

Title

Satellite mapping of urban built-up height reveals extreme gaps and large inequality in infrastructure availability in the Global South

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Abstract

Information on urban built-up infrastructure is essential for understanding the role of cities in shaping local and regional ecological, economic, and social outcomes. The lack of data on built-up heights over large areas has limited our ability to characterize urban infrastructure and its spatial variations across the world. Here we developed a global atlas of urban built-up heights circa 2015 at 500-meter resolution from the Sentinel-1 Ground Range Detected satellite data. Results show extreme gaps in per capita urban built-up infrastructure in the Global South compared to the global average, and even larger gaps compared to the average levels in the Global North. Per capita urban built-up infrastructures in some countries in the Global North are more than 30 times higher than those in the Global South. The results also show that the built-up infrastructure in 45 countries in the Global North combined, with around 16% of the global population, is roughly equivalent to that of 114 countries in the Global South, with around 74% of the global population. The inequality in urban built-up infrastructure, as measured by an inequality index, is large in most countries, but largest in the Global South compared to the Global North. Our analysis reveals the scale of infrastructure demand in the Global South that is required in order to meet sustainable development goals.

Keywords: City, built-up height, built-up infrastructure, inequality, 3-D urban form

Significant Statement

Information on urban built-up heights globally is needed for evaluating the effects of urban form and infrastructure on the environment, the economy, and human well-being. This study provides a global atlas of urban built-up heights and shows large spatial variations in built-up heights at continental, country, and city levels. The results also reveal extreme gaps in urban built-up infrastructure availability in the Global South and large inequality in built-up infrastructure in most countries, but largest in the Global South compared to the Global North. The atlas has potential to improve our understanding of the effects of urbanization on raw material demand, embodied and operational energy use, and urban development intensity.

Urban areas are home to 55% of the world's population today, a proportion that is expected to increase to 68% by 2050 [1]. The majority of global economic development and greenhouse gas emissions are generated in urban areas [2]. However, cities across the world exhibit profound infrastructure inequality, with significant variation in infrastructure availability, provision, and access [3]. Since urban infrastructure is highly correlated with urban economic growth and city-level GDP [4, 5], high levels of infrastructure inequality could contribute to lower levels of economic productivity, social capital, and human well-being [6, 7]. Evaluating infrastructure inequality is critical for understanding the heterogeneous development patterns of cities across different regions and countries [8].

Urban form includes both the 2-D urban areas and density and the 3-D built-up heights, i.e., vertical characteristics of physical patterns, layouts, and structures of cities [5, 9]. Urban areas have been mapped extensively in 2-D using satellite imageries from nighttime lights [10] and time series Landsat [11]. With 60–80% of energy consumption occurring in urban areas [12], it is important to map urban form, which have been shown to influence energy use and greenhouse gas emissions [13, 14]. Since urban form includes the vertical dimension of the built environment, mapping urban built-up heights can provide information about critical elements of urban areas.

There is also a strong correlation between higher urban built-up density, taller buildings, and urban economic growth [4]. A recent study of 477 large cities with a novel time series satellite dataset shows that urban volumetric growth is strongly correlated with city-level GDP [5]. Recent advances in remote sensing have enabled the development of several novel datasets of 3-D built-up areas, including one of dataset on 3-D building stock worldwide [15], a high-resolution map of urban morphology [16], a three-decade time series of vertical built-up area [17], and typologies of urban 2-D and 3-D growth for nearly 478 cities worldwide [18]. However, the wall-to-wall built-up height information over large areas is still limited, which obscures our outlook for anticipated urban development and its implications for energy use and greenhouse emissions [19, 20].

We estimated the global urban built-up heights at a 500-meter grid level to characterize the global coverage and distribution of infrastructures in urban areas (Fig. 1A and Figs. S13-18). The built-up height was calculated as the mean height within a 500 m grid, including both buildings and non-buildings such as streets, parking lots, and green space, using a model we previously developed [21] based on the Sentinel-1 Ground Range Detected (GRD) data. We validated the GRD-derived urban built-up heights using multiple sources of reference data. We found that the estimated urban built-up heights show good agreement with the reference data and can capture the variation in built-up heights from urban cores to suburban areas. This new global built-up height dataset has significant potential to improve our understanding of how human activities shape Earth's surface, reveal spatial inequalities of global urban infrastructure, and contribute to global and large-scale energy and climate studies.

Results

Urban form of cities by combining urban density and built-up height

The global atlas of urban built-up heights (Fig. 1A) provides critical information to characterize urban form in 2-D to 3-D across world cities. Overall, global urban areas are dominated by low density and expansive development with low urban built-up heights. Built-up heights of cities show large spatial variations across cities and regions. Cities with high levels of verticality are predominantly located in East Asia and Western Europe. The two countries with the largest total

urban extents, the United States (US) and China, have contrasting patterns of built-up heights. The mean built-up height in China is two times higher than that in the US. This corroborates other studies which have found similar differences in built-up heights between the two countries [5, 17]. Although their total urban extents are similar, they differ in their capacity to accommodate urban populations due to differences in built-up heights. We evaluated both urban density (i.e., imperviousness) and built-up heights (i.e., mean and variation within a city) and grouped cities worldwide into six categories. Some of these six types of cities show geographic clustering (Fig. 1B). For example, the South Atlantic region of the US is dominated by cities with low density and low and homogeneous built-up heights while cities in East Asia are mainly tall and not very dense.

Although similarities in urban density and built-up heights at the city level can be discerned globally (Fig. 1B), high spatial resolution information on built-up heights is still needed because of the uniqueness of built-up heights within cities (Fig. 2). Generally, most cities have a distinct peak in built-up heights in the urban center, with declining heights from the center outward surrounding areas. There are, however, some cities with multiple urban centers (e.g., Cape Town, South Africa and New Delhi, India), illustrated by more than one built-up height peak. In some cities such as New Delhi where there are policy restrictions on building height [22], the results show both density and built-up heights to be generally low. Some large, low-rise cities such as Atlanta, US, have high-rise buildings in their urban centers, but the proportion of such buildings is very low. Cities such as Seoul, Korea, have large areas with high built-up heights outside of the urban centers, as do some European cities (e.g., Munich, Germany).

Extreme gaps in urban built-up infrastructure in the Global South

We found that the world's wealthiest nations contribute disproportionately to the global total urban built-up infrastructure (Fig. 3). 45 countries in the Global North with combined ~16% of the global population have nearly equal amounts of global urban built-up infrastructure as 114 countries in the Global South which have ~74% of the global population. Together, the top three countries with the largest amount of urban built-up infrastructure, China, the US, and Japan, account for approximately 50% of the global total. Overall, there are more countries in the Global North (e.g., the US, Japan, Russia, Germany, France, and Italy) each contributing over 2% to the global total built-up infrastructure. It is worth noting that lower urbanization levels in the Global South may lead to an underestimation of per capita built-up infrastructure because we only included urban infrastructures in this analysis.

The global atlas of built-up heights reveals large differences in per capita built-up infrastructures across countries and extreme gaps in per capita urban infrastructure availability between the Global North and Global South (Fig. 4A&B). Although the total urban built-up infrastructure is large in some countries such as China in the Global South due to large populations, the per capita level is still considerably lower compared to the average in the Global North. The findings show that per capita infrastructure for approximately 90% of the global total population is lower than the average level of the Global North. The average per capita urban built-up infrastructure of the Global North is approximately 300 m³, which is approximately three times that in the Global South (108 m³). Some countries in the Global North (e.g., the US) have per capita built-up infrastructure larger than 600 m³, while it is as low as 20 m³ in some countries in the Global South such as Bangladesh, resulting in an extreme gap of 30 times in per capita built-up infrastructures. The large range and variation of per capita infrastructure in the Global North suggest that it is possible to have high levels of urban development with low levels of per capita infrastructure. Moreover, with an average of 47 m³, nearly all African countries have a lower level of per capita infrastructure compared to

other countries in the Global South (Fig. 4D). Furthermore, results show a significant and strong association between per capita GDP and per capita urban infrastructure (Fig. 4C and Fig. S7). This relationship implies the potential demand for infrastructure with future economic development, especially in the Global South.

Large inequality in urban built-up infrastructure in the Global South

We also found large inequality in urban built-up infrastructure in most countries, but largest in countries in the Global South compared to those in the Global North (Fig. 5A&B). Using the method proposed by Pandey et al. [3] and Brelsford et al. [23], we calculated an inequality index which measures the level of spatial inequality in urban built-up infrastructure. The higher the value of the index, the larger the inequality in built-up infrastructure. Overall, inequality in built-up infrastructure in the Global South (mean: 0.58) is greater compared to the Global North (mean: 0.49) (Fig. 5B&C and Fig. S8). However, the difference in built-up infrastructure inequality between the Global South and North is smaller compared to that of per capita built-up infrastructure. Furthermore, similar to the per capita infrastructure, inequality in African countries is larger compared to other countries in the Global South (Fig. 5E). A significant number of countries in Africa and Asia have an extremely high inequality index above 0.6. However, different from per capita urban infrastructure, results show no significant association between infrastructure inequality and per capita GDP (Fig. 5D), implying that economic development itself does not lead to infrastructure equality.

Implications of the global urban built-up heights

The global atlas of built-up heights has important implications for energy use and climate change mitigation. For example, urban transport-related energy consumption is of particular importance because of its large share of total energy use and potential for climate change mitigation. Higher population densities are correlated with lower vehicle miles traveled and energy consumption [24]. Built-up heights provide a more direct and spatiotemporally consistent measure of urban form compared to population density, which often needs to be downscaled from surveyed data at the regional level [25]. Furthermore, we found a negative relationship between city's mean built-up heights with transport-related energy consumption (Fig. 6), which did not show a strong relationship with the 2-D measure of city's areas (Fig. S9). Cities with lower built-up heights show higher transport-related energy consumption because of the high proportion of automobile use compared to more vertical cities. This suggests that strategies to increase urban density through vertical growth may lead to lower transport energy consumption. However, the tradeoffs between lower transport energy and greater material and energy intensity to build and operate tall buildings may be considered.

Discussion

The large spatial variations in built-up heights can be attributed to various factors such as land use histories and policies, especially with regard to early infrastructure investments, zoning, building codes, and height restrictions. Land use restrictions and transportation infrastructure and policy are among the most important factors behind building heights. Built-up heights in East Asia are generally higher than those in developed countries in North America and Europe, while relatively lower population density in most US cities leads to lower urban built-up heights. Despite that population density is high in both China and India, urban built-up heights in China are notably taller compared to India, mainly due to Floor Area Ratio regulations in India [22]. Built-up heights

were generally higher in newly urbanized countries compared to those in well-urbanized regions, implying that the policy of compact development can significantly increase heights in existing and newly urbanized areas under urbanization [26]. Moreover, the limited land resources and high land prices led to higher urban heights in Asia and Europe, compared to the US with abundant land resources [27, 28].

The extreme gap in per capita built-up infrastructures in the Global South suggests impending large global demand for materials, and increases in embodied energy and greenhouse emissions if the gap is filled. The association between per capita urban infrastructure and economic level also indicates the increasing trend of per capita infrastructure worldwide under economic development. More than the same amount of current global total urban built-up infrastructure will be needed for those countries below the average level of the industrialized countries to meet the gap even assuming there is no population growth. With the consideration of population growth, this demand could increase by approximately 1.25 and 1.65 times the current global total urban built-up infrastructure under Shared Socioeconomic Pathway (SSP) 1 (Sustainability) and SSP3 (Regional Rivalry) scenarios [29], respectively. Such demand for urban built-up infrastructure can significantly influence future urbanization and resulting urban form in all countries, especially those in the Global South. With a growing demand for construction materials and specialized rare earths, there may be a continued lag in infrastructure development in the Global South, resulting in low human development. Moreover, most projections of future urbanization in current studies only considered 2-D urban land expansion. An improved understanding of vertical urban growth and its role in future urbanization is highly needed to develop a more realistic projection of future urbanization in meeting the high demand for built-up infrastructure.

The large inequality in urban built-up infrastructure worldwide implies great challenges toward sustainable development because infrastructure either directly or indirectly influences 72% of the targets of the United Nations Sustainable Development Goals [30]. The challenge is even larger in the Global South with greater infrastructure inequality, especially in African countries. Because economic development itself will not decrease infrastructure inequality, it is suggested that other efforts and strategies are needed to reduce urban built-up infrastructure inequality. Even though this study explored global infrastructure inequality for the first time, the limited scope of the current study warrants further investigation into what efficient, effective, and economical practices can mitigate infrastructure inequality. Additionally, further investigation of infrastructure inequality beyond the national level in large countries (e.g., China) with substantial regional variations of built-up infrastructure can offer new insights for sustainable development at finer scales.

Information on built-up height variations within a city has a significant potential to advance studies such as urban climate and energy use modeling [31, 32]. Outdoor ventilation can be influenced by building height variation [33]. Gridded built-up heights also serve as a key input for estimating other important urban surface parameters such as roughness, which can significantly affect the simulation performance of the urban atmospheric environment. Transportation energy consumption and emissions are generally higher in cities with a single center, compared to those cities with multiple centers [34] that can increase the overall accessibility, shorten the trip length, and optimize public transport services [35]. The frequency of different built-up heights within the city can help reveal urban land uses and travel patterns, and therefore support studies on city transportation and energy use.

The global atlas of built-up heights has important implications for improving our understanding the demand for building construction material, embodied and operational energy use, and associated carbon [36-38]. For example, building heights have been used to estimate building floor space, a critical variable in energy and material demands modeling [39]. It is clear that areas with high built-up heights contain more building materials such as cement. However, the large spatial variation of built-up heights was not considered in most carbon studies due to data availability, especially in the Global South [40, 41]. Compared with 2-D maps of urban areas, built-up heights could be notably different in cities with similar urban areas, leading to large differences in urban volume and embodied energy use among these cities [42]. In addition, high-rise buildings consume more energy and emit more anthropogenic heat flux (AHF) to the atmosphere compared to low-rise buildings [42]. Accurate estimation of building AHF is helpful to better understand the contribution of buildings to urban climate and further support sustainable development.

The global atlas of built-up heights provides unique information for the estimation and projection of building energy consumption and associated emissions. The information on built-up heights can significantly improve the quantification of building floor space, one of the most important factors in modeling building embodied and operational energy consumption. For example, building floorspace is one of the key variables in the Integrated Assessment Models, such as GCAM [43] and MESSAGE [44], which can project future building energy demands to evaluate the impact of climate change and develop mitigation strategies. However, current information about building floorspace, especially in the Global South, is rather limited [39]. At the large scale, though building floorspaces scale linearly with 2-D urban areas, there are still significant discrepancies because of the variations in built-up heights (Fig. S10). For example, the counties of Hudson in New Jersey and Kings in New York obviously do not follow the relationship between the floorspace and 2-D urban areas because of the substantial difference in built-up heights in these two counties compared to other counties. This example highlights the importance of integrating built-up heights in accurately estimating building floorspace, even at the county level. Without taking built-up heights into account, the bias in the estimated building floorspace could be propagated and exaggerated in the following studies of building energy use and associated emissions.

The dataset on global urban built-up heights and infrastructure can also support applications such as urban scaling [45, 46] and mapping population distribution and dynamics [25, 45, 46]. The extensive studies based on the 2-D measurements of the land or built area of cities demonstrated that urban infrastructure scales faster with population than land area [45]. The simultaneous and consistent measurements of the 3-D urban built-up infrastructure over cities globally provide a new urban indicator to investigate the power-law scaling relations of city size. Built-up heights can also advance our capacity of downscaling population to the grid level with the help of vertical information. Compared to the traditional approaches that consider only 2-D urban areas (e.g., nighttime light) [47], built-up heights can differentiate population in grids with similar urban areas and human activities, but different built-up heights. For example, built-up heights have been used to map hourly population dynamics together with other remotely sensed and geospatial data [25]. Moreover, built-up heights can help map urban land uses (e.g., commercial, residential, and industrial) [48]. With the help of vertical information, urban land uses with different functions can be better identified, and therefore, temporal dynamics (e.g., diurnal) of population in different urban land uses can be better captured.

Materials and Methods

Data

Sentinel-1 data. We collected the Sentinel-1 Ground Range Detected (GRD) data as the main data source in mapping global urban built-up height. The Sentinel-1 GRD data, both with ascending and descending orbits, were collected circa 2015 when a global coverage of Sentinel-1 data became available [49]. Here, the used GRD scenes were collected from the instrument mode of the interferometric wide swath, of which backscatter coefficients (i.e., VV and VH) from a dual-polarization C-band SAR instrument onboard were included with a raw spatial resolution of 10 m.

Reference built-up height data. We collected reference built-up height data in 37 cities in the US (7) and Europe (30) (Fig. S6) for model development and evaluation. These fine spatial resolution (<10 m) reference datasets were mainly derived from airborne LiDAR data in the US [21] and stereo images in Europe (<https://land.copernicus.eu/local/urban-atlas/building-height-2012>). It is worth noting that reference built-up heights of 27 cities in the US and Europe were used to calibrate the urban built-up height model, while the remaining ten cities were used to evaluate the estimated heights from the Sentinel-1 data. The reference data recorded as the floor number in 20 cities in China (<https://www.amap.com>), reference height data in Sao Paulo (Brazil) (<https://osmbuildings.org>), Vancouver (Canada) (<https://opendata.vancouver.ca>), and the gridded (10 m) built-up height product in Germany derived from satellite observations [50], were also collected as additional datasets for evaluation.

Urban Boundary Data. We collected the boundary of urban areas at a fine resolution (30 m) in 2015 from the global urban boundary dataset [51]. Urban areas defined in this dataset were used to calculate per capital infrastructure for countries and counties and delineate urban boundaries of representative cities.

World Bank Data. We collected the population and gross domestic product (GDP) of each country in 2015 from the World Bank (available from <https://data.worldbank.org>). The population was used to calculate per capita GDP and built-up infrastructure in Figs. 3&4. In total, we examined 159 countries, of which 45 countries are in the Global North (e.g., the US and Australia) and 114 countries in the Global South (e.g., China, India, and the Middle East). The Global North and Global South have been defined according to socio-economic and political characteristics and the countries in these two groups vary slightly across studies [52]. In this paper, the names of countries in the Global South, which refer to those developing countries that share a set of vulnerabilities and challenges, were obtained from the United Nations Development Programme [53].

Building Floor Space Data. We collected per capita building floor space of selected U.S. counties from Arehart et al. [39] to explore the implication of urban built-up heights in energy modeling. Taking county as the geographical unit, we calculated the mean built-up height and urban percentage (the ratio of the urban area in a county to the area of a county). The top 25 counties were selected by sorting urban percentages in descending order in the US with the total county area smaller than 400 km² to highlight the importance of built-up heights.

Urban Transport Energy Consumption Data. We used the transport-related energy consumption dataset [24] to show the relationship between urban built-up height and transported-related energy consumption. This dataset included per capita transport-related energy consumption in 31 cities. The mean built-up height for each city was calculated from the gridded built-up height based on the urban boundary.

Methods

Mapping global urban built-up height

We estimated urban built-up heights worldwide using a model we previously developed [21] based on Sentinel-1 Ground Range Detected (GRD) data. We defined the urban built-up height as the mean height within a 500 m grid in the urban domain, including buildings and non-buildings such as streets and parking lots (Fig. S1). First, we aggregated the Sentinel-1 GRD data (i.e., backscatters from VV and VH) in 2015 and the reference building height data in 27 of 37 cities in the US and Europe (Fig. S6) to a 500 m resolution,

which was determined by sensitivity analysis of the resolution from 100 m to 1 km [21]. To mitigate the impact of elevated objects (e.g., trees), we masked out non-urban areas in Sentinel-1 GRD data using the urban extent map from the global human settlement layer [54]. Then, we derived the VVH, an indicator of urban heights, by integrating backscatters from the dual-polarization information (i.e., VV and VH) from the Sentinel-1 GRD data at a 500 m resolution (Eq. 1). Finally, we calibrated the urban built-up height model (Eq. 2), i.e., the relationship between the VVH and the log-transformed urban built-up height. Such a physical-based built-up height model can be used to estimate urban built-up heights worldwide.

$$VVH = VV * r^{VH} \quad (1)$$

$$\ln H = a * VVH^b + c \quad (2)$$

where γ is the parameter to characterize the relative impact of VH on the derived VVH, H is the log-transformed urban built-up height, and a , b , c are the coefficients to be estimated in the urban height model. In this study, γ was set as 5 as suggested by Li et al. [21]. We developed the building height models using the Sentinel-1 data with ascending and descending orbits, with calibrated parameters (i.e., a , b , and c) of -2.16, -0.45, 4.78, and -0.61, -0.79, and 2.31, respectively. The final global built-up heights derived by merging results from the ascending and descending observations can be downloaded from <https://figshare.com/s/7f2b254ed18fac8eb7a0>.

We evaluated the estimated global urban built-up heights based on three indicators: correlation coefficient, Root Mean Square Error (RMSE), and Mean Absolute Error (MAE). First, we conducted a leave-one-out cross-validation using the reference built-up height data in 27 of the 37 cities in the 10 km $\times$ 10 km domain in the urban area in the US and Europe (Fig. S2). The reference built-up height data were randomly divided into 10 folds, and each time one-fold was used for evaluation. Second, we evaluated the estimated urban height using the remaining 10 of the 37 cities in the 10 km $\times$ 10 km domain in the urban area (Fig. S3), and in the entire urban area in all 37 cities. Finally, we evaluated the estimated urban built-up height using the reference data of floor numbers in 20 cities in China (Fig. S4), the reference data of building height in Sao Paulo (Brazil), Vancouver (Canada), and the national built-up height product (10 m) in Germany from satellite observations (Fig. S5).

The global urban built-up heights show a good agreement with the reference data and can capture the variation of built-up heights (Fig. S2). The RMSE between the reference and estimated urban built-up heights is below 0.50 m, and the correlation coefficient is above 0.80 (Fig. S3). The estimated urban built-up heights in China are also reliable, as indicated by the indicators of RMSE and MAE using the reference data of floor numbers (Fig. S4), with a slightly lower correlation coefficient due to the difference between the floor number and heights. Similar results (i.e., RMSE: 0.37~0.47 and MAE: 0.40~0.49) were obtained in Sao Paulo (Brazil), Vancouver (Canada), and Germany (Fig. S5), using the reference data of building height and the gridded built-up height product from satellites.

Urban form by combining 2-D density and 3-D height

We grouped the world cities into six types based on the feature space of their 2-D urban density (imperviousness) as well as 3-D built-up heights (mean and variation within the city) (Fig. S11). We calculated the mean and the quartile coefficient of dispersion (QCD) (Eq. 3) of built-up heights as well as the mean of impervious surface areas (ISA) in each city to describe urban form in vertical and horizontal dimensions. QCD can capture the variation of built-up heights within the city and is also comparable between cities with different mean heights. Mean ISA can represent the overall imperviousness density of the city and was calculated from the 30 m global ISA data [55]. We defined thresholds of imperviousness, mean, and QCD of built-up heights (mean height: 3; QCD: 0.6; mean ISA: 0.75) to classify cities globally into six types, mainly based on the data distribution of each feature. The main purpose is to compare cities and to show a general view of the global landscape of urban form with the consideration of both 2-D density

and 3-D height. These thresholds can be adjusted easily to reclassify the world cities. We found that the variation of built-up heights in tall cities tends to be low. Therefore, we did not have types of cities that are both tall and heterogeneous in built-up heights. These six types of cities are (1) sparse and homogeneously low, (2) dense and homogeneously low, (3) sparse and heterogeneously low, (4) dense and heterogeneously low, (5) sparse and homogeneously high, and (6) dense and homogeneously high.

$$(QCD) = \frac{Q_3 - Q_1}{Q_1 + Q_3} \quad (3)$$

where Q_1 and Q_3 are the first (25th percentile) and third (75th percentile) quantiles of built-up height in each urban area.

Per capita and inequality of urban built-up infrastructure

In this study, we proposed that the urban built-up volume by multiplying urban area and heights can be considered as a proxy for urban built-up infrastructure. We calculated urban built-up infrastructure in each grid and added up all pixels in each country. The accumulative population percentage and per capita infrastructure in each country were calculated using the population records from the World Bank. A total of 159 countries worldwide (those without GDP records, such as North Korea were excluded) were examined in Fig. 3 and Fig. 4. In Fig. 3, the area of each rectangle represents the percentage of total built-up infrastructure in each country. We also explored the relationship between per capita infrastructure and GDP in each country using data from the World Bank.

Using the method proposed by Pandey et al. [3] and Brelsford et al. [23] (Eq. 4), we calculated the inequality index of urban built-up infrastructure that can measure the level of spatial inequality in infrastructure in each of 119 countries (with the total number of urban areas delineated by the 2015 urban boundary data larger than 10) in the Global South and North. This index examines how between-region (Figs. S8 and S12) heterogeneities vary with the overall mean of infrastructure distributions constrained by an upper bound [3]. We also tested three upper bounds (i.e., 90, 95 and 100 quantiles in infrastructure distributions) in calculating the inequality index. First, we calculated quantiles of 90, 95, and 100 from infrastructure distribution in each geographic region as three upper bounds. Second, we generated infrastructure distributions in each geographic region constrained by those three upper bounds. Finally, under each constrained upper bound, standard deviation (σ) and mean values (μ) were derived to calculate the inequality indexes. Our results are robust to varied upper bounds as shown in Fig. S8.

$$I = \frac{\sigma}{\sqrt{\mu(1-\mu)}}; 0 < \mu < 1 \quad (4)$$

where I is the inequality index ranging from 0 (lowest inequality) to 1 (highest inequality). μ and σ are the mean and standard derivation of built-up infrastructure distributions constrained by an upper bound in each geographic region.

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Figure Legends

Fig. 1. (A) The global urban built-up heights derived from satellite observations. The color and height of the bar represent built-up heights in each 500m grid. (B) Urban forms of cities with areas larger than 100 km² in six types based on density (imperviousness) and built-up heights (mean and variation). These six types of cities are (1) sparse and homogeneously low, (2) dense and homogeneously low, (3) sparse and heterogeneously low, (4) dense and heterogeneously low, (5) sparse and homogeneously high, and (6) dense and homogeneously high.

Fig. 2. A 3-D view of representative cities for six types of urban forms in Fig. 1B. None indicates that there is no such city group in that continent.

Fig. 3. The shares of urban built-up infrastructure in the Global North and South. 45 countries in the Global North and 114 countries in the Global South have roughly equivalent percentages of global built-up infrastructure. Country names and their portions are shown in the figure.

Fig. 4. (A) Per capita urban built-up infrastructure by country. The dashed red, green, and blue lines are the averages of the Global North (300 m³ per capita), Global South (108 m³ per capita), and all (163 m³ per capita) countries, respectively. The bar width represents the share of the population of each country. The color represents the GDP per capita of each country. The red dots indicate countries in the Global North. (B) Per capita built-up infrastructure in the Global South (S) and North (N). (C) Relationship between per capita GDP and built-up infrastructure in the Global South (S) and North (N). (D) Map of per capita built-up infrastructure. The green boundaries in the map indicate countries in the Global South.

Fig. 5. (A) Inequalities in urban built-up infrastructure by country. The dashed red, green, and blue lines are the averages of the Global North (0.49), Global South (0.58), and all (0.55) countries, respectively. The bar width represents the share of population of each country. The color represents the GDP per capita of each country. The red dots indicate countries in the Global North. (B) Infrastructure inequalities in countries in the Global South and North. (C) Infrastructure inequalities in countries in the Global South and North derived from mean (μ) and standard deviation (σ) of built-up infrastructure distributions constrained by the upper bound of 95% quantile. (D) Relationship between per capita GDP and infrastructure inequalities. (E) Map of infrastructure inequalities. The green boundaries in the map indicate countries in the Global South.

Fig. 6. Transport-related energy consumption and city's mean built-up heights (m). Horizontal solid lines represent the range of the first and third quantiles of city's built-up heights.

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