Applied Energy 191 (2017) 398–413

Contents lists available at ScienceDirect

Applied Energy

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

Understanding the deterministic and probabilistic business cases for occupant based plug load management strategies in commercial office buildings

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HIGHLIGHTS

- Deterministic and probabilistic business cases for plug load studies are proposed.
- The paper uses empirical data collected over an extended study period.
- Interventions failed to recover the expenses given uncertainties in cost estimates.
- Non-energy benefits can justify the investment from project manager’s view.

ARTICLE INFO

Article history:
Received 21 November 2016
Received in revised form 9 January 2017
Accepted 27 January 2017

Keywords:
Energy management
Energy efficiency
Energy consumption
Occupant behavior
Commercial buildings
Return-on-investment

ABSTRACT

Plug load monitoring and associated occupant behavior interventions can play a critical role in reducing commercial building energy consumption. This study investigates whether the reduction in building energy consumption justify the added cost of plug load monitoring and occupant energy saving interventions. The objective of this study is to conduct deterministic and probabilistic return-on-investment (ROI) analysis of instrumenting workspaces, monitoring plug load usage, and applying interventions to promote building energy reduction. The study uses the findings of actual occupant energy saving intervention investigations conducted with city and federal government offices in which the association between occupant energy savings interventions and energy use risk was evaluated. While the deterministic approach led to a positive net present value, the interventions failed to recapture the initial investment, and operational expenses given the uncertainties in the estimate of costs and energy use. The mean ten-year net present value was −$3914 at a 6% discount rate considering all U.S. states. From the project manager’s perspective, other non-energy benefits can justify the additional resources.

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1. Introduction

Total commercial building energy use in the US is on the rise. Commercial energy consumption in the United States is projected to grow by 0.5% each year through 2040, and it accounts for roughly 18% of the total annual energy use in the United States [1,2]. Some approaches to offset the energy use in buildings include:

- Successful application of advanced building management technology that targets lighting and heating, ventilation and air conditioning (HVAC).
- Integration of renewable energy systems to offset the unavoidable energy use in buildings and to reduce greenhouse gas emissions.
- Occupancy driven energy management systems, including deployment of wireless sensor networks and behavior-driven interventions.

Energy efficiency is improved by interventions. Energy saving interventions includes a combination of technological, operational, and behavioral changes. Studies have found that people believe technology can reduce energy use in buildings, yet people play a larger role in this outcome than technology does. Traditionally, energy-conservation efforts in office environments have been implemented through technological or operational modifications [3]. However, humans are the main operators of technology and,

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http://dx.doi.org/10.1016/j.apenergy.2017.01.082
0306-2619/Published by Elsevier Ltd.

thus, failure to account for this human component of compliance may negatively impact an energy-efficiency initiative. Instead of focusing primarily on technological solutions to energy-use in buildings, recent research has shifted to investigating the effects of occupant behavior on building energy use [4–9]. In the absence of personal financial benefits, the motivation for a reduction in energy consumption in commercial office type buildings is achieved through voluntary behavior change. The results of these studies imply that the energy-saving potential of behavior change is comparable to, and even higher than, that of technological solutions [6,8,9]. Some estimations suggest that building occupants may impact up to 50% of a building's energy use, and that changing the behavior patterns of occupants can offer the most effective reductions in energy use [7].

Studying occupant-driven energy loads in commercial office type buildings (i.e., plug loads) will have a significant impact on future building design. Because individual office occupants do not have full control of a building's HVAC and lighting systems, the potential for behavior change-driven reductions in office electricity use is limited to the miscellaneous electricity load (i.e., the plug load). Plug load is a term used to describe electricity consumption that results from the use of electronic devices not responsible for zone heating and cooling, water heating, or lighting. The term includes everything from office information technology equipment to personal appliances, such as coffee machines, table fans, and personal space heaters. On average, plug loads account for approximately 13% of electricity consumption in office environments [8,10–14]. However, because of regional differences in total energy consumption and electricity end-use distribution, general estimates of plug-load densities are difficult to define. Therefore, the percentages presented in the most recent literature range from as low as 9% [15] to between 30 and 50% [16]. Perhaps a more important implication for the future reduction of building-related energy use is that as construction codes evolve, and existing building stock gradually renews, more and more offices will be categorized as high-performance buildings [17]. High-performance buildings afford the convergence of smart information and technology, as well as improved HVAC efficiency and lighting loads. On the other hand, this shift toward high-performance may proportionally increase the importance of plug loads driven by building occupants. For example, one recent assessment study concluded that plug loads can account for more than 50% of the total energy consumption in a high-efficiency building [11].

A number of recent empirical studies show that interventions targeted toward occupants (i.e., occupant behavioral interventions) are generally effective in reducing energy use in buildings. Unfortunately, most of these interventions employ case study methodologies [18] where the duration is relatively short because of intense resource requirements (e.g. energy monitoring equipment, buy-in from host facilities, cost of personnel to install, monitor, and conduct data analyses) [19–23]. In addition, energy use interventions have moved from using standardized information and basic goal setting to more complex and evolving strategies. To explore opportunities beyond the traditional monitoring-feedback design, recent research projects have combined real-time consumption data with energy-saving tips [21,24,25], historical self-comparison [21,26], peer comparison [21,25,27–30], and different types of social marketing campaigns such as energy education and peer influence campaigns [31–34]. Some innovative research groups have turned energy interventions into online games where an occupant's progress is related to their energy-conservation efforts [25,34].

Many of these occupant behavior intervention strategies do not occur in isolation but are applied in combination with each other. Therefore, because of the multifaceted nature of occupant-driven intervention design, making generalizations about the effectiveness of particular interventions sustained over time (as well as their savings potential) can be difficult. Moreover, the interventions themselves often lack a framework to evaluate effectiveness over an extensive period of time and savings in energy is not discussed in the context of overall cost-effectiveness. Common problems with behavior intervention research range from maturation (i.e., participants become more experienced over time resulting in changes in behavior independent of the intervention) to attrition (participants may drop out of a study or become unwilling to participate further between intervention measures) [35]. Other recent studies demonstrate that people revert to their old behaviors because of a number of barriers and limitations that seem to hamper the behavioral change process. One of these barriers is the response-relapse pattern in occupant energy consumption. While investigating college students' energy-consumption behavior, one study discovered that responses to energy feedback were temporary and that occupants relapsed into their old consumption patterns shortly after receiving feedback [36]. Other studies support these findings and discuss similar issues with long-term occupant engagement. Findings indicate that the design focus of future studies should promote constant activation of occupants' new behaviors and encourage long-term engagement [18,34,37,38]. Recent intervention studies have focused on social networks and social psychology in encouraging energy-saving behaviors [39–43]. One study done in an organizational context used the theory of planned behavior to find that a sense of community is a strong predictor of behavior intentions and self-reported behavior [44]. Another study, with representative sample data from across the United States, found that social interaction was a stronger predictor of weatherization behavior than factual knowledge [45].

So while studies measuring pro-environmental behavior and energy use have gained popularity, further research is still needed to evaluate the overall cost-effectiveness of those occupant behavior interventions to complement those findings. In particular, we need to consider the persistence in savings pattern [46] by evaluating the long term effect. In addition, measured data should be used for that evaluation as opposed to self-reported behavioral outcomes [44]. Hence, the objective of this study is to address those concerns and to conduct a deterministic and probabilistic return-on-investment (ROI) analysis of instrumenting workspaces, monitoring plug load usage, and applying interventions to promote building energy reduction. The empirical data used in this study and the proposed method allows for both generalizable and transferable decision-making guideline for organizations.

2. Research method and material

This study used multiple data sources. Firstly, the study collected publicly available data from the U.S. General Services Administration (GSA) [47] and Bureau of Labor Statistics [48] that provided detailed information about the cost of instrumenting workspaces, monitoring plug load usage, and applying interventions to promote occupant-driven building energy reduction. Next, the study gathered empirical data on the costs and benefits associated with two occupant energy-saving interventions conducted recently by a city government office (see Appendix for detail) and a nonprofit federal government office [49] to perform a deterministic and probabilistic return-on-investment analysis. The analysis period was ten years based on recent research completed by the National Renewable Energy Laboratory [50], which specifically targeted plug load projects in office buildings. Their study recommended that all projects with less than ten-year payback be considered for large-scale deployment. This study required determining the point estimates and probability distribution for all considered parameters to quantify the uncertainties. The analy-