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Electricity time-of-use tariff with consumer behavior consideration

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ABSTRACT

This paper investigates an electricity time-of-use (TOU) tariff problem with the consideration of consumer behavior. Under the TOU tariff, we consider two periods: the peak and base periods. A two-level model is established to solve the TOU tariff problem: in the upper level, the producer determines the TOU tariff with the consideration of consumer behavior; in the lower level, the consumers respond to the TOU tariff through shifting some electricity consumption in the peak period to the base period. Using the traditional flat-rate (FR) tariff as a baseline, we verify the conditions under which the producer has incentives to adopt the TOU tariff. With the adoption of a general consumer transfer cost, we solve for the optimal TOU tariff under different situations. Our results demonstrate that proper adoption of the TOU tariff can create a win–win situation for both the producer and the consumers: the producer can increase its profit and the consumers can save their electricity cost. We further evaluate the effectiveness of the TOU tariff in terms of the peak demand reduction. Using a quadratic transfer cost, we obtain some managerial insights into the TOU tariff problem, and illustrate that the TOU tariff is always beneficial to the producer and the consumers under the quadratic transfer cost.

1. Introduction

Facing the challenge of energy shortage and opportunities from energy technology advancement, both producers and consumers are paying more concern to designing a more efficient pricing mechanism to improve the social welfare and promote energy efficiency. Time-of-use (TOU) tariff is an effective way to achieve these goals. Under the TOU tariff, the electricity price is higher in the peak period, but lower in the off-peak period. The TOU tariff aims to reduce the peak load and enhance the electricity supply security. Under the traditional flat-rate (FR) tariff, consumers do not have the incentive to reduce their electricity use during the peak period and to use electricity wisely. This could lead to a power crisis in the peak period, such as the California's power crisis during 2000 and 2001 (Faruqui and George, 2005). With the adoption of the TOU tariff, consumers have the incentives to shift part of their electricity use from the peak period to the off-peak period, so that the electricity load in the peak period can be reduced. As electricity load is reduced in the peak period, electricity companies can save high electricity generation costs at the peak period and avoid building new generation units for the peak period load. As a result, electricity companies have the opportunities to increase their net profits by adopting the TOU tariff. From the standpoint of the consumers, there are opportunities for them to save their electricity bills by shifting electricity use from the high-rate period (peak period) to the low-rate period (off-peak period).

Industries have paid more attention to the implication of the peak pricing schedule after the California's power crisis during 2000 and 2001. After the crisis, California's three investor-owned utilities conducted the well-known Statewide Pricing Pilot (SPP) experiment from July 2003 to December 2004. The SPP experiment conclusively shows that consumers reduce energy use ranging from 7.6% to 27% in the peak period in response to dynamic pricing (Faruqui and George, 2005), which is a kind of TOU pricing mechanism. Based on the SPP experiment, there are a number of studies focusing on the TOU pricing in the electricity market (e.g., Baskette et al., 2006; Herter et al., 2007; Herter, 2007). Also, some research has pointed out that the highest peak period accounts for a large proportion of the cost of energy (Faruqui and Sergici, 2010; Faruqui et al., 2010). Therefore, designing an efficient electricity pricing mechanism is a possible way to promote and control energy efficiency.

The TOU tariff has been tested and implemented in some European countries and some states in the U.S.A. in the past decade. For example, in the Gulf Power Select Program in Florida in the U.S.A., the reduction in electricity use during the critical peak period was up to 41% (Faruqui and Sergici, 2010). In Norway, there was an 8–9% reduction in electricity use at the peak period

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(Faruqui and Sergici, 2010). From the consumers' perspective, under the TOU tariff, they have incentives to save electricity bills by changing their electricity use from the peak period to the off-peak period or use energy efficient products. On the other hand, electricity load reduction in the peak period may enable electricity companies to avoid high electricity generation cost at the peak period and additional peak capacity installation. To get an in-depth understanding of the TOU tariff, we investigate the TOU tariff with the consideration of consumer behavior in this paper. We further evaluate the effect of the TOU tariff in terms of the increased profit for the producer, the cost saving for the consumers, and the peak load reduction. Using the traditional FR tariff as a baseline, we verify the conditions under which the producer and/or consumers benefit from the TOU tariff structure, and evaluate the effectiveness of the TOU tariff structure. Our results show that proper adoption of the TOU tariff can create a win–win situation for both the consumers and the producer.

In summary, the main contributions of this paper are listed below:

1. We properly formulate the TOU tariff considering both the producer and the consumers in a time horizon including the peak and off-peak periods. Our research fills a research gap in the literature about the TOU tariff by considering consumer behavior.
2. We formulate consumer behavior in response to different prices in different periods through introducing the transfer cost concept. It demonstrates that the consumer behavior of shifting electricity demand is based on consumer interests. Under a proper tariff design, the consumer behavior can benefit the performance of the whole system, i.e., reducing the peak load, lowering the risk of electricity shortage and securing the supply reliability.
3. We identify the conditions under which both the producer and consumers can benefit from the TOU tariff. More importantly, we provide a method to measure how much peak load can be reduced under the TOU tariff, compared with the traditional FR tariff. The peak load reduction enables the producer to secure a reliable supply and save costs from building an additional peak capacity.

2. Literature review

In the literature, there are extensive studies on electricity pricing, such as Doucet and Roland (1993), Crew et al. (1995), Borenstein and Holland (2005) and Chao (2010). Admitting the challenge of energy shortage worldwide, both the supply and demand sides in the electricity market are seeking a more efficient mechanism of pricing to deal with uncertain environments, particularly within the peak periods. Several studies investigated the peak pricing with the consideration of demand uncertainty, such as Brown and Johnson (1969), Carlton (1977), Meyer (1975), Crew and Kleindorfer (1978), Sherman and Visscher (1978) and Borenstein and Holland (2005); while other research studied the peak pricing under supply uncertainty, like Chao (1983), Coate and Panzar (1989) and Kleindorfer and Fernando (1993). Recently, Chao (2011a) provided a unified economic model on efficient pricing and investment in restructured electricity markets in one single pricing period. Despite the extensive studies about electricity pricing, most of these studies focused on pricing in the peak period only. These studies did not consider the impacts of consumer behavior on a shift of some electricity consumption from the peak hours to off-peak hours. Such consumption shift could be an effective way to address the efficiency of electricity pricing. Our research enriches this stream of research by considering both the peak and off-peak periods within a referred horizon to seek for the optimal tariff scheme.

It is observed that the structure of electricity market has a great impact on electricity market price and profit (see, e.g., Garcia et al., 2005; Bunn and Oliveira, 2008). A study conducted by PB power for The Royal Academy of Engineering (PB Power, 2004) reported different costs for different available technologies of electricity generation. With simulation approach, Banal-Estañol and Micola (2009) showed that the relationship between technological diversification of electricity generation and wholesale market prices is mediated by the supply-to-demand ratio. Chao (2011a) investigated electricity pricing through the establishment of a model with multiple technologies, including renewable and non-renewable technologies. Chao (2011b) studied the consumer baseline choice, focusing on administrative and contractual approaches. These studies suggested that in electricity market, the suppliers need to consider the costs of different technologies when designing an efficient tariff structure. Furthermore, the suppliers may be beneficial from the potential cost–savings by adjusting its supply structure.

From the standpoint of electricity producer, it is crucial to design an efficient tariff mechanism to reduce the demands in the peak hours. As the peak load is reduced, the producer can save the cost in installing extra capacity in the peak hours and reduce the shortage risk in the peak hours. Pineau and Zaccour (2007) studied a two-period electricity market with multiple firms under transferable demands between the peak and base periods. Their study highlighted the importance of the tariff structure. However, their study did not consider specific consumer behavior from the consumers' perspective. Triki and Violi (2009) proposed a two-stage retail pricing scheme in an open market with the use of stochastic programming. Colon (2010) investigated how to develop time-of-use tariff structures for residential and small commercial consumers in Ireland's electricity market. Using some numerical examples, Chao (2010) provided a comprehensive discussion about price-responsive demand management for a smart grid world, including benefits and barriers of price-responsive demand. However, these studies mainly focus on the supplier's perspective and do not consider the consumers’ specific responses when designing the electricity tariff. Furthermore, there is little theoretical research to formulate and evaluate the benefits of the TOU tariff with the consideration of consumer behavior.

From the consumers’ perspective, there are chances to save their electricity bills while guaranteeing the electricity use. This could be achieved through adjusting the electricity use from a high-price period to a low-price period. Spector et al. (1995) studied the responses from business consumers about time-of-use electricity rates. Nogales and Conejo (2006) addressed a problem of day-ahead electricity price forecasting by building a time-series model. Herter (2007) showed that high-use consumers respond significantly more in kW reduction than low-use consumers, while low-use consumers save significantly more on the percentage reduction of the annual electricity bills than that of the high-use consumers. Recently, the application of the TOU tariff has given rise to a debate about fairness to consumers (e.g., Faruqui, 2010; Hogan, 2010; Alexander, 2010). The debate emphasizes that successful design and implementation of the TOU tariff should take account of consumer responses to and benefits from the TOU tariff.

As we discussed above, most studies on electricity tariff focus on either the producer's perspective or consumers’ perspective. There is little research investigating the participation of both sides of suppliers and consumers, as well as the interaction between the two sides. In fact, facing different tariffs, the consumers may have different behavior to respond to. For example, under a time-dependent tariff, consumers will try to avoid the peak hours