Building floorspace and stock measurement: A review of global efforts, knowledge gaps, and research priorities

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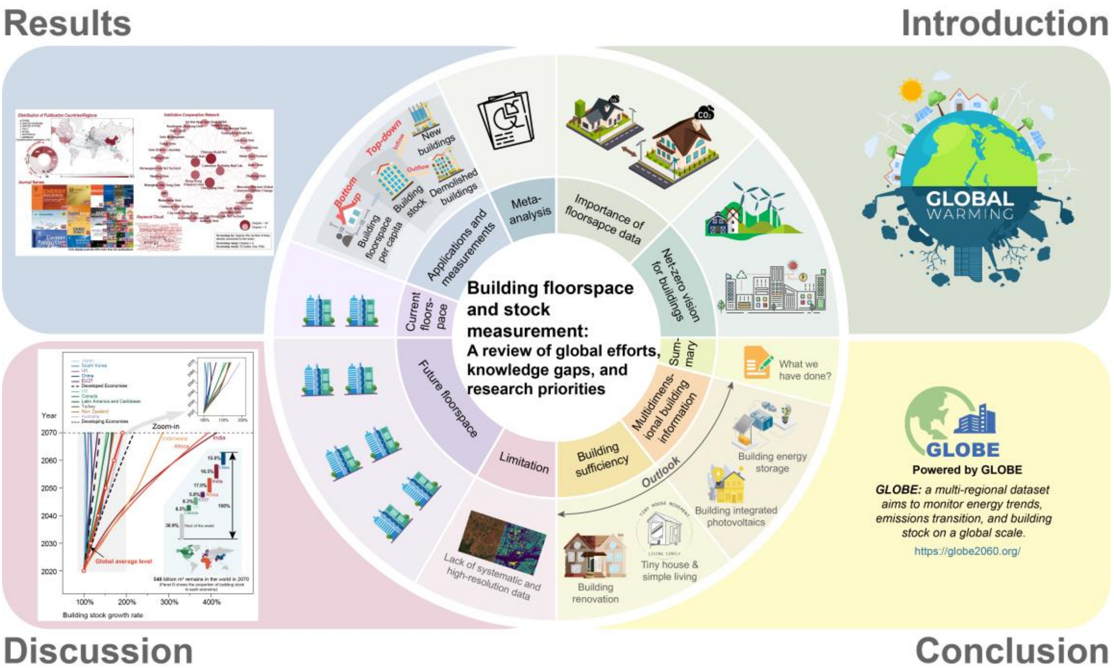
GRAPHICAL ABSTRACT



Graphical abstract. A review of global efforts, knowledge gaps, and research priorities related to building floorspace and stock measurement, focusing on energy use and carbon emissions within the building sector.

HIGHLIGHTS

- We review 2,140 papers on building floorspace and stock, focusing on energy and emissions.
- Floorspace measurement approaches consist of top-down, bottom-up, and hybrid methods.
- By 2070, the global building stock is projected to be 1.87 times its 2022 level (~540 billion m^2).
- High-resolution floorspace imagery is essential for advancing low-carbon progress in buildings.
- Building sufficiency is a critical strategy for accelerating decarbonization in the building sector.

SUMMARY

The lack of global floorspace data presents challenges in achieving building carbon neutrality. We analyze 2,140 peer-reviewed papers on global building floorspace, focusing on energy and emissions. The top five countries publishing the most include China, the UK, the US, Italy, and Spain. The key research topics include energy modeling, emissions analysis, building retrofits, and life cycle assessments, particularly for residential buildings. Measurement approaches—top-down, bottom-up, and hybrid—each face challenges, with top-down methods offering broad estimates but tending to low accuracy, whereas bottom-up approaches are precise but requiring intensive data. Our latest simulations reveal significant floorspace growth in emerging economies, particularly India, Indonesia, and Africa. By 2070, India's per capita residential floorspace is projected to triple, whereas Indonesia's non-residential floorspace could increase sevenfold. We emphasize the need for a high-resolution global floorspace imagery database to compare energy efficiency, track decarbonization progress, and assess renovation impacts, while promoting building sufficiency and accelerating the transition to net-zero building systems.

KEYWORDS

Residential buildings;
Non-residential buildings;
Building floorspace;
Stock turnover;
Building decarbonization;
Sustainable construction;
Building renovation and sufficiency;
Life cycle assessment;
Bibliometric analysis

INTRODUCTION

Buildings contribute more than 37% of global energy-related carbon dioxide (CO_2) emissions,[1] with record-high emissions of more than 13 gigatons of CO_2 observed in 2023.[2] Given the significant potential for commercially available and cost-effective decarbonization measures, the building sector is poised to play a crucial role in achieving net-zero emissions by the middle of this century.[3,4] Since building carbon emissions are a product of carbon intensity (emissions per floorspace) and total floorspace, it is essential to quantify building floorspace. This effort will increase the accuracy of carbon intensity measurements and improve the ability to assess decarbonization strategies throughout the building life cycle.

However, a significant global challenge remains: the lack of comprehensive, high-resolution imagery data on building floorspace. This gap impedes precise carbon intensity measurements and restricts the ability to assess decarbonization strategies at the global, regional, and city levels. Despite the development of our global building stock model (GLOBUS[5])—a long-term forecasting tool that integrates turnover analysis and accounts for building renovations to simulate future building floorspace changes globally (see Figure 1)—data fragmentation and methodological limitations persist. A single approach, such as the stock turnover model, is difficult to apply universally to each country's building sector due to the lack of basic statistical data. The collection of high-resolution imagery data on building floorspace and stock remains urgently needed to address these constraints and advance efforts to reduce building-related emissions.

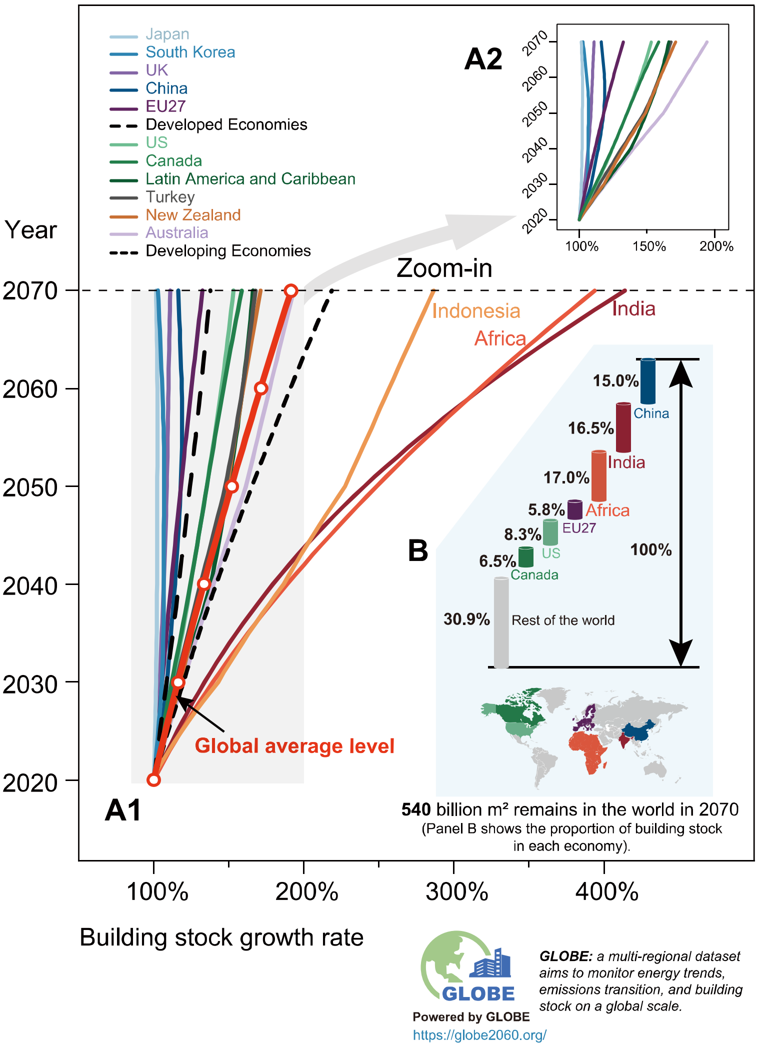


Figure 1. Global trends in building floorspace. (A) Global and regional building stock growth rates, 2020-2070; (B) Regional stock distribution in 2070. Note: the EU27 refers to the 27 countries that are part of the European Union.

Our review of building floorspace measurements

To support the development of a global high-resolution imagery database that tracks changes in building floorspace and stock, this comprehensive review aims to address critical data gaps in current research. Through a systematic bibliometric analysis of studies on floorspace and stock measurements, we examine global efforts, identify knowledge gaps, and highlight research priorities, particularly at the intersection of energy, emissions, and building floorspace/stock. In this review, we raise three key questions.

- Which institutions have conducted extensive research with significant contributions?
- What is the current status of applications and measurements of floorspace and stock?

- What are the current and future trends of floorspace and stock in different economies?

To address the three questions posed above, we review 2,140 peer-reviewed papers indexed by the Web of Science on the topic of building floorspace and stock worldwide, with a specific focus on the intersection of energy/emissions and floorspace/stock. The results of our meta-analysis provide insights into the first question, offering a comprehensive overview of the leading countries, institutions, and journals contributing to this field. For the second question, we further examine the applications and measurements of building floorspace, focusing on two key areas: summarizing the major applications of floorspace and stock and outlining the main approaches used to measure building floorspace. This analysis identifies current practices and highlights gaps in the methodologies employed. Finally, in response to the third question, we conduct an analysis of the global status of building floorspace, estimating future global building stock trends. This analysis provides a broader understanding of the future direction of building stock growth and its potential impact on energy use and emissions. The detailed steps of our bibliometric analysis are provided in the Experimental Procedures section of this paper.

Our most significant contribution is conducting the largest systematic review of global building floorspace and stock measurement, highlighting key trends, gaps, and opportunities for improving data accuracy and consistency across regions and methodologies. Current global efforts to decarbonize the building sector are hampered by fragmented data and methodological limitations. The complexity of measuring floorspace across various building typologies and regional contexts exacerbates the challenge of carbon monitoring and mitigation comparisons. In this review, we examine the influence of floorspace on energy consumption and emissions throughout all building life cycle stages. We categorize existing approaches for measuring floorspace, highlighting their strengths and limitations, and provide an assessment of the current global status of building floorspace, along with future projections of building stock. Our findings emphasize the critical need for a comprehensive global floorspace database, which would enable more accurate comparisons of energy efficiency, decarbonization progress, and the impacts of building renovations. Additionally, we stress the importance of building sufficiency as a key strategy for promoting a low-carbon, sustainable built environment.

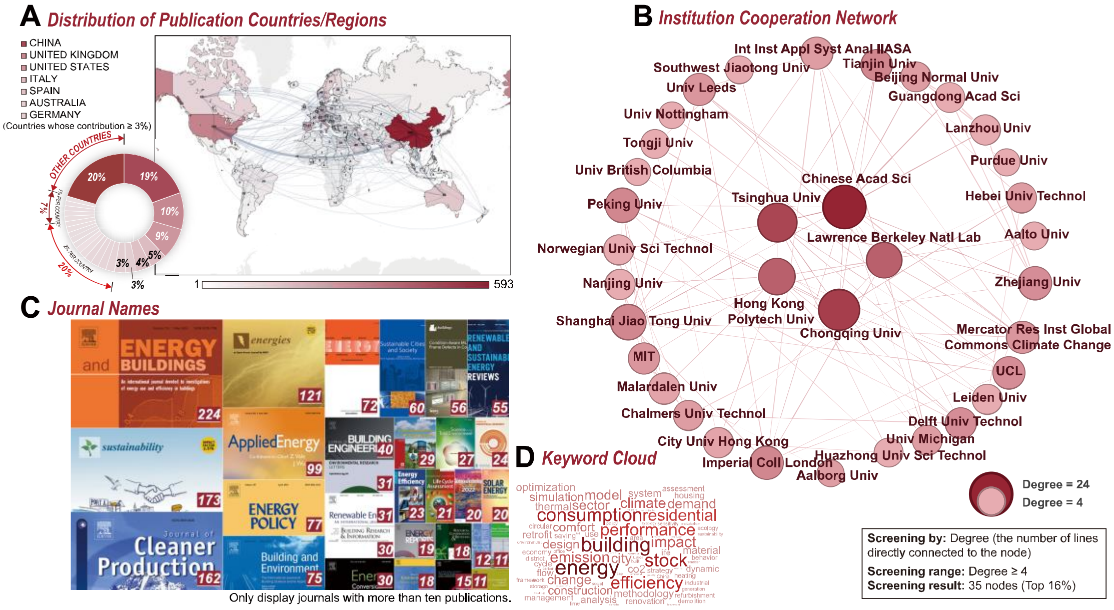
RESULTS

Meta-analysis of the retrieved articles

A systematic literature search conducted in April 2024 identified 2,140 peer-reviewed papers focusing on building energy consumption and carbon emissions related to building floorspace after the exclusion of conference proceedings, data papers, and irrelevant fields. The search spanned over the past 30 years, from 1992 to 2024. Among these papers, 51 (2.4%) were classified as Essential Science Indicators (ESI) Highly Cited Papers. According to the Web of Science, ESI Highly Cited Papers were ranked in the top 1% for citations within the same subject area and publication year. Therefore, the proportion of ESI Highly Cited Papers in this sample exceeded the global baseline by more than twofold, highlighting the significant scholarly attention that research on the links among floorspace, building energy consumption, and carbon emissions has garnered.

Figure 2 provides an overview of the retrieved articles. As shown in Figure 2 A, scholars worldwide were actively discussing building energy consumption and carbon emissions at the unit floorspace scale. Notably, scholars from seven countries contributed more than 3% to this field, including China (19%), the United Kingdom (UK, 10%), the United States (US, 9%), Italy (5%), Spain (4%), Australia (3%), and Germany (3%). Additionally, Figure 2 B highlights the top 35 contributing institutions in this field. The top five institutions with the most complex collaborative relationships were the Chinese Academy of Sciences, Chongqing University, Tsinghua University, Lawrence Berkeley National Laboratory, and Hong Kong Polytechnic University.

Furthermore, Figure 2 C displays the 30 journals with the highest concentration of relevant papers, each containing more than 10 retrieved articles, collectively accounting for approximately 75% of the total retrieved articles. The top five journals with the most retrieved articles were *Energy and Buildings* (224 papers), *Sustainability* (173 papers), *Journal of Cleaner Production* (162 papers), *Energies* (121 papers), and *Applied Energy* (99 papers). Additionally, Figure 2 D presents a keyword cloud derived from the retrieved articles, with font size and color shading indicating the frequency of each keyword's use. The most popular keywords in this field included “Building”, “Stock”, “Energy”, "Consumption", and "Efficiency".



Only display journals with more than ten publications.

Figure 2. Meta-analysis of the retrieved articles. (A) Distribution of publication countries/regions, (B) institution cooperation network, (C) journals with more than ten publications, and (D) the keyword cloud.

To further enhance the precision and relevance of the search results, we implemented an additional filtering mechanism using "Keywords Plus" within Web of Science and subsequently conducted an in-depth analysis of these retrieved articles alongside the previously identified ESI Highly Cited Papers. After manually screening and excluding low-relevance papers, 100 articles focused on building floorspace remained, 26 of which were ESI Highly Cited Papers. This concentration of ESI Highly Cited Papers further underscores the importance of building floorspace-related research. The content of these 100 articles on the applications and measurement of building floorspace is detailed below. Additionally, the search keyword settings, process, and specific results are provided in Sections 1-3 of the Supplemental Information.

Applications and measurement of building floorspace

Building floorspace has distinct implications across all stages of the building life cycle. During the pre-construction and construction stages, energy use and carbon emission intensities are quantified per unit of newly constructed floorspace. In the operation stage, these intensities are typically measured against the building stock, which is defined as the total floorspace of operational buildings. This reflects the net balance between floorspace inflow (i.e., newly constructed and renovated buildings) and outflow (i.e., demolished buildings). During the demolition stage, the floorspace of buildings that have reached the end of their service life and require demolition serves as the denominator for calculating energy and carbon emission intensities.

Before delving into the specifics of building floorspace quantification, the first step is to understand when building floorspace quantification is required across various building types, stages, and goals and which approaches are used in this quantification. To address these questions, we categorized the retrieved articles involving building floorspace and attempted to resolve the following queries:

Building Type: What type of building was the research question focused on (e.g., residential or non-residential)?

Stage: Which stage of the building life cycle did the research address (e.g., pre-construction, construction, operation, demolition, or across all stages)?

Goal: What were the goals of using building floorspace to measure carbon emissions (e.g., energy conservation, emission reduction, climate protection, or sustainable development)?

Approach: How was building floorspace quantified (e.g., top-down, bottom-up, or a hybrid approach combining both)?

Figure 3 illustrates the hierarchical structure of building floorspace applications in the retrieved articles, including building types, life cycle stages, topics, methods, and goals. The width of each area represents the number of studies associated with the corresponding application. With respect to building types, the distribution of studies is as follows: residential buildings (64%), non-residential buildings (5%), and civil buildings* (31%). From the perspective of the building life cycle, studies have focused on the following stages: pre-construction (7%), construction (9%), operation (68%), and all stages (16%). It is clear that the majority of studies on energy consumption and carbon emissions related to building floorspace focus on the operation stage of residential buildings. The goals of using building

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* Civil buildings include the residential and non-residential buildings.

floorspace are as follows: energy conservation (54%), emission reduction (35%), climate protection (4%), and sustainable development (7%).

Among these applications, building floorspace plays a critical role in determining building energy consumption and carbon emissions. While it is primarily used as an intermediate metric in environmental assessments—especially for energy and emissions—its fundamental role in shaping a building's overall environmental impact remains underexplored. Therefore, this review first introduced the applications of floorspace in measuring energy and carbon emissions across various building types and stages, followed by a detailed analysis of the methodologies used to measure floorspace.

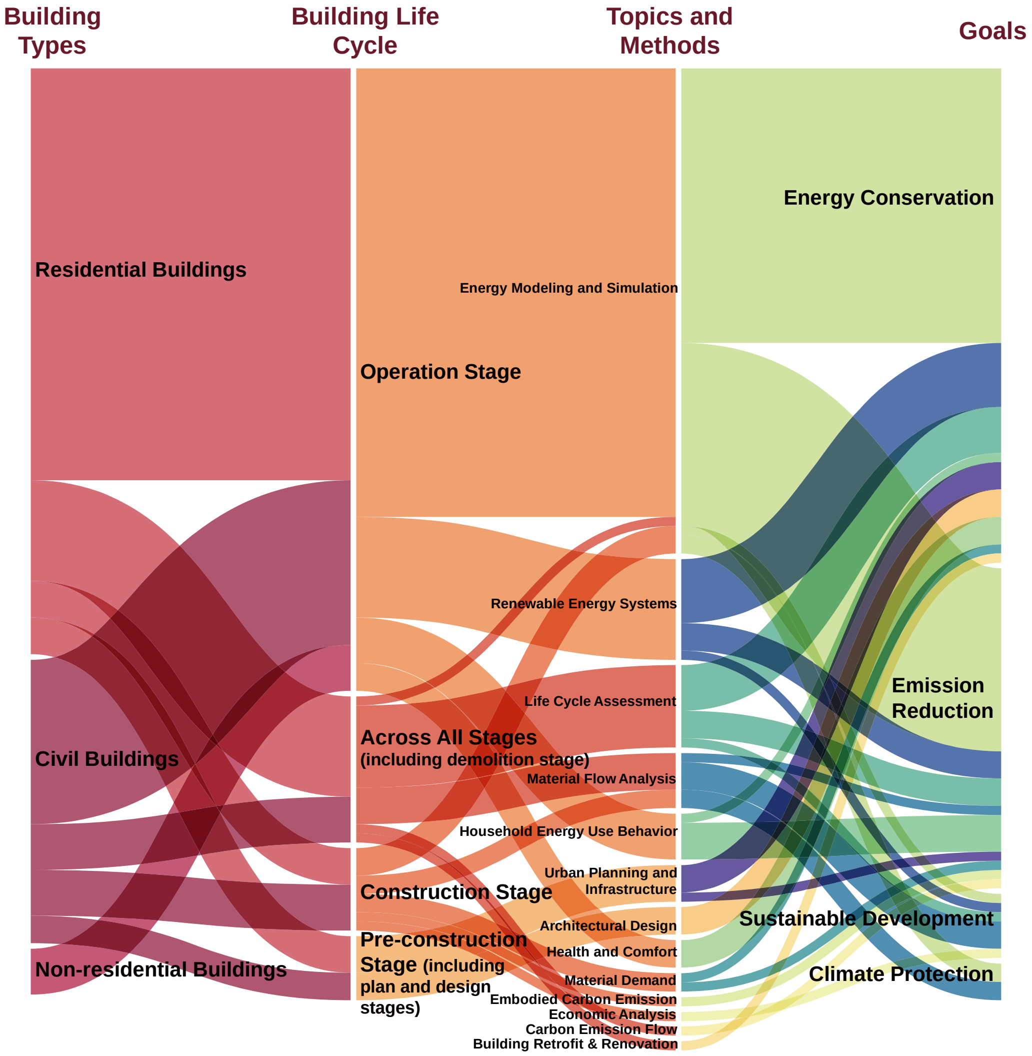

Figure 3. The hierarchical structure of building floorspace applications in the retrieved articles, categorized by building types, life cycle stages, research topics and methods, and goals. Note: the width of each area reflects the number of studies associated with each category.

a. Applications of building floorspace featuring carbon intensity

The retrieved articles on applied building floorspace are categorized into two groups: direct applications (58% of the total) and applications after quantification (42% of the total). The distinction between these two types lies in whether the research includes the quantification of building floorspace. The following section provides a detailed explanation of the direct application of building floorspace.

In the field of energy efficiency assessment and building decarbonization, building floorspace is often used as a fundamental parameter to evaluate energy consumption and emissions. While crucial in these complex studies, floorspace is seldom the primary focus. As a result, some studies have directly utilized existing floorspace data for more detailed analysis of building-related factors, provided that sufficient data are available. This method is especially prevalent in urban planning,[6-8] infrastructure development,[9-12] and architectural design in the pre-construction period of the building life circle.[13] Additionally, the direct use of building floorspace data for research on building energy consumption and carbon emissions is more common during construction, operation, or the whole life cycle of buildings.[14-16] The applications mentioned above are broad, encompassing, but not limited to the following areas:

Embodied decarbonization: Exploring the impact of reduced new construction and improved material efficiency on decarbonization goals.[17-19]

Energy and emission models: Various models for simulating energy use in buildings,[20,21] alongside energy forecasting models,[22-24] as well as decarbonization models[25] for evaluating carbon peak and neutrality, with building floorspace as a key parameter.[2,26]

Factors affecting carbon emissions: Analyzing the influence of population,[27] gross domestic product,[28,29] building floorspace,[30-32] and household conditions[33,34] on building emissions.

Energy efficiency improvements: Assessing the energy efficiency of building operations through building renovation,[35,36] particularly in terms of space heating[39,40] and cooling technologies,[41] with a focus on energy savings, decarbonization benefits,[42] and cost benefits.[43,44]

Building-integrated photovoltaics (BIPVs): Evaluating the development of BIPVs in distributed energy systems, influenced by building floorspace.[45,46]

While building floorspace data are readily available for certain regions, comprehensive global datasets disaggregated by building type and geography remain scarce. This widespread lack of floorspace statistics significantly hampers the measurement and evaluation of building energy consumption and carbon emissions at the intensity level, thus limiting the scope and depth of building-related research.

b. Measurement of building floorspace

While a subset of the retrieved articles does not directly focus on the statistical analysis of floorspace, these studies nevertheless explored the quantification approaches of floorspace to some degree. Since the accounting of building floorspace is usually integrated with the accounting process of building energy consumption and carbon emissions, the existing research on building energy consumption can be divided into three main categories: top-down, bottom-up, and hybrid models, which are classified by the modeling method;[47,48] or white, black, and gray boxes, which are classified by the degree of transparency.[49,50] Therefore, the quantification of building floorspace can refer to the classification logic used in the classification of building energy consumption research, which is categorized into a top-down approach starting from a macro perspective, a bottom-up approach starting from a micro perspective, and a hybrid approach combined with top-down and bottom-up approaches.

Top-down approach: The top-down approach mainly refers to the building stock turnover model, which combines inflow (newly constructed and renovated buildings) and outflow (demolished buildings) buildings at the macro level of regional society to count the net stock of regional buildings (see Figure 4). It usually adheres to the entire life cycle of buildings and focuses on analyzing newly constructed buildings and the building stock.[51] Building stock turnover is often linked to the turnover of building materials. Some studies combined these processes to analyze embodied carbon emissions associated with materials throughout the building life cycle,[52] particularly during the construction stage.[53] Furthermore, the results of the top-down building stock turnover model provide a foundation for bottom-up analyses of the energy consumption of end-use activities in building operations.[54] In addition, some studies used the number of households to represent the building stock, which was calculated by dividing the population by the average household size. While this is a top-down approach, it applies only to residential building research.[55]

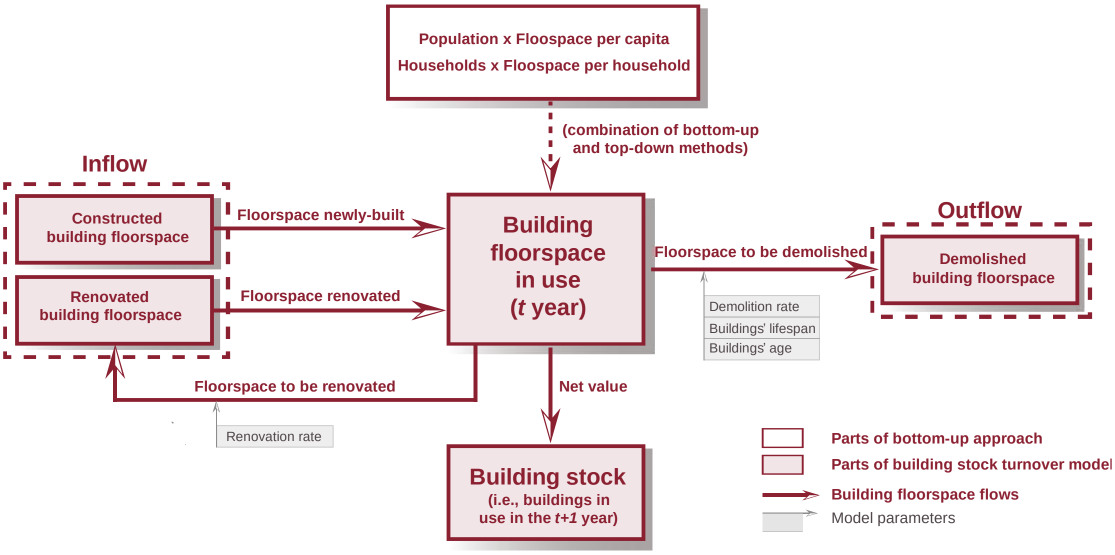

Figure 4. Schematic diagram of the building stock turnover analysis process.

Owing to the research paradigm of the top-down approach, its advantages and limitations are obvious. Compared with the bottom-up microdata-based approach, the top-down approach adopts a macro perspective applicable to a broader range of research domains. In addition, the top-down building stock turnover model can provide more comprehensive macro data related to building floorspace, covering the floorspace of newly constructed, existing, and demolished buildings, which is conducive to top-down analysis of building energy consumption and embodied and operational carbon emissions at the macro level. However, the building stock turnover model is based on macro analysis, with parameters reflecting social averages, which limits its ability to capture spatial differences. For example, the building lifespan and renovation rate involved in the model may show significant regional differences under different climatic and economic conditions. Additionally, the results provided by the top-down approach have limited guiding significance for specific technical improvements to enhance building energy efficiency.

Bottom-up approach: The bottom-up approach can be divided into two main categories: demand-driven and physical modeling. The demand-driven approach considers per capita comfort and environmental quality, estimating regional building stock by multiplying the regional population by the estimated suitable per capita building floorspace,[56] or the number of regional households by the estimated suitable building floorspace per household[57] [e.g., Residential Energy Consumption Survey of U.S. Energy Information Administration (EIA)]. Moreover, for commercial buildings, some studies estimated total building floorspace by multiplying the number of service personnel by the building floorspace per employee.[58] The demand-driven bottom-up approach is widely used in predicting future carbon emission pathways because of its simplicity, enabling quick estimation of building floorspace data and its impact on carbon emissions.[59,60]

The second type of approach is based on physical modeling and is both technology-oriented and data-driven. Two main forms are used: the first form integrates geographic information systems and remote sensing data to perform physical modeling on a small area,[61,62] such as cities[63-65] or neighborhoods,[66] to estimate regional building stock;[67-69] the other form classifies buildings according to typical characteristics,[70-72] selects representative examples to build physical models,[73,74] and extrapolates the results on single building floorspace and energy consumption to the regional level,[75,76] enabling analysis of regional building floorspace and energy consumption from point to surface. Both forms of this approach are often used to quantify energy efficiency improvements,[77] decarbonization benefits,[78] and cost effectiveness[79] resulting from building renovations.[80] In addition to analyzing regional building stock from point to surface, this physical modeling approach has also been applied to the study of specific buildings or specific building types, such as schools.[81,82]

Like the top-down approach, the bottom-up approach also has obvious advantages and disadvantages. The main advantage of the demand-driven bottom-up approach is that the calculation process is simple, and the demand for raw data is relatively small. However, the applicability of this approach largely depends on the availability of key per capita floorspace data. This approach is suitable for national-level studies, allowing separate calculations for residential and non-residential buildings. However, because it relies on per capita floorspace, it is less applicable to studies of specific building types.

The bottom-up physical modeling approach has significant advantages. Compared with the top-down approach, the estimation results of building floorspace are closer to the actual situation and can provide detailed floorspace data, including building size, door and window layout, envelope data, roof area, etc. This information is crucial for evaluating the photovoltaic potential of buildings, improving energy efficiency in space heating and cooling, and evaluating the effects of building renovations and equipment upgrades. This demonstrates that the bottom-up physical modeling approach offers greater breadth and depth in application. Furthermore, this approach is more flexible than the top-down approach in estimating the building stock of a specific area or building type from a micro perspective. Although the bottom-up approach has many advantages, its application relies on large and complex basic data, which limits its applicability at the national or global level.

Hybrid approach with top-down and bottom-up approaches: The hybrid approach combines the top-down building stock turnover model with the demand-driven bottom-up approach.[83] In applying the top-down building stock turnover model, some studies derived static building stock by multiplying population size by per capita building floorspace or the number of households by average building floorspace per household as the input data of the model[57] (as shown by the dotted line in Figure 4), thus reflecting an integration of the top-down and bottom-up approaches. In addition, to increase research reliability, some studies classified regional buildings by typology and apply building stock turnover models to each of them,[84] which also reflects the combination of top-down and bottom-up approaches.[85] Hybrid approaches are commonly employed to calculate potential future building stock,[86] energy consumption,[87] and carbon neutrality pathways under various economic, technological, and emission scenarios.[88] The integration of the demand-driven bottom-up approach has extended the time scale of the building stock turnover model, facilitating the analysis of future renovation potential.[89] In contrast, the physical modeling method encounters greater challenges in forecasting future pathways.

Each approach—top-down, bottom-up, or hybrid—has its own distinct advantages and limitations. The choice of an appropriate building floorspace quantification method should be aligned with the specific needs of the research. Despite the widespread use of floorspace data in building-related studies, in-depth investigations into quantification methodologies are still lacking. The development of a high-resolution and comprehensive building floorspace database is urgently needed to advance this area of research.

Current global building floorspace status

While the preceding analysis underscores the pivotal role of floorspace data, global datasets remain sparse, especially continuous building floorspace data with time series. Among the retrieved articles, less than half addressed the quantification of building floorspace, with time series data on building floorspace being notably scarce. Therefore, we expanded the scope of our search, referring to the research results of authoritative institutions (e.g., the United Nations Environment Programme,[90] the Global Alliance for Buildings and Construction,[91] and the International Energy Agency[92,93]), high-quality articles published by native scholars from different countries,[94-96] and manually screened and summarized building floor space data with reference values. The summarized regions include eight developed economies, namely, the US, Canada, Japan, South Korea, the UK, New Zealand, the EU27 and Australia, and six emerging economies, namely, China, India, Africa, Turkey, Indonesia, Latin America and the Caribbean (LAC). Given comparable conditions, we analyzed global trends in per capita floorspace, as shown in Figure 5, which depicts the per capita floorspace of residential and non-residential buildings across 14 economies from 2000-2022.

For the residential buildings shown in Figure 5 A, the per capita floorspace in developed economies substantially exceeded that of emerging economies, ranging from 35.8 square meters[†] (m^2, South Korea) to 62.4 m^2 (US) in 2022. However, in most emerging economies, per capita residential floorspace was well below 30 m^2, with Indonesia having the lowest value at approximately 11.3 m^2. In China and Turkey, although they are emerging economies, their per capita residential floorspace reached approximately 39.5 and 36.7 m^2, respectively, in 2022. Additionally, the per capita residential floorspace in the US varied greatly, which is to some extent determined by the statistical method of residential buildings in the US. The EIA conducted a Residential Energy Consumption Survey approximately every five years, which is a sampling survey to count the residential building floorspace of that year. This introduces significant randomness in sample selection, which greatly impacts the final results. Additionally, per

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[†] 1 square meter equals to 10.764 square feet.

capita residential floorspace in other regions generally tends to increase.

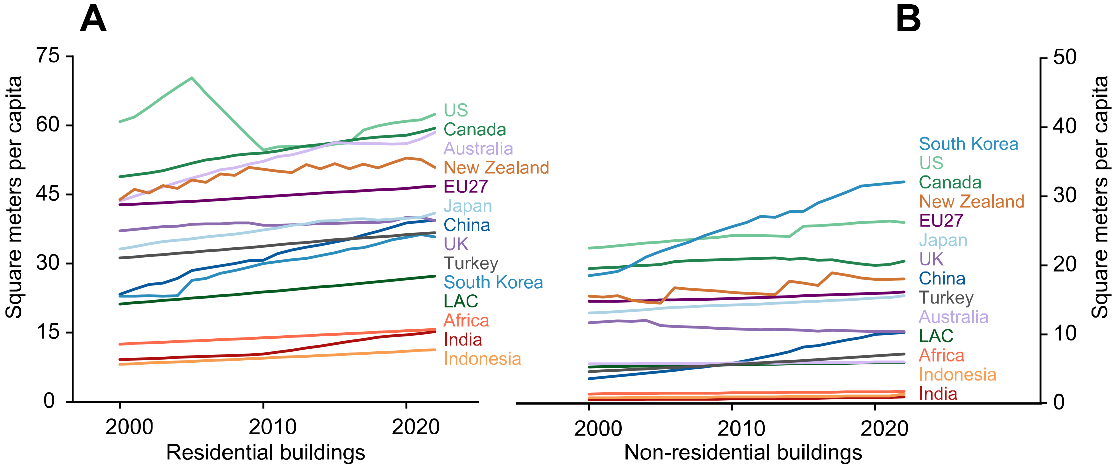

Figure 5. Trends in per capita floorspace for (A) residential and (B) non-residential buildings worldwide, 2000-2022.

As shown in Figure 5 B, the per capita non-residential floorspace in developed economies was also generally greater than that in emerging economies. Compared with other developed economies, South Korea's per capita non-residential floorspace grew rapidly and reached a maximum of 32.1 m^2 in 2022, driven by a rapid decline in population after reaching a peak. Other developed economies with an increasing trend in non-residential floorspace per capita were distributed mainly between 15.6 and 26.2 m^2 in 2022. Owing to Australia's small per capita non-residential floorspace base and slow growth between 2000 and 2022, the per capita non-residential floorspace in 2022 was only 6.0 m^2. In addition, the UK's long-term rapid population growth caused by net immigration has led to a downward trend in per capita non-residential floorspace, which was only 10.4 m^2 in 2022. With respect to emerging economies, only China, Turkey, and LAC had slightly higher per capita non-residential floorspace than Australia did in 2022, at approximately 10.3, 7.2, and 6.0 m^2, respectively. Other emerging economies were significantly less common: India at approximately 0.9 m^2, Africa at approximately 1.8 m^2, and Indonesia at approximately 1.4 m^2. We believe the differences in non-residential floorspace per capita among economies can largely be attributed to the unequal development of each economy's service industry and the varying population sizes across these economies.

DISCUSSION

We focused on several key implications of this review article, including future global building stock estimations, as well as the limitations and future outlook of this work.

Future global building stock estimations

Figure 5 illustrates the global trends in per capita floorspace from 2000-2022. On this basis, we further collected and collated the projected development of global floorspace under the business-as-usual (BAU) scenario. Given comparable conditions, we conducted a preliminary analysis of the potential growth in per capita residential and non-residential building floorspace for 14 economies from 2022-2070 under the BAU scenario (see Figure 6). This analysis is based on representative studies by authoritative institutions (e.g., IEA[97-99], EIA[100]) and native scholars.[101-104]

With respect to the growth rates for per capita residential building floorspace presented in Figure 6 A, emerging economies generally outpace developed economies. For example, emerging economies were projected to achieve an average growth of 61.4% by 2070 compared with 2022, whereas developed economies may grow by only 35.3%. India, the fastest-growing region, was expected to reach approximately 3.2 times its 2022 per capita residential floorspace by 2070. Additionally, Indonesia and Africa were expected to be significant drivers of global residential building floorspace growth, with projected increases of approximately 80.1% and 63.8%, respectively, by 2070. Other emerging economies, such as China, Turkey, and LAC, were expected to experience growth rates similar to those of most developed economies, ranging between 26.2% and 48.0%, close to the global average growth rate of 42.3%. Conversely, the UK was projected to experience minimal growth in per capita residential floorspace, increasing by only approximately 5% by 2070. This modest rise is likely due to rapid population growth, which nearly matches the rate of residential floorspace expansion.

The dotted error bands in Figure 6 A represent other possible growth rate ranges for per capita residential floorspace at key time points (e.g., 2030, 2040, 2050, and 2060) under the BAU scenario, accounting for uncertainties. Berrill, et al.[105,106] proposed that per capita residential floorspace in the US may grow along a faster path and may be 16.3%

higher than the EIA's forecast by 2060. Moreover, Cabrera Serrenho, et al.[107] noted that the per capita residential floorspace in the UK in 2050 may fluctuate between -34.1% and 25.2% of the level determined by Drewniok, et al.[108] (shown by the purple solid line). In addition, the results of Hong, et al.[109] show that China's per capita residential building floorspace in 2050 may fluctuate between -28.9% and 34.4% on the basis of the blue solid line.[110] To synthesize the data, we utilized the most recent research findings as the basis for the solid trend line. While the reference data for uncertainty bands are relatively dated, these historical results are retained to provide comparative insights, given both the substantial uncertainties in floorspace quantification and the limited data availability.

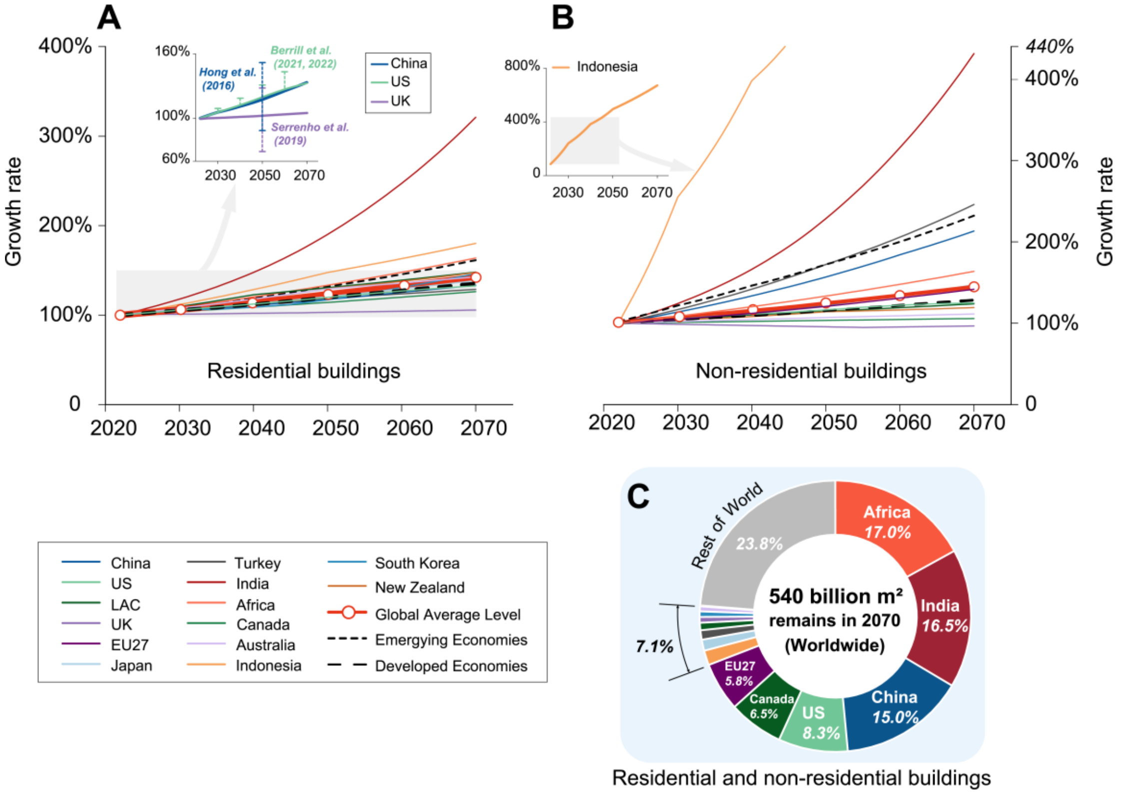

Figure 6. Growth trends in per capita floorspace for (A) residential and (B) non-residential buildings worldwide under the BAU scenario, 2022-2070; (C) Global building stock level in 2070.

Figure 6 B shows that under the BAU scenario, growth in per capita non-residential floorspace parallels that of residential floorspace, with emerging economies generally experiencing faster growth than developed economies. For example, by 2070, emerging economies could grow more than twice as much as they did in 2022, whereas developed economies may only grow by 27.9%. Notably, per capita non-residential floorspace in Indonesia was projected to grow significantly, reaching 6.9 times its 2022 level by 2070.

This sharp increase is attributed both to rapid expansion and to Indonesia's initially low baseline, with per capita non-residential floorspace of approximately 1.4 m^2 in 2022. While India's growth rate in per capita non-residential floorspace is not as fast as that of Indonesia, it is still much higher than that of most other economies, reaching 4.3 times its 2022 level by 2070. India, however, holds the greatest potential for total non-residential floorspace growth, with its population projected to reach 1.69 billion by 2070, which is 5.3 times greater than that of Indonesia.

Although the per capita non-residential building floorspace in China and Turkey exceeded that of Australia in 2022, it remains significantly lower than that in other developed economies. As shown in Figure 6 B, China and Turkey both have considerable growth potential, with projected increases of 113.2% and 145.9%, respectively, by 2070. Among emerging economies, Africa and LAC show relatively modest growth in per capita non-residential floorspace, with projected increases of only 63.8% and 23.8%, respectively, by 2070.

In developed economies (excluding the UK), per capita non-residential building floorspace was projected to grow slowly, with increases ranging from 5.8% to 46.9% by 2070, most of which fall below the global average growth rate of 44.2%. In the UK, where population growth was expected to outpace non-residential building floorspace expansion, per capita non-residential floorspace may decline by 3.4% by 2070. Additionally, owing to the limited availability of data on non-residential floorspace, further discussion of the uncertainty in per capita non-residential floorspace across economies is difficult.

In summary, as illustrated in Figure 6 C, by 2070, the global building stock was expected to be approximately 1.87 times its 2022 level (approximately 540 billion m^2), posing a significant challenge for sustainable development in habitats and the built environment.

Limitations and future outlook

On the basis of the findings in the Results section, we identified three key limitations and their associated solutions, as outlined below:

a. **Systematic and high-resolution measurements of building floorspace data are**

urgently needed. While some studies have explored methods for quantifying building floorspace, in-depth research in this area remains insufficient. Accurate acquisition of building floorspace data and the comprehensive establishment of a global building floorspace database are still critical issues that need to be addressed. A comparison of top-down, bottom-up, and hybrid approaches for building floorspace measurement reveals that the top-down approach offers comprehensive system coverage but struggles with accuracy; the bottom-up physical modeling approach can provide precise data but faces significant challenges in creating large-scale databases; and the hybrid approach, which typically combines building stock turnover models with demand-driven bottom-up methods, also falls short of achieving a precise database.

b. **Focusing on the sufficiency of building floorspace and maximizing building utilization are essential goals.** Importantly, building floorspace serves as the foundation for various energy-consuming activities throughout a building's life cycle. The size of the floorspace fundamentally determines the energy and emissions at each stage of a building's life. Therefore, extending the lifetime of buildings through renovation can help prevent unnecessary reconstruction, thus reducing energy consumption and carbon emissions. Specifically, in the construction stage, leveraging building sufficiency can reduce the upstream and downstream carbon emissions associated with the production, transportation, and use of materials required for new buildings; in the operation stage, maximizing building sufficiency through renovation can lead to energy conservation and emission reduction benefits through improved energy efficiency; and in the demolition stage, utilizing building sufficiency can help avoid unnecessary demolition, thus mitigating the associated energy consumption and emissions. Additionally, more attention should be given to the development of tiny houses that downsize buildings and promote a simple living style. Overall, prioritizing the sufficiency of building stock is essential for fully utilizing available resources and achieving sustainable development.

c. **Measuring multidimensional building information enhances high-resolution building stock assessments and improves photovoltaic potential evaluations.** In addition to floorspace information, multidimensional building information includes the building footprint, height, and envelope area.[111] The building footprint and height are crucial for calculating both the building floorspace and the envelope area. While accurate quantification of building floorspace is essential, developing a comprehensive record of the building envelope, including roofs and exterior walls, opens up significant analytical possibilities. For instance, teams like Google AI have recently launched the Open Buildings 2.5D Temporal Dataset.[112] This dataset leverages machine learning technologies, such as the Teacher–Student model, combined with high-resolution satellite imagery from Sentinel-2 to simulate building presence, height, and fractional building counts in the Southern Hemisphere. In the future, AI-driven high-resolution imagery calculation will significantly accelerate the measurement of multidimensional building information, advancing high-resolution building stock assessments and improving photovoltaic potential evaluations.

The building envelope, which serves as the primary physical infrastructure for BIPVs, plays a pivotal role in determining photovoltaic power generation potential. Enhancing and refining building stock accounting will facilitate the full realization of BIPV potential, drive the widespread adoption of building photovoltaic power systems, and support the transition of buildings from simple energy consumers to distributed energy suppliers within grid-interactive systems.

Conclusions

We reviewed 2,140 peer-reviewed papers indexed by the Web of Science on the topic of building floorspace and stock worldwide, with a particular focus on the intersection of energy/emissions and floorspace/stock. The three countries with the greatest number of publications were China, the UK, and the US. The five leading institutions conducting the most research in this area were the Chinese Academy of Sciences, Chongqing University, Tsinghua University, Lawrence Berkeley National Laboratory, and Hong Kong Polytechnic University. To enhance the relevance of our search results, we identified 100 articles highly relevant to the topic of building floorspace through the “Keywords Plus” limitation in the Web of Science and manual screening for an in-depth review. Furthermore, 26% of the

100 articles were highly cited in the ESI, indicating that research on energy and emissions related to building floorspace and stock has garnered significant academic interest.

These 100 articles focused primarily on the operational stage of residential buildings for energy conservation and emission reduction. The application of floorspace in studies related to energy consumption and carbon emissions in buildings spans the entire building life cycle, with particular emphasis on the construction and operation stages. Key areas of application include material flow analysis, embodied carbon emissions, energy modeling and simulation, renewable energy systems, health and comfort, household energy use behavior, building retrofit and renovation, and life cycle assessment.

Measurement approaches for building floorspace can be categorized into top-down, bottom-up, and hybrid methods. The top-down approach primarily refers to the building stock turnover model, which calculates floorspace at a larger scale from a macro perspective, although with slightly lower accuracy. The bottom-up approach includes demand-driven and physical modeling methods. The demand-driven approach is relatively simple and relies mainly on population size and per capita floorspace. In contrast, the physical modeling approach can achieve high accuracy, but its development and calibration are extremely time-consuming and require large amounts of high-quality data for training and deployment. The hybrid approach, which combines elements of both top-down and bottom-up methods, typically integrates the building stock turnover model with the demand-driven approach but still faces challenges in accurately quantifying building floorspace.

In addition to the literature review, we investigated the current global status of building floorspace and estimated future global building stocks. Specifically, we analyzed the per capita floorspace of residential and non-residential buildings across 14 economies under the BAU scenario from 2000-2070. Our findings reveal that from 2000-2022, the global per capita floorspace for both residential and non-residential buildings showed a slow upward trend, with developed economies being consistently higher than emerging economies. However, from 2023-2070, the growth rates of per capita floorspace in emerging economies were projected to significantly outpace the global average. For example, compared with that in 2022, per capita floorspace in emerging economies was expected to grow by 129.9% by 2070, while the global average growth rate was expected to be only 44.2%. In contrast, the growth rate for developed economies over the same period was projected to be much lower, at 27.9%.

The three economies with the greatest potential for increased per capita residential floorspace are India, Indonesia, and Africa, with growth rates surpassing the average for emerging economies. Among these, India was projected to experience the fastest growth, with per capita residential floorspace in 2070 expected to be more than three times its 2022 level. For non-residential buildings, Indonesia was expected to experience an astonishing growth rate, reaching approximately seven times its 2022 level by 2070. This rapid increase is largely due to Indonesia's low baseline per capita non-residential floorspace in 2022, which was just 1.4 m^2. Similarly, per capita non-residential floorspace in India was expected to increase to more than four times its 2022 level by 2070. Although India's growth rate was slightly lower than that of Indonesia, its population was projected to reach 1.69 billion by 2070, approximately 5.3 times that of Indonesia. As a result, the total growth in non-residential floorspace in India was expected to outpace that of Indonesia.

Through the analysis of applications, measurement approaches, and data analysis of building floorspace and stock, we found that building floorspace data are fundamental to building science research. Accurate measurement of building floorspace enables comparisons of energy conservation and emission reduction across countries and regions on a per-unit floorspace basis. It also allows for assessments of improvements in energy efficiency, decarbonization benefits, and the cost-effectiveness of building renovations over time within the same region. Therefore, there is an urgent need for systematic, comprehensive, and high-resolution imagery data on building floorspace worldwide. Additionally, greater attention should be given to building sufficiency, such as developing tiny houses with downsizing and simple living, improving the renovation rate of old buildings to extend their lifetime and avoid unnecessary reconstruction, and considering co-housing options within neighborhoods. Furthermore, the measurement of multidimensional building information will advance high-resolution building stock assessments and improve the integration potential of building-based power systems, such as BIPVs, in the future.

EXPERIMENTAL PROCEDURES

Resources availability

Lead contact

Further information and requests for resources should be directed to and will be fulfilled by the lead contact, Dr. Nan Zhou (nzhou@lbl.gov).

Data and code availability

This study did not generate new unique code.

Materials availability

This study did not generate new unique materials.

Overview of the bibliometric analysis

This review focused on building floorspace and stock, as they are key factors influencing the carbon emission intensity across the full life cycle of buildings, as well as determining the total carbon emissions of the building sector. For the literature search, we used the Web of Science search engine to explore relevant studies. Table S1 in the Supplemental Information outlines the query set applied in this process. The "OR" logic operator was used to connect synonymous keywords within each query set, whereas the "AND" logic operator was used to link different query sets. Additionally, Figure S1 in the Supplemental Information illustrates the specific steps followed during the search.

SUPPLEMENTAL INFORMATION

The supplemental materials are included at the end of this submission file.

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AUTHOR CONTRIBUTIONS

Conceptualization, M.M., N.Z., and J.Y.; Methodology, M.M., S.Z., J.L., and R.Y.; Software, S.Z., and J.L.; Validation, M.M., R.Y., and W.C.; Writing-Original Draft, M.M., and S.Z.; Writing-Review & Editing, M.M., N.Z., J.Y., R.Y., and W.C.; Funding Acquisition, M.M., and N.Z.; Supervision, M.M., N.Z., and J.Y..

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