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An application of the Analytic Hierarchy Process for prioritizing user preferences in the design of a Home Energy Management System

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ABSTRACT

Most demand response programs focus primarily on commercial and industrial loads. The sheer number of decision-influencing variables combined with a lack of a comprehensive understanding of human behavior make it difficult to develop response programs that encourage greater residential consumer participation. This paper presents a multi-criteria decision making approach using actual survey data for identifying user preferences. The novelty of the work is in considering functionality, cost, and carbon emissions for a given set of home appliances toward energy management. The paper explains the design methodologies used to prioritize the preferences from 1023 survey participants. The results are expected to inform the design of Home Energy Management Systems (HEMS) for participating in demand response programs.

1. Introduction

According to the U.S. Energy Information Administration (EIA), residential electricity sales in the U.S. are expected to grow by 24% based on the long term projection of energy supply, demand, and prices from 2011 data as a reference through the year 2040 [1]. Moreover, residential electricity loads show a higher degree of seasonality and one of the key reasons for peak demand is the high penetration of air conditioning and space heating loads in the residential sector. Fig. 1 shows the energy consumption in billion kWh for the end use sectors – residential, industrial, and commercial – as adapted from the Electric Power Monthly report of June 2016 by EIA [2]. Examination of consumption patterns across the end use sectors demonstrates that the difference between the minimum and maximum energy consumption is the largest for the residential sector at 67 billion kWh as compared to the industrial and commercial sectors and that usage appears to vary with changes in temperature and humidity. This variability makes the residential sector a good target for demand response (DR) programs [3]. Moreover, studies have also shown that similarly sized homes can vary in their energy use by as much as 200% [4,5] which suggests that behavior plays a large role in residential energy usage. However, research [6] reveals that a significant proportion of the residential population is unresponsive to the DR price signal. To date, it is unclear whether this is due to a lack of attention, motivation, or whether the information has simply not been presented in a way that is meaningful to these households. Although most DR programs target commercial and industrial consumers, power system planners are beginning to see the potential of the residential market for peak relief.

A 2005 study on demand side management initiatives across 23 electric utilities in North America showed residential demand savings of up to 120 MW from a single utility alone [7]. There is a growing interest by utilities to explore the contribution of residential DR programs towards system peak reduction in their control area. In 2014, data from EIA shows that more than 90% of the 9.3 million consumers who participated in DR programs in the US were from the residential sector, out of which 360,000 consumers were added in Maryland alone [8,9]. The data also suggests that the average residential consumer saved about 100 kWh annually by participating in DR. A residential DR pilot study conducted across 6000 participants by a utility in Oklahoma achieved a peak load reduction of up to 2 kW from each home during a DR event [10]. The positive result from the study has led the utility to expand their residential DR program to its 150,000 residential consumers. The Electricity Reliability Council of Texas (ERCOT) offers incentives to its residential consumers to reduce their energy usage to tap 150 MW within 30 min during DR events [11]. In most of these pilot

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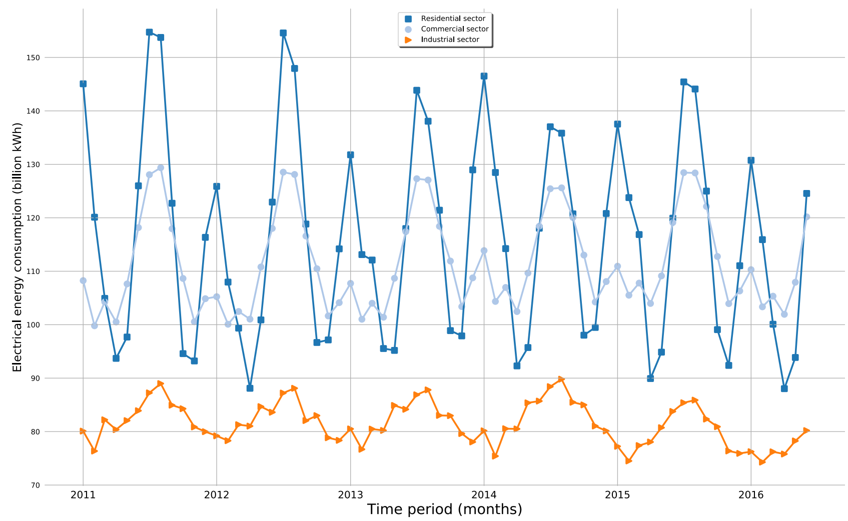

Fig. 1. Electrical energy consumption for the residential, industrial, and commercial sectors recreated from EIA Electric Power Monthly report [2].

DR programs, utilities have resorted to distribution automation, load curtailment by controlling the end use loads, and providing the homeowners with smart appliances to maximize their savings. In one scenario, utilities in Texas have installed smart thermostats that learn from user preferences and optimize the heating and cooling systems in their homes to save on operating costs [12].

The pilot residential DR efforts by utilities show promise but also come with their own challenges. Adoption of new technologies such as smart meters is a concern among homeowners for issues related to information privacy, health concerns, and beliefs that time of use (TOU) will drive up costs [13–15]. A study to assess homeowners' preference for the adoption of smart meters concluded that the participants are not ready for a large scale adoption of smart technologies that enables residential load control [13,16]. One of the main reasons cited by the homeowners in the study was that some of the smart new technologies are difficult to use and understand and also require high capital cost. Educating homeowners to overcome these barriers and curtail their energy use requires a significant monetary investment by the utilities. Convincing a small number of industrial and commercial load owners who are more predictably motivated by financial incentives to curtail their use far outweighs the financial benefits to utilities as compared to creating programs for a large number of diverse homeowners.

Limitations in our understanding of homeowner behavior have constrained the design and implementation of large scale residential DR programs. Furthermore, homeowners lack the ability and motivation to execute dynamic controls as most appliances are operated on *set it and forget it* modes and set points. The literature on price-only based DR programs suggests that a price incentive is not the only motivator for homeowners to participate in DR [17–20]. High income households may not care about monetary savings, low income households may have low energy consumption which translates to almost negligible savings, and there may be households who for any one of a variety of reasons (e.g., language barriers, poor numeracy skills, and time constraints) are unable to respond to a price signal. An experimental study by Gyamfi et al., found that homeowners were more inclined to participate in DR programs when the incentive options were extended to reducing carbon emissions besides price benefits alone [6]. Thus, the authors concluded that a better explanation of DR benefits and allowing homeowners to choose from a range of incentives voluntarily would result in more successful DR participation.

To realize the benefits of residential DR, smart homes equipped with home energy management systems (HEMSs) that can learn and adapt to the preference of homeowners to schedule loads and adjust set points are required. If the HEMS operate as per the requirement of the utility and not by the preference of its user, the system is bound to encounter resistance in its adoption thereby affecting potential DR benefits [14,21]. At the same time, homeowners with HEMS are subjected to complex decision making that involve multiple decision variables or criteria. Too many decision variables can obfuscate the decision maker to correctly identify their preferences while optimizing their energy usage. Multi-criteria decision making (MCDM) techniques help to reconcile such problems by finding the optimal decision among a complex pool of conflicting objectives and criteria [22,23]. It structures the decision making problem to explicitly evaluate multiple criteria by asking the user to trade-off between the available choices to focus on a preferred choice. MCDM based analysis has become an integral part of energy planning due to its flexibility. It helps the decision maker to systematically attain a goal while considering criteria – objective and subjective alike – and alternatives simultaneously [22,24–28].

The novelty of the work presented in this paper is the application of an MCDM method to quantify subjective data from survey respondents and objective information on cost and environmental impact for understanding the behavior of residential electricity customers. Considering cost, comfort, and carbon footprints in a comprehensive approach bridges systems engineering with behavioral science. The results of this work are expected to inform the design of HEMS for Smart Homes capable of participating in DR programs.

The survey was designed to elicit preferences from participants on home appliances usage, and also their energy-related values (money, environment, and functionality). To conduct a trade-off based analysis, Analytic Hierarchy Process (AHP) approach is applied in this study to help establish a framework where appliances are judged against certain criteria as shown in Fig. 2. The quantified preferences are indicative of the trade-offs individuals are willing to make when presented with multi-criteria decision variables to control and coordinate multiple appliances. To minimize user intervention, the survey data can be used to personalize the HEMS, to intelligently manage a homeowner's energy consumption [29,30].

The rest of the paper is organized as follows: Section 2 provides an overview about AHP and the methodologies used in the design of the survey-based AHP. Section 3 shows the analysis and the results of the survey. Section 4 concludes.