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Ten questions concerning housing sufficiency

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ABSTRACT

Housing sufficiency is an emerging concept in the provision of environmentally sustainable housing. It aims for demand-side strategies that reduce excessive, aggregate consumption levels to promote efficient resource utilization and sustainability in the construction sector while providing everyone with a decent standard of housing. However, it is challenging to implement as it interferes with housing-related social and cultural norms. This paper poses and answers ten questions that highlight the challenges, opportunities, and examples of sufficiency strategies in the context of housing provision and the environmental crisis. Question 1 discusses the need for sufficiency as a tool to complement supply-side strategies including efficiency and renewable energy strategies in providing housing. Question 2 examines the concept of housing sufficiency from different perspectives, such as ecological economics and social ecology. Question 3 summarizes the methods used to measure housing sufficiency, with specific focus on the upper and lower limits that respect planetary boundaries and basic human needs. Questions 4 and 5 describe the benefits, potential drawbacks, and rebound effects of housing sufficiency. Questions 6 and 7 examine housing sufficiency in developed and developing countries, respectively. Questions 8 and 9 discuss design strategies, housing occupancy, and tenure models that are needed for housing sufficiency. Finally, Question 10 provides a summary of policies and regulations that are needed to systematically support the implementation of sufficiency strategies. The questions and answers provide insights for wider application of housing sufficiency in research and practice.

1. Introduction

Housing is a human necessity that provides shelter and allows occupants to access employment, essential services, and social activities [1]. At the same time, its provision leads to resource use, resulting in significant greenhouse gas (GHG) emissions that contribute to climate change [2,3]. In 2020, about 31 % of global resource consumption (33 billion tonnes of materials) was attributed to the built environment that supports housing [4]. Cities in most countries need to build more homes to accommodate the growing population due to urbanization, migration, and changes in demographics and household sizes [5–7]. Beyond this absolute need, additional housing demand is driven by factors such as wealth accumulation, welfare function associated with home ownership (e.g., security of investment, tax privileges of homeownership), changing household structure, and security in older age [8]. The demand to build more homes precipitates a growing interest in research and policy to reduce associated resource use and GHG emissions from housing. Three common strategies, including design efficiency (e.g., designing buildings with less hallways, materially efficient structural design), efficiency from technological innovation (e.g., low-carbon concrete, energy efficient and demand-controlled heating, ventilation, and air conditioning (HVAC) systems), and renewables (e.g., installing rooftop or building-integrated photovoltaics), are used to reduce resource use and GHG emissions associated with housing [9,10]. However, the

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utilization of efficient technologies and renewables have limited ability to reduce overall negative environmental impacts over time [4]. For example, the increased energy efficiency of Canadian homes between 1990 and 2013 was associated with a per capita reduction of 18 % housing stock energy use and 29 % in GHG emissions, while dwelling size per capita increased by 28 % during the same period [11]. This increase in space consumption is likely partly due to the rebound effects of efficiency measures (when consumption of one good or service is reduced but leads to the greater consumption of something else) [4] and housing market functions such as higher household incomes, tax incentives, and lower interest rates [8].

Housing sufficiency is an emerging, yet underutilized, pathway for providing housing with lower GHG impacts. In contrast to efficiency and renewable strategies, sufficiency aims for reductions in excessive, aggregate consumption levels. Recent literature associates housing sufficiency with the consumption corridors - or safe operating space - to meet basic human needs for housing and services while respecting ecological limits [12–15]. Fig. 1 illustrates the consumption corridor with an example housing sufficiency model for space standard after Cohen [12]. The traditional definition of sufficiency was used to describe the universal basic needs for every human to achieve a decent living standard, not suffer deprivation, and be able to participate in the society [3,16]. This refers to the bottom of the consumption corridor or the minimum social needs for housing provision and services [12]. Previous works focused on defining the expected outcomes of housing sufficiency by determining the requirements of decent living standards for human well-being [3]. The ecological ceiling of the consumption corridor is a concept associated with the planetary boundaries [17,18] and the remaining carbon or emission budget in climate policy [19]. Focusing on the remaining carbon budget, it is described by the Sixth Assessment Report of the International Panel on Climate Change as "the total net amount of CO_2 that human activities can still release in the atmosphere while keeping global warming to a specified level (e.g., 1.5 °C or 2 °C relative to pre-industrial levels) [20]". This remaining carbon budget is allocated to every sector in the economy including housing and can determine how much we should limit dwelling size per capita to remain within the budget. Table 1 summarizes the different concepts associated with housing sufficiency in the literature.

The literature on housing sufficiency is broad in scope as it pertains to the metrics used for assessment and implementation strategies. Housing sufficiency is often measured quantitatively using a range of metrics (e.g., space, energy, materials, carbon), but the type of metric selected is dependent on the goal of the study [13]. Some works have explored available design strategies, occupancy and tenancy models to realize the outcomes of housing sufficiency (e.g., [12,28,29]). However, discussions on the applicability of these strategies and models to other jurisdictions and their associated risks and pitfalls are rarely examined. Finally, there is lack of studies synthesizing existing policies and regulations that operationalize design strategies, occupancy, and tenancy models.

This paper aims to provide a broader understanding of housing sufficiency by addressing ten key questions. We posit that housing sufficiency requires interactions among housing design, urban planning, policy making, legal and governance frameworks to be effective, and that it needs to challenge the 20th century housing provision practices. Here, we adopt the concept of consumption corridors to define housing sufficiency and emphasize the socio-ecological aspects of housing construction and use. The primary measure of sufficiency used in this paper is space (i.e., dwelling size per capita) but other measures including materials, energy, carbon emissions, and land use are used when discussing broader impacts. This paper does not redefine the expected outcomes of housing sufficiency nor quantitatively determine a sufficient level of housing services, minimum social floor, and maximum ecological ceiling. Instead, we specify systematic changes that are needed to provide people with sufficient housing (with specific examples from a few developed and developing countries) and important areas for future research. Policies and regulations that systematically support the implementation of housing sufficiency strategies are also

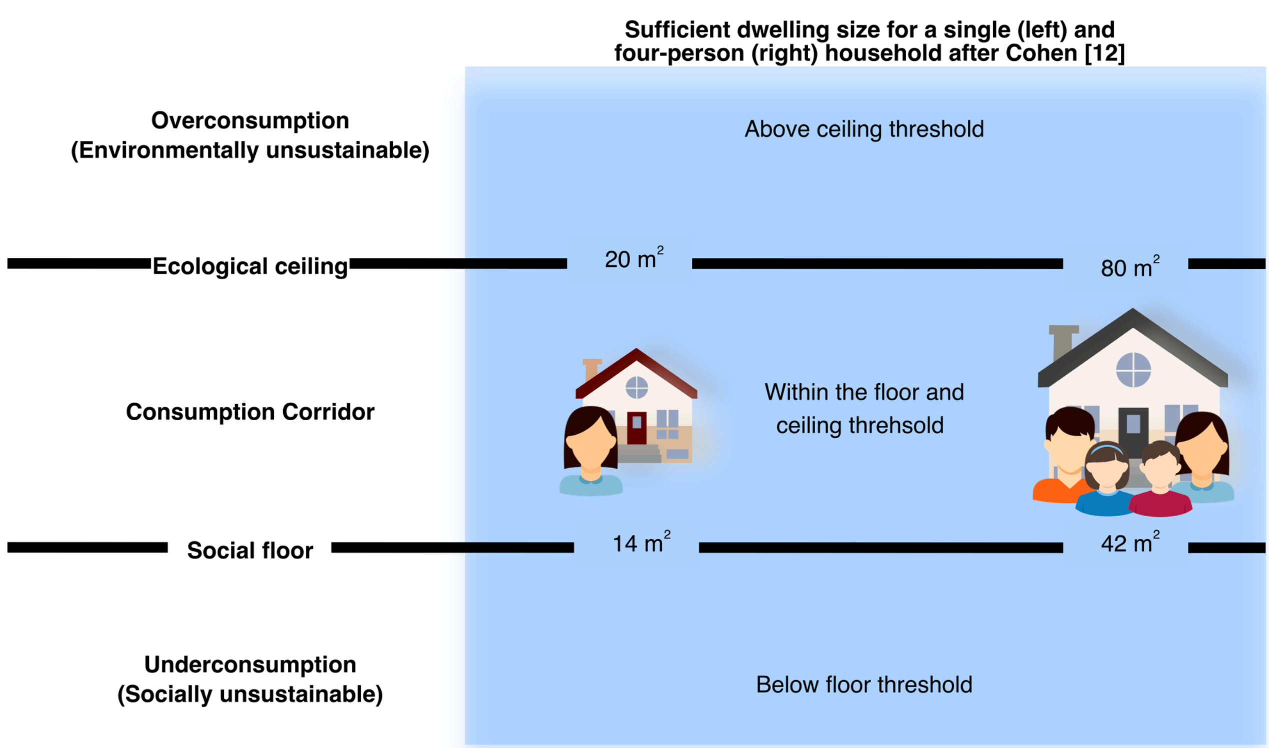

Fig. 1. Illustrations of the consumption corridors, thresholds, and example sufficient home sizes after Cohen [12]. The sufficient home sizes considered for a single- and four-person household are between 14 and 20 m^2 and between 42 and 80 m^2, respectively.

Table 1
Definitions of housing sufficiency and example metrics based on consumption corridor, decent living standard, and emission budget literature.

Concept	Definition	Example metrics and thresholds[a]	Relevant literature
Consumption corridor	Boundary that establishes living standards to meet basic human needs, a space to allow for society to prosper, and a limit for excessive consumption	• Dwelling size (between 14 and 20 m^2 for a single person household; between 42 and 80 m^2 for a household of four people) • Number of bedrooms • Total material consumption • Residential energy use	[1,12,14,15,21]
Decent living standard	Universal basic needs by households	• Dwelling size (10 m^2 of exclusive living space/capita plus 20 m^2 of communal space/house)[b] • Thermal comfort (equivalent energy of 20–60 MJ/m^2/yr) • Water supply (50 liters/capita/day) • Access to public transport or vehicle	[3,16,22,23]
Carbon or emission budget	Total net CO_2 allocated to housing provision while keeping global warming to a specified level	• Greenhouse gas emissions	[24–27]

[a] This list of metrics is based on the relevant literature cited and not exhaustive. Example thresholds for some metrics are provided when they are clearly defined from the literature.
[b] Question 3 discusses different dwelling sizes between countries.

explored.

The structure of the ten questions (Section 2) is illustrated in Fig. 2. We begin answering the ten questions by discussing the need for sufficiency (to add to efficiency and renewables) using examples from key global events and policies (Question 1). We then examine the definitions of housing sufficiency from different perspectives (Question 2) and highlight methods of measurement (Question 3), important benefits (Question 4), potential drawbacks, and rebound effects (Question 5). Next, we examine housing conditions and potential sufficiency applications in developed (Question 6) and developing countries (Question 7). Finally, we discuss design strategies (Question 8), occupancy and tenure models (Question 9) and policies and regulations (Question 10) that are needed to widely adopt housing sufficiency.

2. Questions and answers

2.1. Question 1: Why should we care about sufficiency?

The energy crisis in the 1970s prompted member countries of the Organisation for Economic Co-operation and Development (OECD) to invest in research and development for efficient technologies and alternative energy sources [30]. Energy efficiency emerged as an important policy response for energy security [31]. In the European Union, the European Council adopted resolutions that limited the excessive consumption of energy [32]. Example strategies included directives that targeted the efficiency of heating and water boilers, energy labeling of electrical appliances, and thermal insulation of buildings and distribution networks for heat and domestic hot water [32,33]. Simultaneously, alternative energy sources, particularly renewable energy technologies, gained significant interest as a means of substituting fuel oil [34]. Considering wind energy as an example, research and development in Denmark, Germany, Spain, and the United States led to the development of large-scale wind turbines [35]. This period has accelerated research and development on efficiency and renewable energy strategies, making them the preferred pathways for economic growth and mitigating environmental issues, particularly climate change, in the following decades [28,32].

The United Nations Conference on Environment and Development in 1992 and the succeeding climate change treaties (e.g., the Kyoto Protocol in 1997 and Paris Agreement 2016) have reinforced the need for technological innovations to mitigate GHG emissions across economic sectors [36]. While efficiency and renewable measures have reduced global energy and associated GHG emissions, these reductions have been offset by increases in the levels of consumption outweighing the efficiency gains from technological developments (also known as rebound effects) [36]. Considering the UK housing stock, Horn et al. [1] found that the efficiency improvements from lighting and heating between 2008 and 2018 was associated with reductions in total normalized energy and operational GHG emissions, but dwelling size increased during the same time period (although unevenly distributed across total housing stock [37]) which reduces the total net energy and GHG savings from the improvements. This exemplifies how efficiency and renewables offset only the normalized impacts of high consumption (rather than aggregate impacts) without direct actions to reduce excessive levels of consumption.

The limitations from technological innovations might not achieve the speed and scale needed for a sustainable transition (e.g., carbon neutral or net zero by mid-21st century) [38,39]. As different economic sectors have already made large efficiency gains through supply-side strategies, sufficiency or demand-side strategies must be prioritized to reduce the associated impacts of these economic activities. Unlike efficiency and renewables that decouple the input (energy and materials) for the same demand (products and services), sufficiency reduces the per capita demand altogether (which effectively reduces the input) with some potential reductions in the quality of the products and services [38]. Conceptually, sufficiency overlaps with efficiency and renewables if the units of measure and aims of reductions are focused on the inputs. Implementing sufficiency would require focus and absolute limits to excessive and unsustainable outputs, and as Fuchs et al. [38] stated, "implementing sufficiency as a guiding principle for societies would imply fundamental changes in the way people live, and how societies organize their economic activities."

The need for sufficiency is increasingly critical in the current context of climate change and energy insecurity. The increasing frequency and intensity of extreme events such as heat waves or hurricanes, coupled with rising energy demand, are straining the power grid, leading to more frequent power outages and indoor temperature extremes, necessitating grid and thermal resilience. Sufficiency can improve the resilience of energy systems and buildings by reducing energy demand and avoiding the need for costly infrastructure upgrades. Moreover, sufficiency can also mitigate national or regional energy insecurity issues by moderating

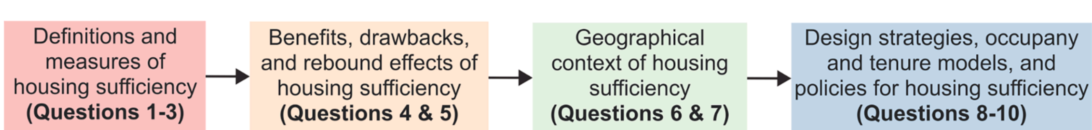

Fig. 2. Structure of the ten questions.

consumption. For example, the 2021 energy crisis led many European countries to implement voluntary and mandatory sufficiency measures related to space heating to improve energy resilience [40]. The growing interest in applying sufficiency within these fields was exemplified by a Scopus search (within article titles, abstracts, and keywords) of published journal articles. The search reveals that research in sufficiency and climate change resulted in 10 journal articles published in 2000 and 834 in 2025, while research in sufficiency and energy security resulted in two articles in 2000 and 163 in 2025.

Focusing now on housing provision, society in the 21st century is striving for two challenging goals at once: 1) decent living standards for all and 2) living within climate limits. From some perspectives, these are in tension - raising living standards increases resource and energy use and has an environmental cost. Continued inequity in infrastructure provision to an extent balances high resource-high energy lifestyles elsewhere. Accordingly, a quantitative understanding of the physical aspects of decent living (e.g., how much housing) and deployable pathways on how to build it within climate limits are needed. Since the energy crisis of the 1970s, efficiency (doing more with less) has received a lot of attention. However, increasingly it appears efficiency alone will not be enough to meet both of our challenges. Sufficiency tells us the floor of service delivery that we should not go below.

The growing demand for housing across the world conflicts with commitments to reduce construction emissions (also referred to as Scope 3 embodied emissions from new construction (A1-A5) and refurbishment (B5) based on BS EN 15,978 [41]). The accelerating demand for the construction of new housing and supporting infrastructure is driven by the deficit in housing supply over the last few decades in high income countries (e.g., United States, Canada) and the population and economic growth in many developing countries [5,42,43]. Research on built environment construction for future growth found that cities and countries will overshoot their carbon budgets with business-as-usual scenarios [29], but considering efficiencies in construction (e.g., choosing denser built forms of housing such as multi-unit residential buildings, best-in-class building designs, technological improvements in material production) is critical to meet these budgets [27,44–46]. The rebound effects (e.g., efficient building design but large per capita floor space) and potential constraints (e.g., restrictive zoning, low adoption rate) of these efficiency strategies are poorly understood and will likely prevent carbon budgets from being met if not significantly changed. Demand-side changes or sufficiency strategies that reduce excessive dwelling size per capita complement efficiency approaches [47] and could help balance housing provision with climate commitments [12].

2.2. *Question 2: How do different disciplines and perspectives approach the concept of housing sufficiency?*

The concept of housing sufficiency has been premised on multiple perspectives with varying degrees of interlinkages between economics, the environment, and society [48]. These perspectives range from ecological economics and political ecology to ecological philosophy, social ecology, and law, among others. Table 2 summarizes a few perspectives of housing sufficiency and the key associated concepts. From the perspective of ecological economics, housing sufficiency challenges the traditional growth-based economic models that prioritize ever-increasing housing sizes, advocating instead for smaller optimally sized and optimally located homes requiring lesser energy and materials. Housing sufficiency, through the lens of political ecology, addresses the power dynamics and social inequalities surrounding access to housing. It includes creating affordable and sustainable housing solutions to promote social justice (i.e., raising the floor to improve living standards and minimize inequality gaps) and limiting the over consumption of housing resources by a few groups and redistributing these resources for others [48]. Ecological philosophy expands the concept of housing sufficiency by prioritizing non-material values to enhance well-being while supporting a fair distribution of the Earth's limited resources. This perspective is similar to the concept of decent living standards [3] and supporting studies that argue that beyond a certain threshold, higher resource and energy use may not lead to any significant improvement in health and happiness [49] or indicate that subjective well-being is not dependent on larger living spaces [50]. Social ecology considers housing sufficiency as an approach to transforming social metabolism (i.e. the flows and stocks of energy and materials associated with social processes), in addition to efficiency and renewable technologies, towards lower ecological impacts [51,52]. In terms of law, the focus has been on quality, safety, and health issues. Minimum standards for dwelling sizes and number of rooms (e.g., [53]) are used to quantify health and safety, but no maximum dwelling size limit is ever set to our knowledge (see Question 3 for extended discussions of minimum dwelling sizes and Question 10 for discussion on building code requirements related to size of dwellings). Urban planning in many countries aims to limit land use, but as far as the content of a construction project is concerned, sufficiency is absent. While the building sector's regulations have integrated efficiency (especially from the energy perspective), sufficiency is not yet a significant part of it.

Table 2
The concept of housing sufficiency from different perspectives.

Perspective	Description	Key Concepts	Relevant literature
Ecological economics	Challenges traditional growth-based economic models	Optimally sized homes, less resource use, energy use and carbon emissions.	[48]
Political ecology	Addresses power dynamics and social inequalities	Affordable housing, social justice, resource distribution	[48]
Ecological philosophy	Prioritizes non-material values and fair distribution of resources	Decent living standards, well-being, respecting planetary boundaries	[3,49,50]
Social ecology	Transforms social metabolism towards lower ecological impacts	Efficiency, renewable technologies, lower consumption	[51,52]
Law	Focuses on quality, safety, and health	Minimum standards	[16,53]

Drawing from these perspectives, early conceptualizations of sufficiency (i.e., [54] and [55]), and housing sufficiency literature (see Table 1), we define housing sufficiency as a housing provision concept that aims to establish the living conditions that meet decent living standards (see [3]) to promote well-being while remaining within our planetary boundaries. This approach entails changes in consumption levels through absolute reductions (e.g., smaller dwelling size per capita), modal shifts (e.g., alternate housing occupancy such as co-housing) and sharing practices (e.g., communal spaces) to optimize the spatial and temporal distribution of homes [9,56]. These sufficiency strategies reconcile the environmental and social goals of housing provision. Examples of environmental and social benefits, drawbacks, and trade-offs of housing sufficiency are synthesized in Questions 4 and 5.

2.3. *Question 3: How do we measure housing sufficiency?*

Measurement of housing sufficiency follows the principles of sustainable consumption and determines the consumption corridors [57] (see Fig. 1). Minimum housing needs are often expressed qualitatively and driven by the need to preserve public health [12]. Doyal and Gough [16] indicate that this should include protection from the elements (e.g., pests and "disease-carrying vectors"), provide access to clean water and sanitation, and not be overcrowded. Rao and Min [3] expanded these minimum housing needs to define the requirements to achieve decent living standards at a household level (e.g., minimum floor space, accessible water supply, and clothing materials) and at some level of social organization (e.g., electricity, water, and sanitation infrastructure, public space).

The International Code Council (ICC) is one example of an international body that sets specifications for absolute minimum dwelling size (e.g., 14 m^2 for a single occupant in a housing unit, and 9 m^2 for every additional occupant) [12]. While originally developed for the United States' context, many countries now use these specifications [12] including France and Italy [53]. However, some developed countries have higher minimum dwelling sizes while other countries have defined minimum housing by function or number and size of specific rooms [58] and room characteristics such as minimum ceiling height or volumes. For context, Fig. 3 presents a comparison of average per capita dwelling size in different countries alongside the minimum ICC dwelling size. Examples of minimum dwelling size are indicated for selected countries in Fig. 3, based on data availability. As shown, there is significant variability in per capita dwelling sizes between countries, though this data is predominantly from developed countries which do not represent the global range. Unsurprisingly, the average per capita dwelling unit size in most of these countries is above the minimum dwelling size set by the ICC (Detailed discussions on potential drivers of large per capita dwelling size in developed countries are presented in Question 6), but many countries around the world fall below this minimum dwelling size requirement and would therefore require more housing resources to have their needs sufficiently met (see answers to Question 7). Nevertheless, there is bound to be a significant range in dwelling size because household needs are driven by the degree of urbanization as well as cultural, historical, climatic, and political factors which vary dramatically between countries.

Floor area is also used to measure the *upper* limit of housing resources as dwelling size is the most significant determinant of residential energy consumption and construction material use [61,64,65]. Housing floor area is often normalized by dwelling unit or on a per capita basis to enable comparisons between buildings and countries, but this normalization can significantly impact the resulting calculations [47]. For example, in a recent comparison of embodied carbon between co-living and traditional apartment layouts, the savings associated with co-living were only 10–20 % per unit floor area but 21–36 % per capita [66]. However, using existing housing floor area per capita as a basis for the consumption of housing resources is incomplete because housing-related matter and energy are also significantly impacted by the location of the housing and the features of the neighbourhood surrounding the home [64]. Furthermore, floor area-based approaches overly simplify the quantification process because they assume that all floor space is created equal, which is usually not the case. As an illustrative example, 15 m^2 of housing in locations with colder climates (where individuals spend most of their time indoors during cold season) is very different (and can be perceived as small) from 15 m^2 in locations with temperate climates.

The upper limit for housing resources has also been quantified by numerous studies using the planet's carrying capacity [12]. Total material consumption (TMC) on a per capita basis is used as a proxy for the planet's carrying capacity. The annual maximum ecological ceiling for a sustainable level of consumption was estimated to range from about 4 to 6 tonnes per person (t/p) [12]. For comparison, in 2017, TMC ranged from 26.3 t/p in developed countries to 2 t/p in developing countries [67]. These TMC ranges include different categories of consumption such as private consumption, government consumption, and investment

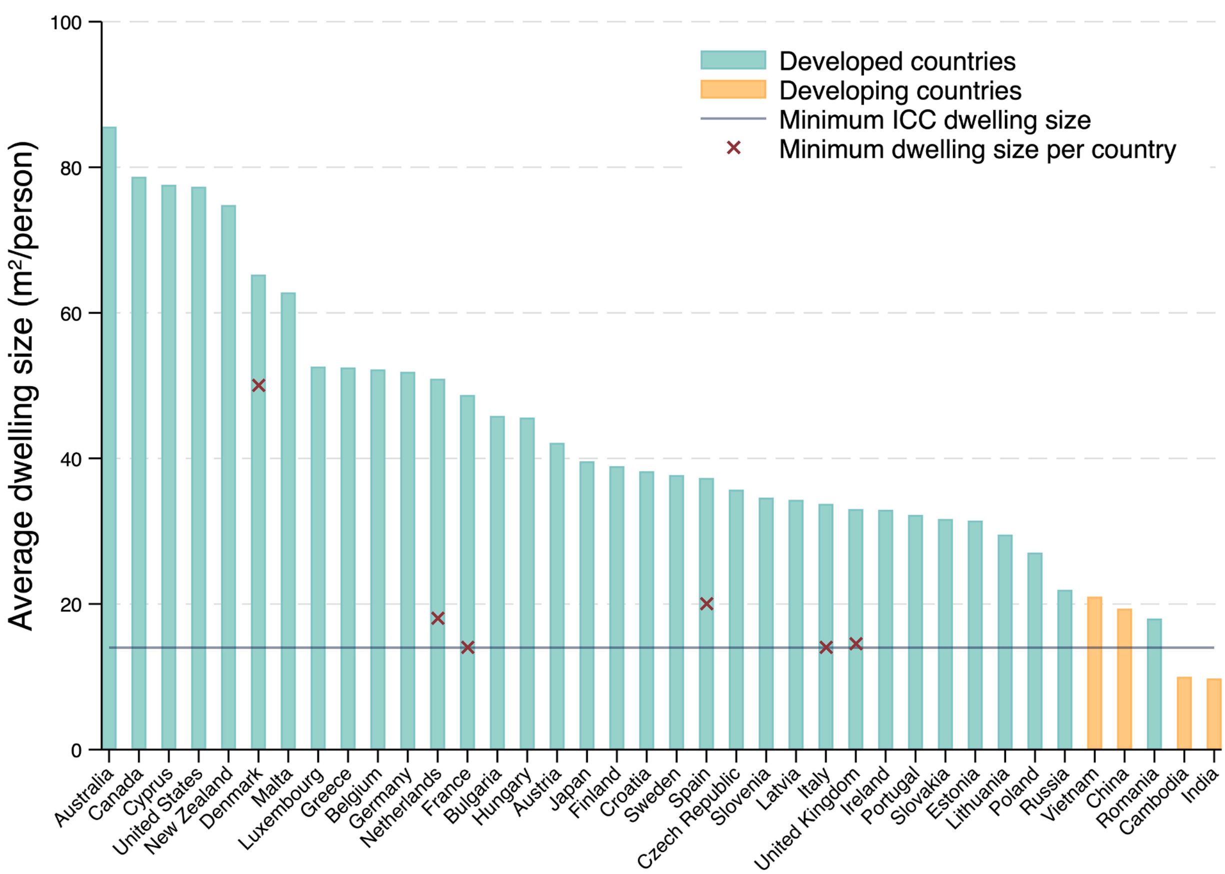

Fig. 3. Mean dwelling size per capita of 38 countries. Data were sourced from the United Nations [59], World Population Review [60], Ellsworth-Krebs [61], and Bierwirth and Thomas [13]. The minimum ICC per capita dwelling size was based on a single-person household (14 m^2). Similarly, minimum dwelling sizes for specific countries are indicated using an 'x' marker where a single minimum value was available [53,58,62]. Developed countries include high income countries after the 2024–2025 World Bank income level classifications [63], while developing countries include middle- and low-income countries. We note that the variability in data sources and methods to estimate dwelling sizes (e.g., secondary residences are included or not) influences the data points.

(e.g., construction) which makes it difficult to determine how much of the TMC to attribute to housing specifically [68].

The impacts that housing has on livability are being considered when measuring the consumption corridors for housing sufficiency. Stefánsdóttir and Xue [69] argue that the location, neighbourhood and dwelling unit quality must all be considered. A location which provides easy access to the essentials of a 'good' life makes 'smaller-scale living' possible as one's living space becomes a combination of the dwelling unit and the surrounding neighbourhood [48]. For example, 15 m^2 of housing at the heart of a global metropolis is very different from 15 m^2 in a rural village without ready access to public transportation, commerce, and amenities. However, one must still consider how the dwelling unit itself impacts livability in isolation from the surrounding community, particularly in the context of those with limited mobility. From a quality perspective, functional quality (e.g., number and size of rooms with different potential uses [1]), aesthetic quality (e.g. satisfaction and enjoyment of the space) and the quality of social interactions (e.g., ability to connect with others afforded by the dwelling unit) [69] should all be considered as well.

Moving forward, future research should establish more comprehensive metrics or borrow metrics from other disciplines to evaluate housing sufficiency. These metrics can include those that can be used to evaluate access to clean, safe indoor air and water, the functions provided by a dwelling unit (e.g., cooking, laundry, entertaining), and the prevalence of sharing practices (i.e., which functions are in exclusive spaces versus easily accessible shared spaces) [48]. However, the value of a functional space, whether private or shared, will depend on what specific activities require separation from others and which activities can be shared with other people inside or outside the dwelling unit (e.g., sleeping, cooking) [69]. From a sufficiency perspective, it would be ideal to limit the number of exclusive spaces and encourage sharing of certain functional spaces with others [69] but the level of acceptable shared versus exclusive space will likely depend on the relationship between those occupying a dwelling unit (e.g., two unrelated housemates versus spouses) which adds a level of subjectivity to the assessment. Metrics from the transportation literature should be integrated with housing sufficiency to evaluate accessibility of homes to essential services such as health care, schools, employment, stores, and recreation [70,71].

However, not all aspects of housing can be captured through quantitative metrics. Subjective measures such as privacy, space quality, stability and security are highly context dependent and culturally specific. As an example of how more subjective housing sufficiency measures can be addressed, the Living Home Standard developed in the UK through extensive public consultation suggests a collection of essential attributes (e.g., affordability, stability, security) that all homes must have and a minimum number of optional attributes to improve housing quality [72]. Furthermore, housing needs are not static as occupants progress through various life stages so the assessment of housing sufficiency will vary over time for a given occupant group and dwelling unit pair. This issue can be addressed in two ways, either enabling greater housing mobility as needs change or scenario testing to ensure housing can remain sufficient for the entire tenancy (see answers to Question 9).

Considering that housing sufficiency is influenced by some cultural and social factors and can be qualitatively or subjectively measured, it is important to determine the differences in housing conditions and living requirements between locations to better identify strategies that will fit specific contexts. Questions 6 and 7 examine housing conditions and potential housing sufficiency applications in developed and developing countries, respectively.

2.4. Question 4: What are the benefits of housing sufficiency?

We examined the environmental and social benefits of housing sufficiency to advance the socio-ecological transformation needed in housing provision. To align with housing sufficiency definitions from Question 2, in terms of social (floor) and ecological (environment) aspects, the economic benefits of housing sufficiency are excluded when answering this specific question. We distinguish between the physical size of the home and the location of the house within the neighbourhood and city to make notable distinctions among the benefits.

The upper limits of housing sufficiency are primarily achieved through reduction of dwelling size per capita. Two approaches for achieving this in exclusive living spaces are 1) enabling downsizing and 2) reducing under-occupation. Both pathways are examined in the literature and demonstrate benefits for space, material, and energy reductions and savings. Table 3 summarizes the benefits of housing sufficiency in the context of downsizing and reducing under-occupation, assuming all other things are equal (e.g., homes consume equal amounts of energy and their location have similar proximity to jobs and essential services). Note that the items listed present a review of the benefits discussed in literature and do not represent an exhaustive list of housing sufficiency benefits or co-benefits (e.g., improved macroeconomic stability [73]).

2.4.1. Environmental benefits

Reducing dwelling space per capita through building smaller homes reduces per capita energy consumption and requires less materials for construction and maintenance [92–94]. Intensifying the use of existing, large homes that are considered under-occupied benefits from economies of scale and results in per capita energy savings [79–82]. Consequently, reductions in energy and material requirements lower associated GHG emissions and costs [74,75]. Pauliuk et al. [78] estimated that intensifying the occupancy of large Norwegian homes (which effectively reduces dwelling size per capita by 15 %) could reduce the housing stock GHG emissions by 9 % in 2050 compared to 2000 levels. Downsizing from larger, under-occupied homes to smaller, sufficiently occupied homes also results in per capita energy savings [51]. Huebner and Shipworth [65] estimated that single-person households in the UK

Table 3
Summary of housing sufficiency benefits and co-benefits for two sufficiency actions.

Sufficiency action	Enable downsizing to smaller dwellings	Reduce under-occupation of large dwellings
Benefits	• Requires less materials for construction and maintenance [74,75] • Supports multi-unit residential buildings (MURBs) [76,77] – Efficient use material usage (shared walls, floors, ceilings) – Efficient land use – Efficient operational costs (heating, cooling, and ventilation) • Opportunities for sharing services (laundry, green spaces, gyms, etc.) • Supports socio-economic transitions towards distribution of space, materials, and energy [48] • Reduces GHG emissions per capita [78] • Increases affordability [74,75]	• Benefit from economies of scale [74,75,79–82] – Results in per capita energy savings – Reduces per capita domestic workload – Increases affordability – Reduces GHG emissions per capita • Supports aging-in-place [65,83,84] • Supports social efficiency [85] • Promotes social connections and reduced loneliness/social isolation [83,85]
Co-benefits	• Supports the densification of urban areas [69,86–91] – Increase proximity to available jobs – Increase proximity to essential services – Increase proximity to social connections including friends, family, and community members. – Promotes compact urban infrastructure – Promote efficient methods of travel (e.g., cycling, walking) which, in turn, promote physical activity and reduce air/noise pollution	

with two or more bedrooms could save 27 % of their energy consumption by downsizing to a one bedroom unit.

Housing sufficiency and urban densification reinforce each other through multi-unit residential building (MURB) occupancy and sharing of infrastructure services. MURBs are a ubiquitous form of housing in urban areas and considered efficient due to their shared walls, floor, and ceilings, reducing the required per capita construction materials, land use, and operational energy (heating, cooling, and ventilation) [76,77]. Sufficiency in MURBs lies in the fact that they offer smaller units and the opportunity for sharing services (e.g., laundry appliances, green spaces, gyms, pools). The compact nature of urban areas enables shared infrastructure (e.g., roads, district heating, electricity distribution, water and sewage networks) and essential services (e.g., municipal waste management, public transit) [86]. This reduces the material and energy associated with constructing and maintaining the infrastructure [87] and can positively influence lifestyle choices of residents (e.g., shorter and/or reduced car trips) [88].

2.4.2. Social benefits

Housing sufficiency promotes the identification of human needs and supports individuals living a good, high-quality life, while ensuring that planetary boundaries are not exceeded [57]. Reducing under-occupation of large dwellings by intensifying occupancy improves social efficiency, resulting in less workload per capita as common activities (e.g., cooking, cleaning) are shared among members. The reduced workload frees up time and money which can then be spent on activities that bring enjoyment [85]. Homes shared among family or non-family households were found to promote greater social connection and reduce loneliness [85]. For example, in Germany, a pilot program called "Wohnenfuer Hilfe" ("Living for help") enables students or apprentices to live with elderly persons with a spare room in their homes for an affordable price and in exchange of providing support (e.g., shopping, chores, companionship) [65]. This program was found to improve affordability to both parties and support aging in place [65]. Homes shared among elderly persons, regardless whether they are retirement homes or senior co-housing, protect elderly persons from risks associated with social isolation, loneliness, and poverty [83]. Overall, sufficiency measures, such as downsizing, should give individuals access to space to accommodate the changes in household needs over time and therefore a margin to help promote wellbeing [1].

Dense urban areas increase the proximity and availability of jobs and essential services to residents [89]. However, urban housing can vary greatly in quality and affordability making access to these benefits reliant on complex intersectional factors. They are more likely to promote efficient methods of travel such as public transit, walking, and cycling, which encourage physical activity and reduce air and noise pollution [69,90,91]. Beyond social benefits, housing sufficiency promotes intergenerational justice centered on the provision of affordable and quality housing to present and future generations. Downsizing supports socio-economic transitions towards distribution of space, materials, and energy [48]. Especially for elderly households, downsizing makes larger homes available for young, growing households [65,84]. This also supports the social well-being of aging populations when they move into shared housing [65,84]. Leach [95] found that English homeowners aged 65 to 70 who downsized reported life as more liberating and less stressful due to lower housing expenses and smaller houses to maintain.

2.5. Question 5: What are the potential drawbacks or rebound effects of housing sufficiency?

The goal of housing sufficiency is to be within the bounds of what is socially and environmentally sustainable. However, depending on how strategies are applied, housing sufficiency can have drawbacks and rebound effects that can discourage its widespread implementation [96]. We examined key drawbacks and rebounds of housing sufficiency and their impacts on households, society, and environment.

2.5.1. Risks of psychological, social, and financial drawbacks from relocation, shared spaces, and higher density housing

Achieving housing sufficiency through voluntary relocations (e.g., downsizing for environmental reasons) has monetary and psychosocial drawbacks [29]. Relocation costs money, such as from labour, temporary accommodations [97], the loss of rental caps (i.e., laws allowing any amount of rent increase between tenants) [28,29], and transaction or inheritance taxes, for example [97]. While some of these relocation cost examples are produced at the individual level, some (e.g., inheritance taxes) are produced and controlled at the institutional level. Relocation disrupts social cohesion [98] and place attachment, which can cause stress and grief by removing people from familiar physical, social, and cultural settings and resources [99]. These impacts are heightened when relocations are sudden or involuntary, as a result of changes in household size (e.g., divorce, death) or changes in spatial requirements (e.g., older adults moving to care homes) [99]. Relocating amid these changes may bring distress and make people more vulnerable if they are removed from their community-based support networks. Negative impacts of place attachment disruptions can be alleviated by flexible sufficiency policies that compassionately consider the nuances of people's situations and needs (e.g., spatial, social, cultural, geographical, impairment-related) over time, rather than taking a simple "one size fits all" approach [12,57]. As a household's needs vary over time, there is a risk that a home becomes insufficient (e.g., overcrowded), though this can be partially mitigated with good quality, moderately flexible housing that allows households to adapt spaces for multiple uses over time [100]. Flexible housing is discussed further in the response to Question 9.

Shared resources and spaces from shared living arrangements (e.g., increased occupancy of housing units) and sufficient housing forms (e.g., MURBs) foster a sense of community and increase social interaction. However, cohousing may conversely have the effect of isolating community members from public amenities, depending on the implementation and definition of cohousing [101,102]. Shared spaces also carry the risk of increased conflicts [85], including maintenance responsibilities [103], and may challenge cultural expectations of privacy, modesty, and independence [104] and cultural norms in some places of viewing homes as individuals' financial assets [12]. Shared living arrangements and communal spaces can increase anxiety for some people and put vulnerable groups at risk of harm from other tenants [105]. There is a risk that shared spaces are inaccessible (i.e., physically, socially) to some users, resulting in exclusion of some users, though inaccessibility may be mitigated with inclusive design, which considers the specific needs of a broad diversity of users and offers choices and flexibility in the design and usability of the space to meet those needs [106]. MURBs in dense urban areas have unique factors, such as reduced privacy due to noise transmission, transfer of air pollutants between attached housing units, and limited opportunities to control the indoor environmental quality (IEQ) in shared spaces, that affect health and comfort compared to less dense neighborhoods (e.g., suburbs) [107]. While proper design, operation, and maintenance could help achieve healthy and comfortable IEQ conditions in MURBs, there may be real or perceived concerns about the lack of flexibility in using shared space that remains to be explored.

2.5.2. Risks of environmental rebound effects

Achieving sufficiency by reducing dwelling size frees up resources including time and money. However, people may use the money saved on housing and time saved from home maintenance for goods, leisure, and travel activities whose associated emissions lessen the environmental gains from sufficiency [74,96]. For example, people living in cities may have cottages or second homes in the countryside, which may require concurrent consumption of energy and resources even when unoccupied [108], though the use of these second homes may enable denser city living in some cases. Similar shifting of emissions occurs if people move their activities outside of the home in response to drastic reductions in home size [74]. By way of example, Heinonen et al. [109] found that the GHG reductions from urban densification in Helsinki due to energy efficient and sufficient housing forms (e.g., MURBs) and transportation services were outweighed by increased consumption of goods (e.g., food, clothing) and services (e.g., air travel, recreation). In these rebound effect scenarios, people might have felt that the environmental benefits from housing sufficiency justify taking successive environmentally harmful actions [96,110]. These rebound effect examples do not represent the global case. There are nuances surrounding rebound effects, such as secondary impacts and causality, that require further research.

2.6. Question 6: What does housing sufficiency look like in developed countries?

In the realm of housing sufficiency, developed countries can be characterized by having average dwelling sizes that are well above most minimum thresholds for sufficiency (e.g., see Fig. 3). This situation is exacerbated by low and declining fertility rates (below the replacement rate) and the associated increasing average population age and shrinking household size in most developed countries [61,111], which tends to further reduce housing stock utilization because family-sized homes are occupied by fewer people than they were designed for [112]. The result is that housing stock per person in many regions continues to climb. For example, Canadian average dwelling sizes have increased by one-third on a per-person basis since 1990 [11]. American homes more than doubled in size in the second half of the last century, despite decreasing household sizes [112].

One of the prevalent housing forms in developed countries – especially in the United States, Canada, Australia, and New Zealand – is detached houses. Detached houses with large yards are often the vision of the "American Dream". However, this vision tends to be the antithesis of sufficiency. Detached homes in developed countries tend to be very large - these four countries are outliers in terms of dwelling size - typically averaging about 200 m^2. These homes are rooted in colonialism and individualism, where households seek large private spaces and isolation from inner cities, industry, and commerce [85,113]. They also tend to avoid shared amenities (e.g., recreational facilities, parking spaces), which yields greater consumption per person [85]. A consequence of large low-density housing is large lots (often leading to heavily landscaped yards) and car-dependency [114]. Car-dependency is exacerbated by curvilinear streets that are primarily designed for cars (versus active transportation) and which increase distances to amenities [115] and the length of sewers and roads construction with greater associated energy to build and operate [116]. Thus, this predominant housing form has several secondary traits that challenge sustainability and sufficiency: yards requiring significant inputs (e.g., water for irrigation and swimming pools, fertilizer, pesticides) and single- or multi-vehicle households with a high modal share of personal vehicles [7,117]. Modern detached homes often feature walk-in closets, as many bathrooms as occupants, multi-car garages, and rooms that are rarely used - all indications of hyper-consumerism [118]. It is noteworthy that detached homes are also prevalent in other developed countries with a lower urbanization rate (Fig. 4), (e.g., Croatia, Hungary, Slovenia, and Romania), but the average dwelling sizes are often significantly smaller than in the above-named countries (Fig. 3). Detached homes are also an aspirational housing form in some developing countries (e.g., in Central and South America [119]) .

Regardless of housing form, homes in developed countries are often culturally ingrained as symbols of wealth and investments, thus encouraging people to consume excessively [12,121]. Moreover, cultural norms, combined with tax advantages and real estate appreciation in some cities (i.e., increase in a home's value over time), strongly encourage home ownership, which reduces flexibility and mobility (e.g., retirees or empty-nesters downsizing) [12]. One potential mitigating trend towards greater sufficiency is that the United States, Canada, Australia, and New Zealand have relatively high immigration rates that embrace multi-generational housing, which helps improve the

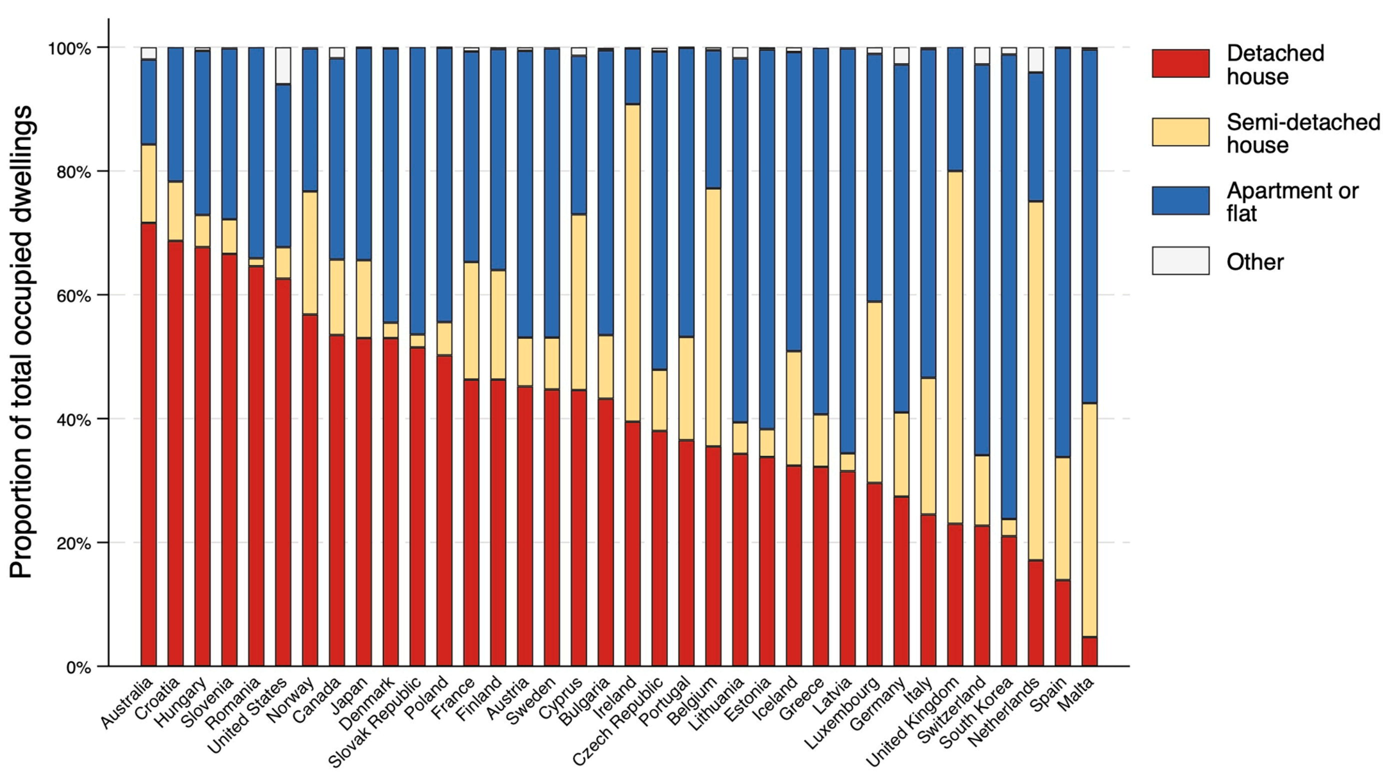

Fig. 4. Occupied private dwellings in developed countries broken down into housing forms. The countries are ordered from left to right in decreasing order of detached housing proportions. Data were sourced from the Organization for Economic Co-operation and Development [120].

utilization of large existing homes. For example, in Ontario, Canada, multi-generational housing is the single fastest growing type of household [122]. There is also some early evidence that growth of dwelling size per person in some developed countries, such as the United States and Australia, is tapering off [61].

Despite housing excess in developed countries, housing inequality exists whereby a substantial portion of the population faces "involuntary sufficiency" and is chronically underhoused, living in overcrowded homes, or even without homes [123,124]. In any form, housing inequality is attributed a plethora of socioeconomic circumstances including a shortage of affordable housing, wages that have not kept up with the cost of housing, unaffordable taxation and interest rates, housing financialization, and other socio-cultural factors that are less likely to prioritize those who need immediate housing support [8,125]. Indigenous communities in the aforementioned four wealthy countries have particularly suffered with homelessness, overcrowding, and poor housing quality [126,127].

While one might expect larger homes to be associated with greater home ownership, our analysis indicates that this relationship is weak and circumstantial. For example, Germany, Austria, and Switzerland are relatively wealthy countries with large homes, yet have low ownership rates (see Fig. 5) owing in part to availability of social housing, lack of subsidies for ownership [128], lack of property value gains [129], and forced mobility at different life cycle stages [130]. In contrast, many countries in Eastern Europe have among the smallest homes in developed countries, yet also high home ownership (>80 %). This may be due to lack of population growth, lack of social housing, and a sell-off of previously state-owned housing for favourable prices after communism [131,132]. Within some of the countries in Fig. 5, however, owner-occupied homes seem to be larger on average. For example, in Switzerland, owner-occupied dwellings tend to be bigger than rental dwellings. In 2022, the average per capita living space was 54 m^2 for owner-occupied dwelling vs. 41 m^2 for rental dwellings [133]. Based on the 2021 American Housing Survey, more than 80 % of owner-occupied dwellings had three or more bedrooms compared with 30 % of rental dwellings. About 84 % of owner-occupied dwellings had more than one bathroom, compared with just 41 % of rental dwellings [134].

Referring to the definitions of housing sufficiency, most of the developed world, on average, greatly exceeds the ceiling of planetary boundaries, offering little by way of best practices on the demand side. (This is notwithstanding the inequities that leave some residents of developed countries un- or under-housed). However, developed countries can be recognized for numerous regulations and enforcement (e.g., building codes for fire safety, structures, air quality, thermal comfort, lighting, pest control; planning laws to maintain minimum municipal services and separate polluting activities from housing; clean water and sewage) that legislate housing above the minimum social floor (e.g., [139,140]). These established principles, institutions, and technologies can be considered best practices for which developing countries can benefit. However, care should be taken to address inequities (e.g., [141, 142]) even with application of these best practices (as we have seen in developed countries).

2.7. *Question 7: What does housing sufficiency look like in developing countries?*

Most of the literature on housing sufficiency is focused on developed countries, where sufficiency potential lies in reducing excess, aggregate consumption patterns to stay within the consumption corridors. Applying housing sufficiency thinking in developing countries present unique sets of challenges due to limited data to elucidate the variety of housing conditions and limited understanding of their cultural and economic factors influencing housing markets [64]. By far, global household statistics tell us that developing countries have different household characteristics compared with developed countries. For example, households in developing countries have bigger household

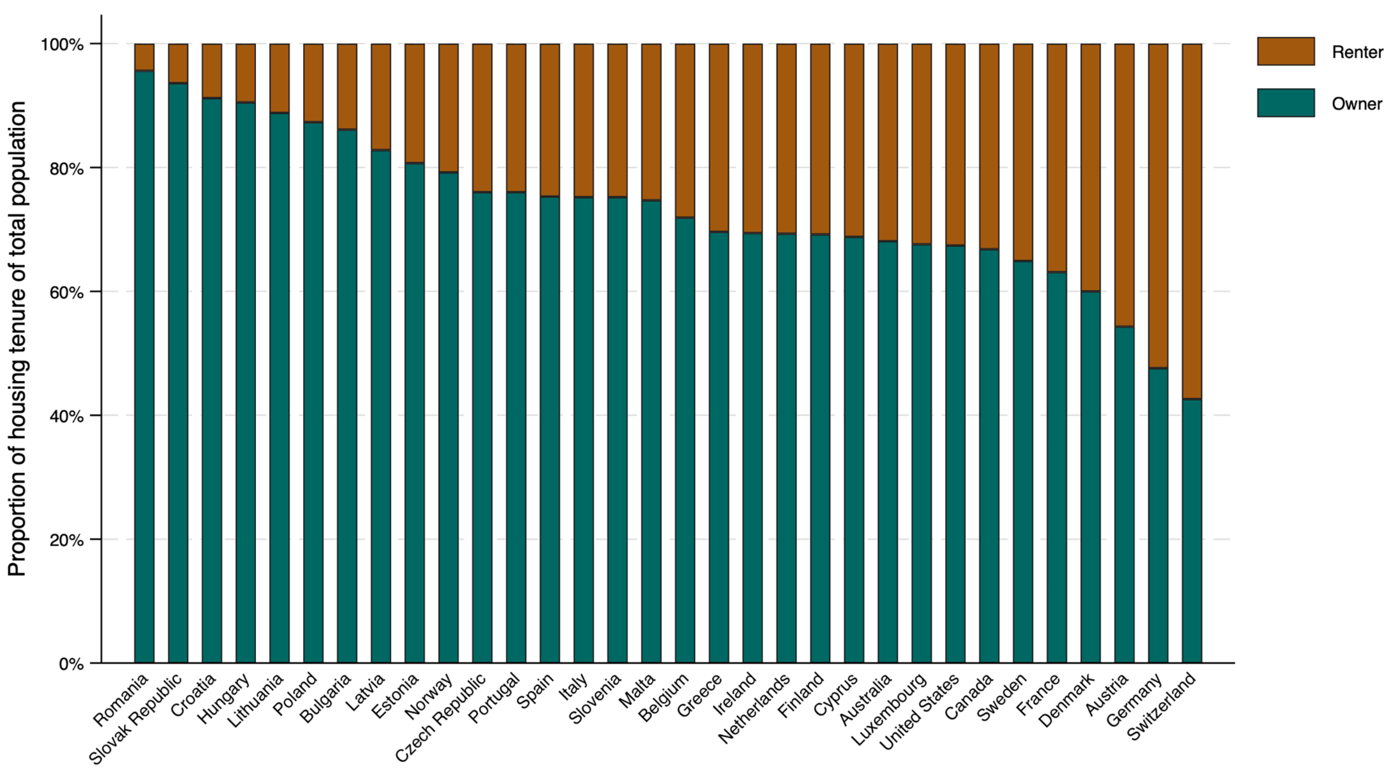

Fig. 5. Proportion of housing tenure in total population in developed countries. The countries are ordered from left to right in decreasing order of homeowner proportions. Data were sourced from Eurostat [135], the United States Census Bureau [136], Statistics Canada [137], and the Australian Institute of Health and Welfare [138]. As the data in Figs. 4 and 5 are from different sources, a few countries in Fig. 4 (i.e., Iceland, Japan, South Korea, United Kingdom) are not included in Fig. 5. Conversely, a few countries in Fig. 5 (i.e., Estonia, Turkey) are not included in Fig. 4.

sizes compared with developed countries (average size of 5.3 for developing countries versus 3 for developed countries) [59]. The average number of children for nuclear families in developing countries is higher than developed countries (2 to 4.5 in developing countries and 1.4 to 2.2 in developed countries) [59]. Reports from international organizations indicate that the main housing challenge for some developing countries is on how to lift the housing conditions to sufficient levels [143,144]. For example, in 2023, about 168 million people or 62 % of the total urban population in the 31 least-developed African countries lived in informal settlements [143]. These settlements have limited or no access to quality housing and urban infrastructure services (e.g., water, sanitation, waste collection) and are poorly connected to employment and health services.

Previous works have shown that sufficiency in the context of developing countries entails meeting decent living standards and allowing prosperity [21,145]. How these will be met requires more nuanced approaches given some of the complexities brought by a range of cultural, climatic, material, and financial variables. Further, exploring sufficiency strategies in developing countries should acknowledge the limitations in applying sufficiency framework from developed countries due to the differences in cultural, economic, and infrastructure contexts between the two economies. Given these complexities, housing sufficiency research on developing countries should focus on understanding specific challenges. As a first step, census data will be essential to understand the variability in household characteristics (e.g., income) and housing conditions (e.g., floor space per household, number, and functional uses of rooms in a home) within countries. Some information that can potentially help understand economic and social factors that will drive housing sufficiency (e.g., data on home financing, number of housing starts, the perception of home ownership and aspirations to wealth across household income brackets) are crucial to have.

The household characteristics of developing countries including overall smaller dwelling size per person (see Fig. 3) and larger households (e.g., due to multigenerational housing) are ideal strategies that could be adapted to achieve sufficiency in developing countries. But as specified earlier, applying these strategies at scale can be limited by some cultural and economic factors. For example, multi-generational households might be desirable for extended care, support, and resource sharing in one culture but uncommon in another [61].

Given the increasingly close link between housing sufficiency, resource consumption, and the climate crisis [146,147], future innovations in housing sufficiency will need to focus on providing adequately sized dwellings in a dynamic manner over time, responding to the changing needs of communities. In the next three questions, we identify emerging design (Question 8), housing models (Question 9), and policymaking trends (Question 10) that aim to deploy sufficient housing at scale. The strategies identified were mostly from developed countries, where there is extensive research on housing sufficiency.

2.8. Question 8: What design strategies are needed for housing sufficiency?

Within buildings, a fundamental sufficiency design approach is to narrow the housing built to its necessary functions to provide a decent standard of living and not build space that is superfluous for this core function. In studies of global sufficiency, the approach to housing has often been to assign a generic dwelling size per person (see Question 3) [3,22]. Accordingly, the simplest design approach it to just build smaller – fewer rooms per dwelling or smaller rooms. In addition to this approach there is potential to consider the different functions provided by built space and if they are needed for sufficiency. Within consideration of function, there are opportunities for sufficiency by (re)considering what is needed for a reasonable quality of life. For example, eliminating underground or attached parking for vehicles has a large impact on reducing the amount of construction needed and/or maximizing the housing utility of what is built [47,148]. Parking, while popular, arguably is not a necessary function of housing, especially if active or public transit options are provided. Especially in North America, changing design rules for MURBs to allow and promote single-point access instead of two-point access for perceived fire safety can reduce the need for communal hallway space from 15 % to under 7 % of floor plate area [149]. With modern approaches to fire suppression (e.g., fire resistant materials, sprinkler systems), single stair buildings are often just as safe as those with two stairs pointing to the second stair as unnecessary [150]. As such, single-point access design can either reduce the amount of space needed overall and/or provide more units at the same environmental cost, while also facilitating better designed units with more light and cross airflow [149].

When designing for sufficiency, tough and controversial questions present themselves on the inclusion of amenities or even accessibility requirements in every unit or every building. Housing sizes have increased dramatically over the last century, largely attributed to increases in amenities (e.g., number of bathrooms, underutilized rooms) [151]. Accordingly, reducing these (e.g., providing one bathroom per unit rather than one bathroom per bedroom) will reduce unit sizes towards sufficiency. Foregoing separate home offices, second living rooms/family rooms - both increasingly part of single-family home construction - brings housing closer to its core function. Similarly, buildings built with lower ceilings heights (e.g., 2.5 m (8 ft) versus 3 m (10 ft)) require less material to construct and less energy to condition with limited impact on the function of the space. However, there can be trade-offs between some sufficiency strategies and the perception or quality of living space and occupant comfort. Higher ceilings can enable daylight penetration, which is required for good indoor environmental quality. Many people like tall ceilings and extra bathrooms, and while this may improve the desirability and economic value of the home, that is beside the point of sufficiency which is to have enough for a reasonable quality of life.

In modern construction, high importance has been placed on conservative approaches to circulation spaces (e.g., [150,152]), which could increase space requirements per unit and per building, requiring more material in construction, more energy in operation, and more upfront GHG emissions. Wheelchair accessibility calls for hallway widths of at least 0.9 m (36 inches) [153]. Similarly, the minimum elevator size is 1.3 m by 1.7 m (51 inches by 68 inches) in the United States [154] and elevators are often required by code for any building bigger than a single-family home [155]. While many people at different stages of life benefit from wheelchair accessible design and would need it to meet their minimum needs, for many or even most people it is an extra and one only required of MURBs (most accessibility rules do not apply to ground oriented housing like single-family homes). Sufficiency in this case could call for providing enough accessible units for the people who need them but no more. For example, the Ontario Building Code requires at least 15 % of all housing units in a MURB to have accessible design rather than all units [156]. In design, when asking "what is enough?", there is the corollary question of "what is too much?". Wrestling with sufficiency in a resource constrained world will require considering/examining any design norms that increase resource use.

The sufficiency concepts proposed address what we need at present to meet carbon budgets and provide livable housing. However, longer term strategies that set dwelling sizes for new construction create tensions with variations in number and composition of occupants and how their needs might change with time. So, there needs to be a compromise between the lower boundary of sufficient design and flexible design, where flexible design often means using more material to accommodate potential future needs. The absolute lower boundary of sufficiency applied across the housing stock is impractical because all housing cannot exactly match each individual or family's minimum sufficiency limit and, as occupants' lives evolve, it is impractical to force people to move each time there is a change in the number and composition of occupants in their household. Some flexibility is likely to be optimal in terms of housing sufficiency for a given individual/family over time to avoid exceeding the upper bound of what is still considered sufficient. Within the housing unit, design for multi-function spaces (e.g., spaces that serve as bedrooms at night and home offices during the day) can help facilitate sufficient housing [66,85] offering modest flexibility on the use of space [157–159], which reduces the need for more space or rooms for different functions. Finally, designing shared spaces for alternative housing (e.g., MURBs) and occupancy forms (e.g., co-housing, co-living) should consider spaces that offer unique and desirable amenities to residents [160]. Further discussions on these occupancy forms are provided in Question 9. Overall, modest flexibility of spaces helps to ensure a home can meet the evolving needs of a household (on varying time scales, from daily to generationally) but only to some extent. Excess flexibility (e.g., extra bedrooms or seldom used spaces) is against the principles of sufficiency, particularly when the upper limit of the consumption corridor is exceeded.

At the neighbourhood scale, in addition to providing a mix of housing forms which makes it easier for people to move as family sizes and space needs change, neighbourhood design with shared public amenities reduces the need for private provision (e.g., public park versus individual backyards) [161]. Constructing dense neighbourhoods with a diversity of opportunities similarly facilitates the provision of high-quality public transport reducing the demand for private transport (and associated space for automobile parking either indoor or outdoor) [162,163]. Renovation of existing under-occupied housing units (e.g., subdividing larger homes into smaller units) or adaptive reuse (e.g., converting non-residential building to housing units) provide an opportunity to redesign for sufficiency. Other forms of renovation and retrofit should be pursued or not depending on the motivation. For sufficiency, purely aesthetically motivated renovations should be entirely avoided, social/equity-motivated renovations (e.g., retrofitting circulation areas for accessibility, creating accessible washrooms) should aim for sufficient accessibility standards, and energy retrofits should be considered if the environmental payback period is justified [164]. Adaptive reuse to promote housing sufficiency should prioritize the suitability of the existing building being converted. Recent examples found opportunities in transforming office and industrial buildings into urban housing when designers took advantage of large windows and high ceilings to create adequately sized and well-proportioned units [165], at the same time, preservation of low utility buildings can be counterproductive to increasing access to housing and amenities. Looking to the future, housing designs must aim for high utility designs that can be renovated in the future. Finally, as the demand for building types within neighborhoods and communities change, repurposing underused buildings for housing allows for construction with fewer new materials [166].

2.9. Question 9: What housing occupancy and tenure models are needed for housing sufficiency?

Building on innovative design strategies, here we explore emerging occupancy and tenure models to effectively implement housing sufficiency. These models complement and operationalize some of the design changes in Question 8 and address key issues including changes in occupancy of a housing unit over time, differences in levels of flexibility in sharing resources within a household, and differences in levels of services available that optimize housing needs at a community scale.

From a design perspective, one of the key issues that needs to be addressed is the temporal nature of sufficiency in housing. For example, a dwelling unit might undergo a series of occupancy scenarios during a single life cycle. The concept of “adjustable housing” maintains sufficient occupancy levels by readjusting the dwelling unit into modular spaces [157]. This enables, for example, rental of spaces when there is single occupancy to fully utilize the entire space when at least two people reside in the house [157]. The process of “rightsizing” an adjustable unit to its occupancy level at any point during its life cycle requires the occupant to be fully informed and act proactively. In order to develop those skills, researchers propose developing a design game where players would face key decision points that a stakeholder would typically need to encounter during the life cycle of an adjustable unit [167]. The introduction of adjustable housing is still in its infancy and expected to reach a wider audience in the coming decades.

Co-housing and co-living are emerging sharing models that support a transition to more flexible housing. These models feature a community arrangement where some of the spatial functions of everyday life like guest rooms, dining areas, office spaces, and laundry are shared [168]. Sharing those spaces allows private living areas to be smaller, thereby reducing net dwelling size per capita [168]. They also offer social benefits of a larger support network for residents. Between the two sharing models, co-housing is more established and offers more collaborative community living where residents share common values and lifestyles, and actively participate in the management and governance of the shared living space [12]. Co-living is a more recent addition to collective housing where residents are not required to share common values and lifestyles, but everyone participates in managing shared spaces [12]. Like other sharing concepts, co-housing and co-living are challenging the traditional ownership structure and give rise to innovative business models including the "lease and operation" and "ownership and management of operations" models [12]. The "lease and operation" model has a third-party operator lease an entire property from an owner and then provides all co-housing or co-living services to the tenants. In the second model, the owner converts the entire property into a co-housing or co-living arrangement, charges rent and manages the ongoing operation of the complex. Key future challenges in this domain include ensuring smooth coexistence among tenants, especially those with alternative lifestyles, and the consistent upkeep of shared spaces and amenities [169]. Concerning the limitations of those models, co-living tends to remove the investment services that many residents seek in developed housing markets. In that regard, it does not directly replace the status quo, nor does it necessarily provide tenure security. At this point, it should also be noted that although collective housing models may imply a form of cultural unity, sufficiency is compatible with societies that value individual choice, where change is driven by incentive structures rather than top-down directives. The sufficiency solutions that are discussed in this section are fully compatible with predominantly owner-occupied markets, as found in many of the developed housing markets [12].

Home swapping is a noteworthy initiative that supports the creation of flexible occupancy models and promotes the desired housing sufficiency at scale into the future. This instrument targets housing redundancies that occur as a result of changes in the size and needs of a household throughout the life cycle of a housing unit. The changes in sufficiency levels in those scenarios could be avoided by allowing greater freedom to swap housing between small and large households, while maintaining current rental rates, mortgage rates, or home ownership [29,130]. For example, allowing a widow living in a large three-bedroom apartment and a young couple living in a two-bedroom apartment to swap homes reduces the need to construct new units. A recent study projecting housing needs in Milan and Oslo in 2030 found that encouraging moving between units would reduce dwelling size per capita (i.e., 5.5 % in Milan and 13 % in Oslo) and eliminate the need to construct new housing in those cities [170]. Despite the benefits, home swapping requires structural changes in the current housing market, which is economically driven, and its successful implementation requires background systems and policies to support moving between housing units in a smooth and affordable manner [29].

All occupancy and tenure models support policies that promote a transition towards lower embodied carbon in the building industry, by reducing material consumption per capita or by avoiding new construction altogether in the case of home swapping.

2.10. Question 10: What policies are needed for housing sufficiency?

Policy strategies are a crucial lever to facilitate housing sufficiency by providing better housing choices to individuals and/or groups based on their needs while optimizing resources such as land and services. These policies support the implementation of design strategies in Question 8 through building codes and standards, occupancy and tenure models in Question 9 through tax incentives and subsidies, and even urban planning beyond buildings such as transportation, land use or zoning regulations [10]. Accordingly, existing, prohibitive policies that contradict housing sufficiency policies should be reconsidered. Table 4 presents the key policy categories that are described below in detail.

Specifications of minimum allowable sizes of dwelling is one of the binding policies for housing. Through integration in local building codes, these specifications encourage the construction of smaller studio apartments or micro housing, thereby reducing the operational and embodied energy use and associated carbon emissions. Cities that have adopted these changes include San Francisco in the United States (reduced the minimum size of dwelling units to 20.4 m^2) [171] and Halifax in Canada (removed minimum housing size requirements) [172]. Incentive-based building codes can also help with minimum dwelling size specifications. For instance, the city of Vancouver in Canada under its Zero Emissions Building Catalyst Policy allows a five percent increase in floor area for housing projects that include smaller and denser units [173]. However, relaxing space standards could potentially lead to unintended consequences such as overcrowding, residential dissatisfaction [180,181] and therefore such policies must be carefully designed to meet the evolving needs such as single person household or teleworking, and socio-cultural demands of the occupants. The new construction policies to meet housing shortages must also be carefully developed given the significant environmental impacts of new construction. Accordingly, existing housing resources and future needs must be evaluated and the feasibility of implementing innovative mechanisms such as moratorium on new construction must be considered [182]. Housing sufficiency may also be facilitated by embodied carbon policies promoting low-carbon or recycled building materials. Some existing examples of setting embodied carbon requirements for new buildings include Vancouver's building by laws [173] or French environmental regulation RE2020 [174]. Policies requiring developers to demonstrate lower lifetime carbon emissions for new buildings compared to renovating existing ones may also be effective. Several pilot projects and policies that promote alternative housing arrangements such as co-housing villages (e.g., Canada) [183], home swapping programs based on household size (e.g., Germany) [184], and dedicated land and permit process for small homes (e.g., Denmark) [185] have been initiated.

Fiscal policies such as tax incentives for smaller homes, bonuses for moving into smaller homes, progressive property taxes with area-based increments or tax penalties for vacant homes can facilitate housing sufficiency. Tax incentives for retirees to downsize homes without impacting their pension (e.g., "Incentivizing Pensions to Downsize" Act in Australia) free up the housing stock for younger generations and reduce barriers for pensioners in finding and moving to right-sized homes [175]. Home swapping programs that provide cash incentives (e.g., "Silver Housing Bonus" in Singapore) [186] and assistance in finding exchange properties, contracting, and moving (e.g., the city of Potsdam in Germany) [187] can encourage households to downsize. In theory, the market provides all the opportunities for home swapping with government incentives or leading policy, except there may be frictions or constraints, e.g., difficulties in finding properties in the same neighborhood, high transaction costs, and time-consuming process with some liabilities undefined or insurance policy related concerns. Imposing taxes on vacant homes (e.g., "Housing Tax Act" in Taiwan) [176] and second home taxes (e.g., Germany and UK) [177,188] can intensify the use of underutilized homes and help reduce excess housing space and the increasingly uneven distribution of the aggregate housing stock [1,37]. Multifamily tax exemptions and credits to owners and developers (e.g., several cities in the United States) may also encourage vertical and horizontal densification [189]. Land value taxes, unlike other forms of property taxation, may also support sufficiency-oriented housing development by discouraging urban sprawl. A successful example is Denmark's property tax system which includes the land value tax and was found to encourage efficient land use and development [190]. Additionally, reforming the mortgage lending criteria such as stricter loan-to-value ratios and higher down payment requirements, incentivizing shorter loan terms or alternate metrics for measuring affordability [191] may be effective solutions to tackle the unsustainable larger home purchases, and in turn excess living space consumption.

Urban planning policies particularly related to land use and zoning reforms are crucial for realizing benefits within housing. Zoning reforms prioritize the construction of "missing middle housing", a term often used to describe a range of housing forms including duplexes, triplexes, townhouses, and low-rise MURBs, over single-family homes. The city of Minneapolis was the first major city in the United States to allow the construction of duplexes and triplexes on previously zoned lots for single-family homes [178]. Similar policies including subdividing plots for developing accessory dwelling units (e.g., the already implemented Senate Bill 9 in California, United States) [179] and reforms prioritizing infill housing (e.g., proposed reforms in Canberra, Australia) [192] can eliminate the need for new greenfield development. For successful implementation and sustained benefits of these policies, there is a need to integrate building bylaws and zoning reforms and streamline the permitting process. Planning concepts such as 15-minute cities or transit-oriented development can encourage sufficiency in housing, as

Table 4
Key policy categories supporting housing sufficiency and existing policy examples from some cities and countries.

Policy category	Description	Applicability	Existing policy examples (if any)
Building codes	Relaxing minimum housing size requirements[a]	New construction and retrofits	San Francisco, United States [171] & Halifax, Canada [172]
	Incentivizing for smaller size housing units[a]	New construction and retrofits	Zero Emissions Building Catalyst Policy, Vancouver, Canada [173]
	Setting embodied carbon requirements	New construction	RE2020, France [174]
Fiscal - tax incentives	Incentivizing downsizing, multifamily tax credits	Existing and new construction	Incentivizing Pensions to Downsize Act, Australia [175]
	Imposing vacant homes taxes, progressive property taxes and/or land tax	Existing and new construction	Housing Tax Act, Taiwan [176] & Second home taxes, Germany [177]
Fiscal - financing homes	Reforming mortgage lending	New construction	–
Land use	Allowing missing middle housing and infill housing units such as accessory dwelling units.	New construction and retrofits	Minneapolis [178], Senate Bill 9, California [179]
	Planning for 15-minute cities or transit-oriented development	New construction and retrofits	Multiple cities such as Barcelona, Spain and Copenhagen, Denmark

[a] As highlighted in the text, these policies should take care to maintain the well-being and decent living standards of occupants.

well as in the transportation sector and the built environment broadly [193,194].

For housing renovation and adaptive reuse, concession contracts that place housing projects under public supervision could encourage large scale renovation for sufficiency. In this strategy, public authorities and companies would take on the administrative tasks and the design and implementation of the renovation project, while the finances are dealt with through tax schemes and savings that are linked to the project [195]. This reduces the financial, technical, and administrative burdens of households (especially low-income households) and could efficiently implement and finish large scale renovation projects in the shortest possible time [195].

In summary, these policies abet housing sufficiency by encouraging right-sized housing units, denser neighborhoods, and optimized use of land and other resources. Most of the housing policies described here have co-benefits such that they also intend to solve challenges related to housing affordability and shortages or social isolation. Moreover, the reviewed policies for housing sufficiency are concentrated in developed countries, which possess significant resources and capacity, higher historical consumption, and mature, widely enforced building codes and regulations. However, sufficiency policies are also crucial for developing nations, which are currently missing due to different national priorities and economic factors, to meet rapidly growing demands and unique vulnerabilities of such nations.

3. Conclusion and future perspectives

The ten questions and answers presented in this paper highlight the drivers, benefits, potential drawbacks, and measures of housing sufficiency, the contextual differences between countries, and design, housing models, and policies to support sufficiency. Question 1 concluded that vastly more research and public attention has been devoted to energy efficiency than housing sufficiency, despite the fact that efficiency is evidently not only incapable of achieving environmental targets, but also partially responsible for increasing demand. Question 2 presented different fields' perspectives of housing sufficiency, with one dimension including the minimum housing for safety and well-being vs. excess, and other dimensions considering equitable distribution. Question 3 took a more quantitative view of the definitions for housing sufficiency, with a focus on floor area per person. While wealthier countries have, on average, three to five times more housing floor area per capita than the minimum recognized by the ICC, that definition lacks the context of climate and culture (e.g., use of outdoor spaces, expectations for privacy). Question 4 provided a comprehensive summary of the environmental and social benefits of housing sufficiency. While the focus of the paper to this point was the direct benefit of smaller homes (less materials, energy use, and emissions), Question 4 covers the many broader benefits of sufficiency such as reduced maintenance, greater access to amenities, housing affordability, and improve social connectedness. On the contrary, Question 5 balanced these benefits with a comprehensive list of drawbacks of housing sufficiency, such as the drawbacks of frequent moving for households and rebound effects of newfound disposable income.

The second half of the questions transitioned from theory to discuss the status quo of housing sufficiency, followed by design and tenancy strategies, and policy. Question 6 found that by and large, housing in the developed world is excessive in floor area, land use, and personal vehicle dependency. There is little that the developed world has to offer regarding housing sufficiency except strong laws and institutions to help ensure that minimum housing standards for health and safety are provided. In contrast, Question 7 concluded that a significant portion of housing in developing countries can be deemed insufficient in floor area and basic amenities such as sanitation. Finally, the paper addressed solutions to housing sufficiency. On design (Question 8), there are tradeoffs between flexibility (efficiently accommodating a household through its life) and the associated increase in material use and embodied carbon in the first place. Question 9 explored three key tenancy models leading to greater housing sufficiency – co-housing, co-living, and home swapping – that can achieve a more optimal use of space and goods, but require a combination of good will and strong government and/or community policies, and in the case of the former two, a neighbourly spirit towards sharing space and amenities. Finally, Question 10 surveyed key policy tools to enhance housing sufficiency, including building codes, fiscal policy (tax or incentives), and land planning. In brief, key policies include removing minimum home sizes (with care to maintain occupant well-being) and promoting construction or retrofit of homes to have better use of space, incentivizing people to downsize their owned or rented home as their household shrinks, and taxing land to incentivize more appropriate levels of housing density. Overall, this ten questions paper provides a reference resource for researchers to inform their work and to help position housing research in the context of sufficiency.

Despite the potential for sufficiency as evidenced by specific housing projects and regional policies, it has not gained nearly the same traction of energy efficiency and renewable energy – whether at the public discourse level or through institutions and laws. Going forward, more research is needed to accelerate the adoption of housing sufficiency in practice. Building on the metrics summarized in Question 3, standardized metrics, especially those that identify minimum and maximum thresholds for housing sufficiency, are needed at different spatial scales. Regionalized and localized metrics should consider dominant social norms, cultural expectations, economic conditions, and evolving needs for resilience and adaptability in context of increasing extreme weather events. These should be benchmarked against a global metric for housing sufficiency, which could be used to minimize or close the housing equity gaps among countries. These metrics should address the overlap between sufficiency and efficiency to prevent inequitable distribution of housing resources.

The environmental implications of housing sufficiency strategies on other planetary boundaries should be examined. Specific focus should be on the impacts of sufficient building and neighbourhood design on land-system change and the influence of housing construction (especially on previously undeveloped lands) on biosphere integrity. Methods to assess the system-scale environmental impacts of housing sufficiency strategies include life cycle assessment and environmentally extended input-output analysis. These approaches have the capability to estimate different environmental impacts and analyze technical and environmental trade-offs. Regarding social impacts, more in-depth analyses are needed to understand the relationship between housing sufficiency, housing quality, affordability, and human well-being. Ethnographic analysis could help examine the interrelationships between space and well-being and could determine the socio-technical approaches to understanding sufficiency and features in relation to design expectations, social, and spatial norms. The outcomes from this analysis can be used to update the requirements of decent living standards for human well-being by Rao and Min [3].

The economic impacts of emerging design strategies, occupancy and tenure models for housing sufficiency should be further examined. Any potential savings from these strategies would be helpful to leverage for their widespread implementation in the housing market and construction sector. Quantitative studies on the effects of sufficiency policy and implications on affordability, prevention of homelessness, or social cohesion would be promising areas that contribute to recent developments in social justice and equity research. Additionally, there is a need for interdisciplinary research spanning across architecture, engineering, social science, economics, and health to evaluate the impact of housing sufficiency on quality of life and environmental sustainability. Finally, formulating and implementing strategies should involve different stakeholders including occupants, architects, designers, urban planners, real estate developers, and policymakers. Social scientists, particularly psychologists and sociologists, can inform effective messaging strategies to facilitate implementation of housing sufficiency policies. As housing provision is a social justice issue, these stakeholders must firstly raise the minimum standard for sufficient housing, prioritizing the housing needs of disadvantaged communities.

CRediT authorship contribution statement

Aldrick Arceo: Writing – review & editing, Writing – original draft, Conceptualization. **Marianne Touchie:** Writing – review & editing, Writing – original draft, Conceptualization, Supervision, Funding Acquisition. **William O'Brien:** Writing – review & editing, Writing – original draft, Conceptualization, Supervision, Funding Acquisition. **Tianzhen Hong:** Writing – review & editing, Writing – original draft, Conceptualization. **Jeetika Malik:** Writing – review & editing, Writing – original draft, Conceptualization. **Matan Mayer:** Writing – review & editing, Writing – original draft, Conceptualization. **Terri Peters:** Writing – review & editing, Writing – original draft, Conceptualization. **Shoshanna Saxe:** Writing – review & editing, Writing – original draft, Conceptualization. **Ruth Tamas:** Writing – review & editing, Writing – original draft, Conceptualization. **Hannah Villeneuve:** Writing – review & editing, Writing – original draft, Conceptualization. **Benoît Schmaltz:** Writing – review & editing, Writing – original draft.

Jeetika Malik and Tianzhen Hong contributed to Questions 2 and 10. The views expressed in other sections of the paper, written by the remaining authors, do not necessarily reflect the perspectives of Jeetika Malik and Tianzhen Hong.

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.

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Data availability

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

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