Applied Energy 163 (2016) 283–294

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

An optimal time-of-use pricing for urban gas: A study with a multi-agent evolutionary game-theoretic perspective

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HIGHLIGHTS

- A multi-agent system for urban gas market is developed.
- Evolutionary game-theoretic is adopted to determine the optimal TOU prices.
- Two types of TOU are assessed to reflect the variation of load and price.
- Significant potential for peak-shaving and load-shifting under TOU pricing.
- Industrial users is better in demand response than residential and commercial users.

ARTICLE INFO

Article history:
Received 28 May 2015
Received in revised form 5 August 2015
Accepted 20 October 2015

Keywords:
Urban gas market
Time-of-use pricing
Demand response
Game theory
Multi-agent system

ABSTRACT

In energy markets, regulators are often tempted to use price schedules to improve economic efficiency and promote a reasonable resource allocation. Time-of-use pricing is very popular with economists, and many researchers have been written estimating and exploring the optimal time-of-use pricing for electricity markets. Yet, such pricing has rarely been used in the natural gas sector. In this paper, we propose an optimal time-of-use pricing in urban gas market based on an evolutionary game-theoretic perspective. As the urban gas market is a nonlinear complex economic system with several interacting agents, we use a multi-agent system comprising a government agent, a local gas distribution operator agent, and different types of end-user agents. A power structure demand response program is employed to simulate the user demand response. A mixed-integer linear programming is formulated to determine the time-of-use price-signal delivering maximum gas operator profit and the optimal load pattern for end-users. In an illustrative example, we simulate and compare the time-of-use block prices and time-of-use hourly prices with traditional fixed pricing using real-world data of Wuhan in China. The numerical results indicate that time-of-use pricing schedules have significant potential for peak-shaving and load-shifting for urban gas pipeline network systems and would thus lower operating costs. Furthermore, different gas users exhibit different demand responsiveness intensity. Finally, we evaluate the impact on total social welfare of regulation scenarios and find that welfare decreases with deregulation, implying that the urban gas market is immature and reasonable regulation is still necessary.

1. Introduction

Price schedules can help to enhance the financial sustainability of urban energy systems [1–3]. In terms of the natural gas sector, a large part of the total cost is accounted for by the installation and maintenance of the distributed pipelines, metering infrastructure, and customer service running costs. Thus, the traditional marginal cost pricing rules, which mainly consider the operation costs, may not provide enough revenue to cover fixed costs. In developed countries, the two-part tariffs allowing for fixed access fees and market-oriented volumetric charges are commonly used [4,5]. In developing countries, on the other hand, the urban gas sector is still developing. The infrastructure of pipelines network and storage facilities is still expanding. As a result, gas supply systems cannot keep up with the rapidly growing demand in gas consumption. Consequently, the current government-regulated gas pricing schemes may fail to deliver allocation and financial objectives,

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http://dx.doi.org/10.1016/j.apenergy.2015.10.125
0306-2619/

Nomenclature

Acronyms
UGPN urban gas pipeline network
DSM demand-side management
TOU time-of-use pricing
MAS multi-agent system

Indices and parameters
t index of model time unit
T time periods in the optimization horizon
μ cost coefficient of gas demand fluctuation

Decision variables
P_t TOU price scheduling by operator
D_t demands response of gas user

Random variables
P_f original fixed price in time horizon T
P_c gas purchase cost of operator
$P_c^{\uparrow}$ gas purchase cost if contract supply shortage
$P_c^{\downarrow}$ gas storage cost if contract supply overmuch
P^{up} up-regulation price at the gas market
P^{down} down-regulation price at the gas market
D_t^0 user nominal demand of gas at the time t
$D^{\uparrow}$ gas purchase amount if contract supply shortage
$D^{\downarrow}$ gas storage amount if contract supply overmuch
$\overline{D}$ mean of gas demand in time horizon T
$D_t^{\max}$ maximum of gas demand at the time t
$D_t^{\min}$ minimum of gas demand at the time t
ξ_t price elasticity of gas demand at the time t

leading to financial losses and harming the prospects for healthy the development of urban gas sector in developing countries.

The natural gas market in China exemplifies this issue. Currently, the natural gas consumption has increased fast in China, growing at an annual rate of 9.6%, with its share in primary energy increasing from 2.6% to 5.1% between 2005 and 2013. To deal with the imbalance of demand and supply, the Chinese government launched a set of policies to encourage domestic and imported gas supply expansion, and promote efficient gas use, including the nationwide natural gas pricing reform program. However, the gas pricing reform progress is going on slowly, and gas shortages occur frequently due to the distortion gas pricing structure and insufficient gas sources [6–9].

To promote the construction of urban gas pipeline network (UGPN) and cover costs, the government has adopted two-part tariffs for urban gas markets, in which all consumers pay a fixed fee for access to the network once and a monthly fixed price volumetric charge based on average long run marginal cost [4,10]. However, the prices hardly reflect the changing operation costs or the imbalances between demand and supply throughout the day [11]. During peak hours, the gas demand is considerable higher than the average consumption. The gas pipeline network lacks pressure during peak demand and requires more storage gas to be injected, leading to running costs that are higher than the average marginal cost. While during off-peak hours, demand drops sharply and the pressure in the network is too high and raises safety concerns. We propose a time-varying gas pricing system to reflect the localized marginal cost in different periods. In the proposed scheme, the volumetric component of the two-part tariff would be replaced with a time-of-use pricing (TOU) while the access fee component of the tariff would remain unchanged.

TOU pricing is an efficient method of demand-side management (DSM) which can be employed by operators to influence user behavior [12–17]. By setting different prices in peak and off-peak periods of a day, the gas operators can encourage end-users to shift flexible demand components to off-peak hours. TOU pricing is commonly used in electricity markets. The TOU program is a well-known time-based demand response (DR) program which has the following advantages [18]: reduced operation costs; improved profits for gas operators; and reduction of peak load demand and the strain on the gas network.

There has been significant and beneficial work in the area of TOU pricing in recent years, highlighting the potential methods of TOU pricing in the DR program. The work in [19] adopts Monte Carlo simulation to quantify residential DR effectiveness of various TOU scenarios based on survey results, it is important to be aware that the results are likely to be quite system specific. The work in [20] establishes a two-stage stochastic mixed-integer linear programming (SMILP) model to determine the optimum TOU rates based on grid reliability index, and solved it using CPLEX. This is, in effect, exploiting the optimal TOU prices to enhance system reliability. The work in [21] proposes a novel method to design feasible TOU tariff rates based on Gaussian mixture model, both energy cost reduction and peak shaving have been investigated to explore the effects of the TOU tariffs on demand response. To describe the interactive relationship of stakeholder, the work in [22] adopts a game theoretical model accounting for the relationship between retailers (leaders) and consumers (followers) in a dynamic price environment. They reformulate a bi-level program as a single-level mixed-integer linear program (MILP). Similarly, the work in [23] presented a game-theoretic approach to optimize TOU pricing strategies by building utility functions of both utility companies and users, which provides optimal prices and user response. Furthermore, the work in [24] introduces a comprehensive demand response model in an agent-based retail environment. Their purpose is to represent customer response to time-based and incentive-based demand response programs with Q-learning method. Papers [25,26] investigate the impacts of TOU tariffs on electricity demand, price savings, peak load shifting and peak electricity demand at sub-station level. All findings indicate that TOU tariffs bring about higher average consumptions and lower payments by end-users. But the demand responding policies are slow to emerge and limited by the knowledge on the scope of potential gains. All these studies are based on models using multi-directional information exchange, where the system operators choose a price sequence based on communicated demand schedules and corresponding load response to that price sequence.

However, since the urban natural gas market appeared relatively late in China, the studies on natural gas TOU pricing are still limited in number. Recently, with the rapid expansion of natural gas market and continuously increasing gas consumption, the price reform and peak shaving of natural gas become an urgent problem to be solved. The work in [27] establishes a static simulation model for natural gas TOU pricing by combining the grey relationship with a Monte-Carlo simulation. The work in [28] introduces the TOU pricing policy for natural gas industrial users, and designed a TOU price multi-agent system based on linear demand response model. This model has been used to simulate the running state of the UGPN in Zhengzhou, China. The results indicated that the peak–valley load difference in the UGPN can be reduced effectively with an optimal peak–valley price relationship.