Decision optimisation study of two-stage hybrid electricity market under renewable energy quota policy

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Abstract. Encouraging renewable electricity in market transactions is vital for its development and reducing reliance on traditional thermal electricity. Yet, the impact of uncertainty in renewable electricity production on markets, especially in a two-stage market setup, remains insufficiently explored. The renewable energy quota policy is a key driver for renewable energy development, but its specific effects on the electricity market, considering increased renewable electricity participation in trading, are not thoroughly examined. This study constructs a two-stage electricity market model using game theory, considering factors like supply and demand uncertainty, two-stage trading, and quota policy. Finally, this paper uses actual data from China's electricity trading for data simulation. The findings indicate that promoting renewable electricity in market-based trading can lower electricity prices, hamper traditional thermal electricity generator profits, and boost renewable electricity generator profits. Additionally, a high renewable energy quota may elevate electricity prices, with the quota policy favoring renewable electricity generator and disadvantaging traditional thermal electricity generator.

Keywords: hybrid electricity; two-stage market; renewable energy quota policy.

1 Introduce

Global concern over escalating global warming has prompted countries to address increased carbon emissions, particularly from energy consumption. To combat the climate crisis, nations are actively restructuring their energy systems and promoting renewable energy technologies. Notably, China has initiated pilot programs for renewable electricity spot trading in Shanghai and Guangdong since August 2021, signaling a move towards market-oriented approaches. However, integrating renewable electricity, especially from climate-sensitive sources like wind power, poses a challenge due to inherent volatility influenced by weather conditions. The fluctuating electricity generation creates difficulties in maintaining stability in both supply and prices within the market.

National and international studies have shown that the marketisation of renewable electricity is a global trend, and current research tends to explore the integration

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strategies of renewable electricity in liberalised electricity markets and their impact on the market. Mitridati et al. (2021) [4] studies analysed the market mechanism for renewable electricity under community-based and market strategies through game theory. At the policy level, quota and green certificate trading have become a hotspot for promoting renewable electricity feed-in and electricity market research. For example, the work of Currier and Rassouli-Currier (2012)[3], among others, provides insights and analyses of quota and green certificate trading on the electricity duopoly problem. The objective of this paper is to provide further insights into the impact of these policies on market-based trading and to provide useful references for policy formulation. Studies such as Alizamir et al. (2016)[1] and Boomsma et al. (2012)[2] support government action to promote renewable electricity feed-in. In particular, Wang and Li (2022)[5] show that green certificate trading and carbon market design have a significant role to play in promoting the development and feed-in of renewable electricity.

The aim of this study is to investigate the impact of renewable electricity participation in market trading on the electricity market by constructing an optimisation model based on game theory, and to consider the decision-making behaviour of electricity generator in the two-stage market, as well as the market effect of the renewable energy quota policy.

2 Model description

The total sales volume of the traditional conventional thermal electricity generator is Q, where the forward sales volume is Q_f and the spot sales volume is $Q - Q_f$. The production cost of the traditional conventional thermal electricity generator is expressed as a linear cost function $C(Q) = cQ$. Considering the seasonality of renewable electricity and weather effects, the total sales volume of the renewable electricity generator is determined by ξk_w, The forward sales of the renewable electricity generator are q_f and the spot sales are $\xi k_w - q_f$. In particular, the output density of renewable energy ξ obeys a $0 - 1$ distribution, i.e., $\xi = [1, \rho; 0, 1 - \rho]$. The production cost of the renewable electricity generator is denoted as $C(\xi k_w) = 0$.

Both traditional thermal electricity generator and renewable electricity generator are mandated by policy to generate a specified percentage, denoted as α, of their total electricity from renewable sources. Traditional thermal electricity generator not meeting this requirement must buy green certificates in the market to cover their shortfall, aligning with policy requirements. In contrast, renewable electricity generator can sell excess green certificates beyond their quota obligations.

3 Basic assumption

Assumption 1: In the forward market, the inverse demand function in the forward market can be expressed as $p_f = a_f - \left(Q_f + q_f\right)$. In the spot market, the inverse demand function in the spot market can be expressed as $p_s = a_s - (Q + q)$.

Assumption 2: It is assumed that all market participants are risk-neutral and there are no external speculators.

Assumption 3: This paper assumes that renewable electricity can be sold in its entirety.

Assumption 4: Under the renewable energy quota set by the Government, all electricity generator, whether they are traditional thermal electricity generator or renewable energy electricity generator, are required to comply with a certain percentage alpha of renewable electricity quota obligations.

Table 1 is parameter description:

Table 1. Parameter description

Parameter	description
p_f	Forward price
p_s	Spot price
c	Thermal power unit cost of electricity generation
ξ	Renewable electricity output intensity
k_W	Renewable energy installed capacity
a_s	Potential demand in spot market
a_s	Potential demand in forward market
α	Renewable energy quota
ρ	Probability of renewable electricity generation
p_g	Green certificate price
Decision variables	
Q	Total sales of traditional thermal electricity generator
Q_f	Forward sales of traditional thermal electricity generator
q_f	Forward sales of renewable electricity generator

4 Modelling and solution

In the two-stage hybrid electricity supply chain model under the renewable energy quota policy, The profit function for traditional thermal electricity generator and renewable electricity generator is as follows:

$$\pi_Q(Q_f, Q) = p_f Q_f + p_s(Q - Q_f) - cQ - \alpha p_g Q \tag{1}$$

$$\pi_{k_w}(q_f) = p_f q_f + p_s(\xi k_w - q_f) + (1 - \alpha) p_g \xi k_w \tag{2}$$

Theorem: The equilibrium solution can be expressed as follows: when $0 \le k_W \le \frac{2a_f + 3(c + \alpha p_g)}{3\mu_\xi}$,

$$p_f = \frac{3a_f + 2(c - \mu_\xi k_W + \alpha p_g)}{5} \tag{3}$$

$$p_s = \frac{2a_f + 3(c - \mu_\xi k_W + \alpha p_g)}{5} \tag{4}$$

$$\pi_Q = \frac{7\left(a_f^2+c^2+\alpha^2 p_g^2+\mu_\xi^2 k_w^2\right)+11\mu_\xi k_W(-a_f+c+\alpha p_g)+14\left(c\alpha p_g-a_f(c+\alpha p_g)\right)}{25} \tag{5}$$

$$\pi_{k_w} = \frac{\begin{array}{c} a_f^2+(c-\mu_\xi k_W)\left(c+\mu_\xi k_W(-1+15\rho)\right)-2a_f(c-\mu_\xi k_W(1+5p)+\alpha p_g) \\ +\left(25\rho\mu_\xi k_W+2\alpha\left(c-\mu_\xi k_W(1+5p)\right)\right)p_g+\alpha^2 p_g^2 \end{array}}{25} \tag{6}$$

Corollary 1: As the installed capacity of renewable energy increases, trends in the electricity market include the following: When $0 \leq k_W \leq \frac{2a_f+3(c+\alpha p_g)}{3\mu_\xi}$, $\frac{\partial p_f}{\partial k_W} < 0$ and $\frac{\partial p_s}{\partial k_W} < 0$ and $\frac{\partial \pi_Q}{\partial k_W} < 0$ and $\frac{\partial \pi_{k_W}}{\partial k_W} > 0$.

In the electricity market, traditional thermal electricity sales decrease as renewable energy capacity rises, driven by the market's preference for cost-effective renewables. Lower marginal costs of renewable electricity lead to higher scheduling and consumption, reducing the market share and profits of traditional thermal electricity generator. This shift also lowers both forward and spot prices. In contrast, profits for renewable electricity generator initially rise due to increased sales volumes outweighing the impact of lower prices.

Corollary 2: As the installed capacity of renewable energy quotas increases, trends in the electricity market include the following: When $0 \leq \alpha \leq 1$, $\frac{\partial p_f}{\partial \alpha} > 0$ and $\frac{\partial p_s}{\partial \alpha} > 0$ and $\frac{\partial \pi_Q}{\partial \alpha} < 0$ and $\frac{\partial \pi_{k_W}}{\partial k_W} < 0$.

Renewable energy quota hikes raised forward and spot prices. The policy imposed additional green certificate fees on traditional thermal electricity generator, compelling them to cut sales, particularly in the forward market. This reduced electricity supply, leading to price increases. Despite the price surge, both traditional thermal electricity generator and renewable electricity generator saw profit declines. Traditional thermal electricity generator faced sales constraints and higher green certificate costs, offsetting price gains. Renewable electricity generator, although unaffected in sales volume, earned less from green certificate sales due to increased quota requirements, impacting their profits.

5 Data simulation

5.1 Impact of installed renewable energy capacity on electricity markets

In order to analyse the impact of different installed renewable energy capacities on the electricity market, the market outcomes of hybrid electricity trading are simulated and analysed separately next, with the following results:

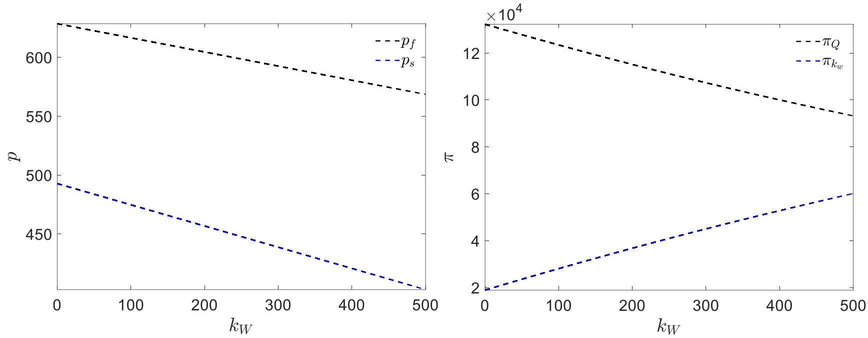

Fig. 1. Impact of installed renewable energy capacity on electricity prices and electricity generators' profits

Fig. 1 show that with the large-scale participation of renewable electricity in the market, the forward and spot prices drop significantly, from $628.5 yuan/MWh$ to $568.5 yuan/MWh$, and the spot price from $492.7 yuan/MWh$ to $402.7 yuan/MWh$. This is because renewable energy generally has a lower marginal cost and its entry into the market can increase supply and reduce overall electricity prices.

For traditional thermal electricity generator, the expansion of renewable energy means that their share of the market is likely to decrease, as the market favours lower-cost renewable energy sources. At the same time, falling electricity prices have reduced their sales revenues, a combination of factors that limits their profit growth. For renewable electricity generator, increased scale means not only a larger market share, but also that they can benefit from higher revenues from electricity sales and green certificate sales. Even if spot market prices are lower, they can still maintain high profit margins because the marginal cost of renewable energy is typically lower.

5.2 Impact of Renewable Energy Quota Ratios on Electricity Markets

In order to analyse the impact of different renewable energy quotas on the electricity market, this paper considers three different scenarios: low renewable energy quota environment: $\alpha = 0.3$; baseline renewable energy quota environment: $\alpha = 0.5$; high renewable energy quota environment: $\alpha = 0.7$. The results are as follows:

Table 2. Electricity market outcomes under different renewable energy quotas

	$\alpha = 0.3$	$\alpha = 0.5$	$\alpha = 0.7$
p_f	563.4~623.4	568.5~628.5	573.6~633.6
p_s	395.1~485.1	402.7~492.7	410.4~500.4
π_Q	94555.7~133896	90514.6~129015	86564.2~124226
π_{k_w}	19128~60501.8	18430.8~59270.4	177465.4~58051.9

Based on the Table 3, it can be observed that as the proportion of renewable energy quota increases, the forward price increase from $563.4 \sim 623.4 yuan/MWh$ to

$573.6 \sim 633.6 yuan/MWh$ and the spot price increase from $395.1 \sim 485.1 yuan/MWh$ to $410.4 \sim 500.4 yuan/MWh$.

Traditional thermal electricity generator experienced negative impacts on profits due to the necessity of reducing sales to meet renewable energy quota requirements and the added expenses for green certificates. Contrary to theoretical expectations, the simulation results reveal that increasing the proportion of renewable energy quotas does not enhance the profits of renewable electricity generator; instead, a downward trend is observed. This outcome may be attributed to market changes resulting from the quota increase, including shifts in green certificate prices and an uptick in the marginal cost of renewable energy.

6 Conclusion

In this paper, this study constructs a competition model based on the Gounod Dual Oligopoly framework to explore the phenomenon of market competition between traditional thermal electricity generator and renewable electricity generator in a two-stage market. The key findings and practical implications are summarised below:

(1) Promoting market-based trading of renewable electricity can help drive down electricity prices and limit the growth of profits for traditional thermal electricity generator. For renewable electricity generator, market-based trading of renewable electricity will contribute to increased profits.

(2) Movements in electricity prices are directly related to the proportion of renewable energy quotas, and forward and spot prices will rise substantially as the proportion of renewable energy quotas increases. The renewable energy quota system policy is always unfavourable to traditional thermal electricity generator, while it is always favourable to renewable electricity generator.

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