \int_{1-I/\lambda q}^1 \lambda q(1-y)dG(y) \quad (8)$$

### C. Profit model of insurance companies

When a wind power company purchases power loss insurance from an insurance company, the insurance company will invest the premiums insured by the wind power company. Assuming the insurance company's insurance yield is, the profit function of the insurance company is:

$$\pi_C(r) = rI + \alpha rI + \min\{L, I\},$$
$$L = (1-\eta)\omega q, 0 \le r \le 1, 0 \le I \le \omega q \quad (9)$$

### D. Optimal decision of market players under the electricity insurance mechanism

The optimal decisions of e-commerce, electricity sales companies, and insurance companies are as follows. See the appendix for the solution process.

a) the wholesale wind price before the insurance:

$$\lambda_1^* = \frac{pau + (p+s)(b-a)u + (b-a)c}{2(b-a)u} \quad (10)$$

b) the electricity sales amount signed by the wind power supplier before the insurance:

$$q_1^* = \frac{pau + (p+s)(b-a)u - (b-a)c}{2p(u^2 + \sigma^2)} \quad (11)$$

c) the expected profit of the wind power supplier and the electricity supplier before the insurance is, respectively:

$$E[\pi_{s2}(\lambda_1^*)] = [pau + (p+s)(b-a)u$$
$$- (b-a)c]^2 \quad (12)$$
$$/[4p(b-a)(u^2+\sigma^2)]$$

$$E[\pi_D(q_1^*)] = puq_1^* + suq_1^* - u\omega_1^* q_1^*$$
$$- \frac{(b-a)s}{2} - \frac{p(u^2+\sigma^2)(q_1^*)^2}{2(b-a)} \quad (13)$$
$$+ \frac{pauq_1^*}{b-a}$$

d) the wind power wholesale price and the amount of wind power signed after the insurance is shown in Equation (19):

$$\begin{cases} \lambda_2^* = \frac{(p+s)(b-a)t + pat + (b-a)c}{2(b-a)t} \\ q_2^* = \frac{[(p+s)(b-a)t + pat - (b-a)c]u}{2pt(u^2+\sigma^2)} \\ t = u + \int_{G^{-1}(r)}^1 (1-y)dG(y) \end{cases} \quad (14)$$

e) the optimal expected profit of the sold power company:

$$E[\pi_D(q_2^*)] = puq_2^* + suq_2^* - u\lambda_2^* q_2^*$$
$$- \frac{(b-a)s}{2} - \frac{p(u^2+\sigma^2)(q_2^*)^2}{2(b-a)} \quad (15)$$
$$+ \frac{pauq_2^*}{b-a}$$

*f)    The optimal expected profit of the wind power supplier and the maximum compensation amount of the wind power supplier are as follows:*

$$E[\pi_s(\lambda_2^*, L_2^*)] = t\lambda_2^* q_2^* - cq_2^* \tag{16}$$

$$I^* = [1 - G^{-1}(r)]\lambda_2^* q_2^* \tag{17}$$

*g)    the optimal profit function of the insurance company:*

$$\pi_C(r) = rI^* + \alpha rI^* + \min\{L^*, I^*\}, \tag{18}$$
$$L^* = (1-\eta)\omega_2^* q_2^*, 0 \le r \le 1$$

$$E[\pi_C(r)] = (1+\alpha)rL^* - \int_0^{1-L^*/\lambda_2^* q_2^*} L^* dG(y)$$
$$- \int_{1-L^*/\lambda_2^* q_2^*}^1 \lambda_2^* q_2^*(1-y)dG(y) \tag{19}$$
$$= \alpha rI^* + (u-t)\lambda_2^* q_2^*$$

## IV.    EXAMPLE ANALYSIS

### A.    Basic data

According to the literature [18], this paper sets the renewable energy electricity market demand of electricity sales companies to be uniformly distributed on [800,1200], the unit of electricity is, the electricity sales price of electricity sales companies is 712, and the electricity sales companies are in the spot market. The electricity purchase and sale price is set at 741.67, and the wind power supplier's power generation cost coefficient is 600. The insurance company's return on investment is 0.3. In the above optimal solution, the upper and lower limits of the integration include the inverse function of the distribution function. The inverse function of the general distribution function is difficult to achieve, which is not conducive to the development of the research work. Therefore, this article assumes that the uniform distribution has a certain representative . In the analysis and analysis of the following examples, the uniform distributions on [0,1], [0.4,1], and [0.8,1] are obeyed, respectively. As the value range decreases, the wind power supplier 's output prediction accuracy improves. , So that it can analyze the different benefits of wind power providers to buy insurance with different forecast accuracy.

### B.    Impact of Electricity Loss Insurance on Wholesale Price and Order Quantity

It can be seen from Figures 2 and 3 that after the wind power supplier purchases power loss insurance, regardless of the value of the insurance rate, the wholesale price of wind power in the medium and long-term contract market will be less than the wholesale price without insurance. Will increase in the case of insurance. However, with the gradual increase in insurance premium rates, the changes in wholesale prices and order volumes have gradually decreased. On the other hand, when comparing different uniform distributions from [0,1] to [0.8,1], it can be analyzed that the lower the forecast accuracy of wind power output, the wider the range of wholesale price and order quantity as the insurance rate fluctuates. Large, which indicates that the forecast accuracy of wind power providers is low, and the influence of insurance strategies on wholesale prices and order volumes is greater. Whether the combined effect of the reverse changes in wholesale prices and order quantities will increase or decrease the profits of wind power and electricity retailers will be analyzed in the next section.
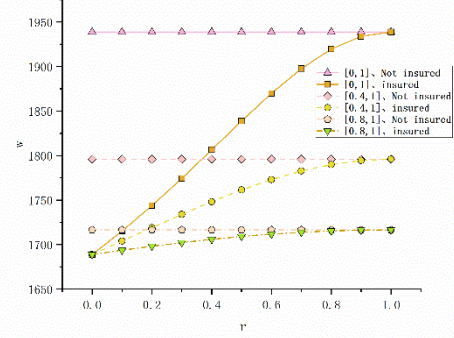


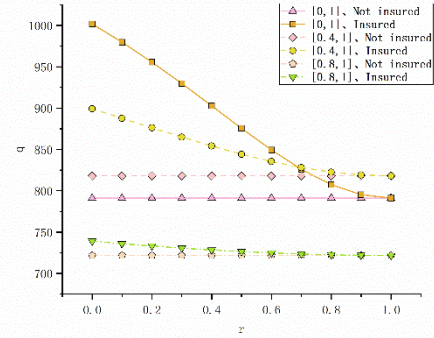Fig. 2 Effect of electricity loss insurance on wholesale price



Fig. 3 Effect of power loss insurance on order quantity

### C.    Impact of Electricity Loss Insurance on Wind Power Vendors and Sales Companies

It can be seen from Figures 4 and 5 that after the wind power supplier purchases electricity loss insurance, regardless of the value of the insurance rate, the profits of the wind power supplier and the electricity sales company are increased. The lower the insurance rate, the higher the profit of the two. The larger the range, that is, as the insurance rate increases, the amount of profit increase will become smaller and smaller. When the insurance rate is 1, it is equivalent to not insured. On the other hand, the comparison is subject to different uniform distributions, which also shows that the lower the forecast accuracy of wind power providers' output, the more obvious the impact of insurance strategies on the profits of wind power providers and electricity sales companies, and the greater the incentive for wind power providers to purchase power loss insurance Also in line with the actual situation. In addition, in the case of a large insurance premium rate (in general, the insurance company's rate is greater than 0.5, which can be found in the next section), the smaller the range of change, the

higher the forecast accuracy of the wind power supplier, and the Profits will also rise by one level, and there will be a significant increase, which is also in line with reality.
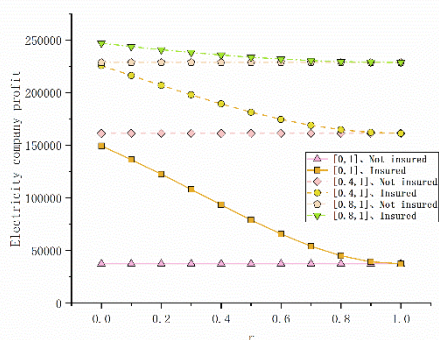


Fig 4 The impact of power loss insurance on the profit of electricity sales companies
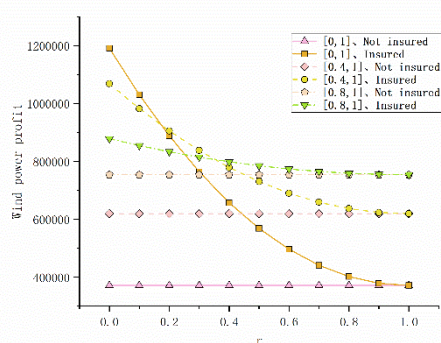


Fig 5 The impact of electricity loss insurance on wind power companies' profits

### D. Impact of Electricity Loss Insurance on Insurance Company Decisions

It can be seen from Figure 6 that the maximum compensation that an insurance company may pay gradually decreases with the increase of the insurance rate, but the premium paid by the wind power company to the insurance company increases first and then decreases as the insurance premium rate increases. . Therefore, the insurance company hopes to increase the premium rate to lower the upper limit of its own compensation amount and prevent the insurance company from losing money. At the same time, excessive insurance premium rates will reduce insurance company premium income. Therefore, the insurance company needs to consider the sum of the sum insured and the size of the premium to weigh the size of the insurance rate, which can be concluded in Figure 7. On the other hand, with the increase in the forecast accuracy of wind power providers, the insurance premiums and premiums will be reduced to a certain extent, which also confirms that the improvement of the forecast accuracy of wind power providers will reduce the demand for insurance.

It can be seen from Figure 7 that the profit of an insurance company increases first and then decreases with the increase of the insurance rate. It is a concave function of the premium rate. When the insurance rate is less than 0.6, the profit of the insurance company is negative. When the rate is between 0.6 and 1, the profit of the insurance company takes a positive value, and

there is a unique maximum value. Therefore, the insurance company determines that the insurance rate is generally taken at about 0.6. In order to attract more wind power companies to take out insurance, insurance companies have even entered the emerging field of the power market, and even set the insurance rate at zero profit.
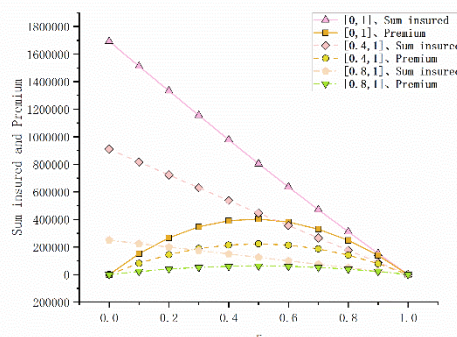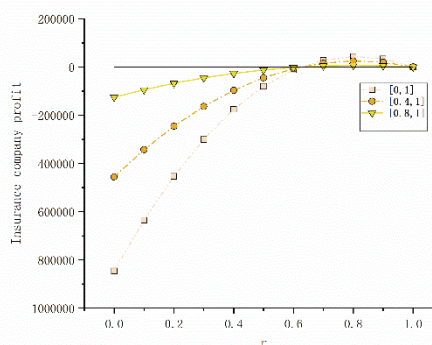


Fig. 6 Guarantee and premium



Fig 7 Profits of insurance companies

### V. CONCLUSION

This paper introduces an insurance mechanism in a wind power supply chain with uncertain supply and demand, establishes a game model involving three parties: wind power providers, electricity sales companies, and insurance companies. influences. The conclusion is as follows:

(a) After the insurance company has reasonably determined the appropriate premium, the insurance can achieve a win-win situation among the wind power supplier, the electricity sales company and the insurance company. When the insurance rate is too low, the insurance company will have less premium income, and the maximum amount of compensation that can be paid is larger. The profit of the insurance company is negative, that is, it is in a loss state. Increasing the insurance rate reduces the maximum amount of compensation that an insurance company may pay, reducing the risk of loss for the insurance company. However, the premium income increases first and then decreases with the increase of the premium rate. Therefore, insurance companies need to weigh premium income, investment income, and insurance compensation to determine the appropriate premium rate. The insurance behavior can realize wind power companies and electricity sales companies. And the three parties of the insurance company win-win.

(b) After the introduction of power loss insurance, the performance of the wind power supply chain with the risk of uncertain supply can be improved. Comparing the data before and after the wind power business is insured, it can be known that after the wind power business is insured, the wholesale price of wind power in the wind power supply chain is reduced, and the amount of wind power signed by the wind power business and the electricity sales company and the profits of both parties have increased to a certain extent. The essence of the increase in profits of wind power companies and electricity sales companies is that insurance companies have brought some compensation to the profit losses of both parties. Therefore, power loss insurance helps to deal with the forecast risks of wind power providers' handling of uncertainty. However, as the premium rate increases, the value of power loss insurance decreases.

(c) The cooperation between the wind power supplier and the electricity sales company and the application of power loss insurance are mutually reinforcing. In the wind power supply chain under the entire insurance mechanism, it is reasonable for wind power providers who take the initiative to benefit from insurance, but uninsured electricity sales companies also get the benefits of the insurance mechanism through the transmission effect of the supply and demand relationship in the electricity market, which indicates that electricity After the loss insurance is applied to the electricity market, its value is diffused. This also makes electricity sales companies more willing to cooperate with insured wind power providers in the future. Therefore, the application of power loss insurance and the cooperation between wind power providers and electricity sales companies are mutually reinforcing.

## APPENDIX

(a)

$$\frac{\partial E[\pi_D(q)]}{\partial q} = pu + su - \omega u$$

$$- p\int_0^1 [yF(yq)]dG(y)$$

$$\frac{\partial^2 E[\pi_D(q)]}{\partial q^2} = -p\int_0^1 y^2 f(yq)dG(y) < 0$$

$$q_1^*(\lambda) = [pau + p(b-a)u + s(b-a)u$$
$$- (b-a)u\omega]/[p(u^2+\sigma^2)]$$

$$\frac{\partial E[\pi_{s2}(\lambda)]}{\partial \lambda} = \{u^2[pa + (p+s)(b-a)$$
$$-2(b-a)\lambda] + u(b-a)c\}$$
$$/[p(u^2+\sigma^2)]$$

$$\frac{\partial^2 E[\pi_{s2}(\lambda)]}{\partial \lambda^2} = \frac{-2u^2(b-a)}{p(u^2+\sigma^2)} < 0$$

$$\lambda_1^* = \frac{pau + (p+s)(b-a)u + (b-a)c}{2(b-a)u}$$

$$q_1^* = \frac{pau + (p+s)(b-a)u - (b-a)c}{2p(u^2+\sigma^2)}$$

$$E[\pi_{s2}(\lambda_1^*)] = [pau + (p+s)(b-a)u$$
$$-(b-a)c]^2$$
$$/[4p(b-a)(u^2+\sigma^2)]$$

$$E[\pi_D(q_1^*)] = puq_1^* + suq_1^* - u\omega_1^* q_1^*$$
$$-\frac{(b-a)s}{2} - \frac{p(u^2+\sigma^2)(q_1^*)^2}{2(b-a)} \quad (b)$$
$$+\frac{pauq_1^*}{b-a}$$

The optimal solution $\lambda_2^*$、 $q_2^*$、 $E[\pi_D(q_2^*)]$、

$E[\pi_s(\lambda_2^*, L_2^*)]$、 $E[\pi_C(r)]$ is solved as follows:

Let $f = E[\pi_s(\lambda, I)]$ , $M = 1 - L/(\lambda q)$ ,

$N = \lambda q$ ,denote the first and second derivatives

ofrespectively, $N'$ and $N''$ denote the first and second derivatives of $N$ about $\lambda$ , respectively, $A'$ and $A''$ denote the first and second partial derivatives of $A$ about $\lambda$ ,respectively.

First, find the first-order and second-order partial derivatives of $f$ in turn about $\lambda$ to obtain:

$$f = uN - cq - rI + \int_0^M IdG(y) + \int_M^1 N(1-y)dG(y)$$

$$f_\lambda' = \frac{\partial E[\pi_s(\lambda, I)]}{\partial \lambda}$$
$$= uN' + \frac{(b-a)cu}{p(u^2+\sigma^2)} + M'Ig(M) -$$
$$M'N(1-N)g(N) + N'\int_A^1 (1-y)dG(y)$$
$$= N'(u + \int_A^1 (1-y)dG(y)) + \frac{(b-a)cu}{p(u^2+\sigma^2)}$$

$$f_{\lambda\lambda}'' = \frac{\partial^2 E[\pi_s(\lambda, I)]}{\partial \lambda^2}$$
$$= uN'' + N''\int_A^1 (1-y)dG(y) - M'N'(1-M)g(M)$$
$$= N''[u + \int_A^1 (1-y)dG(y)] - \frac{(N'I)^2 g(M)}{N^3}$$

Because
$$N' = \frac{(p+s)(b-a)u + pau - 2(b-a)u\lambda}{p(u^2+\sigma^2)},$$
$$N'' = \frac{-2(b-a)u}{p(u^2+\sigma^2)} < 0$$

Therefore $f_{\lambda\lambda}^{"} < 0$ 。

Then find the first-order and second-order partial derivatives of $f$ in turn about $I$ to get:

$$f_I' = \frac{\partial E[\pi_s(\lambda,I)]}{\partial I}$$

$$= -r + \int_0^M dG(y) - \frac{1}{\lambda q} Ig(M) + \frac{1}{\lambda q} N(1-M)g(M)$$

$$= \int_0^A dG(y) - r$$

$$f_{II}^{"} = \frac{\partial^2 E[\pi_s(\lambda,I)]}{\partial I^2} = \frac{-1}{\lambda q} g(M)$$

The other second-order mixed partial derivatives are:

$$f_{\lambda I}^{"} = f_{I\lambda}^{"} = \frac{\partial^2 E[\pi_s(\lambda,I)]}{\partial \lambda \partial I} = \frac{IN'g(M)}{N^2}$$

The resulting Hessian matrix is:

$$H = \begin{vmatrix} f_{\lambda\lambda}^{"} & f_{\lambda I}^{"} \\ f_{I\lambda}^{"} & f_{II}^{"} \end{vmatrix} = \frac{-N''[u + \int_A^1 (1-y)dG(y)]g(M)}{N} > 0$$

And because $f_{\lambda\lambda}^{"} < 0$, it is a concave function of $E[\pi_s(\lambda,I)]$ about $\lambda$、$I$, that is, there is a maximum value and it is obtained at the stagnation point, let:

$$\begin{cases} f_\lambda' = N'(u + \int_A^1 (1-y)dG(y)) + \frac{(b-a)cu}{p(u^2+\sigma^2)} = 0 \\ f_I' = \int_0^A dG(y) - r = 0 \end{cases}$$

Solutions have to
$$\begin{cases} \lambda_2^* = \frac{(p+s)(b-a)t + pat + (b-a)c}{2(b-a)t} \\ q_2^* = \frac{[(p+s)(b-a)t + pat - (b-a)c]u}{2pt(u^2+\sigma^2)} \\ I^* = [1 - G^{-1}(r)]\lambda_2^* q_2^* \\ t = u + \int_{G^{-1}(r)}^1 (1-y)dG(y) \end{cases}$$

By substituting the result of the above formula into $E[\pi_D(q_2^*)]$、 $E[\pi_s(\lambda_2^*, L_2^*)]$, the optimal solution of the wind power supplier and the electricity sales company can be obtained:

$$\begin{cases} E[\pi_D(q_2^*)] = puq_2^* + suq_2^* - u\lambda_2^* q_2^*\left(\frac{\pi}{2} - \theta\right) \\ \qquad - \frac{(b-a)s}{2} - \frac{p(u^2+\sigma^2)(q_2^*)^2}{2(b-a)} + \frac{pauq_2^*}{b-a} \\ E[\pi_s(\lambda_2^*, L_2^*)] = t\lambda_2^* q_2^* - cq_2^* \\ E[\pi_C(r)] = (1+\alpha)rI^* - \int_0^{1-I^*/\lambda_2^* q_2^*} L^* dG(y) \\ \qquad - \int_{1-I^*/\lambda_2^* q_2^*}^1 \lambda_2^* q_2^*(1-y)dG(y) \\ \qquad = \alpha rI^* + (u-t)\lambda_2^* q_2^* \end{cases}$$

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