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The influence of nonlinear pricing policy on residential electricity demand—A case study of Anhui residents

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ABSTRACT

In this paper, we propose a power structure of economic models of price responsive loads, based on price elasticity of electricity demand, perceived price and customer benefit function. Taking Anhui province as an example, we estimate the influences of block pricing policy and TOU-block pricing policy (the combination of blocking pricing policy and time-of-use (TOU) pricing policy) on residential electricity demand and electricity expenses. We find that the present block pricing policy may help lower the residential electricity consumption at about 1.4%–3.0% per year, which indicates that the effect of energy conservation is not obvious; while the TOU-block pricing policy may help lower the yearly electricity consumption at less than 1%, which implies that, compared with block pricing, the TOU-block pricing policy plays a weaker role in reducing electricity consumption. Moreover, block pricing policy results in a yearly increase of 2.34%–4.28% power expenses on urban residents, while TOU-block pricing policy may lower the corresponding expense at 8.17%–14.30%, which shows that block pricing policy plays a limited role in increasing the electricity expense of urban residents. In addition, the TOU-block pricing policy may effectively alleviate the effect of block pricing on urban residents' electricity expense. Generally speaking, we see limited prospect in the goal attainment of the present TOU-block pricing policy.

1. Introduction

With the worsening of global energy supply, climate change and environmental pollution, energy conservation, emission reduction and sustainable development have become an increasing focus of attention in the whole world. Many countries have applied nonlinear pricing policy, such as block pricing policy and TOU-block pricing policy, to natural gas, electricity and water pricing systems. TOU (Time-of-use) pricing, which commonly divides 24 h daytime into three time periods: peak, flat and valley, is the practice of implementing different prices for different periods of use [1]. Higher and lower prices are set for the peak and valley periods, respectively, to motivate consumers to adjust their consumption, thereby load shifting and reducing peak electricity demand, which helps to utilize better the network and possibly the generation infrastructure [2–4]. The block pricing policy sets users' amount of electricity consumption at several levels and sets different price at each level, for example, charges the basic level at a low price, and a high price for those above basic levels. This policy can provide the marginal price signals to guide users' consumption behavior, then restraining excessive power consumption and reducing cross-subsidy, which helps to realize energy saving and improve equity [5–7]. TOU-Block Pricing is the combination of TOU pricing and block pricing. It introduces block pricing into TOU pricing, which implements block pricing in different time periods (namely, peak, flat and valley periods). This has been widely applied in electricity market over the world, including Canada, the U. S. A, Japan, France and Taiwan [8,9].

In 1980, China began a pilot project of TOU pricing in electricity industry. Till 2002, TOU pricing policy has been extended across the whole nation. For the sake of energy conservation and efficient consumption, in 2004, the National Committee of Development and Reform (NCDR) began a series of pilot projects of block pricing policy in Zhejiang, Sichuan, and Fujian provinces. In 2011, it issued a *Guideline for Block Pricing of Electricity Consumption* and clarified the basic policies of block pricing. From July 1, 2012, block pricing has been applied nationwide (except for Xinjiang and Tibet). Moreover, in December 2013, NCDR issued a Notice concerning the Block Pricing Policy of Residential Electricity Consumption which

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clearly stated that the combined policy of TOU pricing and block pricing must be implemented nationwide by the end of 2015. With this principle, 29 provinces of China, except Xinjiang and Tibet, have issued a three-level block pricing policy. And twelve provinces like Hebei, Shanxi, Shanghai, Jiangsu, Anhui, Zhejiang, Fujian, Jiangxi, Sichuan, Shandong, Henan, and Gansu have adopted the TOU-block pricing policy for electricity consumption by the end of 2015.

Studies concerning block pricing policy and TOU pricing policy both at home and abroad mainly concentrate on three aspects:

(1) User's demand response, highlighting the estimation of the price elasticity of user's electricity demand and construction of user's demand response model. Researchers estimated, using such models as discrete/continuous choice model, log-log model and auto-regression model, the price elasticity of users' electricity demand in China, the U.S.A, the U.K, Germany and Europe [10–14]. For example, Bernard et al.(2011) calculated the sampled data of electricity consumption in Quebec city, Canada from 1989 to 2002, and got its short-term price elasticity of electricity as −0.51, long-term as −1.32 [12]. Based on micro data of families in Hangzhou city from Jan. 2009 to Dec. 2011, Feng (2014) studied the long-term electricity demand function under the TOU-block pricing policy, and got the long-term aggregate price elasticity in average between 0.501 and 0.625. He also pointed out that electricity demand in China lack elasticity [13]. Using micro-level survey data collected from 1450 households in 27 provinces in the first-ever China Residential Energy Consumption Survey in 2012, Khanna et al. (2016) estimated the price elasticity of electricity demand under the block pricing as −0.51 [14]. Based on the analysis of the conclusions of existing studies, residential electricity demand in China is found to be price-inelastic. In regard to building user's demand response model, the typical researches are that Aalami et al. (2010; 2015) developed several nonlinear economic models of price responsive loads based on price elasticity of demand and customer benefit function, and these models are widely used to study the user's demand response behavior under the TOU pricing of electricity and natural gas [15–17].
(2) Structure design. Two parameters, the number of time periods and peak-valley price ratio, need to be determined for TOU pricing structure. At present, countries usually divide 24 h in a day into three time periods, peak, flat and valley, or peak and valley periods. Peak-valley price ratio is determined mainly by building optimum models or conducting situation analysis [18,19]. Recently, Gong et al. (2016) explored the time-of-use pricing mechanism of nature gas based on an evolutionary game-theoretic perspective, and proposed an optimal time-of-use pricing in urban gas market [18]. Structure design of blocking pricing mainly focuses on determining three parameters: the number of blocks, the breakpoints of consumption between blocks, and marginal price of blocks. So far no research has properly tackled the structure design of optimum block pricing. Only tentative works were made to choose one or several parameters [20,21]. For example, Liang & cao (2015) presented a new scheme for China's block pricing according to electricity consumption features of Chinese families at different income, price elasticity and income elasticity [20]. The result of Ref. [21] indicates that the increasing block tariffs system with four-tier structure is more reasonable for China, and it will greatly improve the equity and efficiency, and promote the electricity saving and emissions reduction.
(3) Effect evaluation. Researchers are concerned mainly with the effect evaluation from the goal attainment perspective of TOU pricing and block pricing policy [9,22–24]. Niu & Shi (2013), using ELES, simulated the changes of residential electricity consumption after they adopted block pricing in a city of Jiangsu province. The results show that block pricing policy generate minor effect on the amount of residential electricity consumption and the benefits of power plants, which indicates the limited goal attainment of block pricing policy [23]. Liu et al. (2015) find that vivid differences exist between two pricing policies for the goal attainment, i.e. TOU pricing may even the peak and valley gap and save energy; while block pricing have more effect on peak and valley gap and reduce the subsidies [9]. Ref. [24] develops a framework to analyze equity and economic efficiency of increasing block rates (IBR) for regulated products such as electricity or water.

From 2004, Anhui province began to apply for TOU pricing policy over those households with one meter, one household, upon their application; from July 1, 2012, a block pricing policy was adopted across the whole province. One of the main goals of block pricing policy in China is to restrain excessive consumption of electricity and reduce emissions. The paper classifies urban residents in Anhui province into four types: One meter for one household under block pricing, one meter for one household under TOU-block pricing, one meter shared by households, non-residents adopting residential pricing. The paper, based on the data about the amount of electricity consumption and electricity expenses in 2014, constructs an economic model of residential users demand responsive loads and analyses their responsive modes; it also respectively estimates the effect of block pricing and TOU-block pricing on residential electricity consumption and electricity expenses.

2. Models

2.1. Residential users' demand response model

Electricity response model means that users change their consumption behavior when electricity price rises or the safety of power system is threatened, so as to reduce or transfer electricity load at a certain time period and secure electricity grid and restrain prices. In both theories and practices, there are three demand response models: incentive-based, price-based, and information feedback, according to the motivational modes of electricity users.

Residential users adjust their behaviors according to price changes so as to maximize utility. Let i represent the i-th category of users with$i = 1,2,\cdots,n$. Suppose that after implementing a nonlinear pricing policy, the i-th category of residential users change their electricity demand from $d_0(i)$(initial value) to $d(i)$ in response to the perceived price, if the income of the i-th category of residential users by consuming $d(i)$ of electricity is represented by $B(d(i))$, and the benefit of users is represented by $U(d(i))$, then the benefit equals to income minus cost.

$$U(d(i)) = B(d(i)) - p(i) \times d(i) \tag{1}$$

$p(i)$ refers to the perceived price of the i-th category of users under a nonlinear pricing policy.

According to optimization theory, when maximum utility is achieved, we get:

$$\frac{\partial U(d(i))}{\partial d(i)} = \frac{\partial B(d(i))}{\partial d(i)} - p(i) = 0 \quad \Rightarrow \quad \frac{\partial B(d(i))}{\partial d(i)} = p(i) \tag{2}$$

Aalami et al. (2015) constructs several benefit functions, which