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, California 94720, USA

*Corresponding author, thong@lbl.gov, 1(510) 486-7082

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.

Keywords
Human dimensions; energy use; occupant behavior; building life cycle; energy performance; stakeholders

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, humans 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 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 to 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 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 (Figure 1). In this section, we focus on six stakeholders that are particularly important in driving the human dimensions of building energy use (Figure 1).

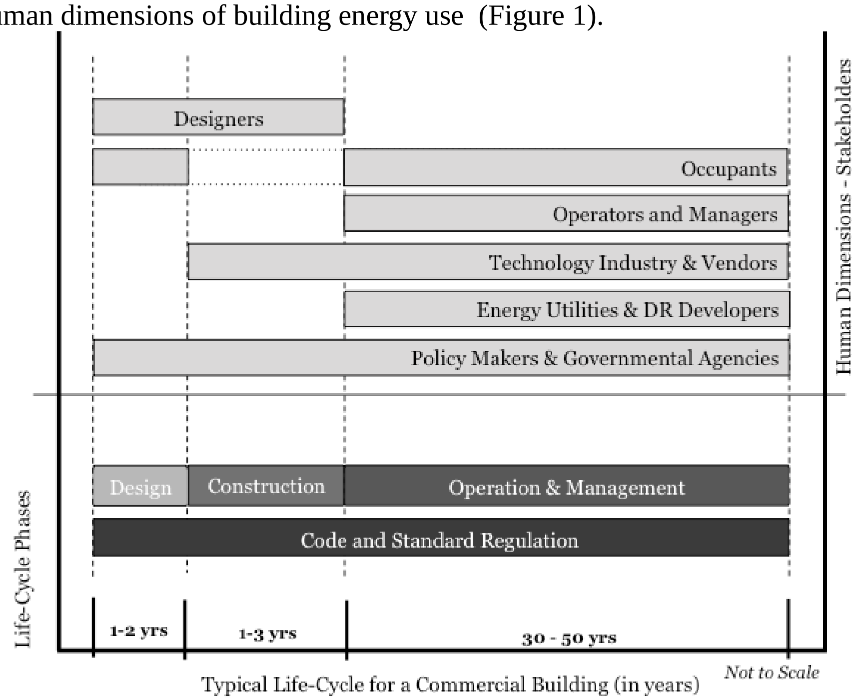

Figure 1. *Six stakeholder groups that are driving the human dimensions of building energy use across different building life-cycle phases: building designers (Section 2.1), occupants (Section 2.2), operators and energy managers (Section 2.3), technology industry and vendors (Section 2.4), energy utilities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

Literature review sub-sections are organized around each of the six stakeholders illustrated in Figure 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. Figure 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.

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., windows being opened/closed [31, 38, 48, 72–82], 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, 99–103]; 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.

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 (Figure 2) leading to unrealistic energy use predictions.

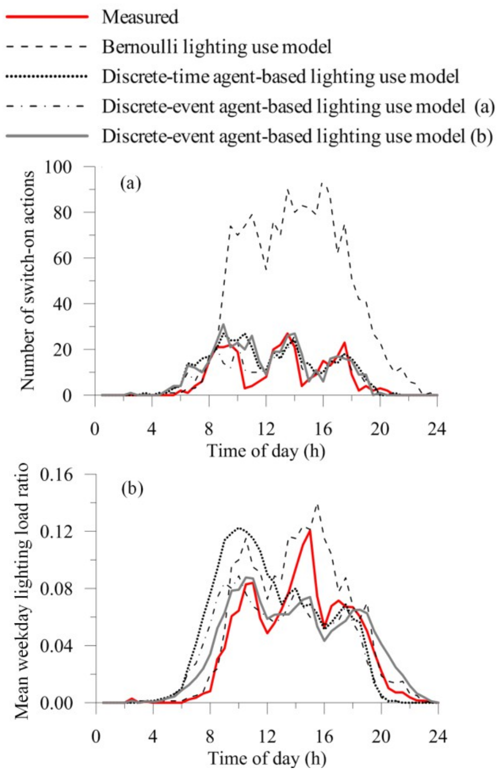

Figure 2: *Comparison of the lighting use models' predictions with observed lighting use [107].*

To achieve better predictions of building energy performance, 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].

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].

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 (Figure 3), indicating a growing research interest in human-centered building energy efficiency.

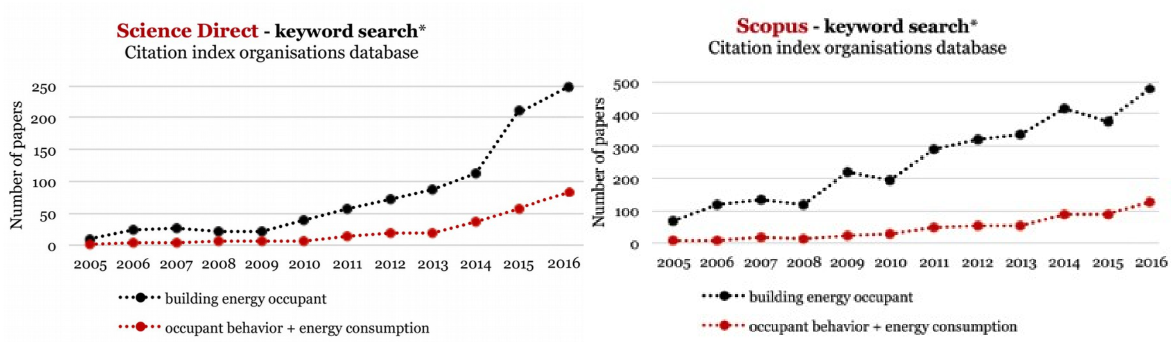

Figure 3. *Screening of the Science Direct and Scopus databases, two of the leading citation index organizations to select papers published over the last decades (2005-2016) using the terms "building energy occupant" and "occupant behavior and energy consumption" in the title, abstract, and keywords.*

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 HIL 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 [96]. 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 building 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 inter-disciplinary 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.

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