

Market Mechanism Design for Renewable Energy based on Risk Theory

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Abstract. Generation trading between renewable energy and thermal power is an efficient market means for transforming supply structure of electric power into sustainable development pattern. But the trading is hampered by the output fluctuations of renewable energy and the cost differences between renewable energy and thermal power at present. In this paper, the external environmental cost (EEC) is defined and the EEC is introduced into the generation cost. At same time, the incentive functions of renewable energy and low-emission thermal power are designed, which are decreasing functions of EEC. On these bases, for the market risks caused by the random variability of EEC, the decision-making model of generation trading between renewable energy and thermal power is constructed according to the risk theory. The feasibility and effectiveness of the proposed model are verified by simulation results.

1. Introduction

With the global resource shortage, the climate change problem is becoming more and more serious, the constraints of resources and environment on energy development are gradually increasing. More and more attention has been paid to the ecological environment in order to achieve sustainable development. Traditional fossil fuel power generation no longer meets the needs of society for the environment, and more and more clean energy is found and used.

The development of renewable energy is very fast in recent years for zero-emission and without the consumption of fossil fuels during the production process of renewable energy. But there are about ten billion kilowatt-hours renewable energy curtailed for output fluctuations every year[1]. At the same time, the electric power supply relies largely on the thermal power with high-emission and high energy consumption, which causes many problems such as energy security, environment pollution and so on. Thus, it is necessary to adjust the structure of electric power supply to ease global environmental and energy security.

Given this situation, according to the proposal of large-scale clean energy integration[2], the study on generation rights trading between renewable energy and thermal power (namely, GRTRET) is carried out in this paper in order to explore the market means of adjusting electric power supply structure. The mechanism of GRTRET is established based on risk decision-making theories: (a) Generation rights trading market composed of high-emission thermal power, low-emission thermal power and renewable energy is constructed. (b) External environmental costs (EEC) of thermal power



and renewable energy are defined respectively, and the EEC are introduced into their basic generation costs. (c) For the market risks caused by random variability of EEC, the model of GRTRET is presented according to the conditional value at risk (CVaR) and the principal agent (PA) theories.

2. Generation Rights Trading Mechanism Between Renewable energy And Thermal Power Based on Cvar_Pa Theories

2.1. Market Structure of GRTRET

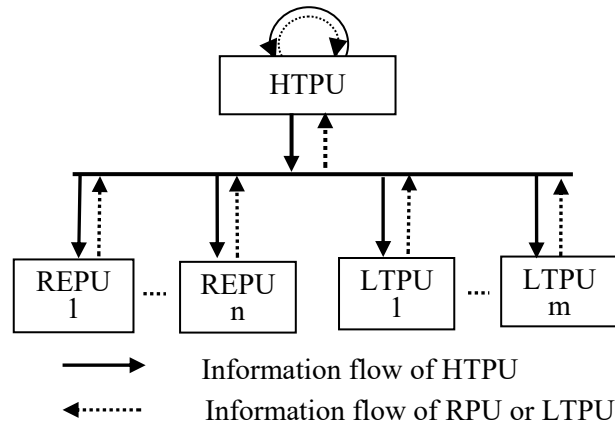


Figure.1 Sketch of GRTRET market

The market structure of GRTRET is shown in figure 1, the GRTRET market is composed of single type sellers and multiple type buyers: high-emission thermal power units (HTPU) are sellers, low-emission thermal power units (LTPU) and renewable energy units (REPU) are buyers. When the LTPU and REPU could not buy all electric power sold by HTPU, HTPU have to generate surplus electric power by themselves, HTPU are also viewed as buyers of generation rights.

2.2. The Decision Model of GRTRET Based on CVaR_PA

The output of some renewable energy sources is stochastic and Volatility. Renewable energy units ally storage devices or other electric power units to smooth output fluctuations[3-8], the charge derived from alliance is defined as EEC of REPU. On the other hand, restrained by environmental policies, thermal power units should spend money on energy and greenhouse reduction (such as the costs of buying carbon-permit, and so on), the charge is defined as EEC of HTPU and LTPU.

EEC of REPU, HTPU and LTPU are prone to volatility, which easily lead to market risks. On the basis of risk management theory of financial investment market, the GRTRET could be regarded as financial investment decisions. But different from investees who are in passive state in financial market, the investment objects in generation rights trading market (namely, the buyers of generation rights) are subjective initiative. CVaR uses statistical thinking for risk assessment, which is expressed as $VCVaR = E[f|f \geq VVaR]$. Where: $VCVaR$ represents the conditional risk value; E represents the expected value; $VVaR$ indicates the risk value of an asset portfolio in a future market under certain market volatility. Obviously, CVaR describes the average potential loss potential that portfolio losses can exceed the VaR threshold, so it can well reflect potential risk values of portfolios. Only given enough incentive by sellers of generation rights, could the buyers of generation rights participate in the generation rights trading. In conclusion, the decision model of buyer and seller are constructed respectively as follow.

2.2.1. Decision-making model of buyers based on PA theory

The EEC of REPU could solve the problem of output fluctuations at some level. But, it will lead to higher costs of electric power supply if the output of renewable energy fluctuating drastically. Then

the stability of GRTRET market will be damaged. Therefore, the incentive HTPU giving to REPU decreases with the increase of EEC of REPU. On the bases mentioned above, the decision-making model of REPU is constructed as follow:

$$\begin{aligned} \Pr(\pi_{rei} \leq R_{rei0}) &\leq 0.1, (i = 1, 2, \dots, n) \\ s.t. \\ \pi_{rei} &= (k_{re} - 1) \times \left\{ \alpha_{rei} Q_{rei} + \left[\int_0^{Q_{rei}} (Q_{rei} - P_{rei}) \left(\frac{1}{\sqrt{2\pi}\delta_i} e^{-\frac{(P_{rei} - \mu_i)^2}{2\delta_i^2}} \right) dP_{rei} \right] \times p_p \right\}; \\ Q_{rei, \min} &\leq Q_{rei} \leq Q_{rei, \max}; \\ k_{re} &= 2e^{100/pp}. \end{aligned} \quad (1)$$

Where π_{rei} and R_{rei0} are benefits and the minimum of the benefits expectation of REPU i participating in generation rights trading by offering Q_{rei} respectively, k_{re} is the incentive of REPU i gained from HTPU, α_{rei} is basic generation costs of REPU i , P_{rei} is the output characteristic of REPU i : $P_{rei} \sim N(\mu_i, \sigma_i^2)$, p_p is price of smoothing output fluctuation: $p_p \sim N(\mu_p, \sigma_p^2)$, $Q_{rei, \max}$ and $Q_{rei, \min}$ are floor and ceiling of bid quantity of REPU i respectively, n is the number of REPU.

The goal of adjusting electric power supply structure is prompting clean energy utilized massively. Therefore, the incentive HTPU giving to LTPU decreases with the increase of EEC of thermal power. On the bases mentioned above, the decision-making model of LTPU is constructed as follow:

$$\begin{aligned} \Pr(\pi_{tj} \leq R_{tj0}) &\leq 0.1, (j = 1, 2, \dots, m) \\ s.t. \\ \pi_{tj} &= (k_t - 1) (\alpha_{tj} Q_{tj} + Q_{tj} \eta_{tj} p_c); \\ Q_{tj, \min} &\leq Q_{tj} \leq Q_{tj, \max}; \\ k_t &= 2e^{60/p_c}. \end{aligned} \quad (2)$$

Where π_{tj} and R_{tj0} are benefits and the minimum of the benefits expectation of LTPU j participating in generation rights trading by offering Q_{tj} respectively, k_t is the incentive of LTPU j gained from HTPU, α_{tj} is basic generation costs of LTPU j , p_c is price of carbon permit: $p_c \sim N(\mu_c, \sigma_c^2)$, η_{tj} is the coefficient of carbon emission of LTPU j , $Q_{tj, \max}$ and $Q_{tj, \min}$ are floor and ceiling of bid quantity of LTPU j respectively, m is the number of LTPU.

2.2.2. Decision-making model of sellers based on CVaR theory

Random fluctuations of EEC will put HTPU at risk of benefits uncertainty. The loss of benefits is the essence of this risk. The HTPU makes generation rights trading decisions on the basis of minimizing the loss. The decision-making model of generation rights transferor is established to minimize the loss.

Given that $\lambda_{11} \dots \lambda_{1n}$, $\lambda_{21} \dots \lambda_{2m}$, λ_3 are the benefits of HTPU dealing with REPU, LTPU and HTPU respectively. Thus,

$$\lambda_{1i} = p_n - k_{re} \left[\alpha_{rei} + 1 - \left(\int_0^{P_{rei}} \frac{1}{\sqrt{2\pi}\delta_i} e^{-\frac{(P_{rei} - \mu_i)^2}{2\delta_i^2}} dP_{rei} \right) \times p_p \right] \quad (3)$$

$$\lambda_{2j} = p_n - k_t (\alpha_{tj} + \eta_{tj} p_c) \quad (4)$$

$$\lambda_3 = p_n - (\alpha_s + \eta_s p_c) \quad (5)$$

Where p_n is feed-in tariff of HTPU given by the grid company, α_s and η_s are unit cost and carbon emission coefficient of HTPU respectively.

Given that $x = \{x_{11}, \dots, x_{1i}, \dots, x_{1n}, x_{21}, \dots, x_{2j}, \dots, x_{2m}, x_3\}$ is a sets of trading results; x_{1i} , x_{2j} and x_3 are the transaction amount of HTPU dealing with REPU, LTPU and HTPU respectively. Thus, the benefits of HTPU selling electric power of Q units is

$$\pi(x, \lambda) = \sum_{i=1}^n x_{1i} \lambda_{1i} + \sum_{j=1}^m x_{2j} \lambda_{2j} + x_3 \lambda_3. \quad (6)$$

s.t.

$$\sum_{i=1}^n x_{1i} + \sum_{j=1}^m x_{2j} + x_3 = Q$$

The expectations of above benefits is

$$\begin{aligned} E[\pi(x, \lambda)] = & \\ & \sum_{i=1}^n x_{1i} E[f(\alpha_{rei}, p_p, k_{re})] + \\ & \sum_{j=1}^m x_{2j} E[f(\alpha_{ij}, p_c, k_t)] + x_3 E[f(\alpha_s, p_c)] \end{aligned} \quad (7)$$

The losses of above benefits is

$$L(x, \gamma) = -\pi(x, \lambda) = \sum_{i=1}^n x_{1i} \gamma_{1i} + \sum_{j=1}^m x_{2j} \gamma_{2j} + x_3 \gamma_3 \quad (8)$$

Where γ_{1i} , γ_{2j} and γ_3 are the losses of HTPU dealing with REPU at x_{1i} , dealing with LTPU at x_{2j} and dealing with HTPU at x_3 respectively, $\gamma_{1i} = -\lambda_{1i}$, $\gamma_{2j} = -\lambda_{2j}$, $\gamma_3 = -\lambda_3$.

Given that $\xi = (\xi_1, \xi_2, \dots, \xi_q)$ is q samples of vector γ . Put equation (8) into estimation formula of CVaR introduced in ref. 9, the model of quantifying the loss that HTPU selling Q units electric power is constructed as follow:

$$F_\beta(x, a) = a + \frac{1}{q(1-\beta)} \sum_{t=1}^q [(L(x, \xi^t) - a)]^+ \quad (9)$$

On above bases, the decision-making model of GRTRET dominated by HTPU is

$$\begin{aligned} \min F_\beta(x, a) = & \min \left[a + \frac{1}{q(1-\beta)} \sum_{t=1}^q \rho_t \right] \\ \text{s.t.} & \\ & \sum_{i=1}^n x_{1i} + \sum_{j=1}^m x_{2j} + x_3 = Q \\ & Q_{rei, \min} \leq x_{1i} \leq Q_{rei} \quad (i = 1, 2, \dots, n) \\ & Q_{ij, \min} \leq x_{2j} \leq Q_{ij} \quad (j = 1, 2, \dots, m) \\ & Q_{s, \min} \leq x_3 \leq Q_{s, \max} \\ & x^T \lambda > r_{s0} Q \\ & \rho^t \geq [L(x, \xi^t) - a]^+, \rho^t \geq 0. \end{aligned} \quad (10)$$

Where $Q_{s, \max}$ and $Q_{s, \min}$ are the floor and ceiling quantity of the output of HTPU, λ is expectation of the benefit that HTPU selling one unit electric power:

$\lambda = (E(\lambda_{11}), \dots, E(\lambda_{1n}), E(\lambda_{21}), \dots, E(\lambda_{2m}), E(\lambda_3))$, r_{s0} is the floor benefits of HTPU selling one unit.

3. Analysis of examples

In this section, the generation rights trading between renewable energy and thermal power in one transaction cycle is taken as example. In this paper, wind power is selected as renewable energy to facilitate the simulation. Experimental data are as follows:

Table 1. The Value of GRTRET Parameters

	p_c	p_p	α_s	α_{re}	α_t
	Yuan/t	Yuan/MW·h	Yuan/MW·h	Yuan/MW·h	Yuan/MW·h
μ	250	100	80	150	100
σ^2	21	15			

Other parameters are as follows: $p_n=550$ Yuan/MW·h, $\eta_s=0.8934$, $Q=100$ MW·h; $P_{re} \sim N(100, 52)$, $R_{re0}=1000$ Yuan, $Q_{re,max}=100$ MW·h, $Q_{re,min}=0$ MW·h; $\eta_t=0.354$, $R_{t0}=1000$ Yuan, $Q_{t,max}=100$ MW·h, $Q_{t,min}=0$ MW·h; $n=1$, $m=1$; Q_{re} , Q_t , Q_s are trading amount of REPU, LTPU and HTPU respectively; Q_{rel} , Q_{tl} are bid amount of REPU and LTPU respectively.

3.1. Analysis of Results of GRTRET

From the above data, a combined vector sample value of 100 sets of power generation transaction losses is generated. Let $r_{s0}=200$, 250 and $\beta=0.90$, 0.99 successively, matching the GRTRET based on the decision-making model presented in section II. The results are as follows:

Table 2. Matching results of GRTRET

r_{s0}	β	Q_{re}	Q_t	Q_s	VaR	CVaR
		MW·h	MW·h	MW·h		
200	0.90	22.9372	20.73	56.3328	7.6519	9.2085
	0.99	30.4506	22.5566	46.9928	12.9971	13.4012
250	0.90	39.1722	51.9418	8.886	13.9768	14.9890
	0.99	46.629	50.5078	2.8632	16.8101	17.6241

Known from the results shown in line 4 of table 2, through the generation rights trading between renewable energy and thermal based on the presented model: REPU and LTPU get 39.1722 and 51.9418 megawatt hour on-grid energy respectively, the benefits of HTPU rise by about 14.83 percent and the carbon dioxide emissions decreases about 63.01 tons. Known from other transaction results of table 2, the REPU could obtain some on-grid energy in each transaction scene, all traders of GRTRET could gain profit and carbon dioxide emissions reduce 31.67 tons, 37.25 tons, 65.72 tons respectively. At same time, (1)Fix the value of r_{s0} , increase the value of β , the results of GRTRET are: the trading amount of HTPU dealing with REPU increase, while the output of HTPU decrease significantly; (2)Fix the value of β , increase the value of r_{s0} , the results of GRTRET are: the trading amount of HTPU dealing with REPU and LTPU increase significantly. Increasing the value of r_{s0} means HTPU aiming to high profit, and increasing the value of β means HTPU aiming to avoiding transaction risks. Thus, it could be concluded that the results of GRTRET based on the presented model could achieve the balance between transaction profit and risk aversion.

3.2. Sensitivity Analysis of EEC

3.2.1. Sensitivity analysis of external environmental costs of thermal power unit (p_c)

Let $r_{s0}=250$ and $\beta=0.90$, adjust the value of p_c , make the decisions of GRTRET based on the presented model, the results are as follows:

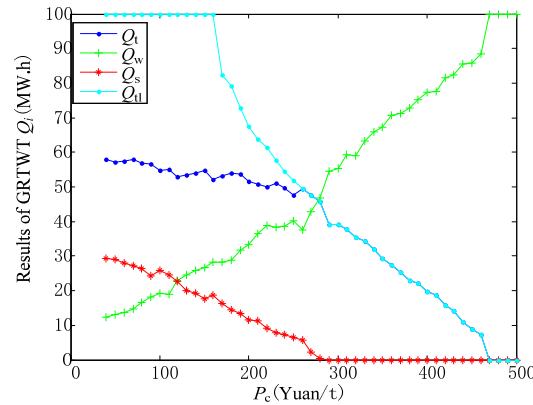


Figure 2. Sensitivity analysis of EEC of thermal power unit (p_c)

As shown in figure 2, GRTWT (generation rights trading between wind power and thermal power) is GRTRET, Q_w is Q_{re} (figure 3 is the same). Known from figure 2: with the increase of p_c , the trading amounts of LTPU and HTPU decrease while the trading amounts of REPU increase significantly. ① When $p_c \leq 281.23$ Yuan/t, the trading amount of LTPU is the largest which means that the competitiveness of LTPU is most powerful. Because LTPU has price advantage in this scene, furthermore, the bid amount of LTPU is bigger than the amount given by HTPU which means that the participation constraint is ineffective temporarily and the trading amount of HTPU dealing with LTPU equal the amount HTPU matching LTPU. ② When $p_c > 281.23$ Yuan/t, the trading amount of REPU is the largest at last which means that the competitiveness of REPU could out-compete thermal power with the increase of p_c . When $p_c > 281.23$ Yuan/t, the costs of thermal power increase significantly, the participation constraint is effective, thus, the bid amounts of LTPU are smaller than the amounts given by HTPU. Therefore, HTPU makes decision dealing with LTPU according to bid amounts of LTPU. On the other hand, the generation costs of HTPU increase seriously with the increase of p_c , the output of HTPU decrease to zero at last.

3.2.2. Sensitivity analysis of external environmental costs of renewable energy unit (p_p)

Let $r_{s0}=250$ and $\beta=0.90$, adjust the value of p_p , make the decisions of GRTRET based on the presented model, the results are as follows:

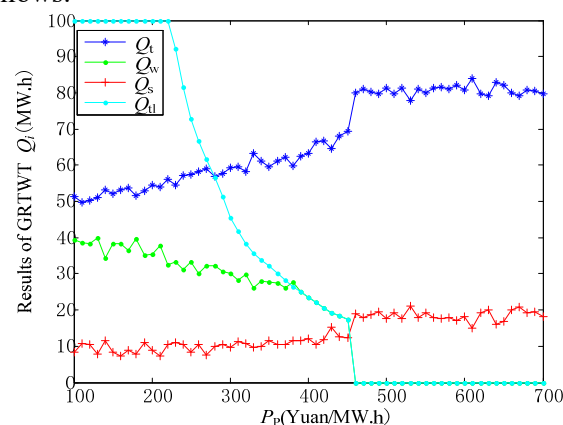


Figure 3. Sensitivity analysis of EEC of renewable energy unit (p_p)

Known from figure 3: with the increase of p_p , the trading amounts of REPU decrease while the trading amounts of LTPU and HTPU increase significantly. ① When $p_p \leq 401.87$ Yuan/MW.h, REPU

could gain some trading amounts through dealing with HTPU. Because the REPU has price advantage comparing with HTPU, the participation constraint is ineffective temporarily and the trading amounts of REPU dealing with HTPU equal the amounts HTPU matching REPU. ② When $p_p > 401.87 \text{ Yuan/MW}\cdot\text{h}$, the competitiveness of REPU weaken while the competitiveness of LTPU and HTPU strengthen significantly. Especially, when $p_p \geq 456.32 \text{ Yuan/MW}\cdot\text{h}$, the bid amounts of REPU decrease to zero which means that the REPU exit the generation rights trading market, the amounts that HTPU given to REPU are redistributed between HTPU and LTPU. The reason is that an increase of p_p leads to an increase in the combined cost of renewable energy. Finally, the wind power will be withdrawn from the market, and the clean thermal power will take advantage of the transaction, under the constraint of the participation of renewable energy and limiting the risk of thermal power loss.

4. Conclusions

Based on conditional value at risk and principle agent theories, the decision-making model of generation rights trading between renewable energy and thermal power is proposed in this paper. Some conclusions could be drawn from simulation results:

The decision-making model of generation rights trading proposed in this paper could balance the trading profit and risk aversion, it provides a reference for carrying out generation rights trading between high-emission thermal power and clean energy with output fluctuations.

Considering the external environmental costs (EEC) reasonably could prompt energy with cleanliness and stable characteristics integrated, make renewable energy possessed capability of competing with thermal power equally in the future. It provides a reference for adjusting electric power structure by market means.

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