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Variability of electricity load patterns and its effect on demand response: A critical peak pricing experiment on Korean commercial and industrial customers

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HIGHLIGHTS

- A method of clustering customers by variability indices is developed.
- Customers in high-variability clusters provide substantial peak reductions.
- Low-variability clusters exhibit limited reductions.
- For low-variability customers, alternative policy instruments is well advised.
- A model of discerning customer's demand response potential is suggested.

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ABSTRACT

To the extent that demand response represents an intentional electricity usage adjustment to price changes or incentive payments, consumers who exhibit more-variable load patterns on normal days may be capable of altering their loads more significantly in response to dynamic pricing plans. This study investigates the variation in the pre-enrollment load patterns of Korean commercial and industrial electricity customers and their impact on event-day loads during a critical peak pricing experiment in the winter of 2013. Contrary to conventional approaches to profiling electricity loads, this study proposes a new clustering technique based on variability indices that collectively represent the potential demand–response resource that these customers would supply. Our analysis reveals that variability in pre-enrollment load patterns does indeed have great predictive power for estimating their impact on demand–response loads. Customers in relatively low-variability clusters provided limited or no response, whereas customers in relatively high-variability clusters consistently presented large load impacts, accounting for most of the program-level peak reductions. This study suggests that dynamic pricing programs themselves may not offer adequate motivation for meaningful adjustments in load patterns, particularly for customers in low-variability clusters.

1. Introduction

Dynamic pricing programs are gradually replacing conventional demand-side management measures, such as direct or interruptible load control and energy efficiency policies (Walawalkar et al., 2010). Motivations for introducing dynamic pricing programs in the electricity sector include stabilizing wholesale electricity prices, managing system reliability, limiting utilities' market power, and promoting integrated resource planning (Herter, 2007). Recently, researchers have also identified dynamic pricing as a key enabler of the smart grid and a promising solution for promoting grid resilience and increasing penetration of renewable power sources (Aghaei and Alizadeh, 2013).

Despite significant progress in dynamic pricing research over the past three decades, many important aspects of how electricity customers respond to price changes remain unanswered. The Electric Power Research Institute (EPRI) has pointed out serious gaps in our current understanding of the demand for electricity, particularly of our ability to influence customer demand through

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time-varying rates, enabling technologies, feedback, and education (Neenan and Eom, 2008). Other major gaps in our knowledge include the size and persistence of dynamic pricing's impact on electricity load profiles, the heterogeneity in the impacts among different customer segments, and the extent to which demand responses observed in pilot experiments can be extrapolated to customers in other utility territories, regions, and countries (Cappers et al., 2013).

One reason for these knowledge gaps is that characterizing differences in the patterns of electricity demand responses among industrial and commercial customers (i.e., non-residential customers) is a highly complex undertaking, given the diverse ways in which firms utilize electricity as a productive input and in which changes in electricity prices can be manifested. The heterogeneity in demand responses has been previously examined by studies concerning time-of-use (TOU), critical peak pricing (CPP), and real-time pricing (RTP) (Herriges et al., 1993; Jang et al., 2015; Quantum Consulting, 2006; Schwarz et al., 2002). Although it is well known that more energy-intensive businesses tend to be more responsive to changes in electricity prices, studies still find major differences in sector-level load impacts (Herriges et al., 1993; Jang et al., 2015; Goldman et al., 2005). To date, however, the issue of the heterogeneity in demand responses has rarely, if ever, been seriously scrutinized in the literature.

Although several studies have attempted to explain heterogeneity in load impacts by employing conventional industrial classification systems, such as the International Standard Industrial Classification (ISIC) or North American Industry Classification System (NAICS) (Braithwait et al., 2010; Goldman et al., 2004; King and Shatrawka, 1994; Prywes, 1986; Quantum Consulting, 2006), others have pointed out that classifications based on business types may have inherent limitations in representing major determinants of patterns in customers' electricity usage (Chicco et al., 2001; Figueiredo et al., 2005; Jang et al., 2015; Yamaguchi et al., 2009). In this regard, FERC (2012) suggests that segmenting customers for demand–response programs would be most effective if based on observed load characteristics rather than on reported business types. Jang et al. (2015) also hails customer-level data-based approaches to customer segmentation as a promising alternative to conventional business-type classification.

One reason that data-based segmentation of electricity customers is likely to become a more common research method is that ongoing restructuring and deregulation within the electric power industry is increasing private and public interest in acquiring customer-level electric load data. This change is also being enabled by the widespread installation of advanced metering equipment that measures and stores individual customers' load information on an hourly basis (Carpaneto et al., 2006). Not coincidentally, recent load-pattern clustering studies utilizing customer-level load data have focused on the identification of suitable load profiles for each subset of customers and on the development of segmentation procedures and algorithms (Chicco, 2012). In this line of study, individual customers are assigned to one of several typical daily load profiles based on several statistical criteria, including mean or median loads on normal working days. Figueiredo et al. (2005), for example, employ both peak values of daily load profiles and normalized representative load patterns, and Chicco (2012) suggests that annual active and reactive energy use, utilization levels, and power factors can be effectively used to categorize electricity customers.

The approach to identifying customer segmentation criteria taken in this study is based on the simple intuition that the degree to which an electricity customer will exhibit demand responses depends mainly upon its latitude and motivation to do so. Here demand response is defined as a change in the customer's normal electricity usage pattern in response to price augmentation or incentive payments designed to encourage reductions in electricity usage at times of peak demand or when system reliability is jeopardized (FERC, 2012). The study assumes that greater price changes or cost-reduction opportunities via peak-load reductions would incentivize customers to exhibit a greater demand response (motivation) and, ceteris paribus, that this response would be greater among those who have fewer operational restrictions on shifting their loads (latitude). For example, if a firm subscribing to a dynamic pricing plan relies heavily on electricity in its ordinary business operations, it is highly likely to alter its daily load profiles in a cost-saving manner. And if that firm has operational flexibility as a result, for example, of its reliance on ad-hoc batch processing schedules rather than continuous or regular working conditions, it is even better positioned to shift its load patterns. This conjecture is consistent with findings that firms equipped with substitutive energy options, such as self-generation and arc furnaces, tend to be more responsive to price changes (Ashok and Banerjee, 2000; Taylor et al., 2005). In this sense, an electricity customer's latitude in exercising its demand response would depend on the nature of its business operations and array of energy-using equipment, which can be accurately identified by a field survey study involving site visits (Coughlin et al., 2009; Piette et al., 2006). Nevertheless, this approach has rarely been explored in the previous literature, presumably because the process of experimentation is costly and time-intensive (Yamaguchi et al., 2009).

As a promising alternative to on-site field surveys, we propose a novel method that employs variability in pre-enrollment load patterns as a proxy for firms' potential latitude in conducting demand responses in event days—an approach that differs from that of previous clustering studies, which have generally focused on identifying typical daily load patterns. Given that demand response is the change in an electricity usage pattern over time in response to given price changes, we expect that electricity customers which exhibit more variable load patterns on normal days are more likely to exhibit greater latitude in adjusting loads in response to price signals on event days. To test this conjecture, we examine a Korean CPP pilot program implemented for commercial and industrial customers in the winter of 2013. Using several statistical variability measures, we categorize customers into five industrial and four commercial clusters. The load impacts of the individual clusters are then assessed by comparing event-day hourly load data with their corresponding hourly baseline load estimates, which are constructed by aggregating individual customers' baseline loads (CBLs), as developed by Jang et al. (2015)

Our study is intended to advance the current understanding of demand response behavior by filling a gap in the literature regarding the sources of heterogeneity in load impacts across various types of business customers. Our analysis clearly identifies two major descriptive sources of this heterogeneity: variability in a firm's pre-enrollment load patterns and, to a lesser extent, its electricity expenditure share. Combined, these factors demonstrate predictive power for the potential extent of a firm's demand response on event days. The study also uncovers surprisingly large differences in the variability of pre-enrollment load patterns and thus large differences in event-day demand response behavior, even among electricity customers within the same ISIC business category, which produce similar goods and services. Methodologically, this study contributes to the literature of load pattern and clustering analyses by suggesting a novel approach to categorizing customers based on what we call variability indices, which effectively characterize the nature and degree of variation in customers' hourly and daily electricity usage on normal days. This practical approach to customer segmentation could be used to help utilities prioritize their implementation of dynamic pricing programs to those who are most willing and able to alter their usage patterns, thereby increasing customer satisfaction and political support for