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# Discriminant effects of consumer electronics use-phase attributes on household energy prediction

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ABSTRACT

The aim of this study is to provide a better understanding of the heterogeneities in user-product relationships and their consequences regarding the household energy predictions. Several supervised and unsupervised machine learning algorithms have been applied to a comprehensive data set of residential energy consumptions collected by the US Energy Information Association. The results of the analyses reveal that, while the heterogeneities in the use-phase of consumer electronics could skew their environmental assessment results, they do not possess the same discriminant influences on the household electricity consumption compared to certain socio-demographics or usage of home appliances. Various cross-comparisons among product features and use-phase behaviors have been made and the most important predictors of the residential electricity consumption based on the data have been introduced. Product-level and user-level discussions on the findings have also been provided.

## 1. Introduction

Environmental assessment techniques usually suffer from uncertainties in the dynamics or heterogeneities of the systems undergoing analysis (Reap et al., 2008a). One of the most important contributors to such uncertainties is the consumer behavior. This can be problematic for consumer electronics for which the usage phase, which is governed by the consumer behavior, plays a pivotal role in contributing to the environmental impacts. For instance, a review of Life Cycle Assessment (LCA) studies about consumer electronics reveals a substantial discrepancy in the results of the environmental assessments, particularly for personal computers (Raihanian Mashhadi and Behdad, 2017a). This discordance is believed to originate from the difference in assumptions regarding the usage mixes (Teehan and Kandlikar, 2012).

The uncertainties and the lack of insight about the consumers' interactions with their electronics and home appliances are not limited to the LCA domain. It has been shown that significant heterogeneity is present in time-use patterns of watching TV (Sekar et al., 2016) that can favor population-specific energy intervention policies targeting TV energy consumption. On the other hand, most of the energy intervention policies implemented during the last decade have been incompetent at capturing the consumer behavior effects. For example, time-of-use tariffs have been reported to create rebound effects (Torriti, 2012), increasing the actual electricity consumption while aiming at reducing its costs. Moreover, there are still certain limitations regarding the effectiveness of feedback for behavioral change with respect to energy consumption (Wilson et al., 2015). Smart feedback devices have also been shown to be only effective when they target consumer behavior by creating comparative norms; while even then, they may motivate some users to increase their consumption (Schultz et al., 2015, 2007).

The importance of considering consumers' behavior and their interactions with electric or electronic products in designing energy intervention policies or conducting LCA studies is undeniable. However, further investigation is required to provide insight into the important behaviors, design features or user-product interactions. Several questions can be asked about the extent to which use-phase attributes matter with respect to the environmental assessment or the household electricity prediction. For instance, if the misconceptions regarding user behavior can skew the results of LCA, as a result of energy consumption miscalculations, what specific behaviors are more important to target? Does only the daily time of use matter or are charging behavior and power management after use also of equal importance? What is the role of product design? Moreover, looking at the big picture, how important can the accumulation of these effects be to create larger trends contributing to the total household energy consumption?

While previous efforts have been made to identify the determinants of the household energy consumption (e.g., see (Kavousian et al., 2013; Hori et al., 2013; Ekholm et al., 2010)), they usually focus on socio-economic properties of households (Hori et al., 2013), appliances stock-ups (Kavousian et al., 2013) and simple considerations of consumer

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behavior (Ek and Söderholm, 2010), ignoring product-specific data including design features and consumer-product interactions. The present study strives to further explore the impact of consumer-product interactions on household energy predictions. This study also builds upon previous efforts to identify key factors of the household energy consumption by applying various supervised and unsupervised learning algorithms on the extensive and comprehensive dataset of the US Residential Energy Consumption Survey (U.S. Energy Information Administration, 2013a) that includes socio-demographics, users' behavior, product features and corresponding energy consumptions.

The rest of the paper is structured as follows. The second section provides a brief presentation of previous findings of the household electricity determinants and solutions to improve sustainable behavior regarding electricity consumption. The third section presents the data under study and the analyses that have been conducted. The fourth section provides a discussion on the findings of the study with respect to the energy policy and design considerations. Finally, the fifth section concludes the paper.

## 2. Background: importance of the use-phase attributes

It has been previously shown that the discrepancies in the results of LCA studies on personal computers mostly originate from the assumptions with respect to the use-phase attributes (Raihanian Mashhadi and Behdad, 2017a; Teehan and Kandlikar, 2012). While several efforts have been made to fortify LCA with simulation techniques (Miller et al., 2013; Bichraoui-Draper et al., 2015; Raihanian Mashhadi and Behdad, 2017b), which help capture heterogeneities and dynamics in the targeted systems, yet a holistic understanding of important use-phase attributes, including users' behaviors and design features, is critical for both policy makers and LCA practitioners. Consumers' use-phase behavior may play a major role in LCA of products whose usage cycle is a fundamental contributor to emissions (Daae and Boks, 2015). For a review of LCA limitations in handling uncertainties and heterogeneous systems, the reader is referred to (Reap et al., 2008b, 2008a). Moreover, for more details on the discordance in LCA results of consumer electronics, the reader may refer to (Raihanian Mashhadi and Behdad, 2017a; Teehan and Kandlikar, 2012). Despite the fact that the role of consumer behavior is acknowledged in the accuracy of the personal computer environmental assessment results, more clarification is required to identify the critical behaviors.

In addition, consumer behavior has shown to drastically affect household energy consumption (Swan and Ugursal, 2009; Seryak and Kissock, 2003). For example, it has been shown that not only the occupant behavior is substantially heterogeneous, but it also can skew the household energy consumption by 100% (Seryak and Kissock, 2003). Sekar et al. (2016) depicted that while the heavy TV watchers account for less than 15% of the population they contribute to more than 30% of the TV energy consumption. Telenko and Seepersad (2010) showed that the amount of electricity consumption of an electric kettle in its usage cycle is determined by the habitual characteristics of its users. Since, the contribution of the residential sector to the national energy consumption is significant (e.g., in the US the residential sector accounts for about 25% of the national energy consumption while in some countries this proportion is up to 50% (Saidur et al., 2007)), such behavioral considerations should not be neglected, particularly, because recent studies on the US population reveal that people tend to spend more time at home (Sekar et al.). The future energy policies should be more focused on tiered interventions.

### 2.1. Determinants of residential electricity consumption

Due to the importance of household electricity consumption prediction, both from the supply and the sustainable consumption perspectives, several studies have been carried out to identify the predictors of residential electricity consumption. Moll et al. (2008) conducted an analysis on the determinants of household energy use across the EU and reported that while the energy requirements were similar among the countries they studied, the determinants of energy requirement within countries were household expenditure and size. Similarly, Maréchal (2009) has recognized that social and cultural differences contribute to the differences in the consumption level across countries that are similar in income level. Tukker et al. (2010) presented a summary of insights learned from the literature about the determining variables related to the household consumption and the generated environmental impacts. Income level, household size, location and social and cultural differences were among the key factors. Sahakian and Steinberger (2011) studied household energy consumption in the context of air-conditioning in an urban megalopolis in Southeast Asia. They have highlighted the distinctions in the choice structures regarding space cooling and sustainable consumption among the different socio-economic groups.

More recent studies have also focused on appliances stock-ups and usages, as well as social interactions, as determinants of electricity consumption. Kavousian et al.(2013) claimed that in addition to weather, location and floor area, the number of refrigerators, entertainment devices and high-consumption appliances are determinants of electricity consumption. Hori et al. (2013) emphasized the linkage between social interactions and energy-saving behaviors. The knowledge gained from such studies may be used in Design for Sustainable Behavior (DfSB) frameworks. While such studies strive to incorporate social-psychological theories into sustainable design frameworks aiming to motivate consumers toward more sustainable behaviors (Tang and Bhamra, 2012; Strömberg et al., 2015; Cor and Zwolinski, 2015), they need to overcome certain challenges and limitations. For instance, Kuijer and Bakker (2015) discuss how such efforts may become product or behavior isolated and fade in the actual larger trends.

Among the previous efforts focused on residential electricity consumption analysis and demand modelling, some have studied various versions of the Residential Energy Consumption Survey (RECS) which is being used in this study. For instance, Kaza (2010) used a quantile regression approach on the RECS data and explored the effect of housing size and type, neighborhood and family characteristics. Heiple and Sailor (2008) used RECS data related to Houston, Texas for building energy profiling at spatial scales. Min et al. (2010) used regression analysis of RECS data and focused on fuel type, urban and rural households and regions. However, none of these studies focused heavily on appliances ownership, usage context, and product-user interactions. For a review of residential energy consumption predictions, the reader may refer to (Fumo and Rafe Biswas, 2015; Kavgic et al., 2010).

While the above-mentioned studies are extremely informative about the determinants of the residential energy consumption, they usually exert a high-level approach and do not provide much information at the *product-level* or about the user-product interactions. In a recent study, Hicks (2017) highlighted such effects by suggesting that the actual lifetime of the multifunctional devices determines whether or not they can improve energy consumption compared to single-use devices. Our study builds upon the current literature on household energy consumption, with the aim of providing more insights on the impact of various *product features* and different types of *user-product interactions* with a focus on consumer electronics and appliances. In the first step, a comprehensive analysis of the US household electricity consumption determinants is conducted to identify the major predictors, as well as the extent to which consumer electronics and home appliances use-phase attributes affect electricity consumption. Then, the study explores the relationship between different use-phase attributes of personal computers and their energy consumption, in order to identify the features and the behaviors that shape the personal computers usage cycle energy consumption.