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Study on the promotion of natural gas-fired electricity with energy market reform in China using a dynamic game-theoretic model

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HIGHLIGHTS

- The impacts of market deregulations on the promotion effect of gas power are focused.
- Market deregulation and the environmental externality are considered together.
- A dynamic game-theoretic model was proposed and employed.
- The competition of gas power and coal power in a deregulated market is studied.

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ABSTRACT

Natural gas-fired electricity (NGFE) has gained great attention in China recently. However, the high generation cost leads to the NGFE cannot compete economically with the coal-fired electricity (CFE) when the value of peak power and positive environment externality of NGEF are not considered. Therefore, the market reform of natural gas (NG), including price deregulation, carbon tax and environmental subsidy are of vital importance to promote the penetration of NGFE. In the present study, a dynamic game-theoretic model was developed to analyze the impacts of market reforming for natural gas on the promotion effect of NGFE, in which the hourly real-time pricing (RTP) was applied in both natural gas and electricity markets. Five scenarios were proposed with different policy combinations of pricing mechanism reform, carbon tax and environmental subsidy. Based on the analysis results, it can be concluded that (i) deregulating the NG price, imposing carbon tax and adopting environment subsidy can promote the market penetration of NGFE greatly; and (ii) the market deregulation can increases the share of NGFE to 5.49%, and imposing the carbon tax of 100 RMB/tonne CO_2 can raise it further to 7.66%, furthermore if the environmental subsidy of 134.3 RMB/MWh is also included, the share of NGFE can reach 15%.

1. Introduction

China has predicted that its CO_2 emissions will reach peak before 2030. In order to mitigate the CO_2 emissions, natural gas (NG), as the“cleanest” fossil fuel, has gained increasing attention in China. NG has already been widely used in residential sector and industry sector nowadays. With the West-East Gas Pipeline and transnational gas pipelines coming into operation, China's NG consumption in recent years has grown rapidly. Its average annual growth rate reached 15.44% in the period of 2000–2014. However, at present, the NG industry is facing a big challenge that the further increase of consumption is hindered by its high price.

Nowadays, the development of natural gas-fired electricity (NGFE) is still at an initial stage in China, accounting for a small amount, 3.3% in power generation composition in 2013 [1]. Although renewable energies are more environment-friendly compared with NGFE, they still cannot economic competitive enough compared with NG especially in a large scale. Moreover, technologies advances [2] are allowing NG to provide power with high ramp-up and ramp-down speed that can deal with the intermittency of renewable energies. Compared to coal-fired electricity (CFE), NGFE is preferable to supply the peak demand due to its fast ramp-up and ramp-down rates and NGFE's carbon dioxide (CO_2) emissions is 60% lower than that of CFE. At present, because the advantages of NGFE are not considered in the markets, it is hard for NGFE to compete with CFE due to the high cost issue. According to the latest national energy strategy plan [3], Chinese

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Nomenclature

Acronyms:

NGFE	natural gas-fired electricity
CFE	coal fired-electricity
NG	natural gas
RCeGe	ratio of coal-fired electricity to gas-fired electricity

Indices

t	hour
u	user type
i	fuel type
gas (subscript)	natural gas-fired electricity
coal (subscript)	coal-fired electricity

Decision variables

$G(ld, gp)$	total revenue of natural gas supplier earned by selling fuel
$rl(u, t)$	electricity demand of user u at time t
$gp(t)$	natural gas price used for generation at time t
$ep(u, t)$	electricity price of user u at time t
$ld(t)$	electricity generation at time t

Parameters

$fp(i)$	fuel price of i
$avp(u)$	average electricity price (current)
fp_{lower}	lower boundary of natural gas price
fp_{upper}	upper boundary of natural gas price
$gtoe$	energy conversion efficiency of natural gas
$ctoe$	energy conversion efficiency of coal
fix	unit fixed generation cost
α	electricity price constraint coefficient
μ	cost coefficient of demand fluctuation
sd	unit amount of environmental subsidy
SD	total environmental subsidy
ct	unit carbon tax per tonne CO_2 emission
Tax	total carbon tax during time T
R	payment rate of capital cost per year
em	emission factor denoted by CO_2 emission volume per kilowatt hour
C_M	total capital cost
C_{MO}	maintenance and operation cost of the unit
CA	capital cost of unit per year
H	operation hour of each unit per year
y	lifetime years of the unit

government has made a plan to increase the share of NG in the total primary energy from 5% in 2013 to 10% by 2020. To achieve that target, a series of policies and measures have been made to promote the market penetration of NGFE [4] to replace CFE [5,6]. Nevertheless, the increase of NGFE is still very slow. Previously, energy prices, such as NG and electricity, are regulated by Chinese government. For example, today's NG price in Beijing is fixed at a relatively high level which is equal to 3.65 RMB/Nm^3 ($17.04/MMBtu) [7]. Moreover, the government doesn't subsidize the power plant when generating power with low CO_2 emissions, such as NGFE. In order to further improve the competitiveness of NGFE, it is of great importance to reform the regulated markets for both NG and electricity and internalize the environmental externality in the pricing mechanism.

Nowadays, the hub-based pricing mechanism is the dominated method applied in the North American NG market. According to this pricing mechanism, only pipelines and local distribution companies are directly regulated with respect to the services they provide, and the NG prices are no longer regulated by the government [8]. The NG pricings in Japan include imported LNG pricing and NG retail pricing. JCC (Japan Crude Cocktail) link price is implemented for imported LNG nowadays that is determined as JCC × negotiated price slope + constant term, which represents the average monthly price of a basket of various crude oil imported into Japan and moves in line with other global crude benchmarks. Slope defines the relationship between oil and NG prices. Constant term generally represents a fixed price element that is independent of oil movement [9]. For example, a crude basket price of $100/barrel with a 15% slope and $2.00/MMBtu premium would yield an LNG import price of $17.00/MMBtu [10]. As for retail price, cost-plus method was used initially and market-oriented pricing mechanism through negotiation between suppliers and consumers was adopted since 1955. In Europe, its mid-stream utilities that are obliged to purchase NG under long term contracts are normally priced in a way linked to oil products [11]. Hub-based pricing, which is similar to the North America [12] has been applied to about 53% of the NG market in Europe in 2013. According to the experiences of the developed countries, one of key points of market reform for China is to introduce price deregulation that can allow the NG price varies dynamically.

There have also been some studies in China evaluating the effect of energy subsidies on promoting the development of clean energy. Adopting the real option model, Jeon et al. optimized the financial subsidies for renewable energy and applied the model for photovoltaic (PV) [13]. Brutt et al. linked the PV subsidy with CO_2 emissions and examined the cost-effectiveness of renewable subsidies [14]. There are also some works about carbon tax and emissions trading in order to reduce CO_2 emissions. For example, Chiu et al. evaluated the effect of emissions trading and carbon tax on energy prices [15]. It has been concluded that carbon tax causes more influence on the energy price compared with emissions trading. Although several studies have focused on the carbon tax, energy subsidy and market deregulation, the marketization of NG has not been considered in a market with carbon tax and environmental subsidy concurrently.

In this study, a game-theoretic model based on a multi-agent system is proposed, in which the real-time-pricing (RTP) is applied to both NG and electricity. The objective is to study the effect of market deregulation, carbon tax and environmental subsidy on the promotion of NGFE and optimize the electricity generation of power producer. Game-theoretic approach has been applied to study the power allocation [16], the optimal operations based on the residential participation level in electricity market [17], and the retail electricity market with high penetration of distributed generation [18] etc. However, the game theory has seldom been used in studying the marketization and the internalization of environmental externality for NGFE and CFE market which can simulate the dynamic interactive relationships among different players and give an equilibrium result.

This paper presents an innovative approach in modeling the interaction between the production and demand sides in NGFE market and employs the game-theoretic model using an optimization technique to calculate the effect of market deregulation, environmental subsidy and carbon tax policy. The main contributions of the study include (1) a simultaneous market deregulation for both NG and electricity is proposed and the generation interaction is investigated dynamically; (2) developing a general game-theoretic model, which can consider the interaction between NG market and electricity market for promoting the share of NGFE in total generation production compared with CFE. Even though