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The peak-shaving efficiency analysis of natural gas time-of-use pricing for residential consumers: Evidence from multi-agent simulation

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ABSTRACT

The present paper proposes a multi-agent simulation model for analyzing the peak-shaving efficiency of natural gas TOU (time-of-use) pricing for residential consumers. Firstly, a natural gas price sensitivity function has been explored according to gas consumption characteristics of residential users, which establishes the residential users demand response model from the perspective of consumer psychology. Secondly, a TOU pricing multi-agent simulation system has been developed, which mainly includes a government agent, a gas operator agent, and seven residential user agents of different income level. Finally, this study takes Zhengzhou city in China as an example to simulate the dynamic change process of running states in the UGPN (Urban Gas Pipeline Network) under the residential users TOU pricing policy. The simulation results indicate that the maximum peak-valley load difference can be reduced by 11.12%, given the residential users' response to TOU tariffs, by shifting load and electricity substitution. The TOU price also increases benefits of gas operators, and reduces residential consumers' energy expenditure. Furthermore, the small ratio of the residential users' consumption will lead to the low peak-valley load difference, but poor peak shaving efficiency and little gas operators' benefits. In addition, the expenditure on energy changes among different kinds of consumers; that is, the high and low income households have a large increased ratio, while the middle income households have a low increased ratio.

1. Introduction

The resource characteristics of "rich in coal, poor in oil and gas" in China resulted in the high proportion of coal energy consumption structure, and placed further burden on the environment [1]. But in the background of the global energy conservation and emissions reduction, as a clean, efficient resource, the demand for natural gas has increased greatly in China. From the 2.6% consumption of natural gas as a primary energy in 2005, this figure rose to 5.8% in 2013, with an average annual growth rate of about 10.5% [2]. Moreover, the "Energy development strategic action plan (2014–2020)", issued by the general office of the State Council of China, recently pointed out that the country should focus on the development of clean and low-carbon energy with the aim to adjust energy structure so that natural gas consumption ratio increases to more than 10% by 2020. There is no doubt that natural gas will play an increasingly important role in Chinese energy structure. Therefore, an overall reform of this industry, with a view to promoting the effective consumption of natural gas, has become a popular research subject. The reform of price is the most sensitive and crucial part, and the price reform of natural gas for residential use in particular involves thousands of households, making it a thorny and an emergent issue.

The current natural gas pricing policy for residential users is based on the cost-plus method, and the price is directly controlled by the government [3]. This pricing policy has the following disadvantages: (1) the natural gas price is separated from its commodity value, and does not reflect the scarcity of natural gas; (2) the natural gas price does not reflect market supply and demand relation because of government intervention; (3) natural gas price adjustment lacks flexibility, which leads to the unreasonable relationship between natural gas price and alternative energy price. Moreover, the current natural gas price for residential users is much lower in China. For example, in 2014, the natural gas price of residential users in Zhengzhou city only accounts for 42% of LNG price and 40% of electricity price, both at equivalent calorific value, and

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the price variance between industrial use and residential use of natural gas is 0.98 Yuan/m^3, both of which are abnormal and rare in other countries (See Table 1), and result in unreasonable or excessive consumption of natural gas for some households. Furthermore, the price of domestic gas is far lower than that of imported gas so that natural gas import business losses have been incurred in the gas operating enterprises (for example, China National Petroleum Corporation). These enterprises lack motivation to increase imports and investments in the natural gas industry, which results in the intensification of "gas shortages". Thus it can be seen that reforming the natural gas price system of residential users has become a very urgent problem.

For residential users, natural gas is mainly used for cooking, scouring bath, heating and gas air conditioning, fuel gas dryer and so on. The consumption is severely affected by factors such as season, temperature, and the attribute of user's consumption. Thus, the load variation of gas network obviously presents inhomogeneity on temporal distribution. The main performances are: first, seasonal inhomogeneity. The consumption of natural gas in winter is far more than it in summer, and the bigger the temperature difference is, the more significant the inhomogeneity. Second, daily inhomogeneity: there are obvious difference of consumption during weekdays, weekends, and holidays. Third, hour's inhomogeneity: generally, the consumption is more during the period of lunch and dinner, and relatively less on wee hours. The distribution of inhomogeneity is the key factor that causes the peak-valley difference in the UGPN (urban gas pipeline network), which is also the foundation for implementing the TOU (time-of-use) price of natural gas. Therefore, based on the demand side of the TOU pricing theory, this paper explores the possibility of implementing TOU pricing for residential users to realize peak load shaving and relieve urban "gas shortage". It then provides relevant data and materials for the reform of natural gas price. We first establish the residential user demand response model from the perspective of consumer psychology based on the proposed natural gas price sensitivity function. Moreover, considering the impact of income on natural gas price sensitivity, urban residential users in the UGPN are divided into seven categories according to household income; i.e., the lowest income households, low income households, lower-middle income households, middle income households, upper-middle income households, high income households, and the highest income households. The responsiveness of each category of residential users is not identical. Then, considering the substitution of electricity and natural gas, we present a design of the TOU price multi-agent system mainly comprising the government, the gas operator, Power Company, and seven categories of residential user agents. Finally, this study examines the case of Zhengzhou, China, in order to simulate the dynamic change process of each agent's inter-behavior, explores the peak-shaving efficiency of residential users' TOU pricing, and analyzes gas operator benefits and the impact of TOU pricing on different categories of users' energy expenditure.

2. Literature review

TOU pricing, which originated in the electric power market, is a well-known time-based demand response program [4–8]. In the 1970s and early 1980s, many American utilities conducted experiments for residential customers to examine the effectiveness of TOU rates [9–13]. Faruqui [10], who conducted twelve pricing experiments involving about 7000 residential customers, pointed out that residential peak-period electricity consumption is generally price-sensitive, and TOU rates should generally reduce peak-period electricity demand. Kohler and Mitchell [11] assessed the changes of residential load caused by TOU rates in three major experiments conducted in Wisconsin, Carolina, and Los Angeles, and noted that residential customer responses to TOU rates were affected by local conditions such as weather, temperature, and household appliances, and households made reductions during peak periods loads in response to TOU rates. Caves et al. [12] estimated a residential consumer demand model using data from five experimental implementations of residential TOU rates, located in California, Connecticut, North Carolina, and Wisconsin, and tested the hypothesis that the elasticities of substitution are identical across experiments. Also, the analysis of residential TOU data from Wisconsin Power, Narragansett Electric Company, Wisconsin Public Service, Pacific Gas & Electric, and Connecticut Light & Power have shown peak load consumption reductions of approximately 4%, 7%, 15%, 18%, and 23% respectively [14].

Unfortunately, in the United States, the TOU pricing was not widely implemented in the electricity market, mainly because the cost of advanced electric metering matching with TOU price was too high in the 1980s. Recently, however, with the development of advance technology, lower technology costs and higher value have made the TOU pricing for residential customer compelling. Many studies have investigated the impacts of TOU pricing for residential customers on peak load and household's electricity cost [15–21]. Rowlands and Furst [15] studied the cost change as the result of a mandatory move to TOU pricing on residential customers using hourly electricity data from 1020 households in Milton, Ontario (Canada) in 2008. Lee [16] studied the residential electricity load scheduling problem considering multi-class appliances with TOU pricing, and developed the electricity load scheduling algorithm to minimize the total electricity bill. Bartusch et al. [17] carried out an empirical study with the intention of estimating the scope of households' response to, and assessing users' perception of, a TOU electricity distribution tariff. Jessoe et al. [18] analyzed short-run household responses to a large-scale mandatory residential TOU program. Torriti [19] assessed the impacts of TOU tariffs on electricity demand, price savings, peak load shifting, and peak electricity demand at sub-station level form a dataset of residential users. Surles and Henze [20] examined the peak energy consumption reduction and energy cost savings for households and utilities using different energy control strategies. He et al. [21] implemented a Monte Carlo simulation to examine residential

Table 1
Natural gas price variance between residential use and industrial use in China and other countries.

Country	NGP_R (Yuan/m^3)	NGP_I (Yuan/m^3)	NGP_R/NGP_I	Chinese cities	NGP_R (Yuan/m^3)	NGP_I (Yuan/m^3)	NGP_R/NGP_I
Canada	2.36	0.96	2.46	Chengdu	1.89	4.03	0.47
U. S	2.38	1.07	2.21	Zhengzhou	2.25	3.23	0.70
Korea	5.29	5.49	0.96	Beijing	2.28	3.65	0.62
France	6.25	3.62	1.73	Shanghai	3.00	3.99	0.75
Germany	6.60	3.48	1.90	Guangzhou	3.45	4.85	0.71
U. K	5.35	2.92	1.83	Wulumuqi	1.37	2.11	0.65

Note: NGP_R represents natural gas price of residential users; NGP_I represents natural gas price of Industrial users; NGP_R/NGP_I represents the ratio of NGP_R and NGP_I.
Data source: IEA and China Price Information Network.