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Assessing the impact of real-time price visualization on residential electricity consumption, costs, and carbon emissions

Anders Nilsson*, Pia Stoll, Nils Brandt

Division of Industrial Ecology, Department of Sustainable Development, Environmental Science and Engineering, School of Architecture and the Built Environment, Royal Institute of Technology (KTH), 100-44 Stockholm, Sweden

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ABSTRACT

The development of smart grid projects, with demand side management as an integral part, has led to an increased interest of households' willingness to react to different types of demand response programs. This paper presents a pilot study assessing the impact of real-time price visualization on residential electricity consumption, and its effects on electricity costs and carbon (CO_2eq) emissions. We analyze changes in electricity consumption based on a test group and a reference group of 12 households, respectively. To allow for analysis on load shift impact on CO_2eq emissions, hourly dynamic CO_2eq intensity of the Swedish electricity grid mix is calculated, using electricity generation data, trading data, and fuel-type specific emission factors. The results suggest that, on average, the test households shifted roughly 5% of their total daily electricity consumption from peak hours (of high electricity price) to off-peak hours (of low electricity price) as an effect of real-time price visualization. However, due to the mechanisms of the Swedish electricity market, with a negative relation between spot price and CO_2eq intensity, the load shift led to a split effect; electricity costs modestly decreased while CO_2eq emissions increased. In addition, any indication of the contribution of real-time spot price visualization to a reduction in overall household electricity consumption level could not be found, as the relative difference in consumption level between the test households and the reference households remained constant during both the baseline period and the test period.

1. Introduction

1.1. Background

Residential electricity consumption constitutes approximately one third of the total electricity use in the world today (Global Energy Statistical Yearbook, 2014). In Sweden, approximately 20% of the total annual electricity consumption is related to private household use of electrical appliances (Swedish Energy Agency, 2013). Although the energy efficiency of appliances has improved substantially during the last decades, electricity demand has increased during the same period as an effect of the increased amount of in-home electrical appliances, calling for additional measures targeting consumer behavior (Bennich et al., 2009).

The increasing focus on the environmental consequences of electricity production and consumption[1] has led to discussions on how to develop new technologies, strategies, and business solutions that promote more effective and sustainable production, distribution, and consumption of electricity (Amin and Wollenberg, 2005; Ipakchi and Albuyeh, 2009; Farhangi, 2010). Demand side management aims to increase the efficiency in electricity use by encouraging electricity consumers to reduce their consumption during critical peak hours, or to adjust their consumption pattern by moving their consumption from peak hours to off-peak hours, referred to as load shift (Strbac, 2008); such programs are referred to as demand response. Although there is no single clear definition of demand response, the U.S. Department of Energy defines it as: "Changes in electric usage by end-customers from their normal consumption pattern in response to changes in the price of electricity over time, or to incentive payments designed to induce

* Corresponding author.
E-mail addresses: anders.nilsson@abe.kth.se (A. Nilsson), pstoll@kth.se (P. Stoll), nils.brandt@abe.kth.se (N. Brandt).

[1] Among many initiatives addressed in the EU directive 2012/27/EU, serving to meet the 20% energy efficiency target of the 20/20/20-targets (EU, 2009).

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lower electricity use at times of high wholesale market prices or when system reliability is jeopardized" (U.S. Department of Energy, 2006).

Demand response programs can be divided into two main categories; (1) incentive-based programs, which provide economic incentives for residential consumers to reduce their consumption at times of high electricity price or shortage in capacity, and (2) price-based programs, which include dynamic price tariffs in order to promote a general change in electricity consumption patterns (Tan and Kirschen, 2010; Albadi and El-Saadany, 2008). The design of different price-based demand response programs and tariffs may be based on, for example, time of use, critical peak pricing or real-time pricing (Xu et al., 2011; Gelazanskas and Gamage, 2014). Real-time price-based demand response programs, which are the subject of this paper, may be considered as a both simple and effective method, as they follows standard economic rules and, in opposite to incentive-based demand response programs, does not include any mandatory limitations to electricity consumption during a certain time period. The success of real-time price-based demand response programs depends on the attitude and the willingness of adoption among electricity consumers (Bartusch et al., 2011).

1.2. Previous demand response studies

Numerous studies have evaluated the impact of dynamic price tariffs on residential electricity consumption with varying results. An early review by Darby (2006), compiling results from different real-time feedback studies in Europe and U.S., suggests an average saving in energy consumption of 5–15%. Also, different demand response programs within Scandinavia show a wide variation in their results. A pilot project in Norway, including a distribution tariff of varying energy rates and demand charges showed a 5% reduction in demand during peak hours (Stokke et al., 2010). However, a Swedish study (Bartusch and Alvehag, 2014), including time-of-use-based electricity distribution tariffs, suggests a more modest result of 0–1% reductions in demand during peak hours.

The potential of load shift of residential electricity consumption should be considered with respect to several factors. One important limiting factor is the level of load flexibility in households, which refers to the electricity consumption related to household activities that may be changed without affecting the daily lifestyle routines in a substantially negative way. The use of dishwashers, washing machines and dryers could be considered as such activities, while, for instance, cooking and TV-watching could be seen as more stable load, with a lower potential to be changed without inhibiting the daily life. A study by Zimmermann (2009), where electricity consumption of 400 Swedish households is measured, suggests that flexible load represents about 10% of the total electricity consumption, implying that the possibility for households to shift a substantial share of their electricity consumption may be considered as highly limited.

Although the interest of the environmental effects of demand response has increased lately (Gyamfi and Krumdieck, 2011), and some recent pilot projects have included analysis of environmental impact of load shift as a secondary aim (e.g. Nilsson et al., 2014), previous studies have primarily focused on savings in electricity demand and costs. An overall reduction in electricity consumption leads to a reduction in negative environmental impact, but the impact of load shift from peak hours to off-peak hours may have both positive and negative impacts on the environment as the carbon intensity of electricity measured in equivalent carbon dioxide (CO_2eq) varies over time. The possible negative environmental impact of load shift is addressed by Stoll et al. (2013), where the correlation between hourly dynamic price and hourly dynamic CO_2eq emissions was analyzed for three different energy markets. The results show that the impact of load shift is strongly connected to the intraday variations in the electricity grid mix. In addition, a study by Song et al. (2014), simulating household consumption behavior under price and CO_2eq signals in Sweden, suggest that carbon emissions may increase by roughly 3%, depending on the amount of load shift.

1.3. Aim and objectives

The aim of this study is to assess the impact of real-time price visualization on residential electricity consumption and the subsequent effects on electricity costs and carbon emissions measured in CO_2eq. This was achieved by conducting a real-time price-based pilot study, where a display visualizing real-time electricity spot price was installed in the stairwell to 12 test households over one year. Based upon two-hourly consumption data from these test households and 12 similar reference households, the changes in electricity consumption were analyzed and electricity costs and carbon emissions were calculated. To allow for analysis of how load shift from peak hours to off-peak hours impacts carbon emissions, we calculate hourly dynamic CO_2eq intensity of the Swedish electricity grid mix, using electricity generation data, trading data, and fuel-type specific emission factors.

This study provides insights into how real-time price-based demand response programs affect residential electricity consumption, and the economic and environmental consequences of the change in consumption behavior. To our knowledge, this is the first pilot study using hourly dynamic CO_2eq intensity of the electricity mix to assess the changes in CO_2eq emissions as an effect of load shift from peak hours to off-peak hours, opening up for novel and significant outcomes that will be valuable for future research in the demand–response area.

2. Data and methods

Firstly, this section describes the calculation of hourly dynamic CO_2eq intensity of the Swedish electricity grid mix, and secondly describes the framework of the pilot study, and the analysis methods used to assess the changes in electricity consumption, costs, and CO_2eq emissions.

2.1. CO_2eq intensity of Swedish electricity grid mix

In order to evaluate how load shift from peak hours to off-peak hours affects CO_2eq emissions from electricity consumption, the first step was to analyze the hourly variation of the CO_2eq intensity of the Swedish electricity grid mix. CO_2eq emissions from electricity consumption in Sweden depend on the domestic electricity generation, but as electricity is exchanged with other countries, emissions from imports and exports also have to be taken into account. Thus, the analysis is based on a consumption perspective where the term "Swedish electricity grid mix" refers to the mix of electricity, where imports are added and exports are subtracted; that is, electricity provided to consumers in Sweden.

The calculation of hourly dynamic CO_2eq intensity of the Swedish electricity grid mix is based upon the method presented by Stoll et al. (2013), where electricity generation data, trading data, and fuel type-specific emission factors are used. The method is based on an accounting approach where all emissions of the Swedish electricity grid mix are summed up and divided by the total consumption in Sweden on an hourly basis. That means that all emissions from electricity generation, domestic as well as abroad, that is provided to Swedish electricity consumers are accounted for.