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The Impact of Building Occupant Behavior on Energy Efficiency and Methods to Influence It: A Review of the State of the Art

Antonio Paone * and **Jean-Philippe Bacher** *

University of Applied Sciences and Arts Western Switzerland—Fribourg, HEIA-FR—Institute for Applied Research in Energy Systems, Bd. de Pérolles 80, CP32, CH-1705 Fribourg, Switzerland
* Correspondence: antonio.paone@hefr.ch (A.P.); jean-philippe.bacher@hefr.ch (J.-P.B.)

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Abstract: Buildings consume a significant amount of energy, estimated at about one-third of total primary energy resources. Building energy efficiency has turned out to be a major issue in limiting the increasing energy demands of the sector. Literature shows that building user behavior can increase the efficiency of the energy used in the building and different strategies have been tested to address and support this issue. These strategies often combine the quantification of energy savings and qualitative interpretation of occupant behavior in order to foster energy efficiency. Strategies that influence building occupant behaviors include eco-feedback, social interaction, and gamification. This review paper presents a study conducted on the state of the art related to the impact of building user behavior on energy efficiency, in order to provide the research community with a better understanding and up-to-date knowledge of energy, comfort-related practices, and potential research opportunities. Achieving and maintaining energy-efficient behavior without decreasing the comfort of building occupants still represents a challenge, despite emerging technologies and strategies as well as general research progress made over the last decade. Conclusions highlight eco-feedback as an effective way to influence behavior, and gamification as a new opportunity to trigger behavioral change. The impact of user behavior is difficult to quantify for methodological reasons. Factors influencing human behavior are numerous and varied. Multi-disciplinary approaches are needed to provide new insights into the inner dynamic nature of occupant's energy behavior.

Keywords: building occupant behavior; energy efficiency; building energy performance; adaptive behaviors; comfort management; eco-feedback

1. Introduction

Buildings consume around one-third of total primary energy resources, making it a prime target for the application of energy-efficiency measures. Global building energy consumption accounts for 30% of CO_2 emissions [1]. For example, in India, the building sector accounts for 35% [2] of total energy consumption. Energy efficiency in residential and commercial buildings plays an important role in the energy and climate strategies that promise carbon reductions.

During the design stage of buildings, energy simulation is used to predict the energy consumption of buildings, however, there is a considerable discrepancy between the predicted and actual energy consumption of buildings [3–6]. Human behavior and occupant preferences are important contributors to the gap between the predicted and actual building energy performance. Efficiency gains will come from technical inventions, but also from parallel changes in human behavior. The impact of building user behavior on energy consumption is usually not considered during the design phase or the post-occupancy optimization phase. Indeed, changes in human behavior can increase the efficiency of the energy used in the building. Lasting changes in behavior are difficult to achieve, but new ways to foster energy efficiency have emerged over the past few years. New technologies to measure, store, and display energy information (e.g., smart meters, dashboards, mobile phone applications) are available and provide data that allow consumers to make informed choices. However, significant investments have already been made in sensing infrastructures that can provide relevant data, while less attention has gone toward making energy information comprehensible, attractive, and relevant [7].

In general, studies of the impact of behavior in public buildings are missing and the impact of user behavior is difficult to quantify for methodological reasons. Those reasons are investigated in this review.

A very recent study [8] answered ten questions related to energy occupant behavior research and applications in buildings in a brilliant way, setting not only a milestone, but also raising new reshaped questions at a more conscious and aware level. Comprehensive reviews focus on behavioral change programs and behavioral impacts on energy savings [9–12]. Other reviews center their attention on simulation of building users' adaptive behaviors and control systems for the energy and comfort management of buildings [13–18]. Awareness about how all these topics are highly interconnected could significantly influence building energy use. This review aims to raise this awareness and to fill the research gap not bridged by other reviews since it is focused on standard quantification methodologies adopted in order to investigate energy behaviors, decision-making processes relative to user behavior, adaptive behaviors to the building environment, and on a selection of studies which quantifies the impact of occupant behavior.

The objective of this review paper is to provide the research community with a better understanding of the impact of user behavior on building energy performance and an up-to-date knowledge on optimized controls and tools for energy and comfort management in buildings, as well as potential research opportunities. The aim is to provide a summary of the extant literature, to identify research trends and gaps for future studies.

The selection criteria of the literature used for this critical review paper were primarily based on the direct relevance to the subject. The Science Direct and Scopus databases were used. The terms "building energy", "occupant", "occupant behavior", and "energy consumption" were considered as the closest key words for the topic of this research and were used in the selection process. In order to further limit this wide scope, only papers directly related to the impact of occupant behavior on building energy consumption were selected.

The third section is focused on standard quantification methodologies adopted in order to investigate energy behaviors. The fourth and fifth sections deal with decision-making processes relative to user behavior and adaptive behaviors to the building environment, respectively. In the sixth section, eco-feedback and gamification as a new ways to trigger and influence behavioral change are investigated. In the seventh section, a review of studies on building automation control systems which take into account occupant interactions and occupant preferences is presented.

2. The Impact and Evaluation of the Users' Behavior on Building Energy Performance

The reviewed papers have been categorized in terms of methodology, building type (i.e., residential, offices, school, university building, and commercial), type of energy investigated (heating - h -, cooling - c -, electricity - e -, lighting - l -), geographical area, and impact of occupant behavior (see Table 1). A brief description of the different methodologies is reported in Table 2.

Table 1. Reviewed papers by citation, methodology, building type, type of energy investigated (heating - h -, cooling - c -, electricity - e -, lighting - l -), geographical area, and impact of occupant behavior.

Citation	Methodology	Building Type	Type of Energy Investigated	Location	Impact Occupant Behaviour
[19]	Case study, survey	Residential	h, c, e	Seoul, Korea	10–30% deviation in energy use
[20]	Pre/post occupancy study	Residential and commercial	h, c, e, l	United States	68% of respondents willing to adopt energy reduction strategies
[21]	Field study	Offices and commercial	e	California, United States	- -
[6]	Field study	Residential	h	Germany	117–41% energy performance gap variation
[22]	Case study	Residential	h	Netherlands	27% energy savings
[23]	Survey	Residential	e	Japan	-
[24]	Field study	Residential	h	China	47% more heating energy
[3]	Case study	Offices	-	Germany	Window opening in summer of 10–40%, not supporting the building concept
[25]	Survey	Residential	-	Japan	83% of respondents in thermal comfort
[26]	Field study	Commercial	e	United Staets	-
[27]	Case study	Residential	c	India	-
[28]	Case study	Commercial	e	United States	Accuracy of 83% for energy pattern prediction
[29]	Case study	School	h, e	Canada	-
[30]	Case study	University building	h, c, e	Italy	Peers' personal habit variability of up to 300%
[31]	Case study, survey, simulations	Offices	h, c, e, l	Helsinki, Finland	Energy savings of between 9 and 60%
[32]	Survey	Offices	c, l, e	Malaysia	A building achieved 50% energy savings
[33]	Case study	Offices	h, c	United States	-
[34]	Case study	Commercial	h, e	United States	-
[35]	Case study	Offices	l, e	China	Error rate between prediction and record below 5%
[36]	Survey	Offices	c	India	-
[37]	Field study, simulations	Offices	-	-	-
[38]	Case study	Residential	h, e, l	London, United Kingdom	62–86% energy savings
[39]	Empirical study	Residential	e	New York, United States	50% more instances of reduced consumption
[40]	Empirical study	Residential	e	New York, United States	10% energy savings
[41]	Field study	Offices	h, c , l, e	United States	23.6% change in energy use

Table 1. *Cont.*

Citation	Methodology	Building Type	Type of Energy Investigated	Location	Impact Occupant Behaviour
[42]	Case study	Residential	h, c , l, e	Japan	-
[43]	Simulations, survey	Residential	e	New York, United States	-
[44]	Case study	Residential	h, c, e	United States	Potential to reduce U.S. emissions by 7.4%
[45]	Case study	Residential	h, c , l, e	United Kingdom	51%, 37%, and 11% variance in heat, electricity, and water consumption, respectively
[46]	Case study, audits	Commercial	h, c , l, e	Botswana, South Africa	>50% of energy is unnecessary waste
[47]	Case study, survey, simulations	University building	-	Switzerland	-
[48]	Case study, simulations	Offices	-	Cambridge, United Kingdom	-
[49]	Case study	Residential	h	Tokyo, Japan	25–30% exergy reduction
[50]	Case study, audits	Offices	e	United States	Less than 50% of equipment is turned off
[51]	Case study	Offices	h, c , l, e	United States	36% site energy reduction

Table 2. Classification of methodologies by description.

Methodology	**Description**
Case study	Describes the behavior of the occupants as a whole within the real-life context, not the behavior of each individual in the group
Empirical study	Describes what is happening based on direct observation. Research study with a limited population that is not necessarily aiming to establish statistical associations between variables
Field study	Studies phenomena in their natural setting, standing from the point of view of those who are observed
Pre/post-occupancy	Evaluates buildings in a systematic and rigorous manner after they have been built and occupied for some time
Simulations	Imitates the operation of a real-world system over time. It requires a model to be developed which represents the system itself
Survey	Method of collecting information by asking questions

The installation of energy-saving technologies must be accompanied by energy-efficient occupant behavior to ensure sustained reductions in energy consumption [39].

Several studies [41–43] have concluded that occupant behavior can have a substantial impact on building energy consumption, and one study [44] states that occupant energy savings have the potential to reduce U.S. emissions by 7.4% with little or no impact on household well-being. Moreover, behavior-based efficiency programs have been proven to be among the most cost-effective energy efficiency strategies on the market [40,52]. Studies have focused on the influence of occupant behavior on building energy consumption with the aim of interpolating behavioral aspects into building energy simulation tools to improve their accuracy [10].

Chung [53], Roetzel et al. [54], and Yun and Steemers [48] stated that building occupant (i.e., user) behaviors and activities are the most common factor causing fluctuations in actual energy consumption versus planned energy consumption. Studies on user behavior and interaction with building systems for energy consumption have increased the knowledge and understanding of building performance. Different types of activities of occupants affecting building energy consumption have been investigated in several studies.

The influence of different types of climatic conditions on occupant energy behavior has been studied [24,25].

The interactions with the systems present in an office building can be modified in order to improve building energy efficiency [55]. Azar and Menassa [41] addressed the 'word of mouth' effect, also known as spoken communication, as a means of transmitting information, which is considered to be a very influential channel of green communication. The manifesto of Cole et al. [56] highlights building user behavior as a key component of any energy efficiency program, and it specifically highlights the necessity (1) to raise a 'social and ethical challenge' in building energy-efficiency programs; and (2) to consider 'dynamic and responsible' involvement of the user and designer during the phase of the architectural design of the project.

In their study, Gill et al. [45] conclude that variations in energy-efficient behaviors affect both heating and electrical consumption significantly, whereas water consumption is only partially affected. Heating and electrical consumption can be positively affected by users reducing consumption during occupied and unoccupied periods and by determining where waste is occurring, i.e., windows open in rooms where heating is in use and lights/appliances on in unoccupied rooms.

Schweiker et al. [49], in their study conducted in Tokyo, showed that: (1) in a specific building, the choice towards a lower indoor room air temperature in winter leads to a reduction of exergy consumption by 25–30%; (2) in regions having moderate outdoor temperature, it might be more important to improve occupant behavior than to invest in building envelope systems; and that (3) the combination of the occupant's behavioral changes and building improvements can result in a reduction as high as 75–95%. These values were found by steady-state estimation of exergy consumption for heating and cooling. In thermodynamics, the exergy (or available work) of a system is the maximum useful work possible during a process, and the potential of a system to cause a change as it achieves equilibrium with its surrounding environment. Exergy is the energy that is available to be used. After the system and surroundings reach equilibrium, the exergy is zero. Another study [38] shows that the behavioral impact on energy saving ranges up to 62–86% in the tested dwelling, and decreases as the building efficiency increases. These values were also found by steady-state estimation of the exergy consumption for heating and cooling. These values obviously strongly depend on the characteristics of the building under study and on the location of the building.

Significant differences in energy savings can be encountered depending on the context of the studies. For example, at the European level, the review of behavioral change programs concludes that behavioral savings potential could reach approximately 20% [11]. A worldwide review [12] states that results may differ up to 100% among case studies. As a result, there are severe limitations to generalizing energy savings and CO_2 emissions.

Finally, studies that quantify potential savings due to behavioral changes in service buildings are scarce. Three studies were found, where two consist of audits [46,50] and one tests a feedback strategy [51]. In particular, one audit [50] reports the user behaviors for specific aspects (lights/appliances off during night or enabling power management of office equipment) in specific environments (offices, schools, and medical buildings). The conclusion of this study (conducted in the United States) is that less than 50% of the equipment is turned off and less than 10% of desktop computers enter low-power mode, while 53% successfully initiate power management in monitors. These results are in accordance with another study [46] that shows clear opportunities not only for energy management but also for behavioral change in services buildings.

Adaptive behaviors such as drinking cold beverages, changing/adjusting clothes, adjusting the room's thermostat, and opening or closing operable window(s) can dramatically reduce building energy consumption. Unfortunately, the dissatisfaction of building users regarding the obligation to adopt these adaptive behaviors can strongly limit the reduction of building energy consumption. In their study, Keyvanfar et al. [32] concluded that building users who are not satisfied with the imposed energy efficient features may adapt building designs and building cooling and lighting technical systems according to their own satisfaction levels, which causes higher energy consumption.

3. Methodologies for Assessing Building Occupant Behaviors

This section is focused on quantification methodologies adopted in order to investigate energy behaviors. According to Lopes et al. [57], energy behavior studies require the integration of disciplines through interdisciplinary approaches, in particular, by bringing engineering and social sciences together. Moreover, energy behaviors are not static; they change with accumulated experiences, and are often inconsistent. These factors increase research difficulties and should be taken into account in any energy behavior study in order to minimize potential bias.

As stated in Lopes et al. [57], even if there is a common agreement in the scientific community that behavioral changes are required to increase energy efficiency levels, and despite the interventions put in place in the last decades, the results have been considered ineffective and have not achieved significant changes. Nonetheless, energy savings through behavior are recognized to be as high as those achieved using technological solutions, but the difficulty in quantifying behavior has been limiting the research in this field. Therefore, standard quantification methodologies of energy behaviors are required and research must contribute to it, thus reinforcing the role of behaviors in energy efficiency policies. Lopes et al., in the previously quoted study, continue stressing that research on energy behaviors has essentially focused on the residential sector. Only few studies have centered their attention on behaviors in services buildings. Therefore, there is a noteworthy unexplored line of research associated with energy behaviors in services buildings.

A survey is required in order to quantify behaviors exhibited by occupants and to compare the effects of those behaviors with the actual monitored performance. The objective is to capture occupants' actual behavior in buildings, to verify the reliability of the survey, and to identify wasteful energy behavior. A framework for the development of such a survey is provided by Francis et al. [58]. This framework, initially dedicated to health service researchers, was based on previous research (of over 800 studies) utilizing the Theory of Planned Behavior (TPB) [59] as the explicit theoretical basis for behavioral analysis. It outlines three levels of analysis with increasing accuracy and, correspondingly, increasing time and analysis requirements.

The most detailed level was used in the development of a domestic user behavior survey [45]. The target behaviors to be assessed in the user behavior survey were the reduction of heat, water, or electricity consumption within the home. In order to determine the dominant factors that contribute to implicit and explicit decisions regarding reduced resource consumption, a study had to be conducted with the home occupants. The survey used a five-point scale, with responses ranging from 'strongly disagree' to 'strongly agree'. The study also presented a methodology to assess the contribution of occupant behaviors (regarding energy efficiency) to real-life heat, electricity, and water consumption.

In their White Book, Rivière et al. [60] propose a framework to represent behavioral changes. This framework consists of eight domains (norms, legitimacy, efficiency, cost–benefit, morality, habits, preconception, and context) that can be linked to three categories: psychological factors, anthropological factors, and behavioral economics.

In conclusion, in order to assess building occupant behaviors, a scientific study which describes the dominant factors that are involved in energy behaviors has to be conducted with the occupants.

4. Decision-Making Process and Its Influence on Energy Behavior

This section wants to describe decision-making processes relative to users' energy behavior and the theoretical frameworks necessary to study this behavior. Wilson and Dowlatabadi [14] presented the most comprehensive review on energy behavior frameworks of the last decade. In their study, the authors focused on the point of view of residential energy use and explored the most relevant social theories that determine individual decision-making:

- utility-based decisions and behavioral economics;
- technology adoption and attitude-based decisions;
- decision theories in social and environmental psychology; and
- sociological theories that cover the influence of social context in decision-making.

The foundation of these theories is that consumers are assumed to behave rationally. This means that they maximize their advantage given budget constraints, with their preferences perfectly well-organized and stable. This theory has been used, for example, in eliciting consumer preferences concerning energy efficient appliances or the choice of electricity suppliers in deregulated markets. However, as Lopes et al. [57] state, there is evidence that consumers do not always make consistent rational decisions, even if they are given perfect information. Some examples of inconsistencies:

- *"Time inconsistency."* Individuals do not make decisions in a regular manner using unchanging time discount rates. Rather, they make decisions with different discount rates correlated depending on the situation.
- *"Bounded rationality and heuristic decision-making."* Consumers are rational but face cognitive constraints in processing information. Therefore, a wide range of simple decision rules is used by users in order to reduce cognitive needs.
- *"Framing and reference dependence."* Consumers' decisions depend on the manner information is presented to them. Introducing the decision as a choice between losses or gains, different outcomes may be attained. Moreover, when making a decision, instead of seeking and processing all relevant information, users tend to "anchor" on fixed convictions, usually the status quo (the reference point with respect to which advantages and disadvantages are estimated) [14,61].

In conclusion, since occupants do not always make rational decisions, the manner of presenting the choice itself becomes determinant in order to adopt energy-efficient behaviors.

5. Adaptive Behaviors to the Building Environment

This section wants to describe how adaptive behaviors and technologies can relate optimally to human behavior, needs, and desire for comfort. As previously mentioned, users adapt their behavior to the building environment. This adaptability can allow energy efficiency gains but user comfort has to be granted, or counterproductive behaviors are likely to occur.

For instance, Holopainen et al. [62] stated that reducing unnecessary heating and cooling by means of adaptive control methods can avoid excessive heating and cooling, while it may also provide an unacceptable degree of user satisfaction. Hoes et al. [17] reported that if decisions about environmental adjustments such as window opening, blind positioning, fan on/off, and thermostat up/down, etc. cannot be made by occupants, occupant comfort perception is negatively affected because they have less control over their environment.

Moreover, Nicol et al. concluded in this study [63] that a building should give users the possibility of adjusting conditions to suit themselves. If control is not provided or if the controls are ineffective, inappropriate, or unusable, then discomfort is increased. Gunay et al. reviewed literature focusing on adaptive occupant behaviors in offices [64]. In their review, they reported the reasons for the occupants' discontent towards automation applications in charge to regulate building systems like ventilation, shading devices, temperature, lights, etc. A dissatisfied desire for a customized indoor climate is the basis for this discontent.

In his doctoral dissertation, Paciuk [65], also focused on the quality of the indoor environment, which can have a significant impact on comfort, health, and sense of wellbeing. He also underlined the importance for the occupants to adjust and control that environment according to their perceptions.

Liu et al. [66] stated that adaptive behavior can be conscious or unconscious, while multiple environmental factors can influence it (e.g. climate, culture and economics). Keyvanfara et al. [55] summarized the users' adaptive behaviors in hot–humid climate.

Some examples of adaptive behaviors that can be self-adopted in response to hot indoor conditions include the drinking of cold beverages, restraining physical activity level, changing/adjusting clothes from warm to cool, or drying body skin moisture. Some examples of adaptive behaviors related to the environment include taking a break and moving to cooler location, opening or closing windows manually, or using remote system, using the portable fan, adjusting room's thermostat, or adjusting air-condition operative hours.

In conclusion, adaptive behaviors are fundamental in order to foster energy efficiency, but any unacceptable degree of user satisfaction or discomfort has to be avoided in order to do not generate counterproductive behaviors.

6. How to Influence Building Occupant Behaviors—Eco-Feedback, Social Interaction, and Gamification

This section is focused on eco-feedback and gamification as new ways to trigger and influence behavioral change. Reviews of the literature on field studies and simulation of building users' adaptive behaviors confirmed that different types of awareness could significantly influence building energy use [15–17].

6.1. Eco-Feedback

An eco-feedback system provides building occupants with information regarding their historical and current energy consumption. Numerous studies [67,68] on empirical eco-feedback experiments concluded that eco-feedback systems are an effective tool for reducing energy consumption. While several eco-feedback studies [69–78] have observed that providing building occupants with information regarding their historical and current energy consumption leads to significant reductions in consumption, there is a paucity of research regarding what specific system design features cause these reductions [40]. More recently, a large-scale study [77] of 2000 households and a study [79] of utility eco-feedback programs concluded that users respond well to eco-feedback with reported energy savings of 15% and 7%, respectively.

Direct energy units, such as kWh, are difficult to comprehend by users [77,80,81] and providing feedback in terms of a tangible unit, such as ”trees”, may increase user comprehension and energy savings [40,82,83]. Building occupants also have a limited comprehension of CO_2 emissions as a representation unit due to their own abstract qualities. Representing eco-feedback through the proxy ”trees needed to offset emissions” as introduced by Wood et al. [84] is a viable alternative to the abstract scientific units of kWh or CO_2 emissions. The metric of trees is a commonly known object that can easily be visualized by users to get a tangible representation of their changes in energy consumption.

Literature about eco-feedback design which incorporates the analysis of empirical energy consumption data is widely found [81,85–88]. Providing users with eco-feedback information regarding their current and historical energy consumption levels has been demonstrated in several studies [67,72,89] that effectively motivate for energy-efficient behavior.

In their study, Jain et al. recommended providing eco-feedback to commercial building users and concluded that it could be a valuable tool for building managers to motivate occupants to decrease energy consumption. They stated that eco-feedback systems have the potential to positively impact building energy consumption, but in order to maximize their potential, continued empirical analysis is fundamental. If conceived and engineered adequately, eco-feedback systems associated with other energy efficiency measures could become the tool required to tackle our transition to a more sustainable and a less carbon/energy-intensive society [40]. In particular, it has been recently reported [90,91] that a co-design and co-creation approach could be the key to engage office occupants to make them conscious of the impact that their actions have on energy use. In the study of Jaskiewicz et al. [90], the co-design process was supported by engineers and designers in order to allow occupants to define the monitoring platform installed on adaptable software. Using modular hardware, self-reporting and feedback displays were co-created in order to stimulate energy-efficient and comfort-efficient actions of the occupants in the context of office practices. In the study of Guerra-Santin et al. [91], research was conducted in order to increase the acceptability of renovation projects and reduce uncertainties related to occupant behavior. Their conclusions reported that people hate to be forced into habit change. The participation process, co-shaping renovations with occupants, brought positive implications for energy-saving behaviors.

Usually a web-based energy dashboard is used as interface between users and eco-feedback. In particular, energy dashboards provide not only self-monitoring, but eventually also comparisons for example to their neighbors' usage [82,92]. Adding advices and tips on the dashboard has been reported to be an effective way to improve the impact of eco-feedback and provide greater energy savings [93–98]. Energy tips on the dashboard are those short-term and long-term recommendations which can immediately point out energy inefficient habits as well as suggestions for using more energy-efficient appliances.

However, one of the first attempts to quantify the effects of individual eco-feedback on energy-saving behaviors in a university building found that such feedback does not necessarily result in sustained long-term energy savings [99]. Individual eco-feedback has an immediate beneficial effect in the short term [100,101], but in the long term this energy-saving behavior might disappear. For instance, Buchanan et al. in their study [102] observed reductions in energy consumption of only 2% and they warned of the possibility that in the long term this energy-saving behavior might disappear. They stated that analytical skills are required to evaluate feedback for in-home-displays (IHDs) and continued with the possibility that consumers may react in unexpected ways, generating undesired consequences such as cold homes or increasing existing levels of consumption. These rebound effects and unintended consequences entirely depend on user engagement. Therefore, they recommended reconsidering the possibility of the U.K. government massively investing in IHDs since IHDs cannot benefit consumers and are characterized by the disadvantage of becoming outdated faster than platforms on smart phone applications and websites. Moreover, they suggested the use of carefully designed feedback that can generate energy-saving actions.

Finally, this very recent study [103] reported that normative messaging positively influenced a behavioral change in the long term.

6.2. Social Interaction

Several studies [74,104–106] have incorporated a normative comparison (user ranking) component within an eco-feedback system that allows users to compare their energy usage with their peers and neighbors. The success of normative eco-feedback relies on the premise that a user is influenced by actions of others in his/her social network [39]. Interactions between users have revealed that social network dynamics significantly affect energy savings [69].

Numerous studies [70,74,75] have expanded eco-feedback to include a normative comparison component that provides users with information regarding the energy consumption of their peers and suggests that normative comparison (through a social network) is an effective component in driving energy use reductions. The energy savings observed in these expanded studies were as high as 55% [39].

Several studies [104,107,108] have successfully elicited energy savings by integrating online social networking tools with eco-feedback systems. In particular, a study by Peschiera et al. [105] combined social networking tools and eco-feedback into a single web interface. This interface allowed users to directly compare their energy consumption with others in their social network. The study revealed that normative feedback is more effective than purely historical feedback in yielding energy savings. A more recent study [69] expanded on this result by analyzing the network position of users in a social network relative to their energy consumption. The authors observed a correlation between the social position of a user in the network and the amount of energy they conserved, finding that the number of social connections of a user is positively correlated to the amount of energy the user conserves [40].

By leveraging and optimizing social influence, researchers can substantially increase the efficacy of eco-feedback systems, leading to long-term sustained reductions in energy consumption and facilitating the spread of information [39,109–111].

A study by Gulbinas et al. [112] presents results from an empirical eco-feedback study conducted in a commercial office building where building occupants were provided with access to energy-use feedback through an advanced eco-feedback system that connects individuals over organizational networks. They demonstrated that if individual energy feedback is provided to commercial building occupants, users are not necessarily motivated to save energy. However, providing occupants with access to energy-use information of their organizational network can result in significant energy savings. Gulbinas et al. recommended the design of future commercial building feedback systems in order to connect users and groups in organizations, to benefit from increased occupant–system interactions [113].

6.3. Gamification

Games offer a new context in which to place important information about personal behavior [114]. Games enable interactive experiences that exploit several sub-processes that govern observational learning [115]. They attract attention because they are emotionally engaging and entertaining. Games encourage new behaviors by suggesting appropriate actions and provide motivation for tangible and social actions [7]. The results obtained from the participation in a serious game named Power House were presented by Reeves et al. [7].

The experience showed that an engaging game could change behavior in the direction of the game experience. The game attracted attention using entertainment features and facilitated retention through repeated practice of the desired behaviors. It provided positive feedback for enacting the desired behaviors through game rewards as well as vicarious incentives that motivated behaviors, including the possibility of social comparison via indicators of success such as levels and points [7].

Reeves et al. [7] reviewed the literature on media and motivated cognition and concluded that game interactions are processed via psychological schemes that do not substantially differentiate media symbols from the real-world people and objects they represent, even though they are accomplished with visual ingredients that seem unique to symbolic communication. In this way, it is possible to suggest to the occupants that they change their incorrect energy usage, for example by remembering to turn off appliances.

In conclusion, co-designed and co-created eco-feedback systems or interactive experiences like games are an effective tool for reducing energy consumption. Moreover, by leveraging and optimizing social influence, the efficacy of eco-feedback systems can be substantially increased.

7. Optimized Control for Energy and Comfort Management in Buildings and Its Link to User Behavior

Operational performance of a building along with safety and comfort of the occupants is normally ensured with control systems. A building automation system is generally centralized, integrated in hardware and software networks. It monitors and controls the indoor climatic conditions in building facilities. The objective of a building automation system is to achieve high comfort levels (thermal, visual, air quality, humidity) for building occupants and satisfaction of their preferences as well as integration of the building comfort conditions with energy and cost-saving strategies. This can be obtained by adopting several technological solutions like heating ventilation and air conditioning (HVAC), and artificial lighting, etc. Teeter et al. described that since the building possesses non-linear thermal behavior related to its structure, construction materials, location, and climatic conditions, advanced control strategies can be used in order to maintain constant performance in the occurrence of variations of the control parameters [116]. However, there are some questions about the design of such control systems in relation to occupant behaviors and preferences. One may mention these questions: How can the building's control systems for energy and comfort interact with and adapt to occupant preferences? How robust is the control system towards occupant behaviors?

Various reviews have already been published on existing research and development, focusing on intelligent control systems for the energy, comfort management of buildings, and occupant interaction for indoor comfort conditions [18]. Dounis et al. [117] also presented advanced control schemes. In the study by Marinakis et al. [118], the hardware enables users to remotely control connected appliances while collecting high-resolution energy-use data, which enables the determination and prediction of building occupancy and occupant energy-use efficiency. These advanced control systems also often improve thermal comfort, for example through the overheating reduction from night cooling.

Building a control algorithm that explicitly takes weather effects into account remains difficult. Dynamic programming is one of the few optimal algorithms which considers weather effects [1]. Hagras et al. [119] studied the thermal response of buildings with respect to the outdoor climate as well as the occupancy loads for the management of building energy and comfort management. One of the most interesting control methods, which has already been applied successfully in Switzerland [120], is the model-based predictive control (MPC) method . This method takes into account disturbance predictions such as the weather in regulating the control activities along with the chosen optimization strategy. This method also takes the energy price variation into consideration, but it is not valid for medium-sized buildings since it involves significant costs of modeling, data collection, and monitoring [1]. Another control method is the multi-agent system technology (MAST), which allows for the learning of building occupancy trends and energy resource coordination as well as the ability to respond to real time indoor environmental conditions [1]. This method manages to coordinate the building's electrical devices and heating to optimize smart grid demands [121] and to control the HVAC system, lighting, and air quality of office buildings in advance [122]. The conflict of multiple user preferences in buildings [123] and the complexity of optimal building environment control have been addressed [124].

In conclusion, advanced control systems are accepted by the occupants because they improve the thermal comfort of the building and provide a perfect integration of energy and cost-saving strategies.

8. Conclusions and Outline

In order to limit the increasing energy demands of the building sector, the impact of occupant behavior has become a growing research topic. Numerous studies have investigated the impact of occupants on the energy consumption in buildings in order to qualitatively and quantitatively interpret occupant behavior, foster energy efficiency, and reduce the gap between the predicted and real energy consumption.

Behavioral impacts on energy savings, simulations of building users' adaptive behaviors, control systems for energy, and comfort management of buildings were the subjects of research conducted in the literature. A growing awareness about how all these topics are highly interconnected seems necessary in order to significantly influence building energy use.

A major conclusion from this state of the art overview is that user behavior has a significant impact on energy consumption in residential and commercial buildings. Behavioral change is crucial in order to foster energy efficiency in the building sector, and users can be influenced to use less energy when exposed to feedback.

Studies of the impact of behavior in commercial or public buildings are scarce, but a fast increase of the number of publications in the period between 2013 and 2016 reflects the development of this research area.

The impact of user behavior is difficult to quantify for methodological reasons. The human decision-making process is complex and multifactorial; thus, factors influencing behavior are also numerous and varied. The inner dynamic nature of occupant's energy behavior represents a challenge and multi-disciplinary approaches are needed to provide new insights into the domain. In order to assess building occupant behaviors, a scientific study which describes the dominant factors that are involved in energy behaviors has to be conducted with the occupants. Since occupants do not always make rational decisions, the manner of presenting the choice itself becomes determinant in adopting energy-efficient behaviors.

Introducing energy conservation measures without taking into account user satisfaction can often be counter-productive because users are likely to try to adapt their environment to obtain satisfying conditions. Emphasizing behavior change would better achieve energy efficiency.

Eco-feedback seems to be an effective way to influence behavior; attention has to be paid to the way information is presented (for instance, "trees" instead of kWh) because the impact of eco-feedback may considerably differ from one eco-feedback system to the other. The question of the long-term efficiency of eco-feedback is still open. Moreover, future research could investigate the impact of feedback on different time scales. In fact, normative comparison increases the outcome of eco-feedback and might have an impact in the longer term.

Gamification opens new opportunities and ways to trigger behavioral change, but examples and studies are rare so far and more research and evidence has to be provided in this field.

Attention has to be paid to the interaction between user preferences and behaviors and advanced building automation systems. There are still some open questions about the design of such control systems in relation to occupant behaviors and preferences. How can the building's control systems for energy and comfort interact with and adapt to occupant preferences? How robust is the control system towards occupant behaviors?

Further analysis on the interactions between technological improvement and behavioral change is needed to influence the energy effect of occupant behavior, to better understand occupant behavior driven by feedback and anticipate actual building performance. Further research on possible conflicts and complexities between building automation systems and multiple user preferences is needed. How should these two components be integrated and aggregated in order to drive a reduction in energy use? Methods to streamline interaction with users and the implications such methods have on user engagement and performance should also be studied.

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