



# The human dimensions of energy use in buildings: A review

Simona D'Oca, Tianzhen Hong\*, Jared Langevin

Building Technology and Urban Systems Division, Lawrence Berkeley National Laboratory, One Cyclotron Road, Berkeley, CA 94720, USA



## ARTICLE INFO

### Keywords:

Human dimensions  
Energy use  
Occupant behavior  
Building life cycle  
Energy performance  
Stakeholders

## ABSTRACT

The “human dimensions” of energy use in buildings refer to the energy-related behaviors of key stakeholders that affect energy use over the building life cycle. Stakeholders include building designers, operators, managers, engineers, occupants, industry, vendors, and policymakers, who directly or indirectly influence the acts of designing, constructing, living, operating, managing, and regulating the built environments, from individual building up to the urban scale. Among factors driving high-performance buildings, human dimensions play a role that is as significant as that of technological advances. However, this factor is not well understood, and, as a result, human dimensions are often ignored or simplified by stakeholders. This paper presents a review of the literature on human dimensions of building energy use to assess the state-of-the-art in this topic area. The paper highlights research needs for fully integrating human dimensions into the building design and operation processes with the goal of reducing energy use in buildings while enhancing occupant comfort and productivity. This research focuses on identifying key needs for each stakeholder involved in a building's life cycle and takes an interdisciplinary focus that spans the fields of architecture and engineering design, sociology, data science, energy policy, codes, and standards to provide targeted insights.

Greater understanding of the human dimensions of energy use has several potential benefits including reductions in operating cost for building owners; enhanced comfort conditions and productivity for building occupants; more effective building energy management and automation systems for building operators and energy managers; and the integration of more accurate control logic into the next generation of human-in-the-loop technologies. The review concludes by summarizing recommendations for policy makers and industry stakeholders for developing codes, standards, and technologies that can leverage the human dimensions of energy use to reliably predict and achieve energy use reductions in the residential and commercial buildings sectors.

## 1. Introduction

Buildings have the potential to act as smart systems that facilitate the shift towards a more sustainable energy use paradigm [1]. They can encourage the accelerated uptake of renewable technologies and the reduction of energy use, carbon emissions, and operating costs while increasing the comfort, satisfaction, health, and productivity of building occupants [2]. While a substantial body of research covers the energy saving potential of improved building performance [3], the variable impact of identical energy conservation measures across different building examples is less understood [4]. An existing base of literature demonstrates that human factors may contribute substantially to this variance in energy use [5–9]. The main conclusion reached by these existing studies, which work across disciplines and are international in scope, is that technology investments alone do not necessarily guarantee low or net-zero energy, or higher comfort

perception, in buildings. Indeed, human factors also play a crucial role, and while the understanding of their impact has improved, it is often ignored in building design and operation.

As an example, office occupants often work beyond typically assumed office hours, and such overtime occupancy drives the increase of internal heat gains due to the use of electrical appliances, lighting, and plug loads and extends the operation of building services such as Heating, Ventilation and Air Conditioning (HVAC) systems and lighting [10]. Furthermore, not all occupants use building services at the same intensity. Researchers [11] demonstrated via computer simulations that occupants with a “wasteful” work style would consume up to double the energy of non-wasteful “austere” coworkers. It has also been widely demonstrated in experimental studies [12–14] that occupants vary in comfort preferences, satisfaction, and indoor environment perceptions due to physiological (i.e., gender and age), psychological, and cultural factors [15–19]. To the extent that these human factors

\* Corresponding author.

E-mail address: [thong@lbl.gov](mailto:thong@lbl.gov) (T. Hong).

impact total energy use, they contribute to prediction gaps [20] regarding energy expenditure and operating costs. Indeed, predicting human occupancy and energy-related behavior, which is stochastic in nature, is a challenging practice [21–25]. Accordingly, human factors in commercial buildings are considered a “dark side” of energy use [26].

In the residential sector, too, understanding the diversity of human energy use has been a topic of great interest [27–29]. For example, residential studies on this topic conducted in Europe [11,30–35], the United States [11,36–38], Asia [39–43], and Australia [44–46] have demonstrated variation by a factor of 3–10 in household energy use that is attributable to human factors. Extended reviews have been performed on independent studies worldwide in an attempt to align these research outcomes and demonstrate the continued future need for studies on this phenomenon [9,29,47–50].

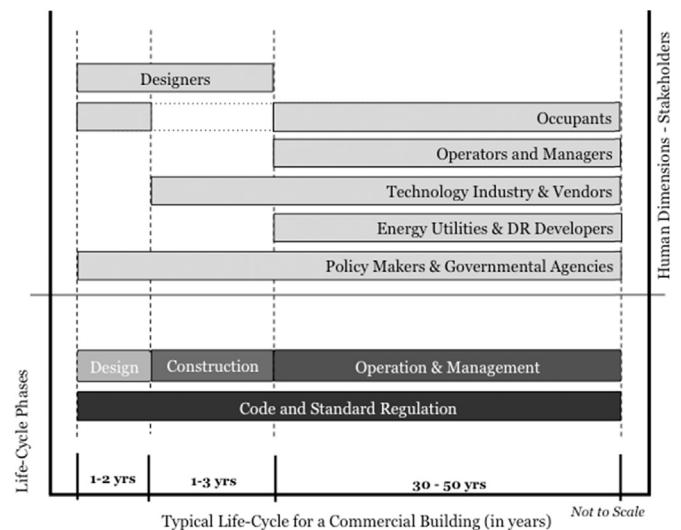
Taking a broader perspective, the *human dimensions* of energy use in buildings refers to an array of actions related to the building life cycle that include designing, constructing, living and controlling, operating, managing, serving, and regulating built environments from the building level up to the urban scale. The term “human” encompasses influencing roles from a variety of stakeholders that have an impact on the actual building performance, with a focus on energy consumption and occupant comfort. For this paper, stakeholders include building designers and owners, the technology industry and vendors, occupants, operators and managers, energy providers, and policy makers. The influence of these stakeholders on building energy use cannot be prescribed *a priori*, leading to inconsistencies between potential and actual building energy performance.

Given the potentially broad impacts of human dimensions on energy use and the need to meet 2020 and 2050 energy and greenhouse gas reduction goals [51], new data, guidelines, and models are needed to leverage human dimensions towards substantial building energy use reductions and improvements in occupant comfort that can be sustained across an entire building life cycle.

In this paper, we argue that compliance with zero-net-energy buildings and other high-performance building guidelines [52] cannot be achieved without state-of-the-art methods for estimating human dimensions impacts on energy use at various stages of the building life cycle (design, operation, retrofit) and at various scales (zone, building, and urban level), both in residential and commercial buildings. Specifically, achieving energy efficiency requires understanding both technological and human dimensions, integrating qualitative and quantitative methods and adopting appropriate tools to guide the design and operation of low-energy residential and commercial building technologies. In this paper, the approach is expanded to the energy-related behaviors of multiple stakeholders, including not only occupants but also building designers, engineers, operators and managers, industry vendors, energy utilities, and policymakers. This paper discusses the state-of-the-art in human dimensions research as it pertains to each stakeholder, highlighting research outcomes that hold particular promise for achieving sustained reductions in energy use and enhanced occupant comfort and productivity across a building's life cycle.

## 2. The human dimensions of building energy use: a literature review

The following section summarizes literature relating to several human dimensions of the building life cycle, including: (1) designing, (2) living and controlling, (3) operating and managing, (4) constructing and regulating, and (5) servicing building environments, from the building level up to the urban scale. As mentioned, these human dimensions impact actual energy use as well as indoor environmental quality in a building, and they relate to a wide range of stakeholders that collectively influence all stages in a building's life cycle (Fig. 1). In this section, we focus on six stakeholders that are particularly important in



**Fig. 1.** Six stakeholder groups that are driving the human dimensions of building energy use across different building life-cycle phases: building designers (Section 2.1), occupants (Section 2.2), operators and energy managers (Section 2.3), technology industry and vendors (Section 2.4), energy utilities and demand response (DR) program developers (Section 2.5) and policy makers and governmental agencies (Section 2.6).

driving the human dimensions of building energy use (Fig. 1).

Literature review sub-sections are organized around each of the six stakeholders illustrated in Fig. 1 as follows: building designers (Section 2.1); occupants (Section 2.2); operators and energy managers (Section 2.3); technology industry and vendors (Section 2.4); energy utilities and demand-response (DR) program developers (Section 2.5); and policy makers and governmental agencies (Section 2.6). Each sub-section identifies the stakeholder group's needs relative to the building life cycle and reviews relevant advancements in building, social, and data sciences to provide targeted guidelines and insights.

It is noted that the identified stakeholder types may encompass individual subjects (i.e., building designers, occupants, operators, managers) as well as groups and associations (building industry, utility users, technology vendors, policy makers), each of which may hold different goals related to building performance outcomes [53]. For example, building energy modelers focus on comparing design scenarios based on performance and accurately predicting building energy consumption; building occupants seek improved comfort and productivity; building operators seek to minimize daily energy use while maintaining comfort for occupants; utilities and policy makers aim to address occupants', operators', and managers' energy savings impacts through codes and standard regulations; and building vendors seek to develop high-performance products that save consumers energy costs with minimal capital investment requirements. Fig. 1 provides a high-level summary of the diverse stakeholder roles that drive these varied interests during the various phases of the building life-cycle.

### 2.1. The human dimensions of building design: architects and engineers

Until recently, architects and engineers rely on computer simulations in evaluating the performance of various building design options; the effects of human-building interactions have largely been ignored or oversimplified in these simulations. For example, a building design incorporating natural ventilation might fail from a comfort perspective because of unanticipated drafts generated by occupant window opening and closing actions that were not considered in a building energy model [54–56].

Similarly, daylighting design failures due to glare issues arising from occupants' dynamic operation of shades and blinds have been largely demonstrated and discussed [57,58]. Finally, the inability to

consider realistic occupant thermostat use behaviors in HVAC design and simulation has been shown to result in problems with occupant discomfort and failure to meet operator energy savings goals in commercial buildings [59–62].

More broadly, insufficient representation of occupant and operator behavior in building simulation has been shown to be a major factor contributing to observed gaps between the designed and actual energy performance of buildings [63]. Indeed, occupant and operator human dimensions were shown to be major influencing factors in total simulated energy use of a building alongside several other factors including climate, building envelope characteristics and equipment, and baseline indoor environmental condition set points [63].

These latter four variables are satisfactorily described by mathematical equations in most of today's widely used building performance simulation (BPS) programs (e.g., EnergyPlus, ESP-r, TRNSYS, IDA ICE, and DeST). However, simulating the impact of operators and occupants during the design stage remains a significant challenge for architects and engineers, due to a general lack of models that can reliably predict these occupant/operator impacts as well as the perceived complexity of modeling frameworks that do exist.

### 2.1.1. Stakeholder needs

Architects, engineers, and energy modelers design buildings with a need to fully consider how occupants will interact with the building and its energy systems and how this interaction will impact building energy use and indoor environmental quality outcomes. Architects, engineers, and energy modelers require more effective means of predicting energy use and occupant comfort as well as a way to achieve building performance targets that relate to these outcomes. Such capabilities are supported by **data** that underpin evidence-based **models**, which can represent occupants' behavior and replicate the stochastic nature of its impact on the designed solutions. These **tools** integrate the developed modeling frameworks and establish **case studies** for occupant and operator behavior impacts on predicted building performance.

### 2.1.2. Supporting research advancements

Ongoing research aims to establish methodologies that support building designers' need to better quantify the influence of human dimensions in building energy performance.

**2.1.2.1. Data.** A large array of objective and subjective monitoring techniques have been used to gather empirical evidence of the impacts of human factors on building energy performance [4,8]. Indeed, gathering data on the human-building interaction has been made increasingly possible by Internet of Things (IoT) and Information and Communication Technology (ICT) products geared towards achieving energy efficiency in the building sector [4,68]. The amount of data available regarding occupancy (i.e., presence and movement), occupants' interactions with the building envelope (i.e., windows, shades, blinds), and occupants' use of control systems (i.e., HVAC, lighting systems, and plug-loads) has shown a particular increase in recent years. Additionally, smart energy meters and pervasive environmental sensing technologies promote data-rich building environments that help to infer which occupant behaviors hold the greatest influence on energy performance outcomes [65–67]. Researchers have drawn from these available data sources in identifying correlations between observed system states (i.e., thermostat being adjusted [68], windows being opened/closed [31,38,48,69–82]), shades and blinds being drawn [79–85]; conditions or variables of the indoor and outdoor environment (i.e., indoor and outdoor air temperature, relative humidity); the attitudes, beliefs, satisfaction [86–94] and socio-demographic aspects of the occupant population [42,95–103]; and actual building energy performance.

Best practices for occupant behavior monitoring and data collection are reported in a new guidebook on occupant behavior modeling [100]. The guidebook offers recommendations on developing an appropriate experimental design for this type of research, and includes comprehensive overviews of sensors for monitoring environmental and behavioral variables. Different types of experimental environments (in-situ, laboratories) are introduced, and their suitability for the respective research question is discussed. Data management, as well ethics and privacy issues are also addressed.

**2.1.2.2. Models.** In parallel, the behavior research community has developed and critically evaluated several behavior modeling approaches that would be useful to building designers [10,29,101–106]. Such reviews have focused on methods to assess the robustness and accuracy of proposed models, to establish the scope of their effective application. For example, one review we recently developed [107] surveyed occupant behavior modeling methods compared to traditional approaches. These innovative modeling approaches include Bernoulli models, agent-based models, and survival models applied to lighting, plug loads, and occupancy data. Methods were explored for modeling the diversity between occupants. The results strongly suggest that current approaches using synthetic occupant schedules (i.e., the ones suggested by ASHRAE Standard 90.1 [108]) for representing occupants in buildings significantly suppress the diversity of real occupant behaviors. One example is a poor representation of occupants' interaction with control systems such as lighting usage (Fig. 2) leading to unrealistic energy use predictions.

To achieve better predictions of building energy performance,

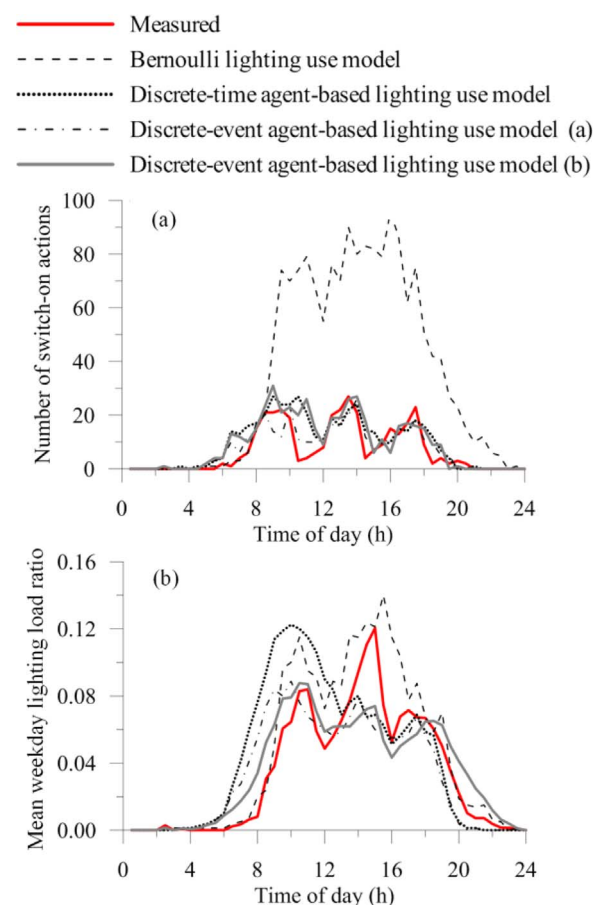
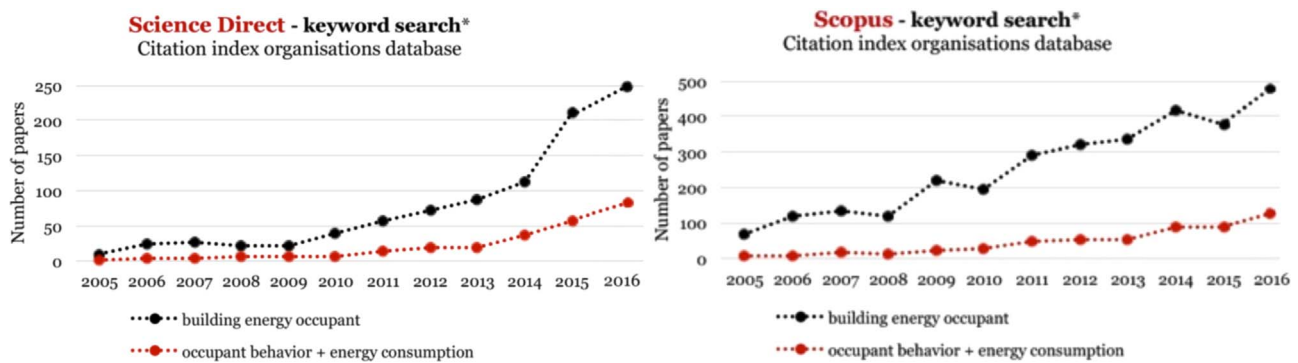


Fig. 2. Comparison of the lighting use models' predictions with observed lighting use [107].



**Fig. 3.** Screening of the Science Direct and Scopus databases, two of the leading citation index organizations to select papers published over the last decades (2005–2016) using the terms “building energy occupant” and “occupant behavior and energy consumption” in the title, abstract, and

models of human-building interaction have increasingly been integrated into building energy simulation algorithms. Such approaches typically rely on mathematical equations representing the relationship between specifically exercised energy-related behaviors (i.e., opening windows, drawing blinds and shades, operating artificial lights, using electrical equipment) and some physical variables of the indoor and outdoor environment, specific to a particular building setting [25,109,110]. Mathematical models are developed based on statistical analysis and data mining of monitored data, with the goal of predicting the probability that a specific behavioral action will occur under diverse environmental conditions [110].

The DNAS (Drivers-Needs-Actions-Systems) framework [50] is an example of the above approach; this framework hypothesizes that human behavior responds to stimuli (drivers of behavior) to accomplish personal needs, using correlations between behavioral drivers and actions to predict an occupant’s interactions with the control systems. Recent advances in engineering and social science research argue that such traditional stochastic behavior modeling approaches—even when refined to capture the diversity of behavior at the different level of granularity—are inaccurate due to their weak representation of the complex cognitive process that leads occupants to take environmentally adaptive actions [8].

**2.1.2.3. Tools.** A questionnaire survey was recently conducted among building designers and researchers on how well commonly used building simulation tools (EnergyPlus, DOE-2, DeST, ESP-r, TRNSYS, IDA-ICE, COMFIE, and DesignBuilder) can represent occupant behavior inputs and energy/environmental effects. Survey results demonstrate that while these programs vary in their approaches to modeling occupant behavior, most are limited to static and simplified behavior inputs and lack interoperability in model exchange or reuse [111]. To address these shortcomings in simulation tools going forward, several behavior modeling options are being integrated. For example:

- Occupancy Simulator: an agent-based model of occupant presence and movement in buildings [24,25].
- obXML: XML schema to represent various occupant behavior models. A library of 52 occupant behavior models was developed in obXML and released [49].
- obFMU: functional mockup unit of occupant behavior models [112]. obFMU enables co-simulation between occupant behavior models and BPS programs using the standard functional mockup interface. obFMU functions as a solver for occupant behavior models that are represented in obXML.
- Model predictive controls (MPC) have been developed combining building emulation model with occupant behavior models (via co-simulation or embedded Modelica code) that predict the likelihood and effect of occupancy and adaptive actions over time [60,113,114].

**2.1.2.4. Case studies.** Simulation-based case studies include quantification of occupants’ human dimensions impacts on building energy performance. These impacts include adaptive behaviors such as interaction with the building envelope (i.e., windows, shades, blinds) and control systems (i.e., thermostats set points, fans, radiator valves) and non-adaptive behaviors (presence, movement, and usage of electrical equipment such as plug loads) [104]. Different scenarios for the building operation and energy management can be simulated, too, by including diversity in lighting and occupancy schedules, set points, and regulation for the HVAC systems for heating, cooling, and ventilation purposes [115]. Such simulated cases support a wide array of stakeholders [4] in improving the robustness of building energy design to realistic occupant behavior [116,117].

## 2.2. The human dimensions of building usage: occupants

A recent study by Hong, et al. [4] framed two main spheres of influence of occupant behavior on building performance (energy use and comfort) including (1) adaptive actions, and (2) non-adaptive actions. When performing energy-related “adaptive behaviors,” occupants engage in actions to adapt the indoor environment to their needs or preferences, such as opening/closing windows, lowering blinds, adjusting thermostats, turning lighting on/off, and using plug-ins (such as personal heaters, fans, and electrical systems for space heating/cooling). Occupants can also adapt themselves to their environment by adjusting clothing levels. Non-adaptive actions include occupant presence and operation of plug-ins and electrical equipment (such as office and home appliances), as well as building occupancy and movement through spaces. Such human-building interactions represent quantitative variables that influence overall building energy use [109]. Over the last decade, the number of scientific articles studying the impact of occupant behavior (adaptive and non-adaptive [4]) on building energy use has dramatically increased (Fig. 3), indicating a growing research interest in human-centered building energy efficiency.

### 2.2.1. Stakeholder needs

Occupants require comfortable and healthy spaces to live and work in as they spend more than 90% of their time, on average, indoors [118]. The energy use attributable to this requirement is substantial: over the last ten years, an average of 40% of the energy use worldwide was consumed to service healthy and comfortable indoor environments for residential and commercial building occupants [119].

Occupants also need to understand the design and operation of building systems such that they may adapt and provide feedback to achieve personal comfort while minimizing energy use. The latter goal is more challenging than the former because while humans directly



perceive comfort conditions, associated energy use outcomes are harder to anticipate [120]. As an example, if a change in the indoor or outdoor environmental parameters occurs (i.e., the variation of the indoor and outdoor temperature, illuminance level, noise, or bad odors), it is plausible that occupants might perceive a situation of discomfort (thermal, visual, acoustic, air quality). Naturally, occupants tend to react to bring about (or restore) a desired comfort condition [51]. The main consequence of these needs is that occupants interact (if feasible) with the control systems of the buildings (i.e., adjusting the thermostats, opening or closing windows, operating shades and blinds, switching or dimming lights, etc.). These adaptive behaviors affect building energy use and must be regulated by providing different stakeholders with informative data, models, technologies, and tools [49]. Providing occupants with smarter controls (real or perceptual), human-in-the-loop technologies, and behavioral programs for feedback through active engagement with building operators and control systems has been shown to allow more flexibility in providing comfort, leading to reduced operating energy expenditure and costs, both in residential [121] and commercial buildings [122].

### 2.2.2. Supporting research advancements

Existing literature highlights residential building occupancy patterns as a key driver of building performance worldwide [30,36,42]. Similarly, simulation studies have shown that office workers who are proactive in saving energy (dimming lights, turning on HVAC systems only when needed, turning off plug loads and equipment when not needed) consume up to 50% less than occupants who do not [11]. Innovative research agendas, both in experimental [14] and field settings [27,123–125], aim to explore and highlight occupant behavior as a fundamental influence on building energy use—an influence that can maximize energy efficiency to the same extent that technological innovation can. This is achieved by combining research and experimental activities for the development and deployment of human comfort-adaptive mechanisms in indoor environments, data-driven analysis, occupancy drive model predictive controls (MPC) for the energy management and control systems (EMCS), modeling and simulation of occupant behavior in buildings, and building physics expertise [126] with social science insights to provide an interdisciplinary, innovative vision on human-centered energy efficiency in buildings [91,127–130]. Research advancements in the building efficiency sector have been fostered around the development of human-in-the-loop (HIL) interaction technologies [131–133]. The notion of HIL as technology innovation enables occupants to become both passive sensors and active controllers of the IEQ. Occupant receiving feedbacks on comfort levels and energy intensity in indoor spaces will perform actions that are more “informed” and aware. The human dimensions refer to the occupant presence, movement in and within the indoor spaces and to the occupant interaction with the building control system. The observation of this “human” system is attained via occupancy and motion sensors, for instance, by monitoring the building occupancy or the occupants’ interaction with the building envelope components, such as windows, shades, and blinds state [134].

### 2.3. The human dimensions of building operation: building operators and energy managers

Building operators and managers have the challenging task of operating buildings efficiently while meeting occupant comfort needs that are diverse, dynamic, and stochastic in nature.

As confirmed by recent meta-analysis review [122], the energy-saving leverage of building’s operators and energy managers varies by building type, size, and vintage. Office spaces entail the greatest energy-saving potential among commercial building types, followed by educational and retail buildings. Lighting is confirmed as the greatest end-use-source of energy saving potential, followed by space heating (especially in cold climates). Regarding building vintage, operational-

driven energy savings opportunities emerge as proportionally greater in small offices (26–27%) than big offices (10–11%). This is true both for lighting (23–10%) and HVAC (15–5%) end uses.

#### 2.3.1. Stakeholder needs

Building operators and energy managers need knowledge and tools to guide them in achieving win-win solutions that maximize occupant comfort with low energy use. These tools allow them to manage, optimize, and predict the variables that contribute to an efficient building’s conditioning and energy usage [61].

#### 2.3.2. Supporting research advancements

Several studies attempt to support building operators and energy managers’ efforts to bridge the divide between technical and achievable behavior-based energy savings in commercial buildings. For example, researchers developed a comprehensive framework to quantify energy savings potential from electricity and natural gas for improving the operational phase of commercial buildings [135]. Building simulation programs were employed in tandem with benchmark data to support building operators to simulate the improvements in occupant behaviors (thermostat set points, equipment, and lighting system usage) on diverse operating end uses. Through extensive analysis of primary energy metering data, a related study [136] determined the energy-saving potential of different types operators’ interventions—including turning off lights, defining thermostat setpoints and lighting settings, and maintenance and energy visualization strategies.

Tools that support building operator decision making processes by guiding them towards optimal operational actions (lighting, cooling, ventilation, refrigeration and office equipment end uses [135,137]) hold an energy savings potential averaging 12–18%. Innovative building EMCS and technologies are now available to support smart building automation and operation [59,138]. Based on machine learning processes, indoor and outdoor environmental parameters, as well as occupant presence, comfort, and action data are labeled, memorized, and re-employed to improve algorithms ruling the control system of the building automation system (BAS) [61,114].

Improvements in BAS and EMCS gravitate around the concepts of bringing the human-in-the-loop (HIL) for sensing and control of buildings over the entire building life cycle. The notion of HIL emerges from the cyber-physical area [39–42], as an application that integrates real-time human feedback with the management of complex systems for control optimization purposes. A variety of existing HIL applications in the energy sector can be classified based on the level of integration of human control over system functioning—as active, passive, or hybrid active-passive sensing and control systems. In such advanced HIL processes, two-way communication occupancy-based MPCs [60,113,139] have been demonstrated to be capable of supporting building operators and energy managers in achieving two-way comfort and energy cost optimization goals. With such tools, building operators can correct undesired control logic on the fly in accordance with occupant feedback and requests—minimizing building energy consumption and waste while maximizing occupant comfort.

### 2.4. The human dimensions of building technologies: manufacturers and vendors

The paramount role of building occupants in achieving high performing buildings that save energy and provide comfort has been documented by diverse market actors. For example, Google has invested in the development of smart home thermostats [140], and energy utility companies now offer human-centered products like smart metering systems [92] and energy use feedback services such as the OPower enhanced energy bill [121,141,142] and System as a Service (SaaS) [143]. In commercial buildings, a broad range of human-building interaction technologies are now available on the market (e.g., Comfy, CrowdComfort, BuildingIQ, Metasys), which

enable advanced HIL building management and automation services. Buildings installing such HIL sensing and control technologies have demonstrated improved operation and management outcomes, achieving savings in the range of 4–22% of annual energy operating costs in commercial buildings [4,131,132,134].

#### 2.4.1. Stakeholder needs

Building technology manufacturers and vendors require a better understanding of how occupants actually use their products. This understanding would allow them to develop technologies that are more attractive to end users and more effective from an operational standpoint. Behavioral science research, including customer research, user-centric design, and behavioral analytics can support HIL technology manufacturers and vendors in devising and conducting product usability and performance tests. Such practices enable these stakeholders to understand users' acceptance of technologies and observe the actual human-building interaction, yielding improved certainty to product performance claims [50,144]. Indeed, uncertainty about product operating cost benefits is one of the adoption barriers facing manufacturers and vendors [66,92,145,146].

Manufacturers and vendors also require data-driven methods for quantifying the non-energy benefits of technologies that relate to human-building interactions. Such non-energy benefits may be a more influential adoption driver than energy cost savings benefits [12,55,147]. Indeed, non-energy benefits can include the increased productivity of employees, which generally represents a much higher percentage of overall organizational expenditures than do energy costs [148].

#### 2.4.2. Supporting research advancements

Recent developments in building sensing technology and control strategies leverage Internet of Things (IoT) data on the human-building interaction, which is projected to grow to more than 29 billion devices in "cognitive" buildings by 2020 [149]. A state-of-the-art review and recommendations for future research in building energy metering and environmental monitoring have been provided by Ahmad, et al. [150]. In 2016, the building efficiency market was the largest advanced energy market segment in the United States, with \$ 2.3 billion in home energy management sector revenue and 1300% growth since 2011 [151]. The fast pace of research and development investments in technologies that leverage such data-rich environments [132], such as home energy monitoring systems [143,152], smart meters [140], and personalized environmental controls [7], indicates the growth of the building efficiency market towards human-driven technology innovations. Despite this growth and the reported potential of such technologies to achieve up to 30% energy consumption reduction [122], the market penetration of these technologies is still low relative to other new building efficiency technologies [53]. Barriers to the adoption of human-centered building technologies include concerns about reliability, the inability to guarantee energy performance, and uncertainty about the replicability of observed technology impacts. Moreover, successful market penetration cannot be achieved by technology advancement alone [50]. Understanding and overcoming occupant concerns regarding comfort, data privacy issues, and preferences and needs will most likely facilitate consumer adoption and exploit the full potential of innovative human-centered building technologies [53].

Another challenge is how to bring occupants' comfort, preference, and needs together with the technical aspect of building automation and control into a comprehensive and scientifically accepted modeling framework of human-building interaction. This achievement depends upon understanding the link between energy use and human factors of behavior and operations. Accordingly, innovative research aims to discern contextual motivational factors affecting, driving, and influencing energy-related behaviors. By understanding the sphere of those motivational factors, research and development in the industry sector are assuming the capability of developing models to explain, predict,

and replicate the decision-making process that leads humans to interact with the indoor environment having comparable endogenous and exogenous characteristics [121,141]. A considerable amount of MPC, behavioral models, modeling approaches, and behavioral campaigns have been developed, tested, evaluated, and critically reviewed over the last 30 years [18,19,64,65].

What emerges from this multi-disciplinary picture is that any ad-hoc rule or technical solution resolving the connection between energy use and the human dimensions must be prioritized. Significant outcomes of ongoing research armed by an international industry perspective on the development of occupancy-based MPC for the optimization of building energy performance (energy, comfort at costs) demonstrate the connection with the vendor and manufacturer needs [153]. This is the case of building automation companies testing the efficacy of innovative HIL products—such as the Comfy app from Building Robotic [61]—making use of machine learning software and active human feedback for personalized comfort in the workplace. Energy savings in the range of 22% are obtained through the expansion of heating and cooling deadbands in occupied and unoccupied zones and the dynamic scheduling of HVAC [154].

#### 2.5. The human dimensions of building services: energy utilities and demand response program developers

Integrating building operating patterns with demand response logics that seek to balance energy loads and reduce the peak power demand in buildings is a current matter of research for energy utilities and program developers [64,155–157]. One of the key challenges is the spread and market adoption of demand-side energy management technologies, bridging the research know-how with the deployment of real-time optimization of DR intelligent building automation systems. Energy consumption in the residential and commercial building sectors can be reduced by providing building operators, managers, and energy utilities with tailored information about consumers' energy-using practices. Unlocking knowledge of the human dimensions of building service is hence twofold. Firstly, building users can reduce peak power demand in buildings by profiting from energy visualization and conservation incentives from their utility company. Second, utility operators can more efficiently manage building energy loads from the zone to the aggregated city level by implementing more effective demand response logic given improved anticipation of demand-side operational patterns.

##### 2.5.1. Stakeholder needs

Human centered DR activities and programs need to be active elements in the energy utility policy decisions process, as tools designed to create more reliable and more sustainable building energy systems [53]. The mission of these programs is to deliver knowledge and tools for utilities to leverage in implementing human-centered policies and measures.

A program that better anticipates the human dimensions of buildings may improve the robustness of energy systems to fluctuate during energy consumption loads, ensuring a more stable energy performance over time in the face of rapid energy market transformations [64,155–159]. Meeting energy users' satisfaction while ensuring energy grid efficiency is one of the most important business goals to energy utilities worldwide; it requires balanced energy loads on the national grid, which is much more important than an increase of revenues from energy bills [160]. However, utilities' capability and expertise to involve the human dimensions of energy use and demand response services are still low [53]. This capability gap impedes utilities at large to deliver behavioral-based effective solutions.

##### 2.5.2. Supporting research advancements

Utilities and DR program developers increasingly rely on data-driven analytics to extrapolate knowledge on patterns of consumption

and provide customized information on the demand (energy users) and production (energy grid) sides [143].

As part of the mission to improve customer satisfaction, many energy utilities worldwide have developed programs engaging occupants to reduce their energy bill cost [160–163]. Through enhanced energy reporting that leverages social norms such as peer comparison [88,164,165], programs have demonstrated achievable energy savings of 2–3% in the residential sector [141], at zero costs in terms of technology investments in energy efficiency measures.

Research findings have helped identify particular utility programs and strategies that yield the most consistently successful results. Examples of such strategies include increased energy savings by coupling customer segmentation (i.e., via cluster analysis and group targets) with social theories (i.e., theories of planned behavior) and practices (i.e., randomized control trials, user experience, surveys questionnaire, etc.) to better understand how to address subjective norms, habits, beliefs, and needs towards energy use behaviors in homes [92,94,99,166,167]. Other examples leverage social dynamics, norms, and group behaviors in office spaces [12,91,168]. Literature in both energy and social science fields [169–171] has documented a wide array of data-analytic driven behavioral based strategies to bridge the divide between potential and achievable energy savings in the residential and commercial energy sectors [67,168,172–175], such as social norms [88,91,176], competition [157], incentives [168,169,177], benchmarks [26,139,178] and energy simulations.

## 2.6. The human dimensions of building regulations: policy makers and government agencies

Policy makers and governmental agencies address occupants' and O & M energy savings impacts through codes and standards regulations and the development of energy efficiency incentives. Behavioral-based energy efficiency programs and benchmarks are also considered in the policy arena as means for achieving certain stock-wide energy mitigation targets in the buildings sector [179,180]. Here, the ability to target the behavior of individual users in achieving energy efficiency goals holds significant potential, but there are opportunities to develop energy policy on broader scales as well.

### 2.6.1. Stakeholder needs

In developing behavioral-based regulations and incentive designs, policymakers need a consistent way to frame human-centered energy efficiency measures and their limits, which often stem from basic comfort needs and expectations. To frame human-centered measures relative to building efficiency technologies, Langevin, et al. [181] discussed some key correlated challenges. A conclusion is that policy makers need a better understanding of the human dimensions of building energy use to be able to provide more compound regulations for the human-sensitive stream of data, as well as to establish a common framework for describing potential and outcomes of HIL technologies. Two types of needs relating to human dimensions present themselves for energy policymakers and governmental agencies. First, actions such as business strategies, awareness campaigns, and technology investments in renewable energy sources must be encouraged to raise energy-conscious behaviors at the building level and to help meet climate change mitigation goals at the urban level [182]. Second, efforts must be put in place to translate actions into regulatory norms for a global behavioral energy mitigation agreement. Policy regulations or incentive designs need to consider the limits for how much energy can be saved through human-centered measures, where these limits stem from basic comfort needs and expectations, as well the diversity of behaviors based on cultural, contextual, and personal factors [164,183–185].

### 2.6.2. Supporting advancements in research

Energy policies and programs that leverage knowledge from build-

ing science and consider behavioral science resolutions when setting behavioral-based energy efficiency goals have yielded improvements in program cost-effectiveness and the development of more robust energy conservation strategies [186]. Energy efficiency measures often deviate from their designed implementation, again oversimplifying the representation of human actions when referring to the human dimensions of building energy use. This has led to suboptimal policies in the past, such as in the achievement of high-performing and sustainably certified buildings (i.e., through the LEED protocol) [36,125]. To meet 2020 and 2050 energy paradigm reduction targets worldwide, as set by the Paris Agreement, this review foresees the need to foster dedicated behavioral-based policies in the building sector as well as more traditional building energy performance directives and financial incentives for adopting renewable energy production and technology.

Similarly, existing energy audit protocols (such as the ASHRAE Commercial Building Energy Audits procedure) and BSP are increasingly including these human dimensions for supporting building owners' capabilities to demonstrate with code compliance. Behavioral audits [177] may contribute to, for example, a building owner's ability to achieve operational energy savings (and hence meet building code compliance) while considering the aleatory nature of some human dimensions influencing building operating phases. In this view, there is a strong need for advances in building auditing tools able to observe, measure, analyze, and evaluate the effects of design practices, behaviors, and operation strategies on global building performance (occupant comfort and energy consumption). On the other hand, dynamic occupant behavior models have been adopted for simulation-aided design through BPS tools to understand the influence of assumptions about occupancy and occupants' interactions with building components and equipment on building energy use and comfort predictions [187].

Practices as such have the twofold intention to support policy makers and government agencies towards the understanding of how these human dimensions must be regulated and how they can provide information to building occupants and operators and managers leading to more efficient energy usage.

## 3. Discussion

Given how broadly the human dimensions of building design and operation may be defined, it is critical that key stakeholders – e.g., researchers, designers, engineers, operators, occupants, utilities, technology vendors and policy makers – are educated on the relevance of human dimensions to their particular perspective [92,188–190]; such education ensures that an understanding of human dimensions becomes integral to the workflow of each stakeholder and achieves large-scale impacts on building energy use, occupant comfort, and associated outcomes like energy, health, and productivity costs.

Stakeholder education on human dimensions may be delivered in various ways, for example: design guidelines that encourage the robustness of building energy use to occupant/operator behavior; qualitative and quantitative projections of building technology adoption and acceptance for policy makers and technology vendors; design-stage behavior simulation methodologies for engineers and architects; and improved tools for managing and optimizing building operations in the face of adaptive human behavior [191].

Such educational approaches must draw from lessons learned outside the buildings sector (e.g., the importance of energy manager education to large-scale renewable energy transition [192]) and require a multi-disciplinary focus [193] that emphasizes the limitations of technology investments alone in achieving low-carbon, passive, high performance buildings. The successful implementation of these approaches will help avoid design misconceptions (the gap between predicted and measured energy performance), operational failures (the gap between assumed and observed usage of building technologies), and HVAC system oversizing or the installation of superfluous energy services (the gap between expected and recorded energy costs).

### 3.1. Main challenges of human dimensions research

There is a growing effort to advance an integrative research agenda that investigates the human and building energy interaction [194]. Some interesting insights into the understanding of energy-related behaviors have recently been yielded by state-of-the-art research, typically examining human dimensions through the multi and interdisciplinary lenses of building science, behavioral science, social science, data science, psychology, user experience design, building automation, and control design. As human behavior is complex, this research leaves some unresolved questions which must be addressed by a multi-faceted investigation of the broad range of perspectives from building stakeholders that contribute to or are affected by the human dimensions of energy use.

Given the need for a multi-disciplinary effort on this topic, this paper has highlighted the human dimensions of building energy use from these key stakeholder perspectives, which relate to all stages of the building life cycle. In this work, we discussed how to pro-actively address the many challenges that such interdisciplinary research faces. By providing a holistic overview of human dimensions research relevant to key stakeholders in the building life cycle, this work tries to move beyond a siloed approach and towards the establishment of a broad set of research needs and opportunities for this topic.

### 3.2. Potential benefits of human dimensions research

This study aims to set the stage for human factors in buildings as a driving source of innovation for energy efficiency in the built environment that contributes to achieving 2020 net-zero-energy buildings and 2050 post carbon goals set by the Paris Agreement [195]. Specifically, it leverages the potential of significant energy conservation opportunities from integrating interdisciplinary knowledge on human dimensions in building design, control, operation, management, service, and regulation.

Outcomes of literature reviews, data analysis, guidelines, energy modeling and simulation tools and scenarios including quantification of human-driven energy impacts aim to (1) support building energy designers, modelers, operators/managers, vendors, and policy makers in pursuing energy conservation measures, (2) evaluate technology performance by taking into account human factors influencing energy demand and consumption, (3) support energy and urban planners in the creation of human-centered energy policies, programs, codes and standards, and (4) develop robust energy planning tools targeting behavioral-based energy efficiency in buildings.

Specific benefits of improved understanding of human dimensions impacts on energy use include: more accurate building performance simulations, which will bridge the gap between predicted and measured building energy use intensity and comfort [36]; operating cost reductions for building owners and managers through optimized building automation systems that provide enhanced comfort conditions for building occupants; increased market uptake of human-building interaction products enabled by product design that responds to real user needs and preferences; and more effective utility demand-response program designs that are tuned to realistic dynamics in demand-side operational patterns.

## 4. Conclusions

This study aimed to highlight the human dimension as a fundamental aspect of building energy use, equal in weight to technological innovations. Given the stochastic nature of human behavior [196], the human dimension of buildings cannot be addressed in the same manner as purely technology-driven building energy efficiency measures. Moreover, a motto suggested by our review is that “technology alone does not guarantee low energy use in buildings” [50].

Acknowledging that the human dimensions of building energy use

cannot be fully examined through the lens of a particular building stakeholder, this outlook provided an overview of human dimensions research needs and opportunities across a variety of stakeholder perspectives relating to the entire building life cycle, including: building designers, occupants, operators and energy managers, technology industry and vendors, energy utilities and demand response program developers, and policy makers and government agencies. A summary of findings is included below.

During the *design stage*, architects and engineers need to fully consider how the interaction of building occupants and operators with the building technologies and its energy systems will impact the final energy use and indoor environmental quality outcomes. Accordingly, building designers need data, models, tools, and case studies able to provide an evidence-based understanding of the human dimensions of energy use. Reviewed advancements in design practices aim to establish methodologies to support the better prediction of energy use and occupant comfort and achievement of building performance targets that focus on these outcomes.

During the *operational phase* of buildings, *occupants* require comfortable and healthy spaces to live and work in. Occupants also need to understand the design and operation of building systems such that they may adapt and provide feedback to achieve optimized personal comfort conditions while minimizing energy use. The latest advances in engineering research argue that interdisciplinary adoption of theories from the social science and psychology disciplines have unlocked new knowledge to meet deeper understanding of the occupant behavior human dimensions in building energy use.

During the *construction and regulation phases* of the building life cycle, the effectiveness of such innovative technologies relies on the building technology manufacturers' and vendors' understanding of how occupants actually use their products. More data-driven research on the human-building interaction processes, including behavioral and energy data analytics, customer research, user-centric design, and behavioral analytics, as well as the economic value of non-energy benefits of including human dimensions in technologies for energy efficiency in buildings, is predicted as the accelerator for the advancement of technologies that are more attractive to end users and effective from an energy, comfort, and economical operational standpoint.

*Utilities and demand response program developers* increasingly rely on data-driven analytics to extrapolate knowledge on the human dimensions of energy use and provide customized information on the demand and production sides. An improved understanding of the human dimensions of building energy use to increase demand and production-side customer satisfaction and the effectiveness of demand response programs emerges.

A better understanding of the means of the human dimensions of building energy use is needed up to the *building regulation stage*, where policy makers need to provide regulations for the human-sensitive stream of data. Revised advances in research mainly focus on the limits on how much energy can be saved in the building sector through human-centered measures, where these limits stem from basic human comfort needs and expectations, as well as an understanding of technological limits, technology adoption, and market penetration based on socio-demographic variables of the targeted population.

Going forward, efforts to strengthen the inter-disciplinary focus on human dimensions of energy use will be supported by research groups like IEA EBC Annex 66 [191] for the understanding of occupant behavior through a definition and simulation framework and tools, Annex 70 [195] for the policy perspective, IEA Task 24 [53] for the demand response and utility and behavioral programs support, as well as by industry-focused communities such as ASHRAE Multidisciplinary Task Group on Occupant Behavior in Buildings.

## Acknowledgments

This work was supported by the Assistant Secretary for Energy



Efficiency and Renewable Energy of the United States Department of Energy under Contract No. DE-AC02-05CH11231. This work is part of the research activities of the International Energy Agency's Energy in Buildings and Communities Program Annex 66, Definition and Simulation of Occupant Behavior in Buildings.

## References

- [1] IEA . World Energy Outlook 2015. <http://dx.doi.org/10.1787/weo-2005-en>.
- [2] Omer AM. Renewable building energy systems and passive human comfort solutions. *Renew Sustain Energy Rev* 2008;12:1562–87. <http://dx.doi.org/10.1016/j.rser.2006.07.010>.
- [3] Shi L, Chew MYL. A review on sustainable design of renewable energy systems. *Renew Sustain Energy Rev* 2012;16:192–207. <http://dx.doi.org/10.1016/j.rser.2011.07.147>.
- [4] Hong T, Yan D, D'Oca S, Chen C. Ten questions concerning occupant behavior in buildings: the big picture. *Build Environ* 2016;1–13. <http://dx.doi.org/10.1016/j.buildenv.2016.12.006>.
- [5] Zhao HX, Magoules F. A review on the prediction of building energy consumption. *Renew Sustain Energy Rev* 2012;16:3586–92. <http://dx.doi.org/10.1016/j.rser.2012.02.049>.
- [6] Jia M, Srinivasan RS, Raheem AA. From occupancy to occupant behavior: an analytical survey of data acquisition technologies, modeling methodologies and simulation coupling mechanisms for building energy efficiency. *Renew Sustain Energy Rev* 2017;68:525–40. <http://dx.doi.org/10.1016/j.rser.2016.10.011>.
- [7] Vesely M, Zeiler W. Personalized conditioning and its impact on thermal comfort and energy performance – a review. *Renew Sustain Energy Rev* 2014;34:401–8. <http://dx.doi.org/10.1016/j.rser.2014.03.024>.
- [8] Hong T, Taylor-Lange SC, D'Oca S, Yan D, Corgnati SP. Advances in research and applications of energy-related occupant behavior in buildings. *Energy Build* 2015. <http://dx.doi.org/10.1016/j.enbuild.2015.11.052>.
- [9] O'Brien W, Gunay HB. The contextual factors contributing to occupants' adaptive comfort behaviors in offices – a review and proposed modeling framework. *Build Environ* 2014;77.
- [10] Sun K, Yan D, Hong T, Guo S. Stochastic modeling of overtime occupancy and its application in building energy simulation and calibration. *Build Environ* 2014;79:1–12. <http://dx.doi.org/10.1016/j.buildenv.2014.04.030>.
- [11] Lin HW, Hong T. On variations of space-heating energy use in office buildings. *Appl Energy* 2013;111:515–28. <http://dx.doi.org/10.1016/j.apenergy.2013.05.040>.
- [12] Feige A, Wallbaum H, Janser M, Windlinger L. Impact of sustainable office buildings on occupant's comfort and productivity. *J Corp Real Estate* 2013;15:7–34. <http://dx.doi.org/10.1108/JCRE-01-2013-0004>.
- [13] Schakib-Ekbatan K, Kakici FZ, Schweiker M, Wagner A. Does the occupant behavior match the energy concept of the building? – analysis of a German naturally ventilated office building. *Build Environ* 2015;84:142–50. <http://dx.doi.org/10.1016/j.buildenv.2014.10.018>.
- [14] Schweiker M, Wagner A. The effect of occupancy on perceived control, neutral temperature, and behavioral patterns. *Energy Build* 2015. <http://dx.doi.org/10.1016/j.enbuild.2015.10.051>.
- [15] Indraganti M, Rao KD. Effect of age, gender, economic group and tenure on thermal comfort: a field study in residential buildings in hot and dry climate with seasonal variations. *Energy Build* 2010;42:273–81. <http://dx.doi.org/10.1016/j.enbuild.2009.09.003>.
- [16] Parsons KC. The effects of gender, acclimation state, the opportunity to adjust clothing and physical disability on requirements for thermal comfort. *Energy Build* 2002;34:593–9. [http://dx.doi.org/10.1016/S0378-7788\(02\)00009-9](http://dx.doi.org/10.1016/S0378-7788(02)00009-9).
- [17] Karjalainen S. Gender differences in thermal comfort and use of thermostats in everyday thermal environments. *Build Environ* 2007;42:1594–603. <http://dx.doi.org/10.1016/j.buildenv.2006.01.009>.
- [18] De Carli M, Olesen BW, Zarrella A, Zecchin R. People's clothing behaviour according to external weather and indoor environment. *Build Environ* 2007;42:3965–73. <http://dx.doi.org/10.1016/j.buildenv.2006.06.038>.
- [19] Langevin J, Wen J, Gurian P. Including occupants in building performance simulation: integration of an agent-based occupant behavior algorithm with Energyplus. *Build Simul Conf Atlanta GA* 2014:417–24. <http://dx.doi.org/10.13140/2.1.2551.4244>.
- [20] Bordass B, Cohen R, Field J. Energy performance of non-domestic buildings: closing the credibility gap. *Build Perform Congr*.
- [21] Wang C, Yan D, Sun H, Jiang Y. A generalized probabilistic formula relating occupant behavior to environmental conditions. *Build Environ* 2016;95:53–62. <http://dx.doi.org/10.1016/j.buildenv.2015.09.004>.
- [22] Robinson D, Haldi F. Modelling Occupants' Presence and Behaviour – Part I. *J Build Perform Simul* 2011;4:301–2. <http://dx.doi.org/10.1080/19401493.2011.599157>.
- [23] Haldi F, Robinson D. On the behaviour and adaptation of office occupants. *Build Environ* 2008;43:2163–77. <http://dx.doi.org/10.1016/j.buildenv.2008.01.003>.
- [24] Wang C, Yan D, Jiang Y. A novel approach for building occupancy simulation. *Build Simul* 2011;4:149–67. <http://dx.doi.org/10.1007/s12273-011-0044-5>.
- [25] Feng X, Yan D, Hong T. Simulation of occupancy in buildings. *Energy Build* 2015;87:348–59. <http://dx.doi.org/10.1016/j.enbuild.2014.11.067>.
- [26] Masoso OT, Grobler LJ. The dark side of occupants' behaviour on building energy use. *Energy Build* 2010;42:173–7. <http://dx.doi.org/10.1016/j.enbuild.2009.08.009>.
- [27] González MC, Hidalgo CA, Barabási A-L. Understanding individual human mobility patterns. *Nature* 2008;453:779–82. <http://dx.doi.org/10.1038/nature07850>.
- [28] Haldi F, Robinson D. The impact of occupants' behaviour on building energy demand. *J Build Perform Simul* 2011;4:323–38. <http://dx.doi.org/10.1080/19401493.2011.558213>.
- [29] Gunay HB, O'Brien W, Beausoleil-Morrison I. A critical review of observation studies, modeling, and simulation of adaptive occupant behaviors in offices. *Build Environ* 2013;70:31–47. <http://dx.doi.org/10.1016/j.buildenv.2013.07.020>.
- [30] Andersen RV, Toftum J, Andersen KK, Olesen BW. Survey of occupant behaviour and control of indoor environment in Danish dwellings. *Energy Build* 2009;41:11–6. <http://dx.doi.org/10.1016/j.enbuild.2008.07.004>.
- [31] Andersen R, Fabi V, Toftum J, Corgnati SP, Olesen BW. Window opening behaviour modelled from measurements in Danish dwellings. *Build Environ* 2013;69:101–13. <http://dx.doi.org/10.1016/j.buildenv.2013.07.005>.
- [32] Fabi V, Andersen RK, Corgnati S. Verification of stochastic behavioural models of occupants' interactions with windows in residential buildings. *Build Environ* 2015;94:371–83. <http://dx.doi.org/10.1016/j.buildenv.2015.08.016>.
- [33] Steemers K, Manchanda S. Energy efficient design and occupant well-being: case studies in the UK and India. *Build Environ* 2010;45:270–8. <http://dx.doi.org/10.1016/j.buildenv.2009.08.025>.
- [34] Majcen D, Itard L, Visscher H. Actual and theoretical gas consumption in Dutch dwellings: what causes the differences? *Energy Policy* 2013;61:460–71. <http://dx.doi.org/10.1016/j.enpol.2013.06.018>.
- [35] J.S. Wehl. Monitored residential ventilation behavior: a seasonal analysis. *Proc from ACEEE 1986, Summer Study Energy Efficiency in Buildings*.
- [36] Turner C, Frankel M. Energy performance of LEED® for new Construction buildings. *New Build Inst* 2008:1–46.
- [37] Parker D, Mills E, Rainer L. Accuracy of the home energy Saver energy calculation methodology. *ACEEE Summer Study Energy Effic Build* 2012;1996:206–22.
- [38] Howard-Reed C, Wallace LA, Ott WR. The effect of opening windows on air change rates in two homes. *J Air Waste Manag Assoc* 2002;52:147–59. <http://dx.doi.org/10.1080/10473289.2002.10470775>.
- [39] Nakaya T, Matsubara N, Kurazumi Y. Use of occupant behaviour to control the indoor climate in Japanese residences. *Air Cond Low* 2008:27–9.
- [40] Schweiker M, Shukuya M. Comparison of theoretical and statistical models of air-conditioning-unit usage behaviour in a residential setting under Japanese climatic conditions. *Build Environ* 2009;44:2137–49. <http://dx.doi.org/10.1016/j.buildenv.2009.03.004>.
- [41] Schweiker M, Haldi F, Shukuya M, Robinson D. Verification of stochastic models of window opening behaviour for residential buildings. *J Build Perform Simul* 2012;5:55–74. <http://dx.doi.org/10.1080/19401493.2011.567422>.
- [42] Fu C, Wang W, Tang J. Exploring the sensitivity of residential energy consumption in China: implications from a micro-demographic analysis. *Energy Res Soc Sci* 2014;2:1–11. <http://dx.doi.org/10.1016/j.erss.2014.04.010>.
- [43] Jian Y, Li Y, Wei S, Zhang Y, Bai Z. A Case Study on Household Electricity Uses and Their Variations Due to Occupant Behavior in Chinese Apartments in Beijing 2015:679–86.
- [44] Hetherington J, Roetzel A, Fuller R. The impact of occupant behaviour on residential greenhouse gas emissions reduction n.d.;12:127–140.
- [45] Roetzel A, Tsangrassoulis A, Dietrich U, Busching S. A review of occupant control on natural ventilation. *Renew Sustain Energy Rev* 2010;14:1001–13. <http://dx.doi.org/10.1016/j.rser.2009.11.005>.
- [46] Roetzel A, Tsangrassoulis A, Dietrich U. Impact of building design and occupancy on office comfort and energy performance in different climates. *Build Environ* 2014;71:165–75. <http://dx.doi.org/10.1016/j.buildenv.2013.10.001>.
- [47] Peffer T, Pritoni M, Meier A, Aragon C, Perry D. How people use thermostats in homes: a review. *Build Environ* 2011;46:2529–41. <http://dx.doi.org/10.1016/j.buildenv.2011.06.002>.
- [48] Fabi V, Andersen RV, Corgnati S, Olesen BW. Occupants' window opening behaviour: a literature review of factors influencing occupant behaviour and models. *Build Environ* 2012;58:188–98. <http://dx.doi.org/10.1016/j.buildenv.2012.07.009>.
- [49] Hong T, D'Oca S, Taylor-Lange SC, Turner WJN, Chen Y, Corgnati SP. An ontology to represent energy-related occupant behavior in buildings. Part II: Implementation of the DNAS framework using an XML Schema. *Build Environ* 2015;94:196–205. <http://dx.doi.org/10.1016/j.buildenv.2015.08.006>.
- [50] Hong T, D'Oca S, Turner WJN, Taylor-Lange SC. An ontology to represent energy-related occupant behavior in buildings. Part I: Introduction to the DNAs framework. *Build Environ* 2015;92:764–77. <http://dx.doi.org/10.1016/j.buil-denv.2015.02.019>.
- [51] Zuo J, Zhao Z-Y. Green building research—current status and future agenda: a review. *Renew Sustain Energy Rev* 2014;30:271–81. <http://dx.doi.org/10.1016/j.rser.2013.10.021>.
- [52] Ruparathna R, Hewage K, Sadiq R. Improving the energy efficiency of the existing building stock: a critical review of commercial and institutional buildings. *Renew Sustain Energy Rev* 2016;53:1032–45. <http://dx.doi.org/10.1016/j.rser.2015.09.084>.
- [53] Rotmann S. IEA Task 24 Annual-Report-2015; 2015.
- [54] Roetzel A, Tsangrassoulis A, Dietrich U, Busching S. A review of occupant control on natural ventilation. *Renew Sustain Energy Rev* 2010;14:1001–13. <http://dx.doi.org/10.1016/j.rser.2009.11.005>.
- [55] Chenari B, Dias Carrilho J, Gameiro da Silva M. Towards sustainable, energy-efficient and healthy ventilation strategies in buildings: a review. *Renew Sustain Energy Rev* 2016;59:1426–47. <http://dx.doi.org/10.1016/j.rser.2016.01.074>.

- [56] Daghigh R. Assessing the thermal comfort and ventilation in Malaysia and the surrounding regions. *Renew Sustain Energy Rev* 2015;48:681–91. <http://dx.doi.org/10.1016/j.rser.2015.04.017>.
- [57] Konstantoglou M, Tsangrassoulis A. Dynamic operation of daylighting and shading systems: a literature review. *Renew Sustain Energy Rev* 2016;60:268–83. <http://dx.doi.org/10.1016/j.rser.2015.12.246>.
- [58] Galatioto A, Beccali M. Aspects and issues of daylighting assessment: a review study. *Renew Sustain Energy Rev* 2016;66:852–60. <http://dx.doi.org/10.1016/j.rser.2016.08.018>.
- [59] Fadzli Haniff M, Selamat H, Yusof R, Buyamin S, Sham Ismail F. Review of HVAC scheduling techniques for buildings towards energy-efficient and cost-effective operations. *Renew Sustain Energy Rev* 2013;27:94–103. <http://dx.doi.org/10.1016/j.rser.2013.06.041>.
- [60] Beltran A, Cerpa AE. Optimal HVAC building control with occupancy prediction. *Proc 1st ACM Conf Embed Syst Energy-Effic Build - Build '2014*;14:168–71. <http://dx.doi.org/10.1145/2674061.2674072>.
- [61] Lindsay Baker. et al. Control for the people: how machine learning enables efficient HVAC use across diverse thermal preferences. *ACEEE Summer Study Energy Effic. Build.*, Pacific Grove, CA; 2016.
- [62] Li Z, Heo Y, Augenbroe G. HVAC design informed by organizational simulation. *Build Simul* 2009;2009:2198–203.
- [63] EBCP I. Final Report Annex 53. Total energy use in buildings Analysis and evaluation methods; 2013.
- [64] Zhou K, Yang S. Understanding household energy consumption behavior: the contribution of energy big data analytics. *Renew Sustain Energy Rev* 2016;56:810–9. <http://dx.doi.org/10.1016/j.rser.2015.12.001>.
- [65] Fayyad P, Piatetsky-Shapiro G & S U. From data mining to knowledge discovery in databases. *Adv Knowl Discov Data Min* 1996;17:1–36.
- [66] Ueno T, Sano F, Saeki O, Tsuji K. Effectiveness of an energy-consumption information system on energy savings in residential houses based on monitored data. *Appl Energy* 2006;83:166–83. <http://dx.doi.org/10.1016/j.apenergy.2005.02.002>.
- [67] Li M. Insights from Smart Meters : The potential for peak-hour savings from behavior- based programs please contact; 2014.
- [68] Haldi F, Robinson D. A comparison of alternative approaches for the modelling of window opening and closing behaviour. *Air Cond Low Carbon Cool Chall* 2008;27–9.
- [69] D'Oca S, Fabi V, Corgnati SP, Andersen RK. Effect of thermostat and window opening occupant behavior models on energy use in homes. *Build Simul* 2014;7:683–94. <http://dx.doi.org/10.1007/s12273-014-0191-6>.
- [70] Rijal HB, Tuohy PG, Nicol JF, Humphreys MA, Samuel A AA, Clarke JA. Development of an adaptive window-opening algorithm to predict the thermal comfort, energy use and overheating in buildings. *J Build Eng* 2008;1:17–30. <http://dx.doi.org/10.1080/19401490701868448>.
- [71] Yun GY, Steemers K. Time-dependent occupant behaviour models of window control in summer. *Build Environ* 2008;43:1471–82. <http://dx.doi.org/10.1016/j.buildenv.2007.08.001>.
- [72] Tuohy P, Rijal HB, Humphreys Ma, Nicol JF, Samuel A, Clarke J. Comfort driven adaptive window opening behavior and the influence of building design Energy Systems Research Unit , University of Strathclyde , Glasgow G1 1XJ , UK Oxford Institute for Sustainable Development , Oxford Brookes University , OX3 0BP , UK. *Build Simulation*; 2007.
- [73] Dutton S, Shao L. Window opening behaviour in a naturally ventilated school. *Fourth Natl. Conference IBPSA-USA New York City, New York August 11–13, 2010, 2010*, p. 260–268.
- [74] Warren PR, Parkins LM. Window-opening behaviour in office buildings. *Build Serv Eng Res Technol* 1984;5:89–101. <http://dx.doi.org/10.1177/014362448400500301>.
- [75] Indraganti M, Ooka R, Rijal HB, Brager GS. Occupant behaviour and obstacles in operating the openings in offices in India. *8th Wind Conf* 2014;2014:10–3.
- [76] Haldi F, Robinson D. Interactions with window openings by office occupants. *Build Environ* 2009;44:2378–95. <http://dx.doi.org/10.1016/j.buildenv.2009.03.025>.
- [77] Inkajrit V, Paliaga G. Indoor climatic influences on the operation of windows in a naturally ventilated building. In: *Proceedings of the 21th PLEA conference*, Eindhoven; 2004. p. 19–22.
- [78] Bekö G, Toftum J, Clausen G. Modeling ventilation rates in bedrooms based on building characteristics and occupant behavior. *Build Environ* 2011;46:2230–7. <http://dx.doi.org/10.1016/j.buildenv.2011.05.002>.
- [79] Yao J. Determining the energy performance of manually controlled solar shades: a stochastic model based co-simulation analysis. *Appl Energy* 2014;127:64–80. <http://dx.doi.org/10.1016/j.apenergy.2014.04.046>.
- [80] Mahdavi A, Mohammadi A, Kabir E, Lambeva L. Occupants' operation of lighting and shading systems in office buildings. *J Build Perform Simul* 2008;1:57–65. <http://dx.doi.org/10.1080/19401490801906502>.
- [81] Van Den Wymelenberg K. Patterns of occupant interaction with window blinds: a literature review. *Energy Build* 2012;51:165–76. <http://dx.doi.org/10.1016/j.enbuild.2012.05.008>.
- [82] Reinhart C, Voss K. Monitoring manual control of electric lighting and blinds. *Light Res Technol* 2003;35:243–60. <http://dx.doi.org/10.1191/1365782803li0640a>.
- [83] Inkajrit V. Balancing comfort: occupants' control of window blinds in private offices; 2005.
- [84] Newsham GR. Manual control of window blinds and electric lighting: implications for comfort and energy consumption. *Indoor Built Environ* 1994;3:135–44. <http://dx.doi.org/10.1177/1420326X9400300307>.
- [85] Sutter Y, Dumortier D, Fontoynt M. The use of shading systems in VDU task offices: a pilot study. *Energy Build* 2006;38:780–9. <http://dx.doi.org/10.1016/j.enbuild.2006.03.010>.
- [86] Ajzen I, Fishbein M. Attitude–behavior relations: a theoretical analysis and review of empirical research. *Psychol Bull* 1977;84:888–918.
- [87] Martinsson J, Lundqvist LJ, Sundstrom A. Energy saving in Swedish households. The (relative) importance of environmental attitudes. *Energy Policy* 2011;39:5182–91. <http://dx.doi.org/10.1016/j.enpol.2011.05.046>.
- [88] Gadenne D, Sharma B, Kerr D, Smith T. The influence of consumers' environmental beliefs and attitudes on energy saving behaviours. *Energy Policy* 2011;39:7684–94. <http://dx.doi.org/10.1016/j.enpol.2011.09.002>.
- [89] Fazio RH. Multiple Processes by which attitudes guide behavior: the mode model as an integrative framework; 1990.
- [90] Whitmarsh L, Upham P, Poortinga W, McLachlan C, Darnton A, Devine-Wright P. et al. Public Attitudes , Understanding , and Engagement in relation to Low-Carbon Energy : A selective review of academic and non-academic literatures. *Rep Res Counc UK Energy Program*; 2011.
- [91] Chen C, Knight K. Energy at work: social psychological factors affecting energy conservation intentions within Chinese electric power companies. *Energy Res Soc Sci* 2014;4:23–31. <http://dx.doi.org/10.1016/j.erss.2014.08.004>.
- [92] D'Oca S, Corgnati SP, Buso T. Smart meters and energy savings in Italy: determining the effectiveness of persuasive communication in dwellings. *Energy Res Soc Sci* 2014;3:131–42. <http://dx.doi.org/10.1016/j.erss.2014.07.015>.
- [93] Deuble MP, de Dear RJ. Green occupants for green buildings: the missing link?. *Build Environ* 2012;56:21–7. <http://dx.doi.org/10.1016/j.buildenv.2012.02.029>.
- [94] Fell MJ, Chiu LF. Children, parents and home energy use: exploring motivations and limits to energy demand reduction. *Energy Policy* 2014;65:351–8. <http://dx.doi.org/10.1016/j.enpol.2013.10.003>.
- [95] D'Oca S, Delmastro C, Fabi V, Corgnati SP. Testing socio-economic Demographic variables on building energy consumption scenarios at the urban scale in Italy. *ClimaMed* 2015;2015.
- [96] Abrahamse W, Steg L. Factors related to household energy use and intention to reduce It: the role of psychological and socio-Demographic variables. *Hum Ecol Rev* 2011;18:30–40.
- [97] Dowd A, Ashworth P, Carr-Cornish S, Stenner K. Energymark: empowering individual Australians to reduce their energy consumption. *Energy Policy* 2012;51:264–76. <http://dx.doi.org/10.1016/j.enpol.2012.07.054>.
- [98] Han Q, Nieuwenhijzen I, de Vries B, Blokhuis E, Schaefer W. Intervention strategy to stimulate energy-saving behavior of local residents. *Energy Policy* 2013;52:706–15. <http://dx.doi.org/10.1016/j.enpol.2012.10.031>.
- [99] Anderson W, White V. Exploring consumer preferences for home energy display functionality. *Report to the Energy Saving Trust*, vol. 123; 2009.
- [100] Madsen Henrik, Møller JanKloppenborg, Wolf Sebastian, Marcel Schweiker B, RKA Gunay, Yilmaz Selin VB. Statistical modelling of occupant behaviour; 2016.
- [101] VSKV Harish, Kumar A. A review on modeling and simulation of building energy systems. *Renew Sustain Energy Rev* 2016;56:1272–92. <http://dx.doi.org/10.1016/j.rser.2015.12.040>.
- [102] Wang D, Federspiel CC, Rubinstein F. Modeling occupancy in single person offices. *Energy Build* 2005;37:121–6. <http://dx.doi.org/10.1016/j.enbuild.2004.06.015>.
- [103] Wen-kuei Chang TH. Statistical analysis and modeling of occupancy patterns in open-plan offices using measured lighting- switch data. vol. LBNL-6080E; 2014.
- [104] Andrews CJ, Chandra Putra CB H. Simulation modeling of occupant behavior in commercial buildings. *EEBHUB Energy Effic Build Hub* 2013.
- [105] D'Oca S, Hong T. A data-mining approach to discover patterns of window opening and closing behavior in offices. *Build Environ* 2014;82:726–39. <http://dx.doi.org/10.1016/j.buildenv.2014.10.021>.
- [106] D'Oca S, Hong T. Occupancy schedules learning process through a data mining framework. *Energy Build* 2015;88:395–408. <http://dx.doi.org/10.1016/j.enbuild.2014.11.065>.
- [107] Gunay HB, O'Brien W, D'Oca S, Corgnati SP. On modelling and simulation of occupant models. *Build Simul Conf Hyderabad, India* 2015:1–9.
- [108] ANSI/ASHRAE/IES Standard 90.1-2013 Energy standard for buildings except low-rise residential buildings. 8400, 2013.
- [109] Wang C, Yan D, Sun H, Jiang Y. A generalized probabilistic formula relating occupant behavior to environmental conditions. *Build Environ* 2016;95:53–62. <http://dx.doi.org/10.1016/j.buildenv.2015.09.004>.
- [110] Yan D, O'Brien W, Hong T, Feng X, Gunay HB, Tahmasebi F, et al. Occupant behavior modeling for building performance simulation: current state and future challenges. *Energy Build* 2015;107:264–78. <http://dx.doi.org/10.1016/j.enbuild.2015.08.032>.
- [111] O'Brien W, Gunay HB. Final report submitted to natural resources Canada attention : Phylroy Lopez B . Eng LEED A . P . NC Implementation of the Occupant Behaviour and Presence Models in OpenStudio. Carleton University; 2016.
- [112] Hong T, Sun H, Chen Y, Taylor-Lange SC, Yan D. An occupant behavior modeling tool for co-simulation. *Energy Build* 2015. <http://dx.doi.org/10.1016/j.enbuild.2015.10.033>.
- [113] Zhao J, Lam KP, Ydstie BE, Loftness V. Occupant-oriented mixed-mode EnergyPlus predictive control simulation. *Energy Build* 2015. <http://dx.doi.org/10.1016/j.enbuild.2015.09.027>.
- [114] Dong B, Lam KP. A real-time model predictive control for building heating and cooling systems based on the occupancy behavior pattern detection and local weather forecasting. *Build Simul* 2014;7:89–106. <http://dx.doi.org/10.1007/s12273-013-0142-7>.
- [115] Tahmasebi F, Mostofi S, Mahdavi A. Exploring the implications of different



- occupancy modelling approaches for building performance simulation results. *Energy Procedia* 2015;78:567–72. <http://dx.doi.org/10.1016/j.egypro.2015.11.737>.
- [116] O'Brien W. Evaluating the performance robustness of fixed and movable shading devices against diverse occupant behaviors. *Proc Symp Simul Archit Urban Des* 2013;2.
- [117] Buso T, Fabi V, Andersen RK, Corgnati SP. Occupant behaviour and robustness of building design. *Build Environ* 2015;94:694–703. <http://dx.doi.org/10.1016/j.buildenv.2015.11.003>.
- [118] Zhao J, Lasternas B, Lam KP, Yun R, Loftness V. Occupant behavior and schedule modeling for building energy simulation through office appliance power consumption data mining. *Energy Build* 2014;82. <http://dx.doi.org/10.1016/j.enbuild.2014.07.033>.
- [119] Dounis AI, Caraiscos C. Advanced control systems engineering for energy and comfort management in a building environment—a review. *Renew Sustain Energy Rev* 2009;13:1246–61. <http://dx.doi.org/10.1016/j.rser.2008.09.015>.
- [120] Brager GS, Paliaga G, De Dear R, Olesen B, Wen J, Nicol F, et al. Operable windows, personal control, and occupant comfort. *ASHRAE Trans* 2004;110(PART 1):17–35.
- [121] Cuddy AJC, Doherty KTMW. OPOWER: increasing energy efficiency through normative influence; 2010.
- [122] Ehrhardt-Martinez K. ACEEE, editor. Behavior-based energy savings opportunities in commercial buildings: estimates for four U.S. cities. Washington, DC: ACEEE Summer Study Energy Effic. Build.; 2016. p. 1–12.
- [123] Lee E, Fernandes L, Coffey B. A post-occupancy Monitored Evaluation of the Dimmable lighting, automated shading, and Underfloor air distribution system in The New York Times building. *Lawrence Berkeley Natl Lab* 2013;1–69.
- [124] Ackerly K, Brager G. Human Behavior Meets Building Intelligence: How Occupants Respond to “Open Window” Signals 2012 ACEEE Summer Study Energy Effic Build 2012:10–21. <http://dx.doi.org/10.1016/j.enbuild.2013.06.009>.
- [125] Altomonte S, Schiavon S. Occupant satisfaction in LEED and non-LEED certified buildings. *Build Environ* 2013;68:66–76. <http://dx.doi.org/10.1016/j.buildenv.2013.06.008>.
- [126] Langevin J, Wen J, Gurian PL. Simulating the human-building interaction: development and validation of an agent-based model of office occupant behaviors. *Build Environ* 2014. <http://dx.doi.org/10.1016/j.buildenv.2014.11.037>.
- [127] D'Oca S, Corgnati S, Pisello AL, Hong T. Introduction to an occupant behavior motivation survey framework. *Clima* 2016;2016.
- [128] Harland P, Staats H, Wilke HAM. Situational and personality factors as direct or personal norm mediated predictors of pro-environmental behavior: questions derived from norm-activation theory. *Basic Appl Soc Psych* 2007;29:323–34. <http://dx.doi.org/10.1080/01973530701665058>.
- [129] Feng X, Yan D, Wang C, Sun H. A preliminary research on the derivation of typical occupant behavior based on large-scale questionnaire surveys. *Energy Build* 2015. <http://dx.doi.org/10.1016/j.enbuild.2015.09.055>.
- [130] Xu X, Arpan LM, Chen C. The moderating role of individual differences in responses to benefit and temporal framing of messages promoting residential energy saving. *J Environ Psychol* 2015;44:95–108. <http://dx.doi.org/10.1016/j.jenvp.2015.09.004>.
- [131] Li Wenchao, Sadigh Dorsa, Sastry SShankar. SAS. Synthesis for human-in-the-loop control systems; 2013.
- [132] Schirmer G, Erdogmus D, Chowdhury K, Padir T. The future of human-in-the-loop cyber-physical systems. *IEEE Comput Soc* 2013.
- [133] Munir S, Stankovic JA, Liang CM, Lin S. Cyber physical system challenges for human-in-the-loop control, n.d.
- [134] Cuzzillo T. Real-World Active Learning. Applications and strategies for human-in-the-loop machine learning, 95472. Sebastopol, CA: O'Reilly Media, Inc., 1005 Gravenstein Highway North; 2015.
- [135] Azar E, Menassa CC. Evaluating the impact of extreme energy use behavior on occupancy interventions in commercial buildings. *Energy Build* 2015;97. <http://dx.doi.org/10.1016/j.enbuild.2015.03.059>.
- [136] Norton W. ComEd Residential and C&I Saturation / End-Use, Market Penetration & Behavioral Study.; 2013.
- [137] Azar E, Menassa CC. Agent-based modeling of occupants and their impact on energy use in commercial buildings. *J Comput Civ Eng* 2012;26:506–18. [http://dx.doi.org/10.1061/\(ASCE\)CP.1943-5487.0000158](http://dx.doi.org/10.1061/(ASCE)CP.1943-5487.0000158).
- [138] Shaikh PH, Nor NBM, Nallagownden P, Elamvazuthi I, Ibrahim T. A review on optimized control systems for building energy and comfort management of smart sustainable buildings. *Renew Sustain Energy Rev* 2014;34:409–29. <http://dx.doi.org/10.1016/j.rser.2014.03.027>.
- [139] Oldewurtel F, Sturzenegger D, Morari M. Importance of occupancy information for building climate control. *Appl Energy* 2013;101:521–32. <http://dx.doi.org/10.1016/j.apenergy.2012.06.014>.
- [140] Kavousian A, Rajagopal R, Fischer M. Determinants of residential electricity consumption: using smart meter data to examine the effect of climate, building characteristics, appliance stock, and occupants' behavior. *Energy* 2013;55:184–94. <http://dx.doi.org/10.1016/j.energy.2013.03.086>.
- [141] Sharon Noell SCL. Home Electricity Report Program (Opower) 2013 Impact Evaluation; 2014.
- [142] OPOWER. Unlocking the Potential of Behavioral Energy Efficiency; 2013.
- [143] Khan AA, Razzaq S, Khan A, Khurshed F, Owais. HEMS and enabled demand response in electricity market: an overview. *Renew Sustain Energy Rev* 2015;42:773–85. <http://dx.doi.org/10.1016/j.rser.2014.10.045>.
- [144] Langevin J, Wen J, Gurian PL. Simulating the human-building interaction: development and validation of an agent-based model of office occupant behaviors. *Build Environ* 2015;88:27–45. <http://dx.doi.org/10.1016/j.buildenv.2014.11.037>.
- [145] Emery AF, Kippenhan CJ. A long term study of residential home heating consumption and the effect of occupant behavior on homes in the Pacific Northwest constructed according to improved thermal standards. *Energy* 2006;31:677–93. <http://dx.doi.org/10.1016/j.energy.2005.04.006>.
- [146] Darby S. The effectiveness of feedback on energy consumption: a review for defra of the literature on metering, billing and direct displays. *Environ Chang Inst Univ Oxf* 2006;22:1–21. <http://dx.doi.org/10.4236/ojee.2013.21002>.
- [147] Langevin J, Wen J, Gurian PL. Quantifying the human-building interaction: considering the active, adaptive occupant in building performance simulation. *Energy Build* 2015. <http://dx.doi.org/10.1016/j.enbuild.2015.09.026>.
- [148] Chwalbińska-Kusek K, Olszewska M. Health and Productivity in Sustainable Buildings. *BuroHappold Eng Constr Mark Gr*; 2015.
- [149] Research IBM. Global Technology Outlook 2015;2015.
- [150] Ahmad MW, Mourshed M, Mundow D, Sisinni M, Rezzuy Y. Building energy metering and environmental monitoring - A state-of-the-art review and directions for future research. *Energy Build* 2016;120. <http://dx.doi.org/10.1016/j.enbuild.2016.03.059>.
- [151] Navigant Research. Advanced Energy Now 2016 Market Report. Global and U.S. Markets by Revenue 2011–2015 and Key Trends in Advanced Energy Growth. *Adv Energy Econ*; 2016.
- [152] Beaudin M, Zareipour H. Home energy management systems: a review of modelling and complexity. *Renew Sustain Energy Rev* 2015;45:318–35. <http://dx.doi.org/10.1016/j.rser.2015.01.046>.
- [153] Blum David, Wetter M. MPCpy: an open-source software platform for model predictive control in buildings. *IBPSA Build Simul Conf* 2017;2017.
- [154] Robotic B. Comfy Case Study: Johnson Controls Inc., 507 Michigan Ave. Oakland, CA; 2015.
- [155] Moura PS, Vieira FM, López GL, Moreno JJ, Almeida AT. De. Demand response and energy storage for zero energy residential buildings; 2014.
- [156] Yilmaz S, Firth SK, Allinson D. Developing a modelling framework to quantify the demand response potential of domestic appliances in UK homes; 2011.
- [157] D'Oca Simona, Fabi Valentina, Verena Marie Barthelmes SC. From consumer smart monitoring to demand response in the domestic sector: Italian case studies; 2015.
- [158] Chappells H, Shove E. Debating the future of comfort: environmental sustainability, energy consumption and the indoor environment. *Build Res Inf* 2005;33:32–40. <http://dx.doi.org/10.1080/0961321042000322762>.
- [159] Janda KB. Building communities and social potential: between and beyond organizations and individuals in commercial properties. *Energy Policy* 2014;67:48–55. <http://dx.doi.org/10.1016/j.enpol.2013.08.058>.
- [160] Ehrhard Martinez K. Meta-review of behavior-based energy-savings potential estimates for commercial buildings. Boulder, CO; 2016.
- [161] Schare S, Gilbert E, Consulting N, Sherman M, Solutions SE. Smart homes and smarter consumers: how the internet and home area networks can enable energy efficient behavior; 2015.
- [162] Consulting N. DOE behavioral potential estimates workshop; 2016.
- [163] Murphy K, Corporation S, Schare S, Consulting N. Balancing real-time supply and demand with high penetration of renewable energy: the case for grid-interactive water heaters introduction: the problem of high penetration of intermittent renewable energy on the electric grid 2014; 2014.
- [164] Jain RK, Gulbinas R, Taylor JE, Culligan PJ. Can social influence drive energy savings? Detecting the impact of social influence on the energy consumption behavior of networked users exposed to normative eco-feedback. *Energy Build* 2013;66:119–27. <http://dx.doi.org/10.1016/j.enbuild.2013.06.029>.
- [165] Ajzen I, Fishbein M. Attitudes and the attitude-behavior relation: reasoned and automatic processes. *Eur Rev Soc Psychol* 2000;11:1–33.
- [166] Jeannet H. Van Houwelingen WFVR. The effect of goal-setting and daily electronic feedback on In-home energy use. *J Consum Res* 1989;98–105.
- [167] Lee T, Yao R, Coker P. An analysis of UK policies for domestic energy reduction using an agent based tool. *Energy Policy* 2014;66:267–79. <http://dx.doi.org/10.1016/j.enpol.2013.11.004>.
- [168] Young W, Davis M, McNeill IM, Malhotra B, Russell S, Unsworth K, et al. Changing behaviour: successful environmental programmes in the workplace. *Bus Strateg Environ* 2015;24:689–703. <http://dx.doi.org/10.1002/bse.1836>.
- [169] Sovacool BK. Rejecting renewables: the socio-technical impediments to renewable electricity in the United States. *Energy Policy* 2009;37:4500–13. <http://dx.doi.org/10.1016/j.enpol.2009.05.073>.
- [170] Sovacool BK. What are we doing here? Analyzing fifteen years of energy scholarship and proposing a social science research agenda. *Energy Res Soc Sci* 2014;1:1–29. <http://dx.doi.org/10.1016/j.erss.2014.02.003>.
- [171] Sovacool BK, Ryan SE, Stern PC, Janda K, Rochlin G, Spreng D, et al. Integrating social science in energy research. *Energy Res Soc Sci* 2015;6:95–9. <http://dx.doi.org/10.1016/j.erss.2014.12.005>.
- [172] Dimetrosky S, Parkinson K, Analytics A, Orrey J, Analytics G. Are savings from behavior programs ready for TRM prime time? Behavior programs and TRMs? *International Energy Progr. Eval. Conference – Chicago*, 2013, p. 1–16.
- [173] Moezzi M, Janda KB. From “if only” to “social potential” in schemes to reduce building energy use. *Energy Res Soc Sci* 2014;1:30–40. <http://dx.doi.org/10.1016/j.erss.2014.03.014>.
- [174] Abrahamse W, Steg L, Vlek K, Rothengatter T. A review of intervention studies aimed at household energy conservation. *J Environ Psychol* 2005;25:273–91. <http://dx.doi.org/10.1016/j.jenvp.2005.08.002>.
- [175] Staats H, Harland P, Wilke HAM. Effecting durable change: a team approach to improve environmental behavior in the household. *Environ Behav*

- 2004;36:341–67. <http://dx.doi.org/10.1177/0013916503260163>.
- [176] Bamberg S, Möser G. Twenty years after Hines, Hungerford, and Tomera: a new meta-analysis of psycho-social determinants of pro-environmental behaviour. *J Environ Psychol* 2007;27:14–25. <http://dx.doi.org/10.1016/j.jenvp.2006.12.002>.
- [177] Delmas MA, Fischlein M, Asensio OI. Information strategies and energy conservation behavior: a meta-analysis of experimental studies from 1975 to 2012. *Energy Policy* 2013;61:729–39. <http://dx.doi.org/10.1016/j.enpol.2013.05.109>.
- [178] WT. P. Behavior: the control of perception. New Canaan, CT: Benchmark; 1973.
- [179] Oikonomou V, Becchis F, Steg L, Russolillo D. Energy saving and energy efficiency concepts for policy making. *Energy Policy* 2009;37:4787–96. <http://dx.doi.org/10.1016/j.enpol.2009.06.035>.
- [180] Biggart NW, Lutzenhiser L. Economic sociology and the social problem of energy inefficiency. *Am Behav Sci* 2007;50:1070–87. <http://dx.doi.org/10.1177/0002764207299355>.
- [181] Langevin J. Framing human-centered measures relative to other building efficiency technologies Key challenges and opportunities 2015. <http://dx.doi.org/10.13140/RG.2.1.4985.6726>.
- [182] Mann S, Harris I, Harris J. The development of urban renewable energy at the existential technology research center (ETRC) in Toronto, Canada. *Renew Sustain Energy Rev* 2006;10:576–89. <http://dx.doi.org/10.1016/j.rser.2004.11.006>.
- [183] O'Brien W, Gunay HB. The contextual factors contributing to occupants' adaptive comfort behaviors in offices – a review and proposed modeling framework. *Build Environ* 2014;77:77–88. <http://dx.doi.org/10.1016/j.buildenv.2014.03.024>.
- [184] Langevin J, Gurian PL, Wen J. Tracking the human-building interaction: a longitudinal field study of occupant behavior in air-conditioned offices. *J Environ Psychol* 2015;42:94–115. <http://dx.doi.org/10.1016/j.jenvp.2015.01.007>.
- [185] Pothitou M, Kolios AJ, Varga L, Gu S. A framework for targeting household energy savings through habitual behavioural change. *Int J Sustain Energy* 2014;6451:1–15. <http://dx.doi.org/10.1080/14786451.2014.936867>.
- [186] Stoknes PE. Rethinking climate communications and the “psychological climate paradox.”. *Energy Res Soc Sci* 2014;1:161–70. <http://dx.doi.org/10.1016/j.erss.2014.03.007>.
- [187] Gilani S, O'Brien W, Gunay HB, Carrizo JS. Use of dynamic occupant behavior models in the building design and code compliance processes. *Energy Build* 2016;117. <http://dx.doi.org/10.1016/j.enbuild.2015.10.044>.
- [188] Zhao D-X, He B-J, Johnson C, Mou B. Social problems of green buildings: from the humanistic needs to social acceptance. *Renew Sustain Energy Rev* 2015;51:1594–609. <http://dx.doi.org/10.1016/j.rser.2015.07.072>.
- [189] Jain RK, Taylor JE, Culligan PJ. Investigating the impact eco-feedback information representation has on building occupant energy consumption behavior and savings. *Energy Build* 2013;64:408–14. <http://dx.doi.org/10.1016/j.enbuild.2013.05.011>.
- [190] Day JK, Gunderson DE. Understanding high performance buildings: the link between occupant knowledge of passive design systems, corresponding behaviors, occupant comfort and environmental satisfaction. *Build Environ* 2015;84:114–24. <http://dx.doi.org/10.1016/j.buildenv.2014.11.003>.
- [191] Yan D, Hong T. IEA EBC Annex 2014;66.
- [192] Ciriminna R, Meneguzzo F, Pecoraino M, Pagliaro M. Reshaping the education of energy managers. *Energy Res Soc Sci* 2016;21. <http://dx.doi.org/10.1016/j.erss.2016.06.022>.
- [193] Ciriminna R, Meneguzzo F, Pecoraino M, Pagliaro M. Rethinking solar energy education on the dawn of the solar economy. *Renew Sustain Energy Rev* 2016;63:13–8. <http://dx.doi.org/10.1016/j.rser.2016.05.008>.
- [194] Stern PC. Individual and household interactions with energy systems: toward integrated understanding. *Energy Res Soc Sci* 2014;1:41–8. <http://dx.doi.org/10.1016/j.erss.2014.03.003>.
- [195] Barbu A, Griffiths N, Morton G. Achieving energy efficiency through behaviour change: what does it take?. *Eur Environ Agency Tech Rep* 2013. <http://dx.doi.org/10.2800/49941>.
- [196] Nicol JF. Characterising occupant behavior in buildings: towards a stochastic model of occupant use of windows, lights, blinds heaters and fans. *Seven- Int IBPSA Conf* 2001:1073–8.