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What can we learn from high-frequency appliance-level energy metering? Results from a field experiment

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HIGHLIGHTS

- Hourly electricity usage was collected from 124 comparable apartments for 24 months.
- Households overestimate lighting use by 75% and underestimate HVAC usage by 29%.
- Households using the same appliances show substantial variations in electricity use.
- Plug load accounts for the largest share of electricity use at all hours of the day.
- Savings of 11% were achieved by replacing old refrigerators.

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ABSTRACT

This study uses high-frequency appliance-level electricity consumption data for 124 apartments over 24 months to provide a better understanding of appliance-level electricity consumption behavior. We conduct our analysis in a standardized set of apartments with similar appliances, which allows us to identify behavioral differences in electricity use. The Results show that households' estimations of appliance-level consumption are inaccurate and that they overestimate lighting use by 75% and underestimate plug-load use by 29%. We find that similar households using the same major appliances exhibit substantial variation in appliance-level electricity consumption. For example, households in the 75th percentile of HVAC usage use over four times as much electricity as a user in the 25th percentile. Additionally, we show that behavior accounts for 25–58% of this variation. Lastly, we find that replacing the existing refrigerator with a more energy-efficient model leads to overall energy savings of approximately 11%. This is equivalent to results from behavioral interventions targeting all appliances but might not be as cost effective. Our findings have important implications for behavior-based energy conservation policies.

1. Introduction

1.1. Background

Electricity generation accounts for over 40% of the carbon dioxide emitted by the United States, with residential and commercial buildings collectively accounting for over two-thirds of total U.S. energy consumption (EIA, 2014; EPA, 2013). Recent studies estimate that behavioral changes can reduce residential energy consumption by about 7.4% (Delmas et al., 2013). Providing more detailed feedback to consumers about their energy usage at the appliance level can potentially encourage such behavioral changes (Ehrhardt-Martinez et al., 2010; Fischer, 2008; Neenan et al., 2009). However, currently, the majority of residents in the United States and around the world do not receive such feedback. Consumers' electricity bills report total consumption, rather than consumption by each appliance, and do not provide information about which appliances offer the consumer the highest potential for energy savings. Kempton and Layne (1994) analogize a household's electricity bill to getting a grocery-shopping receipt each month without knowing how much each good contributed to the total. The planned deployment of more than 65 million digital electricity meters by 2015 (Edison Foundation, 2012) will allow

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utilities to provide a wealth of new information to more than half of the nation's electricity accounts, unlocking new conservation potential (Armel et al., 2013). While this new information could help consumers make better decisions about their appliance use, little is known about energy consumption patterns by appliance and the behavioral component of appliance energy use.

In this paper, high-frequency appliance-level electricity consumption data was collected from 124 apartments over 24 months to answer the following questions: Are consumers cognizant of their electricity usage across different appliances? Are there important differences in the use of the same appliances across households and what is the behavioral component of appliance energy use? Which individual appliances are contributing to peak demand usage? How do the savings from installing new appliances compare with the savings from behavioral changes? The answers to these questions have important implications for the design of more effective policies to encourage energy conservation behavior.

1.2. Related work

There is a growing interest in reducing energy consumption and the associated greenhouse gas emissions in every sector of the economy. According to the International Energy Agency, the continuing demand for newer appliances with improved functionality and more power is leading to an increase in electricity consumption even though appliances are becoming more energy efficient.[1] This increase in energy consumption warrants a detailed understanding of the residential sector's consumption characteristics to prepare for and help guide the sector's energy consumption.

Studies of the effect of different types of energy feedback on energy savings indicate that information on real-time appliance-level energy consumption data has the potential to empower consumers to effectively manage their household energy consumption and encourage conservation (Delmas and Lessem, 2014; Ehrhardt-Martinez et al., 2010; Neenan et al., 2009).

The current study goes beyond previous work analyzing appliance-level consumption in five ways. First, scholars have argued that households are unaware of how much electricity is used by specific appliances and the potential for energy savings from each appliance (Attari et al., 2010). However, so far, the evidence presented is mostly based on surveys and expert recommendations – not on observed household electricity usage. This study compares each household's actual electricity usage with the estimated usage they stated at the beginning of the study. This allows us to precisely evaluate households' knowledge of energy use for each appliance.

Second, studies that have shown variation in usage across households focus on total usage or on usage in a particular subset of appliances. For example, Lutzenhiser (1993) notes that even in energy consumption studies that use nearly identical units, electricity usage can vary as much as 200–300% but did not differentiate among appliances. Other appliance studies include the research by Wood and Newborough (2003), who focused mainly on cooking appliances, Coleman et al. (2012), Rosen and Meier (1999, 2000), and Rosen et al. (2001), who focused on entertainment appliances, and Isaacs et al. (2010), who studied space heating. In contrast, our study includes a broad set of appliances and end uses that are found in most homes. We also use a study site that consists of apartments with little variation in design and identical major appliances, something that most previous studies were unable to provide (Parker, 2003; Pratt et al., 1993). Additionally, since all the apartments are in the same complex, our results are not affected by variations in weather (Hart and de Dear, 2004).

Third, recent studies by de Almeida et al. (2011) and Saldanha and Beausoleil-Morrison (2012) highlight the growing share of non-HVAC sources in electricity consumption. However, neither study was conducted in the United States and both had other shortcomings: de Almeida et al. (2011) had a small sample size and Saldanha and Beausoleil-Morrison (2012) used a non-standard set of appliances across countries. Using a large sample size with a common set of appliances across households, this study assesses lighting and plug load usage during peak demand hours and compares electricity usages for appliances throughout the day.

Fourth, previous studies have attempted to estimate the variation in appliance usage across household types (Bladh and Krantz, 2008; Pratt et al., 1993); however, they were unable to do this for a standardized set of major appliances. The study site used here allows an identical set of major appliances to be compared across households in apartments with little variation in design. Finally, this is the first study that uses real-world observations to estimate energy savings from the installation of a new appliance; previous research relied on simulation techniques to estimate energy savings (de Almeida et al., 2011).

2. Methods

2.1. Field site

The field experiment site, University Village, is an apartment complex for graduate student families. It comprises two sites with 1102 one-, two-, and three-bedroom rental apartment units. Of these, 124 apartments were occupied by residents who agreed to participate in our experiment, also known as the ENGAGE project, and were equipped with an electricity metering system that allows electricity usage to be recorded in real time. During the study period, some participants moved out of the apartment complex and the new occupants of their apartments agreed to participate in the ENGAGE study. This led to a sample of 137 unique households. Each apartment is equipped with heating and cooling systems and a full kitchen including a refrigerator, microwave, stove, dishwasher, and garbage disposal. Except for variations in size and floor plan, apartments are standardized with the same major appliances and amenities.[2] This consistency ensures that variation in electricity usage results from household behaviors and lifestyles, not differences in apartment or appliance features. Furthermore, circuits in University Village are fairly standardized with only minor variations which allowed for a hardware installation kit that would accommodate all of the circuit breaker panels without any hardware reconfiguration.

The electricity usage in the ENGAGE sample is comparable to similar households across California based on information from a nationally representative survey of the share of household electricity usage by appliance. Electricity usage for the current sample was compared with data from the 2009 Residential Energy Consumption Survey (RECS) administered by the United States Energy Information Administration (EIA). To ensure that the comparisons are meaningful, the RECS data was reduced to a subset of households that were similar to households in this study.[3] Since the

[1] https://www.iea.org/Textbase/npsum/Gigawatts2009SUM.pdf. Accessed October 29, 2014.

[2] University Village apartments are rented with the following appliances: refrigerator, dishwasher, lights, microwave, and heating and cooling. We could not control for additional appliances installed by the participants. These could include appliances such as toasters, rice cookers, fans, space heaters, humidifiers/dehumidifiers, etc. Variations in these types of appliances will lead to differences in the other kitchen and plug load categories across households.

[3] The sample includes California households that lived in apartment complexes with more than five units, are renters, have a bachelor's degree or higher, have two