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Behavior analysis of wind power producer in electricity market

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HIGHLIGHTS

- Established closed-form models for WPP's market behavior.
- Analysis on relations between WPP's behavior and various market regulations and statuses.
- Raised a novel index to evaluate fairness and competitiveness of electricity market regarding wind power.
- Proposed beneficial references for market policy formulation.

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ABSTRACT

Renewable energy generation plays an important role in exploiting renewable energy towards green economy. The electricity market should be not only reevaluated with the coming of renewable energy, but also modified for maintaining market fairness and better utilization of renewable energy. Based on a Stackelberg game model, this paper puts forward a closed-form analysis on wind power producer's (WPP's) behavior in the electricity market involving large scale wind power. The WPP acts as a price-maker in DA market and a deviator in RT balancing market. The analytical expression of WPP's behavior indicates how a WPP takes an action under various market regulations and statuses, including bidding regulations, deviation settlements, demand elasticity, market capacity, and renewable subsidy. Furthermore, the two-part compound bidding mode is verified and recommended for restraining WPP's market power when considering ramping constraints of conventional units. The presented models are validated using real-world data based on the IEEE 118-bus test system. Conclusions provide beneficial references for policy formulation of electricity market involving large scale wind power.

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1. Introduction

Nowadays, climate change is within the urgent problems facing humanity. Power sector is a major greenhouse gas emission source, especially in countries with fast economic growth, large power consumption and severe dependence on fossil fuels [1]. The transition from fuel-dominated power system to renewable-dominated or finally the fully renewable power system contributes a lot to emission reduction [2,3]. As the most technically mature one, wind energy is utilized for power generation worldwide and eventually takes up an indispensable part in generation resources [4–6]. Moreover, unlike other distributed renewable resources like photovoltaic power, large scale wind power could be integrated into the power grid more centrally. As a result, one could no longer neglect the influences that wind power brings to the electricity market. Likewise, market policies should never be formulated without considering market participants possessing wind power [7–9].

Due to the intermittent and stochastic nature of wind power, most current researches have been focused on the approaches to bolster profits of the wind power producer (WPP). These studies could be summarized as five main categories, including improving wind power prediction accuracy, modification of market mechanism, coordinated trading, aggregation of demand response, and adopting financial tools. A more accurate prediction of wind power undoubtedly leads to greater profits of the WPP [10]. The intra-day market is believed and confirmed to be important for the profitability of the WPP [11,12]. In addition, Ref. [13] constructed a risky power market that allows WPPs to trade their uncertain future power with each other. In our previous work [14], we proposed a two-part compound bidding mode and verified that it could improve social benefits, enhance market competitiveness

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Nomenclature

a_i, b_i	parameter of supply curve of unit i (€/MWh, €)
a, b	parameter of integrated supply curve (€/MWh, €)
a_c, b_c	parameter of supply curve of coal-fired unit (€/MWh, €)
a_g, b_g	parameter of supply curve of gas-fired unit (€/MWh, €)
a_{con}, b_{con}	parameter of supply curve in conventional bidding mode (€/MWh, €)
$a_{tpc}, b_{tpc}, k_{tpc}$	parameter of supply curve in two-part compound bidding mode (€/MWh, €,€/MWh)
L_t	load in hour t (MW)
$q_{i,max}$	maximum output of unit i (MW)
$q_{w,max}$	maximum output of WPP (MW)
μ_+, μ_-	deviation penalty for delivering more or less quantity in RT market than traded in DA market (€/MWh)
r	ramping quantity (MW)
x_{max}	maximum output (MW)
$q_{i,t}$	quantity of unit i in hour t (MW)
$q_{wDA,t}$ $q_{wRT,t}$	quantity of WPP in DA or RT market in hour t (MW)
$p_{DA,t}$ $p_{RT,t}$	DA or RT price in hour t (€/MWh)
$q_{wBid,t}$	offered quantity of WPP in hour t (MW)
$q_{wPd,t}$ $q_{wPd,t}$	predicted/real quantity of WPP in hour t (MW)
$q_{we,t}$	prediction error of WPP in hour t (MW)
$p_{wBid,t}$	bidding price of WPP in hour t (€/MWh)
x_t	output in hour t (MW)
q_{sbe}	difference between $q^*_{wBid,t}$ and $q_{wPd,t}$ (MW)
π_t	WPP's profit in hour t (€)
$\pi_{DA,t}, \pi_{RT,t}$	WPP's profit in DA or RT market in hour t (€)
$\pi_{+,t}, \pi_{-,t}$	WPP's profit of deviation by delivering more or less in RT market in hour t (€)

for the WPPs, and alleviate the pressure of government subsidies. Integrated trading with other WPPs [15], thermal [16], pumped-hydro [17], and energy storage system [18] also helps mitigate the variability of wind power, thus improving profits of the WPPs. Ref. [19] took the ERCOT power system as an example and certificated that an in-time demand response countervailed more than 75% of costs from the uncertainty of wind power generation. Last but not least, Ref. [20] raised an option contract purchasing methodology, demonstrating that the option contract could be a competitive method for hedging against uncertainties of wind power.

An increasing amount of studies lays stress on the behavior of the WPPs in the electricity market and the corresponding effects. Ref. [21] firstly calculated the optimal offering quantity of wind power based on historical statistics. Ref. [22,23] used the autoregressive integrated moving average (ARIMA) model to describe the wind behavior for generating the optimal trading strategy for the WPPs under various market mechanisms. Ref. [24] deduced an analytical expression of optimal offering model by modeling the wind power as a scalar-valued stochastic process. Ref. [25] decided the energy allocation for the WPP between spot market and bilateral contracts. Ref. [26] maximized profits of the WPPs in a three settlement market in Netherlands and Germany. Ref. [27] discussed the WPP's behavior under perfect competition, monopoly and a duopoly, respectively. Ref. [28] provided a probabilistic bidding model considering the correlation between market price and wind power and emphasized the importance of a proper penalty level to avoid undesirable market distortion. Unlike the literatures mentioned above, Ref. [29,30] allowed a WPP to offer not only quantity but also price, and then studied its behaviors. The analysis in Ref. [31] demonstrated that discovering real marginal cost of wind power benefited the market operation. Thus, the WPPs should be encouraged to offer prices. Ref. [32] used a learning algorithm to analyze the bidding optimization issue considering the marginal price of wind power generation. Ref. [33] mentioned the potentiality that the WPPs may exercise market power by strategic offering. Ref. [31,34–38] showed that wind power's coming to the market reduced the market price level but enhanced price fluctuation.

The market policies and regulations regarding wind power integration are different in countries or regions for their different statuses and objectives of wind power development [8]. Therefore, it is necessary to model and evaluate how the WPP behaves under different market regulations and statuses. These studies often concentrated on generation expansion planning and transmission investment [39,40]. However, few literatures have addressed how different policies affect the fairness and competitiveness of the electricity market. And referring to WPP's market behavior, almost all literatures deal with the situation that the WPP strategically offers based on the historical market data and its past generation data. However, the WPP's realistic prediction also provides crucial information for offering.

Main contributions of this paper include: (1) Closed-form models for the WPP's behavior in the two-settlement market are established. In the models, the WPP's objective is to decide what quantity or price should be offered to the DA market to maximize its profits based on the predicted generation and market data. A Stackelbelg model is utilized where the maximum profit model of the WPP behaves as the leader, and the market clearing model behaves as the follower. (2) The WPP's behavior is analyzed and compared under various market regulations and statuses applied and studied in different regions currently. These regulations and statuses consist of bidding regulations, deviation settlements, demand elasticity, capacity of spot market and renewable subsidy. (3) A novel index is proposed to evaluate the fairness and competitiveness of electricity market involving large scale wind power. By the index, beneficial market policies are recognized. (4) The analysis is validated by conducting real-world data based examples. Conclusions drawn from the results provide beneficial references for formulating market policies regarding wind power.

The following assumptions are made for the sake of clarity:

(1) The two-settlement market mechanism is adopted, including the day-ahead (DA) market and the real-time (RT) market. Contract trading is not considered.
(2) The WPP is a price-maker in DA market and a price-taker in RT market.
(3) System congestion is not considered. Therefore, the RT price remains the same at different buses.
(4) Strategic behavior of conventional units is not considered.

The organization of this paper is as follows. Sections 2 and 3 describe the analytical WPP's behavior models for an individual hour and adjacent hours, respectively. Section 4 raises an index to evaluate the effectiveness of different market policies on the fairness and competitiveness of the electricity market. Test cases and result analysis are conducted in Sections 5, and 6 follows to conclude the paper.

2. Bidding model of an individual hour

This section gives the bidding models of a WPP in an individual hour under different bidding regulations and deviation settlements. The bidding model is generalized as a Stackelberg game.

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