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A review of occupant energy feedback research: Opportunities for methodological fusion at the intersection of experimentation, analytics, surveys and simulation

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HIGHLIGHTS

- Occupant behavior can have a substantial impact on energy consumption in buildings.
- Feedback programs have been developed to make energy consumption more visible.
- We critically review energy feedback literature that has been published to date.
- We identify experiments, analytics, surveys and simulation as four key methods used.
- Our meta-analysis reveals gaps and opportunities for methodological fusion.

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ABSTRACT

Occupants are integral elements of a building ecosystem and their behavior can have a substantial impact on energy consumption in buildings. A wide range of energy feedback programs have been developed to make energy consumption more visible and interpretable to occupants and help them learn how to control and save energy. In this paper, we conduct a critical review of the literature related to energy feedback and identify four key methodological approaches to designing and studying energy feedback programs: experiments, analytics, surveys and simulation. Our meta-analysis reveals five research gaps and opportunities for future methodological fusion at the intersection between such approaches, including the analytics-survey, experiments-analytics, experiments-analytics-surveys, simulation-experiments and analytics-simulation interfaces. Future research at these crucial interfaces could provide the deeper understanding necessary to develop energy feedback programs that yield substantial and persistent energy savings.

1. Introduction

Commercial and residential buildings account for more than 40% of U.S. energy consumption and associated CO_2 emissions [1]. Given that people spend more than 90% of their time indoors [2], occupants play a large role in driving building energy usage. In fact, occupants have been shown to reduce energy usage by 7.4% (on average) simply by adopting more efficient behavioral practices [3] and behavior based approaches have been shown to be one of the most cost effective energy efficiency strategies on the market [4].

As a result, a significant amount of research has been dedicated to exploring various mechanisms to reduce energy usage using behavioral based approaches. Energy feedback programs—one of the most common and effective energy efficiency methods—make energy consumption more visible and interpretable to occupants and enable them to take behavioral actions that better control their energy consumption

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[5]. The research conducted in the energy feedback domain varies from short term [6–8] to long term [9–11] (i.e., the length of experiments varies from a few days to 2 years), psychological [12,13] to technological [14] (i.e., experimenting on psychological factors like social norms and technological factors such as web-based vs. paper-based feedback) and sub-building scale [15,16] to urban scale [17–21].

From a methodological viewpoint, these energy feedback studies have been tackled from different points of view, including surveys [22–34], energy use analysis (i.e., analytics) [35–42], experiments [4,6,7,11,13,43–59], simulations [60–65] and, in certain cases, combinations of these methods. A meta-analytical review of residential energy feedback system savings across numerous studies found a wide range of savings [66], perhaps attributable to inconsistencies in methodological application. Nevertheless, each method investigates an important aspect of occupant energy use behavior with the ultimate goal of developing an effective occupant energy feedback program. To better understand this wide body of literature, a handful of energy feedback literature reviews have been conducted over the years. In recent work, Delmas et al. [3] conducted a meta-analysis on the existing literature to determine the most effective feedback strategies for influencing energy behaviors. In addition to reporting the effectiveness of real time feedback and individualized audits, including higher engagement interventions, their findings suggest a potentially fundamental methodological issue in the current literature. While Delmas et al. [3]'s work highlighted inconsistencies in energy feedback methods, it was limited to meta-analysis of field experiments and did not include analysis related to broader occupant energy feedback methodological approaches (e.g., analytics, simulation) and the integration between them. As a result, there is a need to comprehensively analyze the methodological aspects of energy feedback programs and explore opportunities for methodological fusion.

In this paper, we conduct a comprehensive literature review and analyze the methods currently used to study, design and analyze energy feedback programs. Through this analysis, we identify future research opportunities for methodological fusion that could yield a deeper understanding of how to maximize the efficacy of such programs. Section 2 discusses the scholarly peer reviewed manuscripts in each category based on their methodological approaches and differences. Section 3 identifies the gaps in knowledge and categorizes them based on future research needed to fill these gaps. Section 4 discusses the challenges of occupant energy feedback research that have been either widely reported or were lacking in the literature. Finally, Section 5 proposes a vision to address the identified gaps of knowledge and recommends useful avenues for further research.

2. Meta-analysis process

This paper conducts a comprehensive literature review to identify the linkages between the numerous facets of occupant energy feedback programs. We utilized two complementary research strategies to find relevant studies for our analysis. First, we conducted a manual search for highly cited studies (e.g. [4,5,10,18,21,66–71]) and literature review papers (e.g. [3,14,68,72–83]) that focused on energy feedback research. Then, we traced the papers we cited to their aforementioned journal publications to build a comprehensive pool of 6113 scholarly peer-reviewed publications. Due to significant advancements in technology and major improvements in energy monitoring and feedback resolution, we decided to focus on analyzing the most recent approaches used to conduct energy feedback research. Therefore, we mainly concentrated on recent (i.e., those published 2010 and later) to capture new technologically advanced feedback methods (e.g., cellphone based, web-based, in-home display) in addition to highly cited feedback studies and literature review papers.

Next, we used the Google Scholar search engine to filter the papers based on the most prevalent keywords used in the energy feedback domain. Following Delmas et al. [3], three categories of keywords were used to narrow down our publication pool.

1. Energy-related keywords, such as "energy efficiency", "energy consumption", energy saving", "energy conservation", "energy monitoring" and "building energy efficiency".
2. Feedback-related keywords, such as "eco feedback", "feedback", "in-home display", "demand response" and "smart meter".
3. Occupant and building related keywords; such as "occupant behavior", "household energy consumption", "residential building", "commercial building", "residential sector", "commercial sector" and "dormitory energy consumption".

The above search yielded 341 papers. For the 341 papers, we manually filtered every paper and read its abstract. We reviewed each abstract using the following three criteria:

1. It should focus on electricity consumption. Water and gas consumption-related papers were not considered for this meta-analysis.
2. It should target either residential or commercial buildings.
3. The paper should evaluate at least a single type of feedback method or human behavior that affected feedback studies.

Implementing the three criteria further reduced our pool to 260 scholarly peer reviewed papers. After reading these 260 papers, we selected 89 peer-reviewed journal papers (and conference papers published in IEEE and ACM Transactions) based on rigorous analysis of their methodological approaches, soundness of their data collection approach, subject sample size and the clarity of the methodological steps taken. Although relevant papers were included among those removed from the final analysis, the 89 we analyzed further represent a comprehensive sample, the reliability of which was controlled by selecting only those manuscripts that were methodologically complete and clear in the sample. We provide a list of the papers used in this study in Appendix A and the combination of the methods used for each study in Appendix B.

3. Energy feedback methodological approaches

Analysis of the final set of 89 peer-reviewed papers revealed several key methodological approaches to studying, designing and analyzing energy feedback: (1) surveys (e.g., interviews and questionnaires); (2) analytics (e.g., load profiling and clustering, energy use disaggregation, occupancy detection); (3) experiments (e.g., conducting empirical experiments to evaluate the effect of feedback components); and (4) simulations (e.g., imitating real world energy feedback processes based on mathematical and stochastic models). Furthermore, we identified and categorized several studies that employed a combination of the above methods. We provide a review of the literature related to each of these methodological approaches in the subsequent subsections.

3.1. Surveys

A survey based approach consists of a sample population (e.g., occupants), a method of data collection (e.g., interviews and questionnaires) and questions that can be turned into data for statistical analysis. There is a vast body of research that has focused on understanding occupants' behavioral characteristics, attitudes and similar factors that are not fully interpretable using the quantitative data captured by sensors (e.g., smart meters) deployed in buildings. Some of these characteristics are: occupants' behaviors [25–27,29], perception of energy consumption and information [24,30], understanding of feedback content [22,31], knowledge of energy efficiency [30,32], attitude [84], awareness of energy consumption [26,33], literacy [26,34], motivation [85], demographics [30,86], social and economic information [29,81,85], eco feedback and in-home displays (IHD) and interface design preferences [21,31,34,70,85,87]. In our sample, 45 of the 89

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