Energy and Buildings 84 (2014) 716–726

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Appliance daily energy use in new residential buildings: Use profiles and variation in time-of-use

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ARTICLE INFO

Article history:
Received 28 January 2014
Received in revised form 11 June 2014
Accepted 21 July 2014
Available online 29 July 2014

ABSTRACT

One of the largest user of electricity in the average U.S. household is appliances, which when aggregated, account for approximately 30% of electricity used in the residential building sector. As influencing the time-of-use of energy becomes increasingly important to control the stress on today's electrical grid infrastructure, understanding when appliances use energy and what causes variation in their use are of great importance. However, there is limited appliance-specific data available to understand their use patterns. This study provides daily energy use profiles of four major household appliances: refrigerator, clothes washer, clothes dryer, and dishwasher, through analyzing disaggregated energy use data collected for 40 single family homes in Austin, TX. The results show that when compared to those assumed in current energy simulation software for residential buildings, the averaged appliance load profiles have similar daily distributions. Refrigerators showed the most constant and consistent use. However, the three user-dependent appliances, appliances which depend on users to initiate use, varied more greatly between houses and by time-of-day. During peak use times, on weekends, and in homes with household members working at home, the daily use profiles of appliances were less consistent.

1. Introduction

Currently, buildings consume approximately 40% of site energy in the U.S., over half which is consumed by residential buildings [1]. Residential buildings alone are responsible for over 37% (4.89 EJ) of electricity consumed in the U.S. [1]. In Europe, households are responsible for 25% of total energy needs, including 68% of total building energy use [2]. High peak electricity demands in the afternoon and early evening of the hot months of the year, much of which is due to fluctuation in building use, have further motivated the development of strategies to reduce electric loads during these times. These changes can only be achieved, however, if the current energy use is first understood in detail.

One of the largest portions of electricity use household is from large appliances, which, when aggregated, account for approximately 30% of all electricity used in the residential building sector in the U.S. [1]. This, together with small appliances, home electronics, and lighting, accounts for more than 2/3 of total residential electricity use. Appliances are of particular interest for study due to their high penetration rate, and increasing rate of penetration across the world [3,4]. In recent years, appliances have been targeted by manufacturers and utility companies as methods to shift or reduce peak energy use. In addition, unlike changes to heating and air conditioning use, changes to their time-of-use will not significantly affect the comfort of the indoor environment.

Four large appliances including, refrigerators, clothes washer, clothes dryers, and dishwasher, are among the most common large appliances found in U.S. homes. Refrigerators are the most common, followed by washers, dryers and dishwashers [4]. This order of penetration of appliance ownership is similar in other developed and developing countries [3], and continues to increase globally [5]. According to the 2012 American Housing Survey [4], 99%, 84%, 81% and 66%, respectively, of all single family homes in the United States have each of these appliances, each with an average annual energy consumption of 1240, 120, 1080, and 510 kW h, respectively [6]. New, more energy efficient appliances use up to 40–50% less energy than those sold in 2001 or earlier. This study specifically focuses on directly monitored electricity consumption of appliances. Other indirect impacts on energy due to hot water use, and latent and sensible heat gains that may non-linearly effect whole-home energy use are the subject of on-going research, but not included in this study. While there are many available datasets providing values

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http://dx.doi.org/10.1016/j.enbuild.2014.07.045
0378-7788/

for annual consumption (kW h) of appliances for a household (e.g. [4,6]), there is, however, limited information available regarding when, over the course of a day, these appliances are used.

Studying this, and the influencing factors associated with these use profiles is important for multiple reasons. This includes an improved understanding of the potential electricity use reductions possible from appliances during peak use times, and improved input values of appliance use to improve the accuracy of residential building energy modeling.

The most recent large-scale appliance-specific study to analyze time-of-use of appliances in residential buildings in the U.S. was conducted in 1989 [7]. This study developed daily profiles for major household appliances use using disaggregated circuit-level data, including the four discussed in the current study. It remains, to the authors' knowledge, one of the largest and most detailed studied to-date on residential appliance use in the United States. A large database of appliance energy use in European households has been complied through the REMODECE—Residential Monitoring to Decrease Energy use and Carbon Emissions in Europe project, which is discussed in [8]. For each country this typically includes several weeks of data for multiple households. Several smaller studies have also looked at time of use of appliances [9–11], and have found a wide variation in the time-of-use, with increased use [9] and variability [10] in the mid-morning and evening hours for single and multiple or groups of appliances [9–11]. Refrigerator energy use was found to be the most constant over a 24-h period with small peaks in morning [7,9] and evening hours [9,11]. Several other studies have focused on appliance use trends [12] and identification [13] in the UK, and on day ahead appliance energy use prediction in France [14] using the IRISE database included in [8].

To predict energy use, previous literature has indicated that factors such as occupant behavior and socio-economic status are important [15]. Nielsen attributed 36% of variation in energy consumption of homes to lifestyle and occupant behavior, and 64% to socio-economic influences. Other factors such as climate zone, number of occupants, income level, age of home, and size of home have also been correlated with home energy use. Compared to whole-home energy use, likely the energy use of appliances such as dishwashers, clothes washers and clothes dryers is more highly influenced by occupant behavior since they depend solely on the user for operation. With human behaviors and lifestyles constantly changing since the 1989 study, such as a more than 35% increase in the number of adults that work one or more days a week from home since 1997 [16], this may affect time-of-use of appliances. Other studies have focused on appliance energy use feedback [17]. Additionally, U.S. federal standards for new appliances set in 1987, which have been consistently reviewed and revised since, have reduced energy consumption of appliances significantly, with a predicted savings of 74 EJ of energy through 2020 [18]. Borg [19] found that in Europe, appliance efficiency did reduce energy loads, but not peak electrical demand.

Additional information is thus desired to better characterize appliance energy use in the current residential building stock. The effects on the time-of-use of these and other factors, such as the influence of residents working from home, and the day of the week have not been studied in detail. Establishing a simple and adaptable methodology to assess appliance use over time will also prove helpful as influences on appliance use patterns change. This is particularly useful to predict the potential influence that "smart" appliances, connected to the smart electric grid, and to provide updated inputs to building energy simulation loads.

This study aims to address the need for a more detailed understanding and analysis of daily energy use patterns and several of the factors that influence them. More specifically this study will explore the following questions:

(1) When do appliances use energy throughout the day, and how do their electricity use profiles look?
(2) How much do these load profiles vary each hour between homes and what are possible sources causing this variation?
(3) If appliance load monitoring is to be conducted in future studies, what is the least amount of time needed to achieve a representative load profile of home appliances?

This paper is organized into three sections. The method used to develop a normalized energy use profiles is discussed, followed by the results of using this method for each of the four studied appliances. These results are compared, and two influencing factors on these profiles are also discussed and analyzed.

2. Methodology

Energy use was monitored in this study, as discussed in Lopes et al. [20] and Crosbie [21]. One-min energy consumption data was collected for 40 homes in a concentrated area in Austin, TX. These homes are part of a 250-home smart-grid deployment project (data collected by Pecan Street Research Institute) which began monitoring home energy consumption in 2012. These homes consist of newly constructed single family homes, built in 2007 or later. Several different types of home energy management systems (HEMS) were installed in a subsets of homes to monitor energy use. This study is limited to 40 of the 250 homes monitored, since the data collected by the type of HEMS deployed in these 40 homes was, of those installed, found to provide the best agreement with the electricity utility meters. The utility meters represent the upper bound of accuracy available for HEMS.

The HEMS use "CT" (current transformer) collars which are clamped to the individual circuits of each home's breaker box, and an adapter that connects to the home's internet router for data collection. The HEMS provides root-mean-square (RMS) of current and voltage to calculate average real power and apparent power, which is saved at one-minute increments. Circuit monitoring includes consumption data for the whole house, as well as multiple different individual circuits, including individual appliances for many of the homes. Further information on the data collection methodology of these homes is discussed in detail in [22]."

One year of disaggregated energy use data (March 1, 2012–February 28, 2013) was collected for each of the 40 homes studied. The starting date of monitoring varies, however all but two homes (5%) had begun recording energy consumption data by March of 2012.

To demonstrate the characteristics of the 40 homes sampled in this study, data from home energy audits and resident surveys is compiled in Table 1. Table 1 also includes average demographic and physical characteristics of the homes for U.S. and Texas building stock. The average number of occupants per home in this study (2.86) is similar to the average U.S. residence (2.6). However, this dataset's homes are larger and newer, and have a higher household income. In addition, a relatively high percentage of households (50%) indicating they work from home twenty or more hours per week.

2.1. Appliance circuit-level data

Appliance circuit-level data was available for a subset of the 40 homes studied. Table 1 also provides information on the number of homes with each of the appliance-specific circuits used, and their