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HVAC through a sufficiency Lens: Reframing comfort and energy demand in buildings

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ABSTRACT

While building HVAC system research has long emphasized energy efficiency, efficiency alone cannot deliver the emission reductions required in the building sector. The sufficiency approach aims to reduce overall energy demand while maintaining thermal comfort, well-being, and equity. This article defines the concept of sufficient HVAC; explores existing and emerging strategies such as adaptive comfort, zoning, and occupancy-based operation, and proposes a set of metrics for evaluating HVAC performance from a sufficiency perspective. The indicators capture energy use, greenhouse gas emissions, ventilation provision, thermal comfort, and spatial selectivity at the occupant level, including energy per occupant-hour, greenhouse gas emissions per occupant-hour, ventilation per occupant-hour, comfort compliance fraction, and average zone area. A published building simulation case is used to illustrate how selected metrics can be computed and how sufficiency-oriented indicators reveal differences in HVAC service delivery beyond conventional efficiency measures.

1. Introduction

Heating, ventilation, and air-conditioning (HVAC) systems dominate energy use within buildings, shaping both indoor comfort and carbon emissions. Globally, the building sector accounts for approximately 34% of total final energy consumption and about 37% of energy- and process-related CO_2 emissions [1,2]. While energy efficiency approaches (e.g., well-insulated building envelopes, efficient furnaces and air-conditioners, heat pumps) have significantly reduced resource requirements to maintain comfortable indoor conditions, factors such as growth in space cooling, higher expectations for a narrow range of indoor conditions, and increasing floor area per person have counteracted the benefit. For example, space cooling now accounts for 10% of global electricity use, as air-conditioning transitions from a technology concentrated in developed countries to widespread [3]. The International Energy Agency (IEA) projects that two-thirds of households globally will have air-conditioning installed by 2050, with most growth in developing countries such as China and India. With such exponential growth, alternative sufficiency-based means to maintain comfortable conditions are imperative.

While energy efficiency remains essential, it alone cannot deliver the emission reductions required. The sufficiency approach complements efficiency by addressing the question of how much comfort and conditioning are truly necessary. It challenges the necessity to heat and cool buildings in their entirety and to use air temperature as the indicator for thermal comfort. The Intergovernmental Panel on Climate Change (IPCC) identifies sufficiency as one of the most significant levers for reducing emissions in the building sector. Sufficiency refers to *"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"*. The same report warns that utilizing air-conditioning will continue to increase globally with rising temperatures, resulting in even higher energy demand [4].

Achieving sustainability and emissions targets requires combining sufficiency, efficiency, and renewable energy measures to deliver essential HVAC services such as thermal comfort responsibly and equitably [5]. While energy sufficiency is increasingly recognized as a necessary pathway to reduce building sector demand, major assessments and recent reviews show that it has been addressed primarily through high-level demand side measures rather than operational evaluation of building systems [4,6,7]. Recent reviews explicitly identify the lack of operational, per-capita, and system-level metrics as key gap and call for further research to quantify sufficiency impacts during building use [8,9]. In parallel, adaptive comfort, personal comfort systems, and occupancy-based zoning are widely studied within HVAC research but are typically evaluated through efficiency or control-performance lenses

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rather than demand sufficiency [10,11]. This paper addresses this gap by reframing familiar HVAC strategies through a sufficiency lens and proposing operational metrics to assess whether HVAC energy use is aligned with occupant needs rather than optimized per unit floor area.

2. Defining HVAC sufficiency

While all three of IPCC's pillars to reducing carbon emissions of buildings are critical to achieving targets, sufficiency has received comparatively little attention. Table 1 provides a summary of the strategies of the three pillars to reduce energy use and carbon emissions. Note that because sufficiency approaches the problem from the demand side, but renewables approach it from the supply side, the table has blanks.

While the focus of this paper is HVAC systems, Table 1 situates HVAC sufficiency within the broader building energy chain to clarify how demand-side sufficiency differs conceptually from efficiency- and supply-oriented strategies.

HVAC sufficiency challenges uniform, continuous space conditioning by recognizing occupant adaptability, spatial and temporal heterogeneity in comfort demand, and the multisensory nature of thermal comfort. Accordingly, sufficiency-oriented HVAC strategies employ adaptive comfort and relaxed setpoints, zoning and occupancy-based control, and alternative comfort modalities such as personal comfort systems, radiant exchange, and air movement to deliver targeted, demand-aware comfort at reduced energy intensity [12,13,14]. Table 2 summarizes key approaches and implementation strategies of HVAC sufficiency.

Table 2
Summary of HVAC sufficiency approaches and key implementation strategies.

Sufficiency principle	Implementation strategies
Comfortable people; not buildings (intensity)	• High-resolution HVAC zoning to tailor conditioning to occupied spaces and different activities [15,16,17] • Personal comfort devices (e.g., chairs, desks, and beds with integrated heating and/or cooling systems [18,19]
Holistic comfort; not air temperature (perceptual)	• Localized radiant systems that allow a less energy-intense air temperature [20] • Operable windows to control air movement [21] • Controlled air movement via ceiling, furniture-integrated, or wearable fans [22] • Humidity control for cooling perception
Adaptive opportunities; not HVAC (spatial)	• Ample adaptive opportunities (e.g., freedom on clothing level, access to hot/cold beverages, freedom to relocate) [11,20] • Seasonal occupancy patterns, such as increased use of lower-level or shaded spaces during summer for passive cooling and greater concentration of activity in upper, sun-exposed spaces during winter for passive solar gains.

2.1. *Challenging fixed setpoints and promoting adaptive thermal comfort models (Intensity level)*

Traditional HVAC systems commonly rely on fixed indoor air temperature setpoints, often clustered around 22–23 °C, reflecting static comfort assumption embedded in conventional design practice [23]. Adaptive comfort models, developed through extensive field studies, show that occupants' thermal comfort is influenced by outdoor temperature, prior exposure, and behavioral adjustments such as clothing or activity level. Adjusting heating and cooling setpoints and deadbands in alignment with these models can yield substantial energy savings without compromising comfort [11,24].

Within a sufficiency perspective, these adaptive approaches embody the principle of avoiding unnecessary energy demand rather than simply optimizing efficiency [4,25]. They highlight how comfort can be maintained through adaptation and user engagement rather than continuous mechanical regulation. For instance, Cui and Xue [26] demonstrated that preference-inspired deep reinforcement learning (DRL) controls can dynamically adjust HVAC setpoints while maintaining comfort violations below 0.8%, achieving up to 9.4% energy savings. Similarly, Xue et al. [27] applied a multi-agent DRL framework to balance comfort and efficiency across multiple zones, achieving up to

Table 1
Conceptual comparison of sufficiency, efficiency, and renewable energy strategies across the building energy chain, highlighting implications for HVAC-related design, distribution, and operation.

	Example	Sufficiency	Efficiency	Renewables
Energy supply	Power plant	Displace power plant demand by reduced load	High-efficiency plants, e.g., co-generation	Solar and wind-based plants
Energy delivery to building	Transmission lines, thermal energy network	–	High-voltage lines, well-insulated thermal networks	Distributed grid to reduce transmission losses
HVAC plant	Boiler, heat pump	Eliminate the need where possible	High efficiency or high COP plants; use of ambient heat (e.g., waste heat, ground)	Solar thermal collectors
HVAC distribution	Ducts, hydronic loops	Focus on small-scale localized systems that do not require distribution; eliminate the need where possible	Short, well-insulated pipes/ducts and high-efficiency fans/pumps, e.g., variable speed drives	–
Zoning	Single-zone, multi-zone	Zoned approach to focus conditioning only on occupied spaces	–	Floor plan to promote air-mixing and natural ventilation for passive solar buildings
Terminal units	Radiant panels, diffusers	Alternate and localized means for comfort, e.g., ceiling fans, personal comfort systems, local radiant surfaces	Radiant floors or ceilings	Radiant preferred over air systems for solar thermal applications
Indoor environment sensing	Thermostats	Occupants themselves	Thermostats, thermostatic valves, CO_2 concentration	–
Measurands	Room air temperature	Operative temperature; occupant-reported comfort	Air temperature	–
Control strategies	On-off, PID based on air temperature	Adaptive comfort (e.g., operable windows, clothing, hot beverages); control based on occupant comfort; occupancy-based zoned control; demand-controlled ventilation; change setpoints to or outside of traditional limits	Control based on "ideal temperature ranges"; optimal stop/start	Demand-response to align HVAC use with renewable energy availability
Demand side	Well-insulated envelope	Smaller building footprint and adaptable spaces	Well-insulated air-tight envelope with energy-recovery ventilation	Passive solar

6.7% reductions in total energy use.

Together, these approaches translate sufficiency into practice by embedding flexibility, user adaptation, and real-time responsiveness into building operation. As Malik et al. [25] emphasize, sufficiency requires prioritizing behavioral and systemic adjustments before pursuing technological upgrades. This perspective represents a cultural and operational transformation in HVAC management from fixed, homogeneous comfort standards toward dynamic, occupant-centered adaptability consistent with sufficiency-based building design.

2.2. Comfort through means other than air temperature (Perceptual level)

Sufficiency also extends beyond air temperature regulation to embrace alternative comfort pathways, including air movement, humidity control, radiant exchange, and personal comfort systems. Ceiling fans and fan-integrated air conditioners, for instance, can enhance perceived comfort by increasing convective heat transfer, allowing higher cooling setpoints and reducing energy demand [12,13]. Omrani et al. [13] further demonstrated that fan-assisted ventilation can enhance indoor air quality while lowering dependence on mechanical cooling.

Complementary design and behavioral measures like mixed-mode ventilation, adaptive clothing, and passive cooling can also reduce or replace air-conditioning in appropriate climates [14]. Recent reinforcement learning–based approaches integrate these perceptual strategies with adaptive control to improve thermal resilience and achieve substantial energy reductions [28,29].

In the context of climate change, Berardi and Jafarpur [30] projected that heating demand in Canadian buildings may decline by 18–33%, while cooling demand could rise by up to 126% by 2070. This shift highlights the growing importance of adaptive cooling and perceptual sufficiency strategies, particularly in cold-climate housing where overreliance on mechanical cooling may undermine sustainability goals. By promoting perceptual adaptability through air movement, passive design, and intelligent control, HVAC systems can ensure occupant well-being while staying within planetary limits [4].

2.3. Reducing the conditioned area of buildings through zoning (Spatial level)

At the spatial level, sufficiency focuses on limiting the volume or area of conditioned space while preserving essential comfort. More broadly, sufficiency can be understood as operating between two boundaries: a lower limit defined by minimally acceptable living conditions and an upper limit defined by planetary constraints. Recent housing sufficiency research emphasizes avoiding excess provision of floor area by prioritizing effective space use, flexibility, and demand reduction rather than maximization of conditioned space [31]. This aligns with HVAC zoning strategies that condition only occupied areas, minimizing underutilized spaces while maintaining comfort. From an equity perspective, this approach avoids over-conditioning lightly used spaces while ensuring that occupied zones receive adequate thermal service, reducing per-capita energy demand without lowering comfort standards. Such alignment is particularly relevant for households facing energy affordability constraints, where more targeted conditioning can support access to essential thermal comfort without unnecessary cost burdens. Zoning therefore represents a key sufficiency measure that aligns HVAC operation with occupancy patterns and spatial needs. By conditioning only occupied zones or rooms, significant reductions in heating and cooling loads can be achieved [15,16]. Zoning need not be achieved with advanced equipment and controls and could be as simple as dividing individually conditioned spaces with well-sealed doors. While the examples and implications discussed here are relevant to both residential and commercial buildings, zoning is presented as a general sufficiency principle whose implementation varies by building type, scale, and use.

Empirical research indicates that zoned HVAC systems can reduce energy consumption by 21–42% compared to conventional non-zoned configurations [17]. Hu et al. [20] and Zhou et al. [32] further observed that zoning granularity and control strategy strongly influence energy predictions. Compared to unsegmented building models, refined zoning can increase predicted heating demand by up to 8.7% and amplify cooling demand by as much as 49-fold, as it captures spatial heterogeneity and localized peak loads that are otherwise masked by averaging. Moreover, energy demand and flexibility tend to concentrate in specific areas: the top 30% of building zones often account for nearly 60% of total HVAC energy use [17].

Recent studies also emphasize the integration of intelligent zoning algorithms with occupancy detection. Qaisar et al. [16] found that multi-zone occupancy-based systems that condition only occupied areas significantly reduce energy use while maintaining comfort. In practice, such sufficiency-oriented operation does not require entirely new control architectures, but a shift in control priorities within existing building automation systems. Established BAS functions, such as occupancy-based scheduling, adaptive or widened setpoints, and supervisory logic that prioritizes conditioning in occupied zones while allowing non-critical spaces to operate within broader comfort bounds, can be sequenced to operationalize spatial sufficiency. These findings reinforce sufficiency-oriented control principles that combine spatial precision with operational restraint, ensuring that HVAC energy is delivered only where and when it contributes directly to occupant's well-being.

3. Metrics for HVAC sufficiency evaluation

Traditional approaches to evaluating HVAC performance often take tightly controlled indoor air temperature as a given, reinforcing conventional practice. Common metrics such as plant efficiency and energy use intensity (energy per unit floor area) assess how efficiently energy is delivered, but do not directly question whether conditioning is aligned with occupant needs in space and time.

To evaluate HVAC performance through a sufficiency lens, this paper proposes five metrics that capture energy use, greenhouse gas emissions, ventilation provision, thermal comfort, and spatial selectivity at the occupant level. For thermal comfort, the framework allows the use of applicable criteria (e.g., PMV–PPD, adaptive comfort models, or other standard-based thresholds). Together, these metrics provide a concise and operational framework for assessing whether HVAC energy use is aligned with occupant needs rather than optimized solely per unit floor area. Table 3 summarizes the proposed metrics.

3.1. Illustrative application of sufficiency metrics using a published zoning simulation

To illustrate the operational computability of the proposed sufficiency metrics, selected indicators were applied to a published EnergyPlus simulation of a 135 m^2 detached Canadian dwelling with four occupants. The referenced study compared a conventional single-zone HVAC configuration with a three-zone configuration enabling independent conditioning of basement, first floor, and second floor [33].

For the scenario considered in this section (no telework and no thermostat setback), thermostat setpoints, ventilation schedules, and occupancy patterns are identical across configurations. Under this schedule, the dwelling is occupied during evenings, nights, and weekends, corresponding to approximately 6,136 occupied hours per year (24,544 occupant-hours). Greenhouse gas emissions are assumed proportional to HVAC energy consumption under a constant emission factor [33].

Table 4 summarizes the computation of sample sufficiency metrics using the reported simulation outputs.

For the selected scenario, multi-zone control reduces annual HVAC energy consumption from 62.96 GJ to 46.38 GJ, corresponding to a 26.3% reduction. Because floor area and occupancy patterns remain unchanged between configurations, this reduction is reflected

Table 3
Summary of sample metrics for evaluating HVAC sufficiency.

Metric	Definition / Scope	Formula	Example Units
Energy per occupant-hour (Ep)	Total HVAC energy use normalized by occupant-hour; captures per-capita sufficiency	$Ep = \frac{E_{HVACtotal}}{OccupantHour} = \frac{\sum_{t=1}^{8760} E_{HVAC,t}}{\sum_{t=1}^{8760} N_t}$	kWh per occupant-hour
GHG per occupant-hour (GHGp)	Sufficiency and carbon outcome per occupant-hour	$GHGp = \frac{HVACGHGEmission}{OccupantHour} = \frac{\sum_{t=1}^{8760} EF_t . E_{HVAC,t}}{\sum_{t=1}^{8760} N_t}$	kg CO_2 per occupant-hour
Ventilation per occupant-hour (Vp)	Represents ventilation service delivered relative to occupant presence	$Vp = \frac{Totaldeliveredairflow}{OccupantHour} = \frac{\sum_{t=1}^{8760} V_{OA,t}}{\sum_{t=1}^{8760} N_t}$	Liters per occupant-hour
Comfort compliance fraction (CCF)	Fraction of occupied-hours meeting comfort criteria	$CCF = \frac{Occupied\ hours\ meeting\ comfort}{Total\ occupied\ hours}$	–
Average zone area (AZA)	Total conditioned floor area divided by the number of thermal zones	$AZA = \frac{A_{total}}{N_{zone}}$	m^2 per zone

Table 4
Application of selected sufficiency metrics to published zoning simulation (annual basis).

	Conventional	Sufficient HVAC
Number of HVAC zones	1	3
Total HVAC energy (GJ/yr)	62.96	46.38
Energy use intensity (GJ/m^2.yr)	0.466	0.344
Energy per occupant-hour (kWh/occupant.hour)	0.713	0.525
Average zone area (m^2)	135	45

Note: All values derived from simulation results reported in [33].

consistently in both conventional efficiency indicator (e.g., EUI) and the proposed occupant-normalized metric (energy per occupant-hour). In contrast, the average zone area (AZA) reflects the change in spatial controllability introduced by zoning. The referenced study also reports occasional overheating in the single-zone configuration due to uniform heating control, which was mitigated under multi-zone operation through independent floor-level regulation [33]. In addition to energy indicators, the framework also includes a comfort compliance fraction, representing the share of occupied hours meeting comfort criteria.

Advances in occupancy sensing, modelling, and building automation systems now enable high-resolution detection and representation of occupant presence and behavior [34], facilitating normalization and performance assessment at the occupant level. The proposed metrics are therefore directly computable from standard annual simulation outputs, including annual HVAC energy use, occupancy schedules, zoning configurations, and control assumptions, and can be combined with thermal comfort criteria (e.g., comfort compliance fractions) to assess both energy use and service adequacy. This application is presented to demonstrate metric computability and evaluative differentiation rather than to introduce new empirical modeling.

3.2. *Future Directions*

In modern times, widespread contemporary HVAC approaches and comfort expectations are ingrained in our minds and public discourse. For example, comfort is equated with air temperature. Advancing the concept of HVAC sufficiency will require significant changes in the ways buildings and their systems are designed and operated. It will require validation and public acceptance. Future studies should test and refine the proposed methods and metrics across different climates, building types, and occupancy patterns to assess how they perform in real conditions.

This paper does not introduce new HVAC technologies or control algorithms; rather, it proposes an evaluative reframing of existing strategies through a sufficiency-oriented perspective. However, we hope that reframing HVAC through a sufficiency lens leads to better technologies that yield both sustainability and comfort gains. To bridge the conceptual principles with practical application, developing the control frameworks through adaptive setpoints, zoning, and occupant-responsive strategies will be essential. Integration of these principles within existing building management and retrofit programs can support measurable reductions in energy demand.

At the policy and design level, building codes and performance standards should begin to recognize sufficiency as a complement to efficiency and renewable integration. Incentives for adaptive comfort design, spatial zoning, and user-centered controls could accelerate adoption within both new construction and retrofit contexts.

Finally, future work should examine the behavioral and cultural dimensions of sufficiency, including how occupants perceive and negotiate comfort under changing climatic conditions. A deeper understanding of these human factors will be critical for translating sufficiency from theory to an operational paradigm for low-carbon, resilient buildings.

CRediT authorship contribution statement

Mojtaba Nateqi: Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **William O'Brien:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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