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Electricity markets evolution with the changing generation mix: An empirical analysis based on China 2050 High Renewable Energy Penetration Roadmap ☆

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HIGHLIGHTS

- How electricity markets are evolving with the changing generation mix is studied.
- China 2050 High Renewable Energy Penetration Roadmap are empirically analysed.
- A multi-period Nash-Cournot model is established to study the market equilibrium.
- Energy storages are analysed and compared to reveal their impacts on the equilibrium.

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ABSTRACT

The power generation mix are significantly changing due to the growth of stricter energy policies. The renewables are increasingly penetrating the power systems and leading to more clean energy and lower energy prices. However, they also require much more flexibilities and ancillary services to handle their uncertainties and variabilities. Thus, the requirements for regulation and reserve services may dramatically increase while the supplies of these services, which are mainly from the traditional thermal plants, remain almost invariant. This changing situation will cause higher regulation and reserve prices and impact the profit models and revenue structures of the traditional plants. How electricity markets are actually evolving with the changing generation mix? Can enough backup power plants be given adequate economic incentives and thus remained with the increasing renewables and the decreasing energy prices and productions? Can de-carbonization be fully performed in power systems? To explicitly answer the question, this paper uses a multi-period Nash-Cournot equilibrium model to formulate the evolution of power markets incorporating different types of generators, including thermal units, hydro units, wind farms, solar stations and energy storage systems. The price changes in the co-optimized energy, regulation and reserve markets, and the profit changes of various generators are studied. And the variabilities and uncertainties of renewable generation sources are considered in dynamically determining the requirements of regulation and reserve services. Based on the *China 2050 High Renewable Energy Penetration Scenario and Roadmap Study*, empirical analysis is performed to identify the impacts of the changing generation mix on electricity markets and power industry. The energy storage systems are specifically analysed and compared to reveal their impacts on the profit structures of various generators.

1. Introduction

The 2015 United Nations Climate Change Conference, which was held from 30 November to 12 December in Paris, France, announced that the world would work together to ensure that the increase of global warming not greater than 2 °C compared to pre-industrial levels [1]. Before that, on 30 June 2015, China submitted its Intended Nationally Determined Contribution (INDC), including the target to lower carbon dioxide emissions per unit

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of GDP by 60–65% from the 2005 level, to increase the share of non-fossil fuels in primary energy consumption to around 20% by 2030, etc. [2].

Considering the enforcements of stricter energy and environmental policies all over the world, the power generation mix has been undergoing significant changes. The proportion of renewables, such as wind power and solar power, is rapidly increasing and the conventional fossil-fuel based energy sources represent a continuously declining share in the primal inputs to power generation [3,4]. According to the latest *China 2050 High Renewable Energy Penetration Scenario and Roadmap Study* performed by Energy Research Institute National Development and Reform Commission of China [5], the development goal of both wind power and solar power of China is very ambitious. The installed capacities of wind units and solar units will reach 2400 GW and 2700 GW, respectively, by 2050, indicating that the percentage of renewables in total installed capacity can be as much as 69%.

The ever-increasing wind farms and solar stations not only produce much more clean and eco-friendly power but are also becoming more competitive regarding their low variable generation costs in the energy market. Renewable sources could replace the thermal power plants with high variable costs, leading to lower short-term energy prices because of the merit-order effect.

The benefits of renewable energy are well known to the general public, but the challenges and impacts they bring still require enough attention. In fact, large-scale integration of the renewables would put great pressure on the operation of power systems due to the intermittent outputs and stochastic nature of such sources [6,7]. Ref. [8] analyzes the impacts of renewable energy support mechanisms on the operation of electricity markets. Ref. [9] proposes a cleaner energy system and corresponding electricity market design to support the renewable energy. Ref. [10] studies how to integrate large-scale renewable generations in electricity markets. Ref. [11] analyzes the changing electricity markets in the next five years with increasing renewables. Ref. [12] studies the impacts of wind generation on wholesale electricity prices in the hydro-rich Pacific Northwest.

Therefore, more backup units and flexible generation resources are required to provide ancillary services, such as regulation and reserve services, to handle the uncertainties and variabilities of renewables and to balance the system second by second [13,14]. According to the relevant research, dynamic demands for the regulation and reserve services have a strongly positive correlation with the increase in the amount of renewable generations [15].

Currently, the majority of flexible services are provided by the traditional thermal plants and this situation may not significantly change in the foreseeable future. However, most of the profits that the thermal plants make are from the energy market instead of the ancillary service markets. Thus, the thermal plants are more willing to provide energy instead of regulation or reserve services. Taking the PJM (short for Pennsylvania, New Jersey and Maryland) power market as an example, in 2013, the average energy, regulation and synchronized reserve prices were $37.15/MW h, $26.04/MW and $6.98/MW [16], respectively. From another perspective, the load weighted energy price per MW h is $38.66, while regulation and reserve prices per MW h are $0.24 and $0.1. Therefore, considering that the energy demand is much higher than the demands for ancillary services, the actual revenues of thermal plants obtained from providing the regulation and reserve services may be less than 1% of the total income [16].

However, in the future, with the increasing penetration level of renewable energy, the energy prices might decrease significantly and lower prices reduce incentives to invest backup units. In fact, this situation has been observed in the market with a high penetration of renewables, e.g., the Danish electricity market [17], where the energy prices can be as low as zero or even negative value. This situation would hinder thermal plants from competing with the renewables in the energy market, and consequently, the installed capacities of thermal plants would be gradually reduced.

In this case, the provisions of regulation and reserve services would accordingly reduce while the demands for ancillary services would increase due to the variabilities and uncertainties of the increasing the amount of renewable generations. Meanwhile, the practical and economic approach for wind units and solar units to provide ancillary services is still under discussion due to their uncontrolled weather-dependent time-varying generations [18,19]. Thus, the relation between supply and demand will become increasingly tense in the ancillary service markets and accordingly leads to higher market prices. This would even result in significant changes in the revenue structure of the thermal plants and other kinds of traditional units, that is, with large-scale deployment of renewable generations, thermal plants may make more profits by providing the regulation and reserve services rather than generating energy as in the past. Therefore, the evolving electricity markets and changing prices in the energy and ancillary services markets will provide a new business model for the conventional fossil-fuel based plants. They may choose to allocate their capacities to provide more regulation and reserve services to obtain more profits and to survive in the market with the increasing renewable generations, which are more cost-effective and have many types of supportive policies [20].

In addition, considering the high flexibility and the operational characteristic of energy storage systems, they may become a potential and promising option to provide ancillary services in the future if their capital costs can be made to be sufficiently economical for large-scale applications [21]. By introducing the energy storage systems, the tense supply-demand relationship in the ancillary service markets might be eased, and the prices might accordingly decrease. This could be helpful to improve the benefits and affordability of the integration of large-scale renewables, optimize the changing generation mix and reduce the related side effects. Consequently, the high profits obtained by providing ancillary services for the traditional power plants might no longer be available.

In this new situation, how energy and ancillary service markets are actually evolving with the changing generation mix? What are the impacts of the changing generation mix on the power industry in the long term? Can electricity markets give enough incentives to invest or keep sufficient backup power plants to improve the integration of renewables? What the profit structure of the traditional units from the energy and ancillary services markets will become? Can the traditional plants survive with the increasing renewable generations? If not, is it necessary to provide additional subsidies for traditional plants to provide ancillary services and backup use? Furthermore, can other types of flexible resources, e.g. energy storage systems [22], completely replace the role of traditional plants? What effects would be incurred by the energy storage systems in the market, either on the market prices and their profit structures? All the above problems must urgently be studied in depth, which are the major concerns of this paper.

A quantitative model framework is established to describe the practical electricity markets in North America [23–25], in which energy, regulation and reserve markets are co-optimized to handle the capacity coupling effects of generators and to optimize the utilization of power resources. Market participants simultaneously submit their strategic offers in the above three markets to maximize their individual profits. The profit-driven behaviors of each generator and the strategic interactions between market participants in the three markets should be considered to simulate the real market as closely as possible.

Therefore, the main focuses of this paper are: