The method of achieving grid stability through price demand response under the uncertainty of renewable energy electricity

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Abstract. This study explores the integration of renewable electricity, characterized by its intermittent nature, into the electricity system. Within the framework of a price-based demand response mechanism, a three-tier Stackelberg game model involving the grid, electricity retailers, and end-users was established. The research indicates that enhancing the stability of renewable energy contributes to reducing electricity prices and improving the utility value of the grid, particularly during peak demand periods. However, incentivizing electricity retailers by the grid to provide renewable energy may lead to price increases, thereby potentially diminishing the utility value of the grid.

Keywords: renewable electricity; price-based demand response; Stackelberg game.

1 Introduction

Against the backdrop of the dual carbon goals, there is increasing attention on the development of renewable energy sources. However, the electricity market, as a major consumer of energy, faces the challenge of exacerbated supply-demand imbalances due to the intermittent nature of renewable energy sources. In this context, demand response mechanisms have emerged as a solution. In environments where renewable energy accounts for a high proportion of electricity generation, demand response has become a crucial strategy for mitigating supply fluctuations.

Currently, price-based demand response is one of the important means to achieve grid stability. Monfared et al proposed a price-based hybrid demand response (HPDR), outlining the impact of smart grids on retail electricity prices[2]. Xu et al proposed a hybrid demand response mechanism that combines real-time pricing with real-time incentives, demonstrating its effectiveness in alleviating peak load[4]. Alsalloum et al describes the integration of renewable energy into the grid, exploring optimal pricing and electricity demand[1]. Pourramezan describes the relationship between price and load response, considering both renewable energy and common thermal technologies[3].

Building on existing literature, this study aims to address the following questions within the context of renewable energy integration into the electricity market: Can a

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price-based demand response mechanism mitigate the imbalance between supply and demand in the electricity market? How should the grid determine the incentive values for renewable energy electricity, and what impact do changes in these values have on electricity prices and the utility value of the grid? What effect does improving the stability of renewable energy generation have on the electricity retail prices and the achievement of supply-demand balance in the electricity system?

2 Model Description

In the context of the integrated energy market, this paper establishes a electricity system model that includes the grid, electricity retailers, and end-users. Initially, the grid, as the provider of traditional energy electricity, can ensure the stability of energy supply. At the same time, it sets optimal incentive values for renewable energy electricity for retailers and the optimal wholesale electricity price for traditional energy, aiming to maximize its own utility. Subsequently, electricity retailers, in addition to purchasing electricity from the grid, also need to produce and sell renewable energy electricity to meet consumer demands. For example, Tesla's Powerwall project combines energy storage and solar power. In 2021, Tesla Energy's venture into selling electricity was officially approved, allowing it to provide retail electricity services directly to customers and the local grid. Retailers set optimal electricity prices for users with the aim of maximizing profits. Finally, consumers determine their optimal electricity demand for different energy sources based on the electricity price.

The paper assumes that the production of renewable energy electricity by electricity retailers has intermittent characteristics, therefore, a random variable ζ representing the renewable energy generation output density is introduced, assumed to be $\zeta = [1,1-\rho;\alpha,\rho]$, where α is distributed in the interval $[0,1)$, with $\alpha = 0$ indicating no renewable energy generation output density. The expected value of ζ is $E(\zeta) = 1 - \rho + \alpha\rho$. Table 1 shows the symbols for this article.

Table 1. Summary of notations

Parameters	Definitions
a, b, c	Electricity retailer a cost coefficient for electricity supply.
d	Cost function coefficient of electricity network load fluctuation
ρ	Intermittent parameters of renewable energy generation
$m_{n,l,t}$	Cost coefficient of electricity transfer for user n in time period t
$\omega_{n,l,t}, \varphi_{n,l,t}$	Quadratic utility function coefficient of user n in time period t
$d^0_{n,l,t}$	Power demand of user before demand response in time period t
$\eta_{n,l,t}$	User pays transfer cost weight
$\lambda_{n,l,t}$	Environmental awareness of users

For users, the utility function includes the utility derived from consuming renewable energy electricity; the cost of losses incurred from using conventional energy electricity; the cost of purchasing electricity; and the cost associated with electricity demand shifting following demand response.

$$\max \sum_{t\in T} U_{n,l,t}\left(d_{n,l,r,t}, d_{n,l,c,t}\right) = \max \sum_{t\in T} \left[\left(\omega_{n,l,t} d_{n,l,r,t} - \frac{1}{2}\varphi_{n,l,t} {d_{n,l,r,t}}^2\right) - \lambda_{n,l,t}\left(d_{n,l,c,t}\right)^2 - P_{e,t}\left(d_{n,l,r,t} + d_{n,l,c,t}\right) - \eta_{n,l,t}\left(\frac{1}{2} m_{n,l,t}\left(d_{n,l,t}^0 - d_{n,l,r,t} - d_{n,l,c,t}\right)^2\right)\right] \quad (1)$$

For electricity retailers, the profit function includes revenue from selling electricity, the supply cost of renewable energy electricity, the cost of purchasing electricity, and income from monetary incentives.

$$\max \sum_{t\in T} U_l\left(P_{e,t}\right) = \max \sum_{t\in T}\left[P_{e,t}\left(D_{l,r,t} + D_{l,c,t}\right) - \left(a{D_{l,r,t}}^2 + bD_{l,r,t} + c\right) - P_{c,t}D_{l,c,t} + \pi_t D_{l,r,t}\right] \quad (2)$$

For the grid, the utility function includes revenue from selling electricity, expenditures on monetary incentives, and the cost of load fluctuations.

$$\max U_{GO}\left(P_{c,t}, \pi_t\right) = P_{c,t}D_{l,c,t} - \pi_t D_{l,r,t} - d\left(D_{l,r,t} + D_{l,c,t} - \frac{d_{n,l,t}^0}{H}\right)^2 \quad (3)$$

Theorem: By employing the reverse solving method, we respectively obtain the user's renewable energy consumption $d_{n,l,r,t}$, traditional energy consumption $d_{n,l,c,t}$, the retailer's electricity price $P_{e,t}$, the grid's wholesale electricity price $P_{c,t}$, and the incentive value π_t, as follows:

$$d_{n,l,r,t} = \frac{-P_{e,t} + d_{n,l,t}^0 m_{n,l,t}\eta_{n,l,t} - d_{n,l,c,t} m_{n,l,t}\eta_{n,l,t} + \omega_{n,l,t}}{(1+\alpha\rho-\rho)\left(m_{n,l,t}\eta_{n,l,t} + \varphi_{n,l,t}\right)} \quad (4)$$

$$d_{n,l,c,t} = \frac{-P_{e,t} + d_{n,l,t}^0 m_{n,l,t}\eta_{n,l,t} - m_{n,l,t}\eta_{n,l,t} q_{n,l,r,t}(1+\alpha\rho-\rho)}{m_{n,l,t}\eta_{n,l,t} + 2\lambda_{n,l,t}} \quad (5)$$

$$P_{e,t} = \frac{4a\lambda_{n,l,t}\left(2\lambda_{n,l,t}\varphi_{n,l,t} + m_{n,l,t}\eta_{n,l,t}\left(2\lambda_{n,l,t} + \varphi_{n,l,t}\right)\right)}{8a\lambda_{n,l,t}\lambda_{n,l,t} + 2\left(2\lambda_{n,l,t} + \varphi_{n,l,t}\right)\left(2\lambda_{n,l,t}\varphi_{n,l,t} + m_{n,l,t}\eta_{n,l,t}\left(2\lambda_{n,l,t} + \varphi_{n,l,t}\right)\right)}\left(2b\lambda_{n,l,t} - 2\pi_t\lambda_{n,l,t} + P_{c,t}\varphi_{n,l,t} + 2d_{n,l,t}^0 m_{n,l,t}\eta_{n,l,t}\lambda_{n,l,t} + 2\lambda_{n,l,t}\omega_{n,l,t}\right)\left(2d_{n,l,t}^0 m_{n,l,t}\eta_{n,l,t}\lambda_{n,l,t} + 2\lambda_{n,l,t}\omega_{n,l,t} + m_{n,l,t}\eta_{n,l,t}\omega_{n,l,t}\right)\left(2\lambda_{n,l,t}\varphi_{n,l,t} + m_{n,l,t}\eta_{n,l,t}\left(2\lambda_{n,l,t} + \varphi_{n,l,t}\right)\right) \quad (6)$$

$$\pi_t = \left(-2bA_2(1-\rho+\alpha\rho)^2\left(A_1 - A_3P_{c,t}\right) - 2bB_2\left(B_1 - B_3P_{c,t}\right) + \frac{2bd_{n,l,t}^0 B_2}{H} + B_2P_{c,t} + A_2(1-\rho+\alpha\rho)\left(-2b\left(B_1 - B_3P_{c,t}\right) + \frac{2bd_{n,l,t}^0}{H}\right) + (-2bB_2 - 1)(1-\rho+\alpha\rho)\left(A_1 - A_3P_{c,t}\right) - \left(B_1 - B_3P_{c,t}\right)\right) / \left(2b{A_2}^2(1-\rho+\alpha\rho)^2 + 2b{B_2}^2 + A_2(2bB_2 + 1)(1-\rho+\alpha\rho) + (2bB_2+1)(1-\rho+\alpha\rho)\left(A_1 + A_2\pi_t - A_3P_{c,t}\right) + 2B_2\right) \quad (7)$$

$$P_{c,t}=\frac{B_1+B_2\pi_t+B_3\pi_t}{2bA_3{}^2(1-\rho+\alpha\rho)^2+2bB_3{}^2+2B_3+2bA_3B_3(1-\rho+\alpha\rho)+2bA_3B_3(1-\rho+\alpha\rho)}\Bigg(2bA_3(1-\rho+\alpha\rho)^2(A_1+A_2\pi_t)-A_3(1-\rho+\alpha\rho)\left(-2b(B_1+B_2\pi_t)+\frac{2bd^0_{n,l,t}}{H}-\pi_t\right)+2bB_3(B_1+B_2\pi_t)-\frac{2bd^0_{n,l,t}B_3}{H}\Bigg)+2bB_3(1-\rho+\alpha\rho)(A_1+A_2\pi_t) \tag{8}$$

Among them, the algebraic part of the above formula is expressed as follows:

$$A_1=\Big(\big(2\lambda_{n,l,t}(\lambda_{n,l,t}+\varphi_{n,l,t})+m_{n,l,t}\eta_{n,l,t}(2\lambda_{n,l,t}+\varphi_{n,l,t})\big)\,\omega_{n,l,t}+\lambda_{n,l,t}\left(-2b\lambda_{n,l,t}+d^0_{n,l,t}m_{n,l,t}\eta_{n,l,t}(2\lambda_{n,l,t}+\varphi_{n,l,t})\right)\Big)\Big/\Big(\big(2\lambda_{n,l,t}\varphi_{n,l,t}+m_{n,l,t}\eta_{n,l,t}(2\lambda_{n,l,t}+\varphi_{n,l,t})\big)(1+\alpha\rho-\rho)\left(4a\lambda_{n,l,t}{}^2(2\lambda_{n,l,t}+\varphi_{n,l,t})\right)\Big) \tag{9}$$

$$A_2=\frac{2\lambda_{n,l,t}{}^2}{\big(2\lambda_{n,l,t}\varphi_{n,l,t}+m_{n,l,t}\eta_{n,l,t}(2\lambda_{n,l,t}+\varphi_{n,l,t})\big)(1+\alpha\rho-\rho)\left(4a\lambda_{n,l,t}{}^2(2\lambda_{n,l,t}+\varphi_{n,l,t})\right)} \tag{10}$$

$$A_3=\frac{\lambda_{n,l,t}\varphi_{n,l,t}}{\big(2\lambda_{n,l,t}\varphi_{n,l,t}+m_{n,l,t}\eta_{n,l,t}(2\lambda_{n,l,t}+\varphi_{n,l,t})\big)(1+\alpha\rho-\rho)\left(4a\lambda_{n,l,t}{}^2(2\lambda_{n,l,t}+\varphi_{n,l,t})\right)} \tag{11}$$

$$B_1=\Big(\varphi_{n,l,t}\left(-2b\lambda_{n,l,t}+d^0_{n,l,t}m_{n,l,t}\eta_{n,l,t}(2\lambda_{n,l,t}+\varphi_{n,l,t})\right)-2\left(2a\lambda_{n,l,t}+\lambda_{n,l,t}\varphi_{n,l,t}+m_{n,l,t}\eta_{n,l,t}(2\lambda_{n,l,t}+\varphi_{n,l,t})\right)\omega_{n,l,t}\Big)\Big/\Big(8a\lambda_{n,l,t}{}^2+2(2\lambda_{n,l,t}+\varphi_{n,l,t})(2\lambda_{n,l,t}\varphi_{n,l,t}+m_{n,l,t}\eta_{n,l,t}(2\lambda_{n,l,t}+\varphi_{n,l,t})\Big) \tag{12}$$

$$B_2=\frac{2\lambda_{n,l,t}\varphi_{n,l,t}}{8a\lambda_{n,l,t}{}^2+2(2\lambda_{n,l,t}+\varphi_{n,l,t})(2\lambda_{n,l,t}\varphi_{n,l,t}+m_{n,l,t}\eta_{n,l,t}(2\lambda_{n,l,t}+\varphi_{n,l,t})} \tag{13}$$

$$B_3=\frac{\varphi_{n,l,t}{}^2}{8a\lambda_{n,l,t}{}^2+2(2\lambda_{n,l,t}+\varphi_{n,l,t})(2\lambda_{n,l,t}\varphi_{n,l,t}+m_{n,l,t}\eta_{n,l,t}(2\lambda_{n,l,t}+\varphi_{n,l,t})} \tag{14}$$

3 Numerical simulation

In this electricity market, it is assumed that a day can be divided into twenty-four periods, consisting of one grid, one electricity retailer, and three electricity users. Based on data from the National Energy Administration and Zhu et al, the relevant data are set as follows: $a=0.01$, $b=0.02$, $c=0$, $\rho=0.5$, $\eta_{n,l,t}=0.32$, $d^0_{n,l,t}=30kw$, $d=3$, $\omega_{n,l,t}=[1,1.5,2]$, $\varphi_{n,l,t}=[0.149,0.224,0.299]$, $m_{n,l,t}=[0.5,0.62,0.7]$, $\lambda_{n,l,t}=[0.08,0.12,0.16]$[5].

3.1 The grid's optimal incentive for renewable electricity

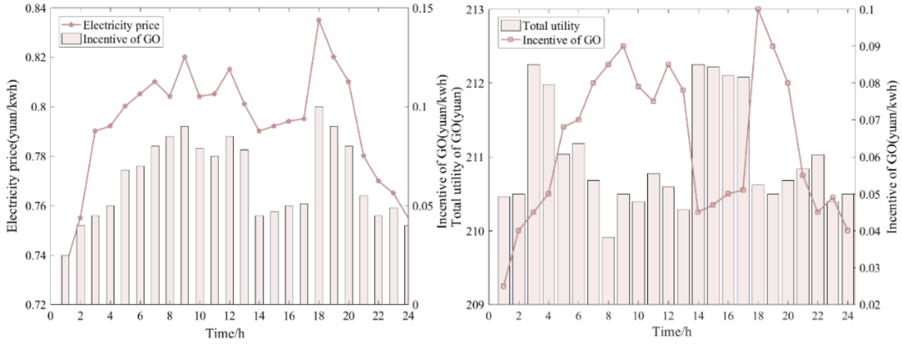

Fig. 1. Incentive values of GO impact on electricity prices and GO's total utility

In the Fig. 1, the higher the incentive value, the higher the electricity price also becomes. When the incentive value increases, the electricity retailer will invest more in renewable energy projects, leading to an increase in renewable energy electricity and consequently higher costs. However, subsidies from the grid cannot cover these costs, resulting in higher electricity prices. However, the utility value of the grid decreases with the increase of the incentive value, and the utility of the grid is lower during peak electricity usage periods. This is because an increase in the incentive value will inevitably bring additional costs to the grid itself, hence the trend where higher incentive values lead to lower utility values.

3.2 Intermittency parameter for renewable electricity

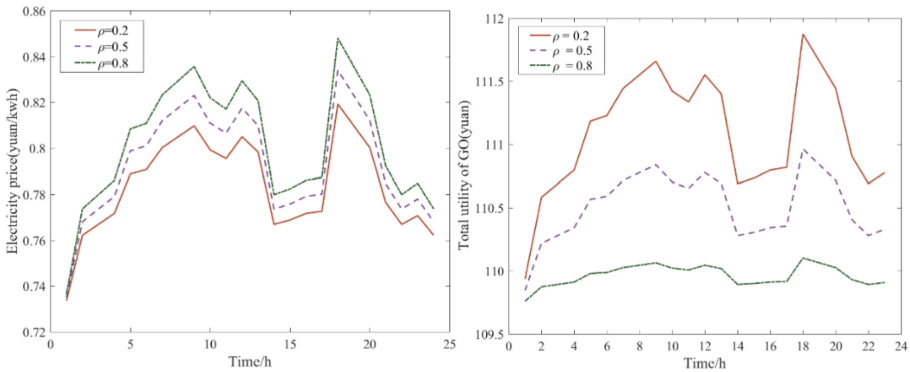

Fig. 2. Intermittency for renewable energy impact on electricity prices and GO's total utility

In the Fig. 2, the electricity price increases with the increase of the intermittency parameter ρ for renewable energy electricity. This is because a higher ρ indicates a less stable supply of renewable energy electricity, necessitating retailers to purchase more stable traditional energy electricity to meet users demands, thus the increase in purchasing costs leads to higher electricity prices. Moreover, the utility value of the grid decreases with the increase of the intermittency parameter ρ for renewable energy electricity. An increase in ρ results in a less stable and reduced supply of renewable energy electricity; consequently, the grid needs to pay more incentives to the retailers to boost their confidence in developing renewable energy electricity, leading to an increase in incentive costs and a decrease in utility.

4 Conclusion

This paper considers a power system structure composed of a grid providing traditional energy electricity, retailers producing their own renewable energy electricity, and users. The model's equilibrium outcomes are solved using a reverse inductive method. Subsequently, the impact of renewable energy grid integration on electricity prices and the utility value of the grid is explored through numerical simulation.

Initially, the grid provides incentives for retailers to produce their own renewable energy electricity, which will increase electricity prices but lead to a decrease in the grid's utility value. Notably, during periods of low electricity demand, even low incentive values provided by the grid can increase the consumption of renewable energy, due to the price-based demand response mechanism. Secondly, improving the stability of renewable energy electricity helps reduce electricity prices, particularly during peak electricity demand periods. At the same time, enhanced stability of renewable energy often increases the utility value of the grid.

Therefore, from the above conclusions, it can be seen that enhancing the willingness of users to respond to demand and accelerating the integration of renewable energy electricity into the grid can effectively solve the problem of supply and demand imbalance in the electricity market.

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