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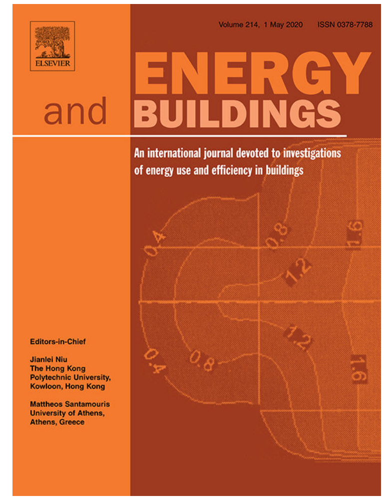

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Human-centric buildings for a changing climate: Introducing a new International Energy Agency research network

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Abstract

As building energy and health targets increase, occupants' influence on (and interactions with) their buildings is becoming more significant. Behaviors, such as daily routines, purchasing decisions, and responses to extreme events, directly impact energy use and health-related conditions within buildings. This dynamic is further shaped by global shifts such as teleworking, co-working, and home-sharing, which disrupt traditionally assumed occupancy patterns. Additionally, growing expectations for comfort and the integration of new technologies intensify the need to reassess how humans are considered in building design, maintenance, renovation, and operation—bringing a human-centric lens to traditionally building-focused approaches. This paper introduces a new research network that explores four key areas in the context of human-centric buildings in a changing climate: (1) individual human-building interactions, (2) community-scale interactions, (3) building (re)design, and (4) building operations. The Human-Centric Buildings for a Changing Climate (HCB) Network includes over 210 researchers from approximately 30 countries and multiple disciplines, including engineering, architecture, computer science, psychology, urban planning, sociology, public health, economics, and medicine. The objective of this paper is to establish the importance and relevance of these topics and to summarize the planned outcomes of a joint International Energy Agency (IEA) initiative between the Energy in Buildings and Communities (EBC) Programme Annex 95 and a Users Technology Collaboration Programme Task. This work aligns with and advances the goals of the UN Sustainable Development Goals (SDGs), particularly SDGs 3 (Health), 7 (Energy), 11 (Sustainable Cities), and 12 (Responsible Consumption), by centering human agency in climate-resilient building strategies.

Keywords: *human-centric, energy use, energy transition, buildings, climate change, health, behavior*

Highlights:

- The Human-Centric Buildings for a Changing Climate (HCB) Network is introduced
- Key research: individual/community interactions, building (re)design and operations
- Research goals, framework, and considerations presented for the four subtasks

1. Introduction

1.1 Background and Key Outcomes of IEA EBC Annexes 53, 66 and 79

Humans are central to building performance and adaptation to climate change, influencing outcomes across spatial and temporal scales [1]. A diverse range of stakeholders shape the design, construction, maintenance and ongoing operation of buildings throughout their life cycle. For example, in residential buildings, owners and occupants play a key role in purchasing decisions, interface or control selections, and renovation investments, and in turn, they greatly impact building performance outcomes through their subsequent building use [2–4]. In contrast, non-residential buildings typically separate operators from occupants, with operators exerting significant control over operational conditions experienced by the occupants and building environmental performance [5,6]. For all building types, building design professionals, installers and contractors hold influential roles as advisors on design, construction, retrofits and maintenance while both building managers and occupants impact building operations (e.g., [7]). In the context of a rapidly changing climate, having these varied stakeholders work synergistically is essential to achieving optimal building performance across three key dimensions: resilience and adaptability to climate change and the associated extreme events; climate change mitigation; and equitable access to comfortable and healthy spaces [8]. By addressing the intersection of human behavior, building design, and energy use, this initiative seeks to unlock human-centric insights that can accelerate progress toward sustainable development.

The research network introduced by this paper aims to reframe the role of humans in the built environment, positioning them as a solution rather than a problem, shifting the narrative from human behavior as a cause of performance gaps to human agency as a lever for positive change. As the built environment continues to fall short of climate targets, especially those outlined in the U.N.' Sustainable Development Goals [i.e., SDGs 3 (Good Health and Well-being), 7 (Affordable and Clean Energy), 11 (Sustainable Cities and Communities), and 12 (Responsible Consumption and Production)] [9], this work offers a timely opportunity to shift from building-centric models to strategies that are responsive to human needs, behaviors, and agency in a rapidly evolving world. This approach builds on the foundational work of IEA EBC Annexes 53, 66, and 79 [1], all of which made significant contributions to understanding how buildings can be designed and operated more effectively, taking into account human needs and their impact on performance.

Most recently, efforts led by IEA EBC Annex 79 (Occupant-Centric Building Design and Operation) yielded the following major outcomes:

- New knowledge, ontologies, and methods to understand multi-domain comfort and its influence on occupant behavior in buildings (e.g., [10–15]
- An occupant behavior database and library of data-driven modeling tools to model occupant behavior at various scales (from room to city), where data are obtained from novel methods such as social media and advanced sensing technologies [16]
- An open access book that provides new methods for occupant-centric simulation-aided building design with demonstrative case studies [17]

- Definitions, methods, and case studies for best practices in occupant-centric control (e.g., [18]).

Despite these advancements, experts within Annex 79 and beyond have identified significant gaps in knowledge, methodologies, and policy frameworks, highlighting the need for continued research (see [1,19]. Key focus areas for future work include:

- How to design buildings and communities for health and comfort in the context of a changing climate, while ensuring other priorities like environmental impact are managed (e.g., [20];
- How to ensure that resources and considerations are allocated equitably, through the lens of sufficiency [21]; and
- How to design/retrofit buildings considering climate change and extreme events, while considering multiple diverse stakeholders [8,22].

1.2 Objective/Scope of the Network

The overall goal of this new Network is to: ***Determine the role that occupants and other building stakeholders must play to facilitate the energy transition while adapting to our changing climate. We also aim to develop, demonstrate, and deploy approaches to improve occupants' comfort and health in buildings, using principles of sufficiency and equity.***

This new Network will explore the intersection of building design, retrofit, and operation with the evolving needs of owners, occupants, and other stakeholders in the context of climate change and the energy transition. Its primary objectives include enhancing building resilience and energy performance, occupant comfort, and health, while promoting sufficiency and equity. Key research areas encompass adaptation to future climate scenarios, shifts in occupant demographics, and the integration of emerging technologies and energy solutions. By drawing on interdisciplinary insights, this large international research group aims to develop practical, sustainable strategies to address human and environmental needs in a changing climate that can be operationalized in the building sector through standards and codes. The research incorporates methodologies from engineering, architecture, information technology, psychology, and health and social sciences, offering comprehensive and interdisciplinary solutions for building design and occupant adaptation to climate change. This new network, called the "Human Centric Buildings for a Changing Climate" or HCB Network is operated under both the IEA's Energy in Buildings and Communities (EBC) Program (as Annex 95) and the User-Centered Energy Systems Technology Collaboration Programme. Herein, we will refer to this as the "Network." The Network includes over 210 researchers from approximately 30 countries across multiple disciplines including engineering, architecture, computer science, psychology, urban planning, sociology, public health, economics, medicine, and more.

1.3 Overarching Research Questions

To achieve these objectives and explore the role of occupants and other building stakeholders in the energy transition and climate adaptation, the following research questions have been defined to guide the work of this Network.

- How do occupants' interactions with their buildings change under extreme and unprecedented conditions driven by climate change, and why?
- Do these behaviors help or hinder their ability to survive and thrive?
- How will extreme events specifically impact building function (and indoor conditions, comfort, health)?
- How do our expectations of building performance (e.g. comfort, energy performance) need to shift due to a changing climate and energy transition?
- How should we design and retrofit our buildings to best address human and environmental needs in a changing climate?

To best achieve our primary goal and to explore our broader research questions, the Network is organized into four "subtasks" (ST) which intersect to form research areas that incorporate various scales and parts of the building life cycle, as shown in Figure 1.

Overall, the organizational framework of the Network is defined as follows: Overarching Objectives → Research Questions → Subtasks (1–4) → Themes within Subtasks → Research Activities. This hierarchy ensures conceptual alignment between the Network's overarching research questions and goals, as related to specific aims pursued within each Subtask. The overarching objectives helped to guide and establish the targeted research questions. Each Subtask operationalizes these questions through distinct thematic areas that structure related research activities and promote interdisciplinary collaboration. This structure is further defined in the following section.

1.4 Structure of the Network

The subtasks (ST) considering scales include ST1 focused on individual interactions and ST2 focused on community interactions while those considering the building life cycle include ST3 on the building design and redesign process and ST4 on operations. All research activities belong to one primary subtask and an intersecting secondary subtask to encourage collaboration between subtask members. This intersecting structure is intended to encourage a holistic approach to understanding buildings and their stakeholders across various scales and lifecycle stages to address research questions and promote interdisciplinarity.

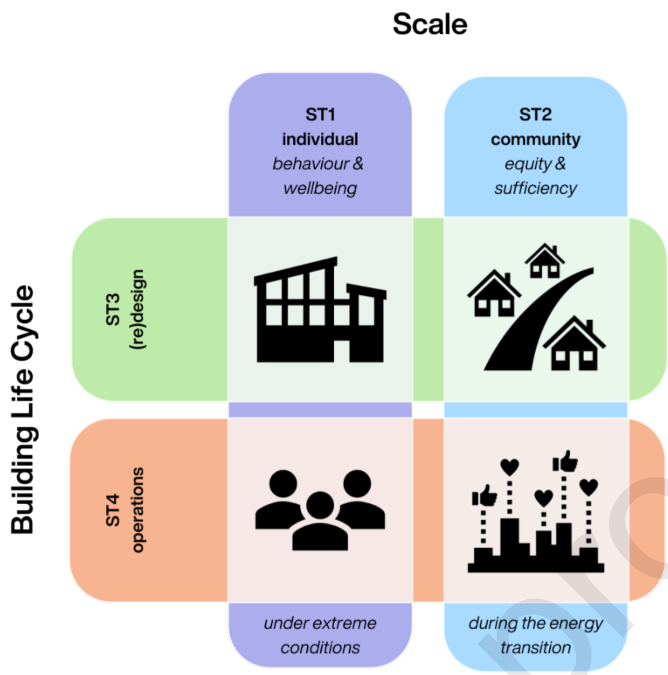

Figure 1: Network structure with four subtasks to maximize interdisciplinarity and collaboration and integrate research outcomes.

Through experience with Annex 79, the researchers gained new insights about organization, dissemination, and multidisciplinary research that will be implemented in this new Network. Two committees have been struck: the Representation Committee and the Knowledge Mobilization Committee. These cross-cutting committees are essential to the Network's success, ensuring broad representation and effective knowledge mobilization across all subtasks and activities.

The Representation Committee is designed to actively recruit new Network members from all relevant disciplines and demographics to identify differential effect, reduce bias and improve the generalizability of findings to ensure that the research is state-of-the-art and considers all critical angles, and from a wide range of researcher demographics to identify differential effects, reduce bias and improve the generalizability of findings. Representation within the Network is fundamental to ensuring that the research and knowledge production are inclusive, equitable, and impactful. A diverse academic community—comprising individuals from various demographic backgrounds, e.g., race, gender, socioeconomic status, and culture, with diverse disciplinary expertise, e.g., engineering, economics, physiology, architecture, policy—enhances innovation within the Network by bringing multiple perspectives to problem-solving.

This diversity not only challenges biases but also broadens the scope of inquiry, leading to more comprehensive and applicable research. The Representation Committee aims to ensure that solutions produced by the Network address the needs of all communities, rather than reinforcing existing inequalities. The Network's approach—actively recruiting participants who focus on, work in, or are originally from the Global South, and hosting Network activities in the Global South organized with and by local participants—

helps to embed the perspective of diverse voices within human-centric building design, uncover systemic barriers, and informs equitable strategies for addressing building and energy use within a changing climate. Ultimately, fostering broader representation in both research and design ensures that the solutions developed are not only innovative but also just, inclusive, and globally relevant.

The Knowledge Mobilization Committee is designed to maximize impact by facilitating the translation of shift focus from literature reviews and research papers toward more future-forward-looking and action-oriented outcomes with real world impacts (e.g. demonstration projects, tool development, guidelines and policy recommendations, etc.) The Network's Knowledge Mobilization Committee will foster the systematic exchange of knowledge among the subtasks to: learn from each other's successes and challenges to foster continuous improvement and mutual capacity-building; reduce redundancy and duplication to streamline efforts and use resources more efficiently; ensure alignment across tasks and sub-projects to maintain shared goals, timelines, and standards for coherence and quality; and share findings and insights early to accelerate the translation of knowledge into practice and facilitate innovation through cross-pollination to encourage creative ideas and solutions across subtasks.

The Knowledge Mobilization Committee will also engage with key stakeholders outside of the Network, including scientists, policymakers, and practitioners in the building industry, to effectively translate research into practice. Knowledge mobilization is a highly interdisciplinary activity, and this will support the development of effective collaboration models to synthesize insights from engineering, architecture, computer science, psychology, sociology, amongst others. The effective mobilization of such collaboration will ensure the Network methods and findings are shared with key stakeholders who can maximize research impact.

The Network follows a structured timeline, with research activities spanning a total of five years, ending in 2029. Key deliverables include knowledge-sharing initiatives such as workshops, seminars, and code committee engagements, as well as the development of definitions, tools, and policy recommendations to integrate occupant behavior considerations into standards. More broadly, expected outcomes include a better understanding of how the energy transition affects diverse building types and their various stakeholders, actionable occupant-centric design strategies for both new and existing buildings, and guidance for resilient, equitable, and sustainable building practices. With this broader context established, the following section presents the objective and specific contribution of this paper.

1.5 Objective and contribution of this paper

The objective of this paper is to establish the relevance and urgency of advancing human-centric building research within the context of global energy and climate transitions. It introduces the scope and structure of the newly launched joint project between the IEA EBC and Users TCP, which focuses on understanding and improving human-building interactions across four key domains: individual behavior (Section 2), community-scale engagement (Section 3), building (re)design (Section 4), and operations (Section 5). In each of these sections, the state of the art is first summarized, then existing challenges and knowledge gaps are identified followed by the research objectives of each subtask. By outlining the motivation and goals of the Network, this paper sets the stage for coordinated international and interdisciplinary research efforts aimed at aligning energy performance goals with occupant well-being. In doing so, it builds on the legacy of prior IEA EBC Annexes (66 and 79), while expanding the scope to meet emerging challenges related to comfort expectations, technological adoption, and evolving patterns of building use. This paper also summarizes the expected outputs of the Network in each respective subtask section, including methodological advancements, knowledge synthesis, and actionable strategies for designing and operating buildings that are adaptive, resilient, and responsive to human needs.

2 Subtask 1: Individual Scale: Behavior & Well-being

This subtask explores the effect of interactions between building technologies and operational performance on the health and well-being of building occupants. Studies will examine what can be learned from other climates and cultures, and how education, communication, and nudging might lead to more positive outcomes via the interactions as illustrated in Figure 2.

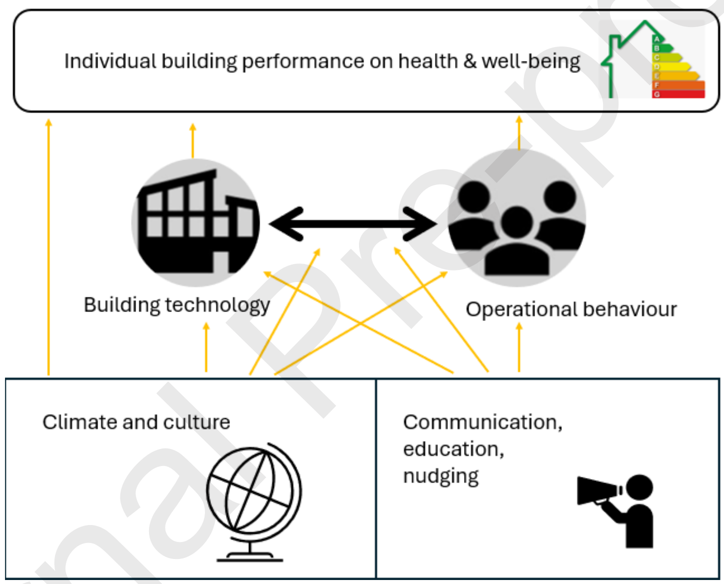

Figure 2: Schematic overview of Subtask 1 objective

2.1 State of the Art

Climate change and extreme events, such as natural disasters and severe weather conditions, can have profound and multifaceted effects on occupant health and well-being if buildings fail to provide good indoor environmental quality. This is particularly evident during extreme heat events, which can drive overheating in buildings.

A consistent association between exposure to extreme heat and increased mortality risk has been identified [23]. Additionally, chronic heat stress can lead to increased stress, anxiety, and cognitive impairment, especially in vulnerable populations/priority communities, such as the very young, older adults, and individuals with pre-existing mental health conditions [24]. Adverse effects on thermal comfort are also present in extreme cold events which can be more severe than extreme heat [25]. While national health statistics in the United States do not distinguish between indoor and outdoor exposure, data from 2006 to 2010 indicate that cold-related deaths were twice as numerous as those caused by heat [26]. Many of these cold-related fatalities can be attributed to inadequate indoor heating and building performance during extreme cold events [30].

The effects of extreme events on buildings negatively impacts not only the occupants of buildings but also other stakeholders as well including the reduction of property marketability and property values and the rise of operation and maintenance costs [8] . Additionally, risks related to property damage will increase, leading to higher insurance premiums. The economic valuation of extreme heat on subjective well-being is significant. One study found that one additional exceptionally hot day within a recent 30-day period significantly lowered survey participants' reports of subjective well-being by approximately 0.5% on average, which is comparable to the well-being loss resulting from GDP decreasing by several percentage points [27].

It is evident that climate change and extreme events have far-reaching consequences and that there is a need for effective coping behaviors and technological options to help building occupants adapt to changing climates and extreme events.

2.2 Existing Challenges and Knowledge gaps

Several existing coping behaviors, technological approaches, and retrofit strategies have been suggested to maintain occupant health and well-being in the face of a changing climate and extreme weather events, but research indicates these strategies vary widely in terms of effectiveness, consistent and appropriate practice, availability, and financial requirements.

For example, use of air-conditioning to help reduce heat strain and mortality is becoming more prevalent globally, but its use stresses the power grid, which can lead to outages during times of peak demand and extreme weather events. Further, it contributes significantly to climate change and it is often unavailable to the most vulnerable occupants [20,28]. Modest HVAC set-point adjustments can reduce grid stress, and evidence suggests individuals are willing to make those adjustments during extreme events [25]. However, modest set-point changes are likely to maintain adequate thermal comfort only in geographic areas with milder climates [29]. Additionally, lower-income occupants might not use HVAC systems to their full extent for economic reasons [22,30], limiting the ability of these devices to reduce health risks associated with extreme weather events.

Building-level interventions or retrofit actions such as adding solar shades, changes to roof reflectivity, adding window overhangs, improving windows and insulation, and planting shade trees have been found to reduce negative health effects associated with climate change, extreme events, and air pollution but can be costly [31].

Use of fans can reduce heat stress but are less effective at very high indoor temperatures (e.g., above 35°C) as well as among older occupants [20,32]. Similarly, window operation can greatly reduce overheating, but effectiveness depends on how and when windows are opened [33] as well as the outdoor conditions. Safety concerns, high levels of air pollution (e.g., induced by extreme weather, like wildfires), noise pollution or light intrusion may also limit window use [8]. Personal adaptive strategies such as adjusting clothing and drinking warm or cold beverages can mitigate heat and cold impacts, but these are typically more effective when combined with other measures [20,30,34].

Technology-based approaches to educating and nudging occupants toward protective behaviors have also been examined. For example, the CoolDownCoach, an in-home device, gives real-time recommendations on how to manage window operation and solar shading, based on temperatures and weather forecasts [35]. While it raises awareness, changing established behaviors remains challenging. Additionally, virtual assistants (e.g., Alexa) could encourage adaptive behaviors in response to temperature changes, but evidence is based on research participants' intentions to respond to the virtual assistant's recommendations, not their actual behaviors [36]. Field testing is needed to assess impacts on health and energy use.

Although research has found that the above-described strategies can mitigate negative health effects associated with climate change and extreme weather events, identifying effective ways to encourage and/or facilitate their correct and consistent use among occupants remains a significant challenge. The appropriateness and adoption of various strategies will depend on the specific type of occupant (e.g., elderly, general health status) as well as occupants' levels of knowledge, skills, and abilities to take adaptive action [8]. Additionally, appropriate strategies will likely need to change and could become more complicated as energy distribution and sources (e.g., solar and wind) shift and as variable pricing, demand-response programs, and energy-choice programs proliferate. More research is needed to illuminate more and better occupant education and technological approaches that encourage appropriate changes to energy use while protecting occupant health. Additionally, more data are needed regarding occupants' current coping methods across demographics and geographic locations as well as occupants' perceived effectiveness of those methods, especially during extreme weather events and during unprecedented increases in global temperatures.

2.4 Research Priorities

Starting from the existing challenges, this subtask focuses on two themes: individual coping mechanisms across cultures, and communication, education, and nudging.

2.4.1 Coping Mechanisms across cultures

Given variations in climate, building traditions, system solutions, and habits, the impact of extreme events and climate change on occupant behavior and well-being will vary across cultures and demographics. This theme focuses on examining existing practices cross-culturally to provide a better understanding of how, when, and why occupants take adaptive actions in various extreme circumstances. Such understanding can inform efforts to educate and assist occupants in coping or adapting effectively.

Existing qualitative and quantitative data will be collected from different climates and cultures to better understand current adaptive strategies and how climate and culture influence behavior. Then, new data will be gathered to investigate adaptive behaviors across climates and cultures, focusing on the influence of cultural backgrounds on spatial behavior, thermal preferences and comfort in transient spaces.

2.4.2 Communication, Education, and Nudging Adaptive Behavior

The second research priority focuses on supporting occupants in adapting to extreme events and climate change by developing resilient interfaces and improving communication and user engagement.

As a starting point for designing resilient interfaces that ensures smooth user experience under extreme conditions and that might adapt when these conditions change, existing designs will be examined to identify characteristics of effective interfaces under normal and extreme conditions. To increase user engagement, studies will investigate communication and nudging approaches to encourage adaptive behavior via apps or in-home devices. Promising ways to engage users and promote ongoing participation in load flexibility programs will also be explored.

These activities aim to understand adaptive behaviors during extreme events and improve education and technology to promote sustainable practices by individuals in buildings.

3 Subtask 2: Community Scale: Equity & Sufficiency

To fully understand the role of human stakeholders in the built environment in the context of the climate crisis and the energy transition, humans at a larger, collective scale must be considered. The impacts of climate change are felt both at the individual level, as discussed in ST1, but also at the community level. For example, burdens resulting from climate change can be inequitably distributed, as can be access to local solutions. In this context, this subtask is focused on how the built environment supports equity among its collective users, specifically with regard to indoor environmental quality, energy consumption, resilience, and associated costs.

Similarly, collective action is necessary to adapt to and mitigate the climate crisis. When consideration for well-being in the built environment is scaled up, it can lead to shifts in understanding of how built environments should be organized and provisioned. Asking what is sufficient to promote well-being in this context could create opportunities for scalable reductions in the resources demanded by buildings. This sufficiency-oriented mindset is an emerging area of research in the built environment that will be investigated further in this subtask. Community-scale questions of equity and sufficiency and how they intersect with more established concepts of sustainability, resilience, and efficiency will also be explored.

3.1 State of the art: equity and sufficiency

3.1.1 Equity

Thriving and healthy communities emerge from the intersection of multiple critical factors, including culture, the built environment, and ecological conditions. Among these, the built environment plays a crucial role in shaping human well-being by influencing access to essential services such as housing, transportation, public spaces, energy, and water infrastructure. However, disparities in infrastructure quality and investment allocation often reinforce systemic inequities, disproportionately affecting historically underserved populations.

Research highlights that historically priority communities—including low-income populations, racial minorities, people with disabilities, and displaced individuals—experience compounding challenges due to structural and systemic inequalities. These inequities shape access to essential services, infrastructure quality, and overall living conditions [37], yet they are frequently overlooked in urban development and infrastructure planning [38]. As a result, cycles of exclusion and disadvantage persist. Climate change further exacerbates these disparities, intensifying risks such as extreme heat, flooding, and energy insecurity, which disproportionately burden vulnerable populations. While climate risks are often portrayed as uniform within regions and populations, in reality, the most at-risk communities frequently lack the capacity to implement resilience measures resulting in higher exposure to environmental hazards, increased sensitivity to these risks, and limited adaptive capacity [39–41].

3.1.2 Sufficiency

The concept of sufficiency has gained attention in sustainability movements across domains, including the built environment [42]. Princen [43] produced a seminal work that established the concept of sufficiency as an organizing principle of society in which absolute ecological limits are respected. In this way, sufficiency is complementary to efficiency, which seeks to get the most output from the least input. The problem with efficiency, Princen argued, is that it can lead to rebound effects where consumption continues to rise, potentially offsetting the benefits of more efficient production. The IPCC embraced sufficiency in its sixth assessment report on mitigation of climate change, stating, "sufficiency policies are a set of measures and daily practices that avoid demand for energy, materials, land and water while delivering human well-being for all within planetary boundaries" [44]. Sufficiency questions the notion of demand, rather than seeking to meet demand at minimum cost [45]. In recent years, the concept of sufficiency has led to the identification of important questions and opportunities for a more sustainable built environment.

Sufficiency has been applied to built environment research in the context of living space, energy consumption, heating and cooling practices, transportation and mobility, and sharing facilities [45]. A sufficiency lens can be applied to both the provision of space in the built environment as well as the operation of these spaces. A natural question of sufficiency relates to the necessary space required for well-being. This has been researched both with respect to residential buildings [46] as well as commercial buildings [47]. With the rise of hybrid working since 2020, an open question has emerged on the required space for organizations that have embraced flexible working policies. Furthermore, the sufficiency lens has been applied to the urban form as a whole, with authors suggesting that neighborhood spatial organization itself can lead to significant reductions in resource demand [48,49]. Nick demonstrated how a sufficiency mindset could be leveraged to meet growing demands for building space without needing to construct new buildings [49].

Similarly, recent research has considered the concept of sufficiency in the operational phase of buildings. Sufficiency in operation largely depends on linking building energy consumption to specific needs of building users, including indoor environmental conditions such as thermal comfort [50]. In its pathway to net zero by 2050 report, the IEA assumes average space heating and cooling temperatures of 19-20ºC and 24-25ºC, respectively, indicating required behavioral changes that align with sufficiency mindsets and are outside the ranges of current standards [51].

3.2 Existing challenges and knowledge gaps

Despite increasing recognition of equity and sufficiency challenges, significant research gaps remain.

Many equity studies focus on isolated contexts, often exploring specific technical aspects of the built environment in isolation, while lacking a broader understanding of the systemic impacts, interconnected factors, and cascading effects of inequities. This lack of a systemic perspective limits the ability to develop holistic solutions that effectively address disparities in the built environment [37].

Geographically, research is largely concentrated in high-income regions of the Global North, providing limited insights into how climate vulnerabilities and infrastructure inequities manifest in low-income, rural, and underserved settings [52]. Furthermore, many studies fail to consider intersecting factors such as gender, disability, race, and economic status compound disparities in access, resilience, and infrastructure quality. This uneven focus restricts our understanding of how built environment factors contribute to equity and resilience across diverse contexts, making it difficult to develop targeted and inclusive policy solutions [53].

Community-led resilience efforts, such as informal adaptation strategies and local governance initiatives, are often overlooked, reinforcing a deficit-based perspective that fails to recognize existing strengths within structurally disadvantaged populations. Historically, bottom-up, community-led resilience efforts (e.g., informal adaptation strategies and local governance initiatives) have been central to addressing systemic inequities in the built environment, filling gaps left by top-down urban planning approaches [41]. However, while these local initiatives have proven effective in increasing resilience at smaller scales, there remains a significant challenge in scaling them up and integrating them into formal governance structures [38,41].

Given the nascent nature of sufficiency research in the built environment, there is a need to better understand sufficiency metrics when considering building design, renovation, and operation across diverse geographical contexts. Doing so will enable the identification of key metrics and data to evaluate how sufficiency can impact resource dependency and planetary boundaries. Additionally, there is a need to define the relationships and intersections between various community-scale concepts considered within this subtask. A guiding framework that firmly establishes how these concepts relate to each other and to the design and operation of built environments would help set a clear path for human-centric research in a changing climate.

3.3 Research priorities

ST2 will address critical gaps in understanding and application related to: Fundamentals & Definitions; Data, Methods, & Tools; and Applications & Case Studies.

3.3.1 Fundamentals & Definitions

This theme explores the fundamental concepts underpinning equity and sufficiency in the built environment. It examines how these principles interact, at times reinforcing one another and at other times creating trade-offs that must be carefully balanced. A key focus is on establishing clear functional definitions for equity and sufficiency, alongside developing robust indicators and metrics that are applicable across diverse geographic and socioeconomic contexts. Additionally, this theme investigates the role of intersectionality in shaping lived experiences, and the role of community-led initiatives for urban resilience planning.

3.3.2 Data, Methods, and Tools

This theme focuses on the development of data-driven methodologies and analytical tools to better understand and address inequities in the built environment. It explores how datasets and participatory methods can enhance equity-focused planning, how diverse data sources can be linked to provide a more comprehensive picture of systemic disparities, and how systems modeling can reveal hidden feedback loops that contribute to inequities.

A key focus is on creating datasets and analytical tools that capture disparities in housing, energy access, infrastructure quality, and environmental risks at the community scale. Methods for integrating fragmented datasets—such as census data, climate models, and real-time sensor networks—to improve the accessibility and interoperability of data for policymakers and community stakeholders will be investigated. To better understand systemic inequities, this research will apply systems modeling approaches, such as causal loop diagramming and qualitative scenario analysis, to identify feedback loops that perpetuate disparities in access, infrastructure investment, and climate adaptation. Case studies will be used to validate these models, ensuring their real-world applicability to urban development challenges.

3.3.3 Applications & Case Studies

This theme focuses on applying equity and sufficiency research to real-world contexts by exploring case studies and community-led initiatives that address disparities in the built environment. It examines how issues such as energy poverty, aging populations, and participatory planning can inform best practices and policy development. Additionally, this research investigates how lessons from diverse geographic contexts, including those with historically limited representation in research (e.g., the Global South), can contribute to a more comprehensive understanding of equitable urban resilience strategies. A key objective is refining strategies for meaningful community engagement to ensure that decision-making processes reflect the needs and perspectives of structurally disadvantaged groups while supporting inclusive urban development.

4 Subtask 3: (Re)design

The increasing severity of the climate crisis necessitates new approaches that integrate energy-efficiency, occupant well-being, life cycle assessment, and long-term adaptability in new construction and retrofits, recognizing that the majority of the building stock in the coming decades will be adapted rather than newly constructed. To this end, there is a need for an integrated approach that considers diverse stakeholders, decision-making processes, policy implications, and practical tools. The objective of ST3 is to ensure that both new construction and renovation efforts align with anticipated future climate conditions, evolving demographics, market trends, and sustainability targets.

4.1. State of the art

The integration of climate change considerations, stakeholder needs, and innovative policies and tools into building (re)design is gaining momentum. Traditionally, research in this domain has primarily focused on new building design and its relationship to climate change, with significant emphasis on life cycle carbon emissions [30,54] and, even more so, on energy efficiency [55]. In general, studies investigating renovation and new design strategies in response to climate change have largely centered around technology-driven solutions, including high-performance building materials, advanced envelope solutions, renewable energy integration, smart sensing and control systems, and energy storage or backup systems [56]. However, many of these studies are narrowly tied to energy efficiency, often neglecting broader implications for the changing climate. Consequently, there is a notable gap in understanding the multifaceted mitigation potential of different design approaches and technologies [56].

Moreover, research has largely overlooked the implications of building (re)design solutions on human-centric indicators, such as comfort, health, adaptive capacity, and sufficiency. Only a few studies have attempted to balance multiple objectives, including energy performance, economic benefits, environmental sustainability, user satisfaction, and heritage conservation [58].

Numerous simulation studies have been used to explore region-specific solutions to address climate change effects [59]. Some studies have utilized modified weather files[10,59,61–63]. However, the use of projected future climate scenarios remains uncommon in conventional studies and in practice, as it requires the development of customized weather datasets and interdisciplinary collaboration between energy simulation experts and climate scientists [64]. As a result, many simulations still rely on historical weather data averaged over the past 30 years, which no longer reflects the increasingly dynamic and unpredictable climate conditions.

Additionally, simulations predominantly focus on energy performance metrics, while multi-domain indicators such as thermal comfort, air quality, and adaptive capacity are often overlooked [65]. In this context, there is a pressing need to examine performance gaps between predicted and actual outcomes related to occupant comfort, indoor air quality, and overall building resilience. Rather than prioritizing energy efficiency in isolation, the next generation of building (re)design must ensure that indoor spaces remain habitable and resilient under climate stressors while actively enhancing occupant well-being and health.

Research on decision-making processes related to climate-resilient and human-centric building (re)design is also critical but scarce. One such study integrates tacit knowledge into a multi-objective method embedded with machine learning algorithms to support decision-making in building retrofit program planning, helping determine which buildings should be renovated and which strategies should be implemented [67]. Another study examined homeowners' decision-making processes and the factors influencing their willingness to renovate their homes [68]. Understanding these behavioral patterns is crucial for bridging the gap between technological advancements and real-world implementation. Additionally, while some studies have focused on co-benefits beyond energy savings, further research is needed to assess the socio-economic and environmental co-benefits of human-centric building (re)design for different stakeholders [69].

4.2. Existing challenges

A major challenge in human-centric (re)design is the uncertainty in design methodologies. Current approaches typically assume static climatic and occupancy conditions, even though real-world scenarios involve significant variability [70,71]. The industry must shift towards designing for uncertainty, incorporating adaptability, sufficiency, and performance robustness into new construction and renovation projects. This requires the development of methodologies that account for this variability to ensure that buildings remain functional and comfortable under diverse conditions [64,72].

Despite advancements in research, many evidence-based strategies for human-centric (re)design remain underutilized in practice. Many designers and architects continue to prioritize traditional aesthetics over performance-driven solutions [73], limiting the integration of energy efficiency, indoor environmental quality, and resilience measures into actual building projects. Stakeholder resistance and fragmented decision-making further hinder the adoption of new knowledge. Building owners, developers, and investors often prioritize short-term economic returns, making it difficult to justify upfront costs for long-term sustainability strategies, especially if such costs are high [68]. Renters, who have little to no control over property upgrades, lack the agency to demand energy-efficient renovations, leaving a significant portion of the building stock unchanged despite growing awareness of sustainability and climate resilience [74].

Regulatory and policy constraints also contribute to the slow adoption of innovative (re)design strategies. Building codes and standards vary significantly across regions, leading to inconsistencies in the implementation of climate-responsive solutions [75]. While some jurisdictions have integrated sustainability requirements, many regulatory frameworks remain outdated or lack enforcement mechanisms, preventing widespread adoption of best practices in climate-resilient design. Additionally, the lack of performance-driven incentives and limited financial support for building owners further discourages the implementation of necessary upgrades [76].

4.3. Research Priorities

To address these challenges and advance the state of the art, future research will focus on four interrelated priorities (Figure 3): problem definition, stakeholder integration, policy development, and tool innovation.

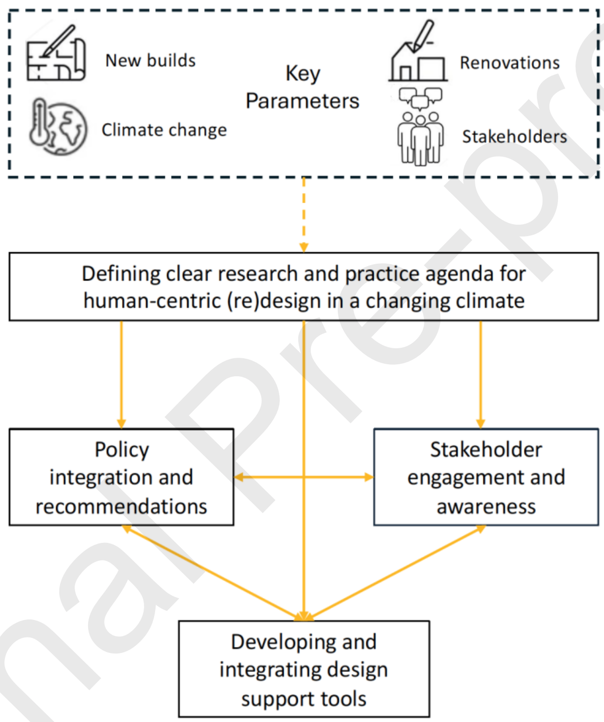

Figure 3: Human-centric re(design) research priorities for a changing climate

4.3.1. Defining a clear research and practice agenda

Defining a clear research and practice guidelines for human-centric building (re)design in a changing climate is a first priority. This involves identifying what is already known about mitigating the climate emergency, as well as the knowledge gaps. This includes establishing consensus definitions for key concepts such as resilience in the context of buildings (in collaboration with ST2) and performance indicators that account for varying climate conditions and occupancy scenarios. Adaptation, another fundamental concept, must be clearly defined and contextualized to ensure its relevance across different building types and socio-demographic contexts. Additionally, clear guidelines will be established for future research, outlining which methods should be followed, which factors should be considered, and how findings can be complementary rather than redundant.

4.3.2. Stakeholder engagement and awareness

A truly human-centric approach to building (re)design must actively involve all relevant stakeholders, including designers, building owners, policymakers, and occupants. This research priority will explore how different stakeholders influence and are affected by design and renovation decisions, ensuring that human-centric strategies are not only technologically feasible but also socially and economically viable. To this end, a global survey will be conducted to gauge stakeholder knowledge and awareness regarding human-centric design, providing insights into prevailing attitudes, barriers to adoption, and opportunities for improved engagement. A significant outcome of this effort will be the development of a novel Reflective Practice Framework for building design and construction practitioners, recognizing the absence of structured systems that allow professionals to learn from past design failures effectively, particularly those identified through post-occupancy evaluations. Strategies for effectively communicating the benefits of human-centric design to different audiences, ensuring that decision-makers, from developers to policymakers to end-users, are equipped with the necessary knowledge to support and implement human-centric solutions.

4.3.3. Policy integration and recommendations

Policies and regulations play a fundamental role in shaping building (re)design by establishing the requirements and incentives that drive industry practices and decision-making. A critical area of investigation is understanding how building codes and standards vary across different countries and how they have evolved in response to climate change. A cross-country review of building codes and guidelines will be conducted to trace their development over time, highlighting regulatory responses to extreme weather events such as heat waves, wildfires, flooding and carbon emission reductions.

A critical evaluation of the applicability and effectiveness of current standards and certifications to address the climate emergency will be undertaken as many of these frameworks are often complex, fragmented, or outdated, limiting their ability to drive meaningful change. Aligning with the goals of ST2, future research will also explore how policies can be structured to support fair and inclusive solutions, such as financial incentives, tiered regulatory requirements, or targeted assistance programs that help under-resourced communities adopt sustainable building practices.

4.3.4. Developing and integrating new tools

To support practitioners, researchers and policy makers in conceptualization and realization of human-centric built environment (re)designs, new tools are needed to integrate changing climate into decision-making. While building performance simulation tools have been used for decades in a rather disintegrated manner, there is a growing demand for development and integration of multi-domain building simulation platforms, covering operational performance, life cycle assessment (LCA), indoor environmental quality (IEQ), occupant comfort, health and well-being, and thermal resilience. Further, specialized databases and analysis platforms need to be investigated and developed for macro- and micro-climate data under different climate change scenarios, along with libraries of occupant prototypes usable in computational design support workflows. Lastly, the potential of both historic and emerging design practices should be explored in the context of climate emergency. These span from revisiting the role of an integrated design studio to the state-of-the-art design practices assisted by virtual reality (VR) and generative artificial intelligence.

5. Subtask 4: Operations

ST4 seeks to generate a better understanding of how the roles and behaviors of stakeholders—such as occupants and facility operators—change throughout the building services life in the context of climate change and the energy transition

5.1. State of the art

Occupant-centric control (OCC) is defined as an indoor climate control approach whereby occupancy and occupant preference information are used in the operation of building energy systems [77,78]. Occupancy-centric controls research aims at developing models that forecast occupant presence and/or counts in a given room/zone based on sparse low-cost sensor networks including but not limited to motion detectors, CO_2 sensors, and Wi-Fi-enabled device counts which are then used to adapt temperature setpoints and/or outdoor airflow rates. However, occupant-behavior (OB)-centric controls research is primarily aimed at developing methods to learn/infer preferences with the goal to create personalized indoor climates [18] to eliminate the inherent conservativeness in finding a global setpoint intended to make the majority of occupants in a building comfortable [79]. State-of-the-art OCC treats occupants as a source of information [77], where occupant data (i.e., presence, count, activity/preference) flow from occupants to a building management system (BMS) to execute control decisions. In the literature, this is also referred to as human-*in*-the-loop controls [80].

Modelling energy-related occupant behavior (OB) has been an area of interest in human-centric operation for the past two decades [1,81]. Models have been developed to represent occupants' interactions with operable windows, thermostats, electric lighting, window shades, plug-in office equipment, and household appliances. These models were intended to account for the stochastic patterns in user behavior as well as the inter-occupant diversity in a sample population and have been used to design OCC strategies or simply to better understand occupancy and OB patterns.

An important line of inquiry for both OB modelling and OCC has been to understand how control interface design affects OB patterns and the performance of OCC strategies, which relates to ST1 objectives. Design of control interfaces, those integrated into BMS (e.g., thermostats, lighting, energy management systems) and others (e.g., windows), play a profound role on occupant behavior and represent the shared boundary between users and building technologies [2].

5.2. Existing challenges and knowledge gaps

This subtask focuses on building users (e.g., occupants, facility managers, maintenance technicians) and their interactions with building systems and other stakeholders during the operations phase of buildings. The building operations phase is a broad problem area, encompassing operations, maintenance, and management. However, some major gaps in knowledge remain. For example, OB-centric controls largely focused on adapting operation to individual comfort preferences. Behavior nudging, in lieu of preference learning, remains as an understudied branch of OB-centric controls which are needed to encourage the sufficiency behaviors described in ST2. Moreover, in most OCC implementations, occupant data is used in making control decisions but little, if any, information is shared with the occupants in terms of how their presence, count, or activity data are used. Further research is needed in conjunction with ST1 to examine how occupant engagement and feedback can improve the comfort and energy performance of OCC strategies.

On the modelling front, OB has been modelled by using physical measurements of indoor and outdoor climate variables. This approach largely disregarded the impact of energy cost on OB, which is particularly problematic in residential buildings where occupants are responsible for the utility costs [82]. Moreover, adoption of dynamic electricity pricing in many jurisdictions calls the suitability of existing OB models into question.

OCC strategies and OB modelling have not focused on different socioeconomic segments of the population, which result in OCC strategies and OB models largely disregarding building typologies widely used by priority communities (e.g., older adults, children, people with disabilities). As indoor climate plays an important role in health and well-being, emerging sensing technologies (mobile devices, wearables like smartwatches and rings) represent an untapped opportunity for monitoring of priority populations [83].

Finally, OCC strategies so far largely overlooked recent trends in hybrid work arrangements. Widespread adoption of hybrid work requires a renewed thinking of space use and indoor climate control. Matching indoor climate preferences of individuals and their personal schedules remains a major challenge for organizations with hybrid work arrangements [84]. Strategies optimizing space use and indoor climate control in hybrid work environments have the potential to dramatically reduce operational energy use and GHG emissions.

Notably, these knowledge gaps are a direct outcome of emerging societal trends, the energy transition and climate change. For example, increased popularity of dynamic electricity pricing, as a financial driver of OB, can be seen as an outcome of the adoption of electrification as a primary decarbonization strategy.

5.3. Research priorities

To address these challenges and knowledge gaps, ST4 activities are grouped within six themes: (1) behavior nudging in OCC; (2) human-*on*-the-loop controls; (3) econometric models for OB; (4) control interface design; (5) improving health and wellbeing of priority populations via indoor climate monitoring and control; and (6) space management and optimization for hybrid work environments.

5.3.1. Behavior nudging in OCC

Behavior nudging is a new branch of OB-centric controls alongside preference-learning. The nudges, in this context, create just-in-time minor interventions to encourage energy-saving behavior which will be critical in the energy transition and for joint optimization of human-building relationships necessary for adapting to extreme events. For example, a paternal nudge can be defined as reducing temperature setpoints in winter, which induces a minor thermal discomfort, to encourage windows closing actions, if windows are left open at cold outdoor temperatures [87]. The activities in this theme will create a library of behavior nudges suitable to improve energy performance and promote climate resilience in buildings and document field experience and success of behavior nudges. The field implementation studies of behavior nudges will be appended to the OCC case study library of Annex 79 [18].

5.3.2 Human-on-the-loop control

Human-on-the-loop control swaps the unidirectional data flow from occupants to a BMS with bi-directional data exchange between occupants and a BMS. The goal is to elevate occupants to a supervisory role on the control loop by providing them with relevant information and custom-curated automation options to select from. Simply put, while traditional OCC treats occupants as sensors, human-on-the-loop considers them as humans – capable of making rational decisions when presented with choices and relevant information. For example, an occupant can be occasionally prompted to select a choice from several discrete sets of automation options. Activities planned in this theme will develop different human-on-the-loop control algorithms and conduct field implementation studies to document occupant experience, implementation challenges, and energy performance.

5.3.3. Econometric models for residential OB

This theme explores how households adapt their energy use with dynamic electricity pricing. For example: How do households alter their appliance and thermostat use behavior during on-peak periods (when the electricity prices are higher)? The objective is to develop a suite of residential appliance and thermostat use behavior models that explain variations in OB with different utility tariff structures. This includes comparing alternatives like introducing penalties for on-peak energy use vs. offering rebates for reducing on-peak energy use or offering a fixed steady-periodic time-of-use vs. critical peak pricing (advance notifications sent via email or mobile app alerts sent by the utility) [89]. The subtask will also study how technology ownership (e.g., smart thermostats and appliances) affects households' ability to reduce demand during peak periods. Finally, behavioral response of different socioeconomic clusters to dynamic price signals will be compared.

5.3.4. Control interfaces design

The objective of this theme is to document the complex interactions between control design features and OB [91-93] to develop recommendations for future control interface designs. . Surveys will be conducted with participants testing different design features, and expert interviews will be conducted with key stakeholders (e.g., thermostat manufacturers) [94]. These efforts will provide evidence towards the standardization of control interfaces which has been identified as a critical step toward 1) improving the user experience during the building operations phase and 2) enabling more accurate modeling of HBI during the operations phase.

5.3.5. Improving health and wellbeing of priority communities via indoor climate monitoring and control

Emerging sensing technologies (mobile devices, wearables like smartwatches and rings) represent an untapped opportunity to improve the health and wellbeing of priority communities/vulnerable populations [83]. Specifically, just-in-time adaptive interventions (JITAIs) [95] and gamification [96] relying on these technologies can provide guidance to enhance occupant well-being through behavioral adaptation (e.g., opening/closing windows for indoor air quality and noise mitigation, adjusting shades before overheating). The activities planned in this theme consider how building operations, controls, and sensing can better support the health and well-being. Data collected in this theme will enable new OB models and OCC strategies intended for building typologies widely used by these populations (e.g., retirement homes, school buildings including daycares, and hospitals).

5.3.6. Space management and optimization for hybrid work environments

Aligning individual indoor climate preferences with personal schedules presents a significant challenge for organizations adopting hybrid work models. Effective space use in hybrid work environments enable consolidation of building portfolios into smaller clusters, which is expected to reduce energy use and GHG emissions. Addressing this issue necessitates the collection and analysis of occupant-level data, including environmental preferences and other factors that support collaboration, social interaction, and the minimization of distractions. To this end, the activities in this theme will develop solutions to optimize the space management process to maximize occupant well-being, space utilization, and energy performance.

Notably, the six themes of ST4 are all directions emerging from recent trends in electrification of the building sector (e.g., dynamic electricity pricing, automated demand response, direct load control, ownership and use of heat pumps, electric vehicles, smart appliances, thermostats, and automation), hybrid/telework work, solutions enabling bi-directional information exchange with building operators (e.g., just-in-time adaptive interventions (JITAI), ecological momentary assessments, sensors in wearable devices). Through a multidisciplinary group of experts, the subtask will blend domain expertise in building engineering (e.g., HVAC systems; control and automation; indoor environmental quality) with human behavior (e.g., behavioral economics, social scientists) with the aim of readying building operations for the energy transition and buttressing existing operations strategies and developing new strategies for operating buildings during extreme events.

6 Discussion and Next Steps

This paper introduces the Human-Centric Buildings for a Changing Climate (HCB) Network—a global research initiative responding to the urgent need for more integrative, equity-informed approaches to building design, operation, and performance. While building systems have advanced significantly in energy efficiency and technology, occupant behavior and well-being remain underrepresented in both modeling and policy frameworks. This omission limits the effectiveness of current strategies, particularly in the face of extreme climate events, rising energy demand, and unequal access to resilient infrastructure.

The Network addresses this gap by targeting the intersection of building performance and human needs through an integrated research approach. The four subtasks outlined—spanning individual behavior, community-scale dynamics, design, and operations—reflect a systems-level strategy that bridges technical and social dimensions across diverse contexts. A key strength of the Network is its interdisciplinary composition, enabling the development of robust tools, frameworks, and guidelines that are both evidence-based and adaptable to regional variation.

The Network seeks to redefine the role of building occupants and stakeholders in advancing the energy transition, while promoting resilience, equity, and comfort. It aims to achieve this by investigating occupant responses to climate change, developing performance indicators for sufficiency and resilience, and providing design and operational guidance that accounts for climate adaptation and stakeholder diversity. By integrating insights from engineering, social sciences, health sciences, and urban planning, the Network delivers actionable strategies to bridge the gap between occupant behavior and energy-efficient building performance.

This work is not without limitations. Integrating behavioral data into technical models remains a methodological challenge, and the diversity of cultural, climatic, and regulatory conditions necessitates careful adaptation of proposed strategies. Future efforts will focus on piloting and validating the tools developed, strengthening partnerships with policymakers, industry, and practitioners, and expanding data collection in underrepresented regions. By centering human agency and lived experience, the HCB Network offers a timely and critical contribution to the global effort to decarbonize the built environment while enhancing health, equity, and climate resilience.

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Human-centric buildings for a changing climate. Introducing a new International Energy Agency Research Network

Highlights:

- The Human-Centric Buildings for a Changing Climate (HCB) Network is introduced
- Key research: individual/community interactions, building (re)design and operations
- Research goals, framework, and considerations presented for the four subtasks