



Multi-agent simulation of the time-of-use pricing policy in an urban natural gas pipeline network: A case study of Zhengzhou



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ABSTRACT

This paper establishes a multi-agent system comprising a government agent, a gas operator agent, and an industrial and commercial users agent. The system simulates the dynamic change process of demands and running states in an UGPN (urban gas pipeline network) and explores the optimal TOU (time-of-use) natural gas price to minimize the peak–valley load difference. The government agent plays a monitoring role of providing the upper and lower limits of natural gas price. The gas operator dynamically sets natural gas price based on user response, within the bounds established by a government authority. Then, the industrial and commercial users modify their consumption according to the price provided by the gas operator. This study considers the case of Zhengzhou, China to simulate the hourly gas-usage behavior of industrial and commercial users under the TOU pricing policy. The results indicate the existence of an optimal peak–valley price difference through which both the gas operator and users can gain benefits. Further, rising peak price also increases the benefits of the end-users, while those of the gas operator decrease; however, at some threshold value, the gas operator benefits from further increases in the peak price.

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1. Introduction

The use of global energy is at an all-time high, and a range of sources, including fossil fuels, nuclear power and renewable sources, generate the energy. According to BP (British Petroleum) energy statistics, the primary energy consumption of China in 2011 is equivalent to 2.613 billion tons of oil. Since 2009, China has become one of the biggest energy consumers for three years now. In particular, natural gas consumption has increased greatly; from the 2.6% proportion of natural gas in primary energy in 2005, consumption has risen to 4.5% in 2011, with an average annual growth rate of about 9.6% [1,2]. Moreover, the Chinese Government has tried to improve the gas consumption ratio due to its relative cleanliness in recent years. The Outline of the 12th Five-Year Plan of the People's Republic of China for the National Economy and Social Development stipulates that the country should strengthen the construction of the clean energy industry so that the natural gas consumption ratio can increase to 8.3% by 2015.

However, the combination of this increased demand and the scarcity of natural gas has led to gas shortage in some cities in

China. Moreover, issues concerning the rigidity of the natural gas price system exacerbate the problem. In China, the current natural gas pricing method is based on the cost-plus policy, where the government directly controls the price; such method separates the natural gas price from its commodity value, and does not reflect the scarcity of the natural gas. Another problem stems from the lack of peak shaving and stability capabilities in an UGPN (urban gas pipe network) in China. The excessive demand in the peak period leads to low pressure in the UGPN, and as a result, several gas users are unable to use natural gas. Conversely, the low gas demand in the valley period leads to high pressure in the gas pipeline, causing the network to run with low efficiency and introducing safety concerns.

TOU (Time-of-use) pricing, which is commonly utilized in the electric power market, is the practice of implementing different prices for different times of use. Power companies determine peak and valley times, and then set higher and lower prices during the peak and valley periods, respectively, to motivate consumers to adjust their consumption, thereby easing the strain on the network during peak periods [3–5]. The TOU program is a well-known time-based DR (demand response) program, and has the following advantages: reducing operation cost, increasing profit, shifting and reducing peak loads [6–11].

Previous studies have considered different TOU pricing methods and models [12–16]. A multi-objective non-linear optimization model of TOU price has been established on the power demand

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side, and has been solved by maximum satisfaction method in fuzzy optimization theory [13]. Nikzad et al. proposed a two-stage SMILP (stochastic mixed-integer linear programming) model to determine the optimum TOU rates based on grid reliability index, and solved it using CPLEX as a powerful solver for MILP (mixed-integer linear program) [14]. He et al. presented a method to quantify residential DR based on both survey results and Monte-Carlo simulation of TOU rates [15].

Several studies have considered the optimal contract capacity problems of TOU rate users [17–19]. A multi-pass dynamic programming technique has been proposed to decide the optimal operation scheme of a battery energy storage system for a TOU rate user in Ref. [18]; this study sought to optimize the contract capacities of a TOU rate user. Lee and Chen presented an IPSO (iterative particle swarm optimization) algorithm for solving the optimal contract capacities of a TOU rate industrial user [19].

Few studies have investigated the relationship between TOU tariffs and energy consumption [20–23]. In particular, Torriti has assessed the impact of TOU tariffs in terms of changes in electricity demand, price savings, peak load shifting and peak electricity demand at the sub-station level [23].

Although the gas pipeline network and the electricity network are both in the business of energy supply, they differ in their pricing mechanisms and the methods they use for peak shaving. At present, the natural gas TOU pricing research is limited. Ou et al. have established a TOU pricing decision model for natural gas by combining the grey relationship with a Monte-Carlo simulation [24]. However, Ou et al. only proposed a static simulation model without considering the dynamic relationship between government, gas operator, and end-users. A TOU variation of natural gas price is known to result in a dynamically changing demand, which affects the operational state of the UGPN. This variation can result in the emergence of complex phenomena and characteristics. The ABMS (Agent-Based Modeling and Simulation) method is an effective tool for capturing and studying complex phenomena and systems, thus allowing the realization of complex adaptive calculations. The ABMS method has been gradually applied in studying TOU pricing in the power market [25,26].

This paper develops a simulation model to explore the possibility of TOU pricing in Zhengzhou, China. We first introduced the TOU pricing policy for natural gas market, which is implemented for industrial and commercial users. Then, a TOU price multi-agent system, involving the government, gas operator and users agents, is designed to simulate the running state of the UGPN in Zhengzhou. Using the multi-agent simulation model, we obtained an optimal

peak–valley price relationship and achieve two goals. First, both the gas operator and industrial and commercial users can benefit from this peak–valley price. Second, the peak–valley load difference can be reduced effectively to lower the risk of UGPN operation.

2. Problem formulation

The UGPN has a mixture of residential, industrial, and business users. For residential users, their relatively fixed patterns of behavior result in a small price elasticity of demand compared with other user types [27,28]. Given that their gas consumption is mainly for heating, cooling and cooking, modifying their consumption behaviors by varying the natural gas price is difficult.

However, for industrial and commercial users, natural gas is mainly used as a raw material or as fuel. Consequently, such users can more readily modify their consumption to achieve savings by targeting the valley periods. The price elasticity of demand for industrial and commercial users is relatively large. This characteristic suggests that the TOU pricing policy would be effective for industrial and commercial users. On this basis, this study only considers the industrial and commercial users in the UGPN.

The UGPN is a complex economic system with non-linear interaction mechanisms, and the different modules comprising the government, gas operators, and multiple types of users form a supply and demand network. This system can be transformed into a multi-agent system, wherein each module is regarded as an independent agent, while the various interactions among people, organizations, and machines can be described as independent activities between agents. An illustration of the TOU price multi-agent simulation model of the UGPN is shown in Fig. 1.

In a multi-agent system, agents are generally categorized into one of three different types according to their structures and functions, namely, cognitive, reaction, and hybrid. Each type of agent can be described using a set of elements, i.e., Agent = {ID, objective, knowledge base, rule set, internal state, external environment, attribute, parameter}. This set of elements defines the behavior rules and interaction mechanisms of the agent at a microscopic level.

In Fig. 1, there are four categories of agents, i.e., the government, gas operator, user, and real-time monitoring agent; the first three categories are hybrid type agents, while the last category is a reaction type agent. Their functions are described in detail below.

- (1) Government agent: This agent determines the upper and lower limits of the natural gas TOU price by considering natural gas

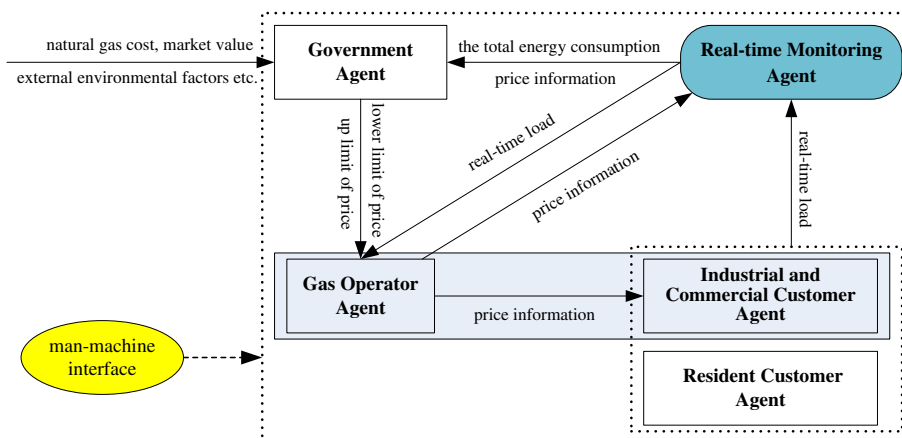


Fig. 1. TOU price multi-agent simulation model of the UGPN.

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