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Market equilibrium analysis with high penetration of renewables and gas-fired generation: An empirical case of the Beijing-Tianjin-Tangshan power system

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HIGHLIGHTS

- A modified multi-period Nash-Cournot model is established.
- The large-scale of renewables and flexible resources are considered in the model.
- The renewables curtailment situations are considered in the model.
- An empirical example is provided, based on the real data of BTT region, China.
- Suggestions for future electricity and environment policies are presented.

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ABSTRACT

Facing stricter energy policies, the power mix in China is experiencing significant changes. First, the proportion of renewables, which have intermittent and stochastic generation, is assumed to be rapidly increasing. Thus, there is an increasing requirement to install more flexible generation capacity in the power system. According to the Chinese government's energy planning, in the near future, the proportion of gas-fired units will be greatly promoted to add flexibility to the power system. The impacts incurred by developing a high proportion of both renewables and gas-fired generation on the power market should be formulated and analyzed. In this study, a modified Nash-Cournot equilibrium model is proposed, considering renewable curtailment situations during valley times. Then, a large-scale and multi-period unit commitment model that considers the combined heat and power characteristics is presented to simulate market behaviors. On this basis, an empirical analysis of the Beijing-Tianjin-Tangshan power system equilibrium is illustrated as numerical examples, presenting the influences of the changing power mix on electricity prices, renewable energy integration, carbon emissions and air pollutant emissions. Finally, some suggestions on future electrical and environmental policies are presented.

1. Introduction

Facing more stringent restrictions on low-carbon operations and air pollutant emissions, it is inevitable that the traditional coal-fired generation capacity is experiencing a significant decline. In the meantime, the penetration of renewable energy is growing rapidly worldwide [1–3], especially in China [4].

Renewable energy, such as wind power and solar energy, is eco-friendly and low-carbon. With their intermittent and stochastic generating nature [5,6], there is plenty of pressure on the operation of power systems as well as on electricity markets [7,8]. Specifically, when the penetration of renewables reaches sufficiently high levels (exceeding 20% of total generation), the negative effects on the entire grid could be noticeable [9]. Thus, there is an increasing requirement to install more flexible generation capacity in the power system. Gas-fired units, which have faster ramping rates and lower air pollutant emissions than coal-fired units, with acceptable economical costs, have become appropriate options worldwide [10,11]. Therefore, the development of gas-fired units has become an important strategy for power mix transformation in the near future.

As an example, the Chinese government has recently issued a series of policies aimed at promoting the accommodation of renewable energy and increasing the proportion of gas-fired units at the same time [12,13]. According to the Chinese "Thirteenth Five Year" plan for renewable energy, renewable power generation will account for 27% of the total electricity generation by 2020, equivalent to supplanting 730

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Nomenclature

Acronyms

BTT Beijing-Tianjin-Tangshan area
ESS energy storage systems
CHP combined heat and power unit
MCP marginal clearing price
TSF thermal storage facility
NCP nonlinear complementarity programming
KKT Karush-Kuhn-Tucker
MPEC mathematical program with equilibrium constraints
MIQCP mixed integer quadratic constrained programming

Indices

t time period, set as 15 min
i generator sequence number

Sets

G set of gas-fired units
R set of renewable generation
C set of coal-fired units
H set of hydropower units
TH set of CHP units

Decision variables

$\lambda(t)$ price of the market at time t
$P_{\mathrm{D}}(t)$ electricity demand at time t
$\lambda(t)$ energy market MCP at time t
$\pi_{\mathrm{G}i}(t)$ profit of the gas-fired unit i at time t
$\pi_{\mathrm{R}i}(t)$ profit of the renewable generator i at time t
$P_{\mathrm{G}i}(t)$ power output of the gas-fired unit Gi at time t
$P_{\mathrm{R}i}(t)$ generation output determined by the renewables Ri at time t
$P_{\mathrm{C}i}(t)$ generation output decided by the coal-fired unit Ci at time t
$P_{\mathrm{H}i}(t)$ generation output decided by the hydropower unit Hi at time t
$C_{\mathrm{G}i}(t)$ operation cost of Gi at time t
$S_{\mathrm{G}i}(t)$ start-up and shutdown cost of Gi at time t
$W_{\mathrm{TH}i}^{AP}(t)$ air pollutant outputs at time t of thermal unit THi at time t
$W_{\mathrm{TH}i}^{CE}(t)$ CO_2 emissions of thermal unit THi at time t

Binary variables

$b_{\mathrm{G}i}(t)$ working status of Gi
$b_{\mathrm{G}i}^{up}(t)$ start-up status of Gi
$b_{\mathrm{G}i}^{down}(t)$ shutdown status of Gi
$b_{\mathrm{TH}i}^{Heat}(t)$ thermal unit THi heat supply status

Parameters

N total number of all generators
T total time period
$\alpha(t)$ intercept coefficient of the inverse demand function at time t
$\beta(t)$ ratio coefficient of the inverse demand function at time t
$P_{\mathrm{D}0}(t)$ referenced power demand curve based on the historical data at time t
$\sigma(t)$ power upper limit coefficient during the valley time at time t
$a_{\mathrm{G}i}$, $b_{\mathrm{G}i}$, $c_{\mathrm{G}i}$ coefficients of the total generation cost
$C_{\mathrm{G}i}^{up}$ start-up cost of the gas-fired unit Gi
$C_{\mathrm{G}i}^{down}$ shutdown cost of the gas-fired unit Gi
$P_{\mathrm{G}i\ \min}$ minimum generation output limits of the gas-fired unit Gi
$P_{\mathrm{G}i\ \max}$ maximum generation output limits of the gas-fired unit Gi
$P_{\mathrm{G}i}^{SU}$ ramping up limit of Gi during its start-up period
$P_{\mathrm{G}i}^{SD}$ ramping down limits of Gi during its shutdown period
$P_{\mathrm{G}i}^{SD}$ ramping up limits during operation time
$P_{\mathrm{G}i}^{RD}$ ramping down limits during operation time
$T_{\mathrm{G}i}^{up}$ minimum operation time
$T_{\mathrm{G}i}^{down}$ minimum cool-down time
$P_{\mathrm{R}i\ \min}(t)$ minimum generation output limit of Ri
$P_{\mathrm{R}i\ \max}(t)$ maximum generation output limits

million tons of standard coal [14]. According to the Chinese "Thirteenth Five Year" plan for the electricity industry, the average growth rate of gas-fired installed capacity will exceed 10% in the next 5 years [15]. Taking Beijing city as an example, with the transformation of gasification in Beijing in recent years, there are already 8.2 GW of gas-fired installed capacity, accounting for more than 90% of the thermal unit capacity. Extended to the entire Beijing-Tianjin-Tangshan (BTT) region, with a total of 71.3 GW installed generation capacity, the proportion of gas-fired capacity exceeds 15% of the total installed capacity as of September 2016 [16].

This significant change in the generation mix will impose significant impacts on the operation of power systems and power markets. The impacts incurred by developing a high proportion of renewables and gas-fired generation on the power market should be formulated and analyzed. On the one hand, as flexible generation resources, the contribution of gas-fired units to promoting the integration of renewables should be quantitatively identified. On the other hand, the operational cost of gas-fired units is relatively high, especially when they are required to start-up and shut down frequently to handle the intermittent renewable outputs, while the operation cost of renewables is always relatively quite low [17]. Thus, the marginal operation units in the market might be frequently switched, and sharp price spikes might be expected. It would be necessary to determine the renewable accommodation capability, price stability, pollutant output, profit potential and operational capability of the future system under the planed generation mix. Furthermore, if the forecasting simulations are not satisfied with the current policies, it will be detrimental to give advice on the decision-making of future policies.

Since it has been widely used in many electricity market analyses, the equilibrium model is known to be a good tool for electricity market analysis [6,13–16]. Ref. [10] analyzed the competitiveness of gas-fired units under different environmental policies. In this study, the market participants act as the price-taker, bidding on historical price data. Ref. [18] used a stochastic Cournot model to represent the strategic behavior of wind generators. With the bidding strategy proposed in the study, the profit for wind farms could be increased. Ref. [19] proposed a Cournot model solved by a potential function to evaluate the contribution of energy storage to supporting large-scale renewable generation in joint energy and ancillary service markets. It focused on the market behaviors of energy storage systems (ESS). Ref. [1] presented a multi-nodal intertemporal Cournot gaming model to simulate capacity-energy and energy-only markets under high penetration of renewables with an aim to compare the two markets. Ref. [20] empirically analyzes the electricity market evolution with a changing generation mix based on the China 2050 High Renewable Energy Penetration Roadmap, using a multi-period Nash-Cournot model. In this study, the impacts of a high proportion of renewables and ESS on the market were examined. In Ref. [21], a dynamic game-theoretic model was developed to analyze the