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RESEARCH ARTICLE

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Weighing the global built environment

High-resolution mapping and quantification of material stocks in buildings

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Abstract

Buildings provide indispensable services for human well-being, but their construction and use are responsible for a substantial fraction of societies' resource requirements and greenhouse gas emissions. Mapping and quantifying the material stocks in buildings is a key research frontier in industrial ecology. Reliable and spatially highly resolved maps of material stocks in buildings worldwide are so far not available. Existing approaches based on nighttime light data allow large-scale coverage, but their spatial resolution is usually ~0.5–1 km. Other methods using light detection and ranging (LiDAR) and cadaster data achieve higher resolution and accuracy, but do not allow wall-to-wall mapping of large regions. Based on high-resolution Earth Observation data combined with material intensity factors (kg per m^3 of building volume), we quantify and map material stocks in buildings at the unprecedented resolution of 90 m globally. We distinguish 18 types of materials in five types of buildings. We find that global material stocks in buildings amount to 547 (391–672) Gt, approximately half of total global societal material stocks. We find highly unequal distributions of material stocks in buildings per capita and per unit area of each country. Our results agree well with previous detailed estimates of material stocks in buildings in dedicated regions or individual cities. Improved and harmonized material intensity factors emerge as a key research area for improving the accuracy of material stock maps. Our results are available as data products with high spatial and thematic resolution to facilitate future studies; for example, of secondary resource potentials. This article met the requirements for a gold-gold *JIE* data openness badge described at http://jie.click/badges.

KEYWORDS
buildings, Earth Observation, industrial ecology, mapping, material flow analysis, material stocks

1 | INTRODUCTION

Given the key role of shelter for almost all human activities, buildings are of great importance for provision of decent living conditions (Millward-Hopkins et al., 2020). Provision of housing is a prerequisite for achieving the Sustainable Development Goals (SDG), as specified in Target 11.1 of SDG no. 11. Moreover, buildings are directly or indirectly required for most other SDGs, such as 1, 3, 4, 6, 8, 9, or 12, as they enable and provide functions like education, healthcare, nutrition, sanitation, energy supply, and other production and consumption activities. Adequate housing is lacking in many parts of the world (Tusting et al., 2019).

At the same time, construction, maintenance, and use of buildings is associated with enormous resource flows (Deetman et al., 2020; Tanikawa et al., 2020; Wiedenhofer et al., 2015) and greenhouse gas (GHG) emissions (Lamb et al., 2021) as well as other environmental pressures. They are hence of crucial importance for other SDGs such as those related to clean energy and climate action (SDGs 12–13) and responsible production and consumption (SDG11). The extent, spatial patterns, and design of buildings strongly co-determine energy requirements for heating, cooling, lighting, and transport as well as the related GHG emissions (Creutzig et al., 2016; Haberl et al., 2023) and result in carbon lock-in, determining societal development pathways for decades to come (Seto et al., 2016). Quantifying materials in buildings (Marinova et al., 2020) and mapping their spatial patterns (Haberl et al., 2021; Lanau & Liu, 2020; Peled & Fishman, 2021; Schandl et al., 2020; Tanikawa & Hashimoto, 2009; Tanikawa et al., 2020) have emerged as important research areas in industrial ecology. Recent progress has been summarized in topical reviews (Fu et al., 2022; Lanau et al., 2019).

So far, global estimates of socioeconomic material stocks assessed material stocks in all human-made structures. As no explicit breakdowns to specific end-uses, respectively, types of structures were available, buildings were an unknown part of the total stock. These studies are often at global or regional levels and lack national (and even more so sub-national) resolution. Estimates of total global socioeconomic material stocks derived from data on material flows combined with lifetime estimates have recently become available (Krausmann et al., 2017; Wiedenhofer et al., 2021), with methodological and empirical improvements underway to enable resolving different types of stocks and end-uses, including differentiation of built structures such as buildings, roads and other civil engineering (Streeck et al., 2023a,b; Plank et al., 2022). Several studies have quantified the mass of buildings for specific cities, regions, or countries (Gontia et al., 2020; Lanau & Liu, 2020; Noll et al., 2022; Schandl et al., 2020; Tanikawa & Hashimoto, 2009; Wiedenhofer et al., 2015), but not for larger areas. One study quantified material stocks in global residential buildings (Marinova et al., 2020), another modeled the quantity of cement and metal stocks in residential buildings (Pauliuk et al., 2021); both these studies are not spatially explicit and were not comprehensive in terms of materials found in buildings.

Mapping is important, among others because spatial patterns of built structures influence levels of resource use (Haberl et al., 2023; Duro et al., 2024). Although not all end-of-life materials can be recycled, maps of built structures can help in locating secondary resource potentials (Haberl et al., 2021). As maps of mobility infrastructures are becoming available (Wiedenhofer et al., 2024), building maps can provide complementary data toward that end. Building maps can also help in gauging impacts of extreme events or sea-level rise (Symmes et al., 2020). Approaches that quantify material stocks in a spatially explicit manner have used nighttime lights (Peled & Fishman, 2021; Takahashi et al., 2010), cadaster information (Lanau & Liu, 2020; Tanikawa et al., 2015), big-data approaches (Mao et al., 2020), or remote-sensing light detection and ranging (LiDAR) techniques (Schandl et al., 2020). Nighttime light data allow mapping material stocks in buildings for large regions but can only achieve relatively low spatial resolution (usually >300–750 m). Moreover, these methods have limited capacity to separate material stocks in buildings from those in roads or distinguish building types. They also suffer from methodological problems such as saturation effects or differences in luminosity between regions. Other data sources such as cadasters or LiDAR are only consistently available for small regions and cannot be used for wall-to-wall mapping of large regions. A combination of optical multi-spectral satellite-borne Earth Observation data for buildings and crowd-sourced data such as Open Street

TABLE 1 Building types and related thresholds classified on the basis of the WSF3Dv2 data.

Class ID	Building type	WSF3Dv2 building height [m]	GHS-BUILT-S [class]
LW	Lightweight	<3	Residential + non-residential
RS	Residential single-family house (residential, single)	3–12	Residential
RM	Residential multi-family house (residential, multi)	12–50	Residential
NR	Non-residential	3–50	Non-residential
HR	High-rise	50–100	Residential + non-residential

Map (OSM) for roads has been proposed to alleviate that tradeoff, as demonstrated via mapping stocks in Germany and Austria (Haberl et al., 2021) and the United States (Frantz et al., 2023). For buildings, however, a global study of 13,000 cities found that OSM is too incomplete for reliable mapping (Q. Zhou et al., 2022). A global, comprehensive, and spatially highly resolved map (i.e., at 100 m or less) of material stocks in buildings is yet lacking, to the best of our knowledge.

Using a global 3D building map derived from Earth Observation data (Esch et al., 2022), our research closes this crucial knowledge gap. This map, published by co-authors of this article, represents global building volumes and underlying building areas and heights at 90 m spatial resolution. The data therein can be linked with material intensity (MI) factors quantifying the mass of building materials per m^2 or m^3 of building area and volume, respectively (Heeren & Fishman, 2019). We used these data sources to (1) quantify the mass of materials in buildings worldwide, thereby further improving the differentiation of building types, and (2) map the material stocks in buildings globally at a spatial resolution of 90 m. We assessed the robustness of the results by comparing them with other published material stock estimates and conducted a sensitivity analysis. In Section 3, we analyze the inequality of global distribution of material stocks in buildings per capita and the density of material stocks per each nation's land area, and discuss implications.

2 | METHODS

Most approaches for quantifying and mapping material stocks in buildings proceed by multiplying data on the physical dimensions of buildings, usually floor area [m^2] or building volume [m^3], with suitable material intensity (MI) factors (either [kg/m^2] or [kg/m^3], depending on input data). We here use the volume-based approach developed in previous work for national studies (Frantz et al., 2023; Haberl et al., 2021) and extend it to the global level, thereby harnessing core strengths of the underlying building dataset (Esch et al., 2022).

2.1 | Building volumes and building type classification

The World Settlement Footprint 3D (WSF3D; Esch et al., 2022) is a global dataset quantifying the fraction, total area, average height, and total volume of buildings for a grid with 90 m cell size. It was generated using a modified version of the World Settlement Footprint 2019 (WSF2019) human settlements mask (Marconcini et al., 2021) derived from Sentinel-1 and Sentinel-2 satellite data at 10 m spatial resolution in combination with 12 m digital elevation data derived by radar imagery collected by the TanDEM-X mission. The WSF3D refers to the year 2019. Due to data security regulations, the original geometric resolution of 12 m for the building height and volume estimations was finally spatially aggregated to a 90 m gridding to allow for an open and free distribution.

As reported in Esch et al. (2022), the original WSF3D exhibits a systematic underestimation of the heights of high-rise buildings (>50 m). For this study, we therefore created an enhanced version WSF3Dv2, where local height information for a total of 711,448 skyscrapers and high-rise buildings provided by the Emporis database (Emporis, 2022) was integrated (Section 2 of Supplementary Information S1). A new validation based on the reference sites already used by Esch et al. (2022) documents that the average height estimation error of −2.3 m in the WSF3D could now be reduced to −0.22 m for the new WSF3Dv2 (Section 2.3 and Table S6 in Supplementary Information S1).

Based on the information provided by the building height layer of the improved WSF3Dv2, we then implemented a new approach toward the classification of five building types using a threshold-driven categorization (Table 1). All buildings <3 m height were classified as lightweight. A height threshold of 12 m was used to distinguish single-family and multi-family houses for buildings of intermediate height (3–50 m). The outcome of this classification was a map assigning the dominant building type per 90 m grid cell. The separation between residential and non-residential use was applied to all buildings using the GHS-BUILT-S R2023A (JRC, 2022) dataset. The defined classes and the underlying threshold settings are listed in Table 1.

2.2 | Material intensity factors

We compiled and quality-controlled material intensity factors from recent literature, in particular from data compilations (Heeren & Fishman, 2019; Li et al., 2023), reviews (Lanau et al., 2019), and datasets developed for own previous studies (Baumgart et al., 2022; Frantz et al., 2023; Haberl et al., 2021) to assemble a globally representative set of MI factors used for this study (Supplementary Information S1).

One difficulty is that some countries or regions are very well covered in the literature, while few, if any, studies exist for others. Furthermore, varying building definitions and scopes of the underlying studies make extensive harmonization and quality control necessary. We therefore decided for the following regional subdivision: We developed specific MI factors for three large countries/regions with good data availability: North America (United States and Canada), China, and Japan. For North America, we used a detailed MI dataset developed for a separate project covering the conterminous United States (Frantz et al., 2023) based on a large number of studies for most building categories used here. For China, we relied on a recent compilation of MI factors for non-residential and multi-family residential buildings (Li et al., 2023), complemented by additional literature for building types not covered in that dataset (Supplementary Information S1). Japan's building stock has very specific characteristics and is well researched (Tanikawa & Hashimoto, 2009; Tanikawa et al., 2014), hence we developed a specific dataset despite the low number of available studies. For other OECD countries, averages of available data points were used. For all other regions, we used global averages that we deemed more reliable than the available studies, mostly because their quality and comprehensiveness varied substantially and it was unclear how representative the individual studies were for the entire region. For lightweight and high-rise buildings, we used global averages for all regions except United States/Canada due to lack of region-specific data. Detailed information is available in Supplementary Information S1 (Tables S4 and S5).

Our MI dataset distinguishes five building types: residential single-family house (abbreviated residential, single), residential multi-family house (abbreviated residential, multi), non-residential, lightweight, high-rise; the latter two building categories can be either residential or non-residential (Table S4 in Supplementary Information S1). We use MI factors for 18 individual materials clustered in four groups: (1) metals (iron/steel, copper, aluminum, and other metals), (2) biomass (timber and other biomass), (3) mineral materials (concrete, aggregates not used in concrete, clay bricks, mortar, gypsum, ceramics, glass, and other minerals), (4) fossil-fuel based and other materials (bitumen and plastics), and (5) other materials not directly attributable to either category (e.g., undefined insulation and paint). Table S4 in Supplementary Information S1 reports the sources of the MI factors used in the calculations; all factors used in the calculations are reported in Table S5 in the Supplementary Information S1. We used the same MI factors for United States and Canada because buildings are similar in these countries, hence case studies from both countries were used to generate the factors used in our analysis (while Canada is part of "Other OECD" in summary tables later on). For EU-27 (shown separately in the results section), we used the MI factors for "Other OECD."

2.3 | Uncertainty analysis

We assessed the robustness of our approach by comparing our material stock estimates with results from other available literature on global material stocks in buildings (Marinova et al., 2020; Pauliuk et al., 2021) as well as 16 regional or city-level cases for which we were able to obtain or reconstruct their respective regional boundaries. To explore the influence of the variability of MI factors on stock estimates, we conducted a sensitivity analysis (Saltelli et al., 2000). A systematic quantification of uncertainties (e.g., through Monte Carlo analysis) was out of scope due to data limitations, in particular regarding material intensities of buildings, as well as the novel interdisciplinary combination of multiple methods, data streams, and domain expertise needed for this study.

Because the uncertainty of the building map was previously discussed (Esch et al., 2022), here we focused on the uncertainty of the MI factors. For all regions and building types where a sufficient number of estimates (more than ~10, except for Japan, see above) was available, we calculated the interquartile range of all MI factors and used the 25th and 75th percentile as lower, respectively, upper bound MI factor in addition to the average. For the other regions we derived ranges in the same manner from the global total of all regions and building types. For details see Supplementary Information S1.

3 | RESULTS AND DISCUSSION

3.1 | Mass of material stocks in global buildings

We found that the mass of all material stocks in buildings worldwide in the year 2019 amounted to 547 Gt, with a minimum estimate of 391 Gt and a maximum of 672 Gt (Table 2). The "best guess" amounts to 53% of the total mass of socioeconomic material stocks of 1033 Gt ± 8% in 2015 (Wiedenhofer et al., 2021). A third of the building stock is located in China, 15% in the EU-27, 11% in Other Asia, and 10% in the Middle East and Africa; building stocks in all other regions are <10% each. The 89% of all material stocks in buildings are minerals (a broad group of materials that includes aggregates, concrete, bricks, glass, and other materials). Metals amount to 5.4%, most of which is iron/steel, but aluminum, copper,

TABLE 2 Mass of materials in the global building stock in the year 2019, breakdown by groups of materials and building types for "best guess" material intensity factors [Gt]. Note that the global total may slightly differ from the sum of regions due to rounding.

	Global	China	EU-27	FSU	Japan	LAM	MAF	Other Asia	Other OECD	USA
Total material stocks										
Minimum	391.0	161.2	52.8	23.4	9.7	19.8	34.3	39.1	19.3	31.4
"Best guess"	547.3	200.4	80.7	34.8	10.3	31.1	53.4	60.8	29.5	46.3
Maximum	671.6	240.7	99.3	43.9	11.2	39.7	68.4	77.5	36.0	54.9
Breakdown by groups of materials										
Metals	29.3	6.2	3.8	2.9	0.7	2.4	5.4	4.8	1.6	1.4
Minerals	484.8	190.3	70.6	29.3	9.7	26.2	43.8	51.3	25.4	39.1
Biomass	21.8	3.8	3.5	1.6	0.6	1.6	2.6	3.0	1.5	3.6
Fossil/other	11.4	0.1	2.7	1.0	0.2	0.9	1.5	1.8	1.0	2.2
Breakdown by building types										
Residential, single	326.6	106.4	49.0	18.5	3.0	22.3	36.4	41.6	18.4	30.9
Residential, multi	147.0	79.5	17.8	9.9	5.9	4.0	7.5	9.6	5.8	7.0
Non-residential	32.7	6.7	10.4	2.3	0.5	1.2	1.2	2.1	3.2	5.1
Lightweight	37.9	7.2	3.3	3.7	0.8	3.2	8.2	6.5	1.9	3.1
High-rise	3.2	0.6	0.2	0.3	0.1	0.3	0.1	1.0	0.2	0.2

Abbreviations: ASIA, other Asia (excluding China); EU-27, European Union (27 countries); FSU, former Soviet Union; LAM, Latin and Middle America; MAF, Middle East and Africa; Other OECD, other countries belonging to the Organization of Economic Co-Operation and Development (excluding Japan, USA and EU-27); USA, United States of America . . Gt … Gigatons (1 Gt = 10^9 t = 1 Pg = 10^{15} g = 1 billion metric tons).

and other metals also play important roles. Biomass—mostly wood—contributes 4.0% to the total. Fossil-fuel-based materials such as plastics and bitumen as well as other materials such as insulation or paint play a relatively minor role.

Globally, residential single-family houses ("residential, single") are the most important building type (60%), although this differs widely between regions (see Table 2 and Figure 4a). Residential multi-family houses ("residential, multi") are the second-most important category (27%), while the others play a minor role. It should be noted, however, that the distinction of residential and non-residential buildings using satellite-based Earth Observation data carries substantial uncertainty. This partly results from mixed uses within the same building which frequently occur in multi-family buildings in many cities that cannot be recognized from space. The data shown in Table 2 for the global total are reported in Supporting Information S2 for all countries and with full resolution of material types.

Comparisons with previous studies show similarities as well as differences. In Table S8 in Supplement S1 we report our global building stock estimates along with those of Marinova et al. (2020). Overall, our estimate for material stocks in residential buildings is almost one-third lower than that found by Marinova et al. (2020); even our estimate for all buildings is a bit (11%) lower. Because the distinction between residential and non-residential buildings in our study is not very robust, it is at present not clear which of these two comparisons is more meaningful. The built-up mass of six material categories (concrete, iron/steel, timber, aluminum, copper, and glass) found in the two studies is also reported in Table S8.

Comparison with results of Pauliuk et al. (2021) are not straightforward because they report cement, not concrete, and also refer only to residential buildings. When we extrapolate Pauliuk et al.'s cement results assuming that cement has an average share of 11% in concrete (Portland Cement Association, 2023), their result implies a global total of 127 Gt of concrete in residential buildings, which compares well with our result for residential buildings (126 Gt), in particular considering possible inaccuracies in distinguishing residential from non-residential buildings. When adding up aggregates and cement in Pauliuk et al.'s study (which—in contrast to ours—do not include aggregates used for other purposes than making concrete), we get 106 Gt, 16% lower than our result. For timber, Pauliuk et al. report 16 Gt (our result for residential buildings is 19 Gt) and for steel 6 Gt (our result: 8 Gt).

Differences emerge from two categories of input data used in calculations: (1) the inventory of housing stocks, and (2) the material intensity (MI) values. We here utilized remotely sensed estimates of building volumes, whereas both Marinova et al. (2020) and Pauliuk et al. (2021) used outcomes of integrated assessment models. Databases used to derive MI factors also differ. We here considered 587 MI factors drawn from 93 studies. Just as Pauliuk et al. and Marinova et al., we used MI factors derived from the literature. All three studies used mostly (but not entirely) the same primary sources; we added some that had not been available in the earlier work. Furthermore, MI factors were derived differently. Individual MI data points had to be aggregated, which introduces further differences: studies used different numbers of regions as well as varying numbers and definitions of building types to best suit their methods to calculate building volumes. Some study-specific assumptions and different procedures

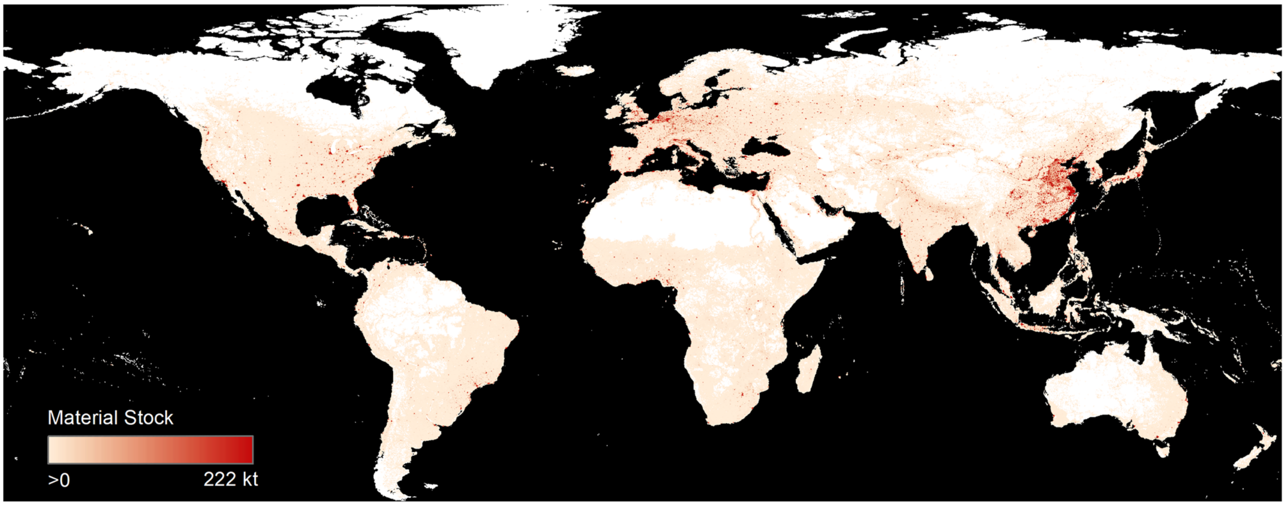

FIGURE 1 Global high-resolution map of the mass of materials in buildings. This global map displays values of "kt per pixel" aggregated over larger regions for visualization purposes. Values for individual pixels (of approximately 8200 m^2 at the equator) cannot be displayed at global scale. The global maximum for a single pixel is 222 kt. The image uses a Standard Deviation stretch of 2 to increase the visibility of higher values. Data behind this map are available at full spatial and temporal resolution as DLR data product (*"World Settlement Footprint (WSF) 3D - Material Stock - Global, 90m"*) at https://doi.org/10.15489/h80jhtr41x48 (DOI: 10.15489/h80jhtr41x48).

in deriving means may cause further variation. These considerations imply that this research field is still in flux, and further harmonization and data collection will be required to derive more robust results.

3.2 | Global patterns of material stocks in buildings

Figure 1 shows the global distribution of material stocks in buildings. The map has a spatial resolution of 90 m and, for each pixel, contains data on the mass of 18 materials in five categories of buildings (see lower part of Table 2; full resolution in terms of materials in Supplementary Information S2). The map is available DLR data product "World Settlement Footprint (WSF) 3D - Material Stock - Global, 90m" at https://doi.org/10.15489/h80jhtr41x48 (DOI: 10.15489/h80jhtr41x48).

In Figure 2 we show examples for eight cities, one per region, demonstrating the amount of spatial detail present (but scarcely visible) in the global map. The "height" in the pseudo-3D maps in the outtakes indicates the mass of buildings per 90 m pixel.

With a resolution of 90 m, our results are substantially more fine-grained than a previous global analysis that quantified building volumes at 500 m resolution (Y. Zhou et al., 2022). Moreover, we present a global wall-to-wall data product covering material stocks in buildings, while the Zhou et al. dataset is restricted to building volumes in selected urban areas. In addition, Zhou et al. modeled building volumes indirectly from synthetic aperture radar (SAR) backscatter intensity, instead of deriving height differences from a high-resolution digital elevation model (as done in the case of the WSF3D processing).

Our results reveal substantial global differences between countries in terms of material stocks in buildings per capita and per km^2 of each country's territory (here denoted as "land area"; see Figure 3). The share of building types in total building material stocks per region differ substantially. High-rise buildings play a minor role everywhere. The share of lightweight buildings differs substantially, and is lowest in China and highest in Middle East and Africa. Residential single-family buildings play a small role in Japan, most likely due to its high population density and limited land availability for settlements. Moreover, the mass of single-family houses in Japan is small due to the prevalence of wooden buildings with low material intensity. In several other regions, roughly two thirds of the mass of buildings is in residential single-family houses (EU-27, Latin and Middle America, Middle East and Africa, Other Asia, and Other OECD). Residential multi-family houses play a large role in China and Japan, while their mass is comparatively small in Latin and Middle America and Middle East and Africa.

Income can partially explain these patterns (Table 3a), in line with previous analyses (Schiller & Roscher, 2023). Per-capita stocks in high-income countries are 6.6 times larger than those in low-income countries, the inequality in available building volume per capita (m^3/cap) is almost as large (factor 5.5). Income inequalities reported in World Bank data are even larger (factor 28), and stocks per unit gross domestic product (GDP) differ substantially as well. This also implies (last column) that building mass per unit of GDP is lower in the high-income group than in low-income countries. This tendency toward lower stock values per unit of GDP in high-income countries needs further scrutiny; it could result from tendencies toward stock saturation in higher-income regions (Wiedenhofer et al., 2021). The mass of buildings per unit GDP differs considerably

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FIGURE 2 Maps of material stocks in buildings in eight selected cities (one per region) around the world. The squares delimiting the 3D outtakes measure 5 × 5 km. Due to the projection used, the size of pixels differs between cities: At the equator, they measure 90 × 90 m, but their exact size varies according to the location of each city in relation to the equator. Data behind this map are available at full spatial and temporal resolution as DLR data product (*"World Settlement Footprint (WSF) 3D Material Stock - Material Stock- Global, 90m"*) at https://doi.org/10.15489/h80jhtr41x48 (DOI: 10.15489/h80jhtr41x48).

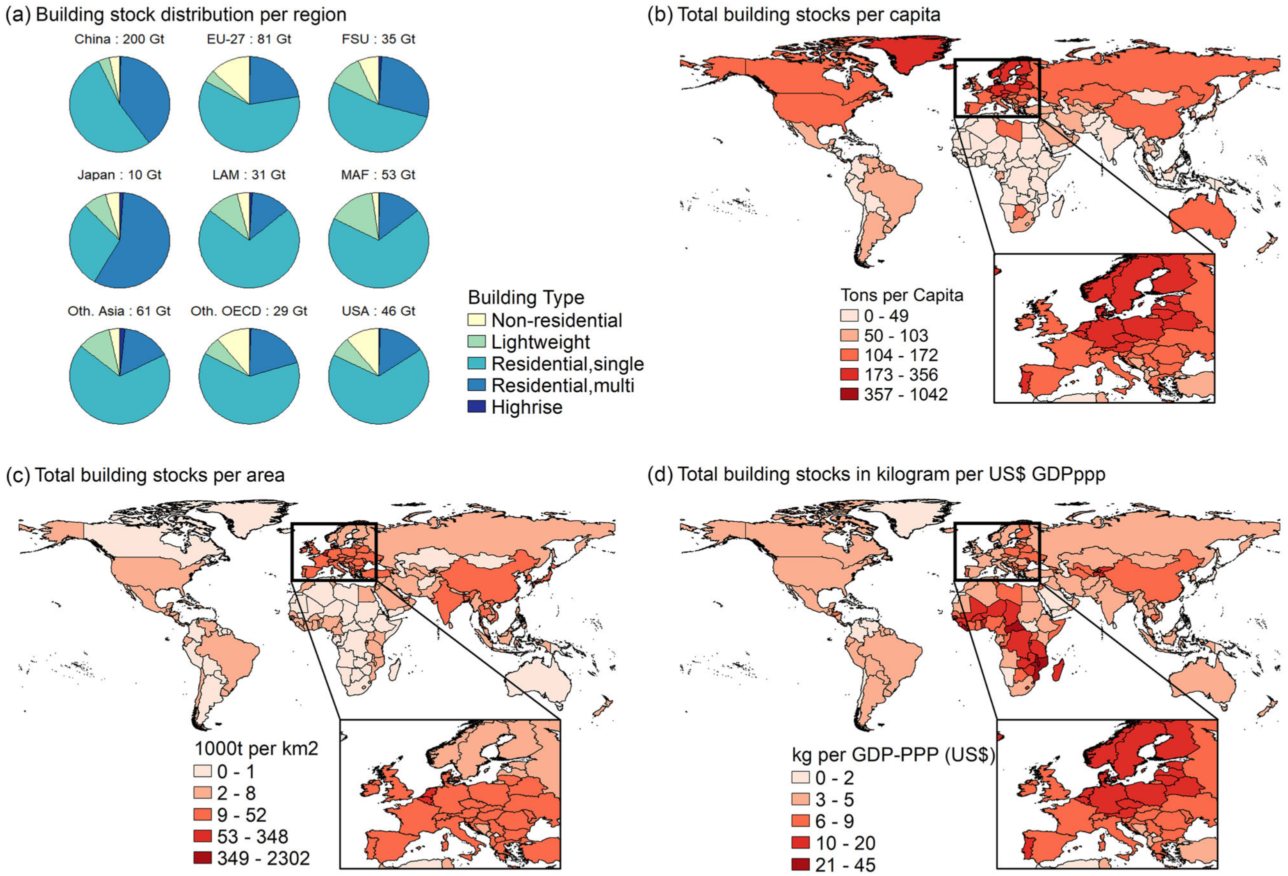

FIGURE 3 Global distribution and inequality of materials in buildings. (a) Distribution of total material stocks to building types per region. (b) Total material stocks in buildings per capita in each country [t/cap]. (c) Total material stocks in buildings per unit land area of each country's territory [kt/km^2]. (d) Material stocks in buildings per unit of GDP in purchasing power parities (GDP$_{ppp}$) [kg/$]. Data behind this figure are available in Supporting Information S2.

between regions and countries as well (Figure 3d, Table 3b). Note that these differences should not be overinterpreted, in particular in regions where economic activities outside formal markets (not or only partially reflected in GDP) play an important role.

In terms of regional patterns (Table 3b), we found the highest building volumes per capita in the EU-27 and the United States, lowest in Other Asia. Per unit area, material stocks are highest in Japan, which is plausible given its very high population density; values for China and the EU-27 are only slightly lower, despite their substantially lower population density. This results from higher per-capita material stocks and building volumes in these regions. Material stocks per unit GDP are lowest in Japan, followed closely by the United States. This may result from the prevalence of timber in buildings and the larger role of lightweight buildings, as well as the high importance of the tertiary sector in these regions. China's material stocks per capita already exceed the average value of the group of high-income countries, despite being classified as an upper middle-income country and despite its lower building volume per capita. This may result from the prevalence of concrete buildings in China, reflected in relatively high MI factors reported in the recent data compilation (Li et al., 2023) upon which our work relies. Note that we can offer only speculative conjectures, as explaining these patterns would require additional analyses beyond the scope of this paper.

At the country level, per-capita inequalities of material stocks in buildings are substantial and range from less than 10 tons/capita in some least-developed countries to >300 tons/capita in Finland, the Vatican, and the Christmas Islands. Building volumes available per person range from <10 to >500 m^3/cap; that is, vary by a factor of >50 (Supplementary Information S2). These patterns are analyzed in Figure 4 that displays Lorenz curves for building volume and material stocks in buildings per capita as well as GDP per capita. We found that the inequality of building volumes per capita is slightly smaller (Gini coefficient 0.41) than that of material stocks (0.45), which is slightly smaller than the inequality in per-capita GDP$_{ppp}$. Because population density can be assumed to influence building volumes per capita, we also depict per-capita land area (the inverse of population density) in Figure 4. Per-capita land area is still more unequally distributed, reflecting the large global differences in population density. Inequality in material stocks and volume of buildings rather resembles GDP inequalities than differences in population density.

TABLE 3 Indicators showing differences, respectively, inequalities between regions in terms of total material stocks in buildings, stocks per capita and land area, building volume per capita, population density, and gross domestic product in purchasing power parities (GDP_{ppp}) per capita as well as stocks per unit of GDP. All data refer to 2019; data on population, GDP, and land area are from World Bank databases.

	Total stocks [Mt]	Stocks per capita [t/cap]	Stocks per land area [kt/km^2]	Building volume per capita [m^3/cap]	Population density [cap/km^2]	GDP_{ppp} per capita [US$/cap]	Stocks per unit GDP_{ppp} [kg/US$]
(a) Breakdown by income groups							
High income	172,794	140	4.79	453	34	51,396	2.72
Upper middle income	290,899	103	4.99	244	49	17,397	5.91
Lower middle income	68,994	24	3.13	86	132	7030	3.37
Low income	14,223	21	0.92	83	43	1817	11.76
(b) Breakdown by regions							
China	200,430	146	21.45	278	147	17,067	8.55
EU-27	80,733	183	19.83	532	108	47,906	3.82
FSU	34,792	119	1.59	406	13	21,909	5.45
Japan	10,270	81	27.49	326	338	42,394	1.92
LAM	31,072	48	1.52	171	32	15,455	3.12
MAF	53,417	34	1.53	126	45	7920	4.32
Other Asia	60,837	23	5.24	82	226	9068	2.56
Other OECD	29,450	115	1.35	357	12	41,242	2.78
United States	46,278	141	4.88	518	35	65,120	2.16

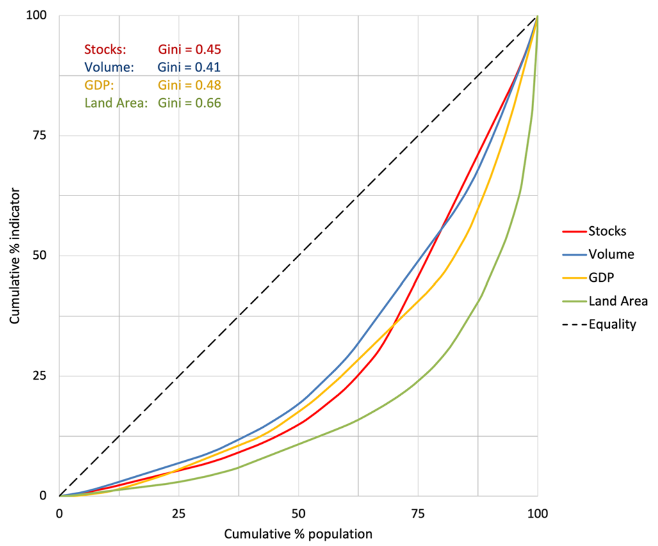

FIGURE 4 Lorenz curves representing the inequality in global country-level per-capita values of GDP_{ppp}, building volume and material stocks in buildings. The more a curve deviates from the dashed 45° line, and the larger the Gini index, the larger the inequality. Data behind this figure are available in Supporting Information S2.

3.3 | Data quality and sensitivity

Our material stock results hinge on the accuracy of (1) quantification of building volumes and (2) material intensity (MI) factors. Building volume data were validated in the underlying remote-sensing study (Esch et al., 2022). In order to gauge the effect of MI factors, we conducted a sensitivity analysis.

The results of the sensitivity analysis (minimum/maximum values compared to "Best guess" estimates obtained by varying the MI factors) are presented in Figure 5a for the 20 countries with the largest total material stocks in buildings. Minimum and maximum values differ from the "Best guess" result by between one quarter and one third, depending on the data quality in the respective region; for example, in terms of availability and

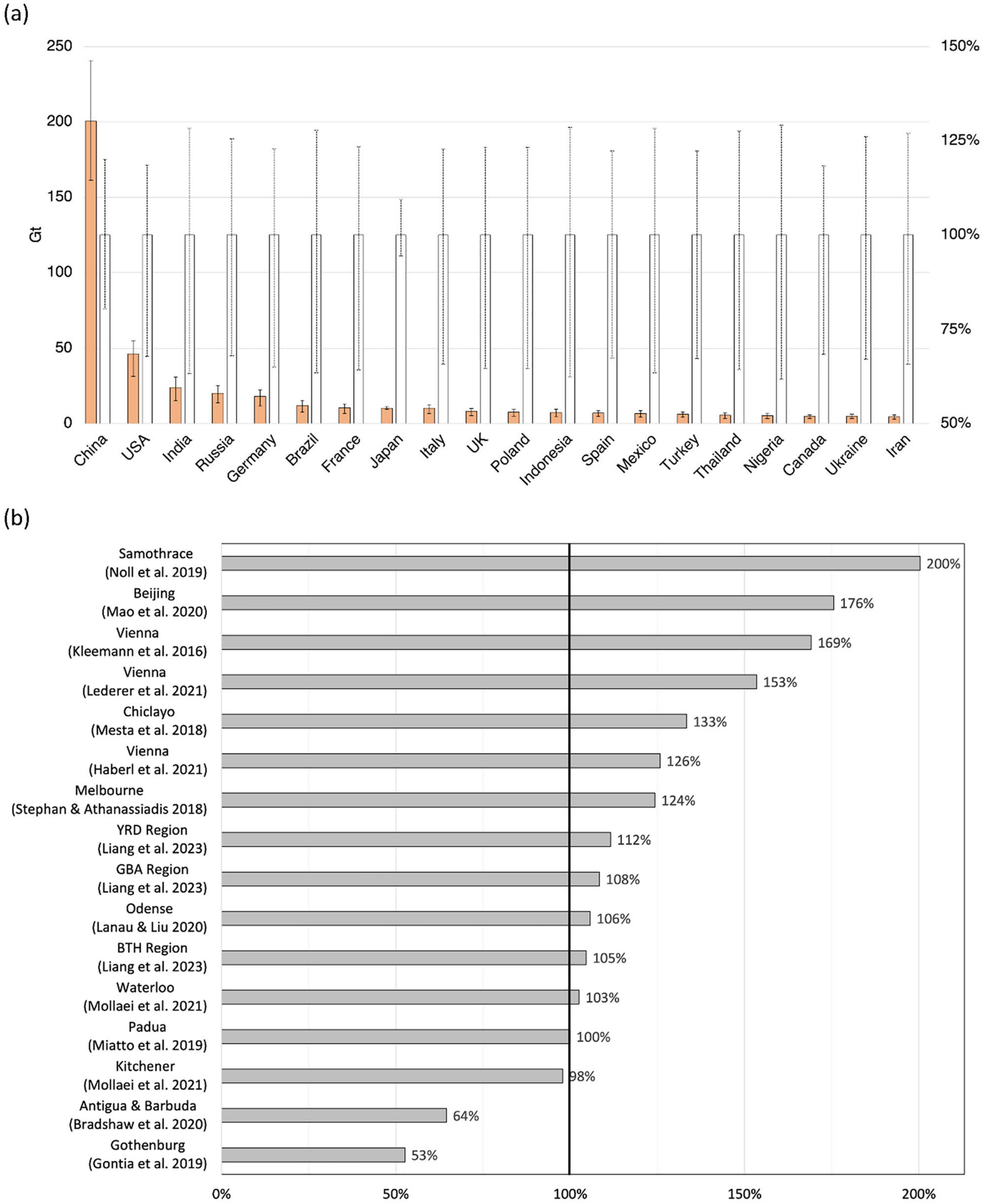

FIGURE 5 Sensitivity analysis and comparison with previous local/regional studies. (a) Results of the sensitivity analysis for MI factors obtained with 25/75 percentiles for the 20 countries with highest absolute material stock amounts. Sensitivity of the results to changes in MI factors is represented as error bars. The primary (left) axis shows results in absolute numbers, the secondary (right) axis as percent of the "best guess" result for each region. (b) Comparison of our results from our global mapping exercise (100%) with results of case studies for specific cities and regions. See Supplementary Information S1 for details (Bradshaw et al., 2020; Gontia et al., 2019; Haberl et al., 2021; Kleemann et al., 2017; Lanau & Liu, 2020; Lederer et al., 2021; Liang et al., 2023; Mao et al., 2020; Miatto et al., 2019; Mollaei et al., 2021; Noll et al., 2022; Stephan & Athanassiadis, 2018). Data behind this figure are available in Supporting Information S2.

consistency of data to derive MI factors. Full information on the sensitivity for all countries and building types is available in Supporting Information S2.

Our validation and sensitivity analysis suggest that our results are useful as first comprehensive database with global coverage and high spatial resolution, but they also reveal limitations requiring future work. The large spread of overall results emerging from the sensitivity analysis (Figure 5a) suggests that more primary research to determine MI factors is required to obtain more accurate results, in particular for regions where they are currently absent or very scarce, and where our sensitivity analysis most likely underestimates uncertainties.

Figure 5b compares snippets from our global map with 16 individual results for 14 sub-national regions, mostly cities, from 13 independent studies (for details see Supporting Information S2). The number of results exceeds the number of cities because for one city (Vienna, Austria), three different results were available. Material stocks found in the independent studies range from 53% (Gothenburg, Sweden) to 200% (Samothrace, Greece) of our results, but reasonable agreement is found for most cities/studies. Generally, our results compare to other studies within the range suggested by our uncertainty estimate. Deviations are up- and downward; that is, they show that there are uncertainties, but do not indicate a bias. Larger deviations were found for older studies (Kleemann et al., 2017), for very specific locations like the Greek island Samothrace (Noll et al., 2022) and Gothenburg, Sweden (Gontia et al., 2020). The latter two cases have untypical building styles not captured in region-averaged MI factors due to a prevalence of traditional stone buildings in Samothrace and of wood buildings in Gothenburg that also showed in other mapping exercises (Peled & Fishman, 2021). Deviations for Chiclayo (Mesta et al., 2019) and Antigua and Barbuda (Bradshaw et al., 2020) affect data-scarce regions for which we had to rely on global-average MI factors due to lacking regional MI datasets. While our results are well in line with other Chinese regions (Liang et al., 2023), we find substantial deviations for Beijing (Mao et al., 2020) that may, among other aspects, have to do with deviations in coverage that cannot be excluded with respect to our reconstruction of the boundary shape file (more detail in Supporting Information S1). In general, global results are expected to deviate from local case studies because global or regional factors cannot capture all local context-specific conditions (Schiller et al., 2019).

For some of these problems, research is under way that should allow narrowing the ranges in the foreseeable future. Construction technologies, and with them the material composition of buildings, as well as the mass of materials required per m^2 of floor space and per m^3 of building volume, differ between countries or regions. In large countries, they may even differ between regions, and of course change over time. Efforts to harmonize building definitions and improvements of factors to convert area-based to volume-based material intensity factors (Section 1.2 and Table S2 in Supporting Information S1) would be helpful. At present, most empirical research into the material intensity of buildings is carried out in Europe, North America, and Japan, while few studies are available for other regions (Supplementary Information S1). Improved regional coverage will allow more robust quantifications and mappings. Better MI factor databases would be a precondition for improving these results and would allow a systematic assessment of uncertainties; for example, using Monte Carlo approaches. Building age is another important factor that could not be considered here, but improved models that infer building age from urban form indicators are gradually becoming available (Nachtigall et al., 2023); inclusion of such data, respectively, model outcomes could help improving future maps. In June 2023, which was too late to be included in this work, the Joint Research Centre (JRC) released a new GHSL 2023 version; integrating these data for building type separation could help further improving our results.

4 | CONCLUDING REMARKS

Buildings contain about two thirds of all socioeconomic material stocks, which includes substantial fractions of energy- and emission-intensive materials such as concrete and metals. Global material stocks in buildings amount to 547 Gt in the year 2019, which is ~72 t/cap. Inequalities in per-capita stocks and building volumes are substantial. Our results represent progress in terms of spatial resolution and are based on state-of-the art methods, but substantial uncertainties prevail for world regions with scarce data as well as for important differentiations such as that between residential and other buildings. More accurate quantifications and maps will require additional work, among others better harmonization of building definitions and more empirical studies of the material intensity of buildings.

The data discussed in this article are freely available as “World Settlement Footprint (WSF) 3D - Material Stock - Global, 90m” data product through the DLR EOC GeoService https://doi.org/10.15489/h80jhtr41x48 (DOI: 10.15489/h80jhtr41x48). They open a host of future research avenues. For example, they can be used to calculate resources (materials and energy) and emissions (e.g., GHG emissions) “embodied” in current building stock using recently developed methods (Kennedy, 2020; Stephan & Athanassiadis, 2017; Vélez-Henao & Pauliuk, 2023). Our results can contribute to future analyses of the role of material stocks and their spatial patterns as co-determinants of energy use, material flows, or GHG emissions (Duro et al., 2024; Haberl et al., 2023). They can help localizing secondary resource potentials (Marinova et al., 2020), calculating future waste flows (Streeck et al., 2020, 2021), and analyzing lock-in effects (Seto et al., 2016). Analyses of the patterns presented above, in particular of the inequalities in building volumes and material stocks per capita in the context of the SDG, also emerge as worthwhile endeavors.

AUTHOR CONTRIBUTIONS

Helmut Haberl: Conceptualization; methodology; investigation; writing—original draft; writing—review and editing; supervision; project administration; funding acquisition. **André Baumgart**: Methodology; validation; formal analysis; investigation; data curation; writing—review and editing.

Julian Zeidler: Formal analysis; investigation; data curation; writing—review and editing. **Franz Schug**: Conceptualization; methodology; investigation; data curation; writing—review and editing. **David Frantz**: Conceptualization; methodology; investigation; data curation; writing—review and editing. **Daniela Palacios-Lopez**: Data curation; visualization; writing—review and editing. **Tomer Fishman**: Methodology; investigation; data curation; writing—review and editing. **Yoav Peled**: Methodology; investigation; data curation; writing—review and editing. **Bowen Cai**: Methodology; investigation; data curation; writing—review and editing. **Doris Virág**: Methodology; investigation; data curation; writing—review and editing. **Patrick Hostert**: Conceptualization; writing—review and editing. **Dominik Wiedenhofer**: Conceptualization; methodology; investigation; data curation; writing—review and editing; supervision; project administration. **Thomas Esch**: Conceptualization; methodology; software; validation; formal analysis; investigation; resources; data curation; visualization; writing—original draft; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The authors agree with an open and free data policy. Data supporting the findings of this study are available in two supporting information files. The maps of material stocks in buildings ("*World Settlement Footprint (WSF) 3D - Material Stock - Global, 90m*", DOI: 10.15489/h80jhtr41x48) are available with full spatial (90 m) and thematic (18 materials for 5 building types) resolution through the DLR EOC GeoService at https://geoservice.dlr.de/data-assets/h80jhtr41x48.html

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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