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Contrasting patterns in urban energy and emission scaling

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Abstract: Cities drive most global energy use and emissions of greenhouse gases and other pollutants, yet how these quantities scale with urban population remains debated. Scaling analysis captures this relationship through the exponent β, which defines whether a quantity increases sublinearly ($\beta < 1$), linearly ($\beta = 1$), or superlinearly ($\beta > 1$) with population. Here we conduct a meta-analysis of 27 scaling studies encompassing 362 scaling exponents across cities worldwide. Results show that energy consumption scales near-linearly to superlinearly: electricity, gas, and transportation fuel have median scaling exponents of 1.06 [25th percentile: 0.94, 75th percentile: 1.13], 1.18 [1.05, 1.34], and 1.22 [1.19, 1.27], respectively. These results suggest that gas use and congestion-related transportation fuel tend to intensify faster than population growth. In contrast, most pollutant emissions ($PM_{2.5}$, PM_{10}, NO_2, SO_2, and CO) scale sublinearly. CO_2 emissions are sublinear globally and in China, with median scaling exponent of 0.86 [0.80, 1.03] and 0.63 [0.59, 0.99], respectively, although a few countries show superlinear scaling (e.g., U.S., Australia, and Canada), pointing to regional differences in technology and policy. Energy consumption and its associated emissions thus scale in opposite directions, a pattern we attribute to the spatial decoupling of production and consumption. Our analysis reveals that inconsistent city definitions, fragmented energy and emissions data, and limited analyses of temporal evolution introduce variability in reported scaling exponents and constrain the generalization of these findings. Standardized, long-term datasets and mechanistic models linking urban metabolism to emissions are needed to resolve these uncertainties and guide sustainable, low-carbon urban transitions.

Keywords: Scaling, urban metabolism, energy, air pollution, greenhouse gases emissions

1. Introduction

Cities are complex systems that integrate engineered infrastructures, socioeconomic activities, and natural landscapes (Batty 2008, Ramaswami *et al* 2012, Sugar and Kennedy 2021). They now accommodate more than half of the global population, account for over 75% of primary energy consumption and more than 80% of global greenhouse gas (GHG) emissions, and are increasingly responsible for strain on critical natural resources such as water (Wang *et al* 2023, Kontokosta and Jain 2015, Li *et al* 2021b, Ascione *et al* 2021, Shen *et al* 2023, Gudipudi *et al* 2019a, 2019b, Ríos-Ocampo and Gary 2025, Nlend *et al* 2025). This reality complicates the once-prevailing notion that larger cities are generally greener and more efficient for resource consumption compared to smaller or rural settlements (Louf and Barthelemy 2014b, Bettencourt and West 2011, 2010, Bettencourt *et al* 2007, Gudipudi *et al* 2019b, 2019a, 2016, Chen *et al* 2025). For centuries, urban growth and technological innovation have led to an unprecedented increase in energy demand and pollutant emissions (Decker *et al* 2007, Lengyel *et al* 2020, Lu *et al* 2024). As cities continue to expand and concentrate capital, labor, and economic activity (Li *et al* 2021a), energy remains paramount for sustaining productivity and development (Elliott *et al* 2015, Dalgaard and Strulik 2011, Sugar and Kennedy 2021).

Urbanization is both a consequence and a driver of global economic growth, making cities focal points for innovation, opportunity, and environmental pressure (Bettencourt *et al* 2010, Lamsal *et al* 2013, Sugar and Kennedy 2021). The concentration of population and economic activities in cities gives rise to agglomeration effects, which influence patterns of energy consumption and other urban attributes (Riahi *et al* 2017, Güneralp *et al* 2017). A large body of research in urban economics and economic geography has shown that population density plays an important role in shaping urban energy use and emissions, with denser cities often exhibiting lower per-capita infrastructure and transport energy demand due to more efficient land use and shared services, although these relationships remain context-dependent (Güneralp *et al* 2017, Larson and Yezer 2015, Castells-Quintana *et al* 2021, Carozzi and Roth 2023). In fact, the social and economic advantages of spatial concentration and clustering can generate both efficiencies and intensifications in energy consumption and emissions (Facchini *et al* 2017, Gudipudi *et al* 2019a, Chen *et al* 2025, Gudipudi *et al* 2016). On the one hand, these efficiency gains are associated with shared infrastructure and more compact urban form (Chen *et al* 2025, Gudipudi *et al* 2016, Huang and Lu 2025). On the other hand, the concentration of wealth and economic productivity can amplify consumption, inequality, and pollution, which places cities at the center of global sustainability challenges (Lengyel *et al* 2020, Creutzig *et al* 2015, Pu and Xia 2025).

The concept of urban scaling laws provides a quantitative framework to describe how urban attributes, such as wealth, innovation, energy use, and emissions, vary systematically with population size (Bettencourt *et al* 2007, Batty 2008, Louf and Barthelemy 2014a, Lu *et al* 2024). Originating from analogies to biological allometry, this framework has revealed many scaling relationships across cities despite substantial heterogeneity in their histories, geographies, and socioeconomic structures (West 2017, Conticelli *et al* 2024, Pu and Xia 2025, Wang and Wang 2017). Early work emphasized the possibility of universal laws or common underlying principles, whereas subsequent studies have highlighted the influence of context, city definitions, and methodological choices on estimated scaling exponents. Meanwhile, theoretical developments have sought to explain these patterns through underlying mechanisms, particularly the role of human interactions, which scale with population size and generate aggregate socioeconomic outputs, as well as the constraints imposed by spatial structure and infrastructure networks that mediate these interactions (Bettencourt 2013, Ribeiro and Rybski 2023). However, these mechanisms are often inferred rather than explicitly tested in empirical studies.

The scaling relationship is typically expressed as

$$Y = Y_0 N^{\beta}, \tag{1}$$

where Y represents an urban property, Y_0 is a normalization constant, N denotes urban population, and β is the scaling exponent. Specifically, sublinear ($\beta < 1$) behavior implies economies of scale, with larger cities requiring less Y per capita. Sublinear relationships are commonly found in urban infrastructure-related quantities, such as electricity networks and roads (Sugar and Kennedy 2020, Fragkias *et al* 2013, West 2017, Bettencourt and West 2010, Bettencourt *et al* 2007, Bettencourt 2013). Linear behavior ($\beta = 1$) indicates proportional growth, which is often associated with individual or household demands insensitive to city size (Bettencourt *et al* 2007, Rao *et al* 2023, West 2017, Bettencourt and West 2010, Bettencourt 2013). Superlinear behavior ($\beta > 1$) scaling is often associated with social and economic quantities (e.g., wages, GDP, and patent production) where network effects are at play, which reflect enhanced connections and interactions in larger cities (Sugar and Kennedy 2020, Zhao *et al* 2018, Zhou *et al* 2022, West 2017, Bettencourt *et al* 2007).

It should be noted that energy consumption and its associated emissions are tightly coupled (Li *et al* 2021b, Jung *et al* 2024). Carbon dioxide (CO_2), methane (CH_4), nitrogen dioxide (NO_2), and particulate matter (PM) are primarily emitted through anthropogenic activities that require fossil fuels (e.g., transportation and energy production) (Yatzkan *et al* 2024, Lamsal *et al* 2013, Liang *et al* 2024, Li *et al* 2020, Leffel *et al* 2025). Consequentially, as urban energy demand increases with population, so do associated pollution emissions. However, whether cities exhibit net gains in efficiency as their populations grow remains an open question (Gudipudi *et al* 2019a). Some studies found that larger cities achieve higher per-capita efficiency through denser infrastructure and innovation (Li *et al* 2021b, Brelsford *et al* 2020, Mohajeri *et al* 2015, Louf and Barthelemy 2014b, Bettencourt and West 2010, 2011, Bettencourt *et al* 2007, Huang and Lu 2025), while other studies demonstrate these higher per-capita efficiencies to be dependent on wealth (Lu *et al* 2024, Gudipudi *et al* 2019a, Fragkias *et al* 2013).

Urban scaling relationships can offer a useful high-level perspective for understanding how aggregate urban attributes respond to population growth and may help inform city-level assessments of current and projected future energy use and pollutant emissions (Molinero and Thurner 2021). Despite decades of research on scaling laws and urban metabolism, literature remains fragmented in terms of how energy consumption and pollutant emissions scale with city size. To address this gap, this meta-analysis compiles and critically evaluates empirical findings across diverse studies of urban energy use and emissions. We aim to identify recurring scaling patterns, reconcile conflicting interpretations, and highlight the need to address key limitations that would improve the holistic understanding of urban metabolism at scale and eventually inform pathways toward sustainable, low-carbon urban systems.

2. Methods

Guided by the theoretical framework that many facets of urban life can be described with a simple power-law function (Eq. 1), previous reviews have examined the mathematical origins of the scaling law (Ribeiro and Rybski 2023) and energy metabolism in cities (Liu and Wu 2024). However, to our knowledge, no prior synthesis has systematically evaluated empirical scaling exponents describing how urban energy consumption and pollutant emissions scale with population size. Here we conducted a meta-analysis to quantify and compare these relationships across 18-years of existing studies. Such a meta-analysis can enable a synthesis of findings across dozens of studies to reveal patterns and insights that would not otherwise emerge from independently analyzing each study.

Peer-reviewed literature was systematically searched using the Web of Science Core Collection database. The search included all publications prior to July 2025 and used keywords such as "urban", "city", "cities", "energy", "emission", and "scaling". Studies were included if they (1) reported empirical scaling exponent (β) for any form of energy consumption, such as electricity, gas, total, primary, and secondary energy use, or (2) analyzed energy-related pollutant emissions such as CO_2, NO_2, CH_4, $PM_{2.5}$, and PM_{10}. To ensure comparability across studies, only scaling relationships that used total population (not per capita) as the independent variable were included. Studies that expressed the dependent variable (Y) as concentrations (which are intensive properties) rather than total emissions (extensive properties) were excluded. We also removed cases where the scaling was performed against non-urban or aggregated populations (e.g., national or state-level total populations). Finally, we only retained single-variable regression to maintain consistency in model interpretation. Given the lack of a standardized definition of "city" across studies, we retained the original definitions used in each study and evaluated their implications as part of the synthesis.

For each eligible study, the reported β values were extracted directly from the main text and supplementary materials or derived from the source data repositories. Sample size, 95% confidence intervals, and/or standard deviations were included where possible to help characterize the overall uncertainty across the meta-analysis. Although our literature search was not restricted by publication year, the first study to formally introduce the population-based urban scaling framework was Bettencourt *et al* (2007). Consequently, all eligible publications identified in our search were published in or after 2007. Most identified studies were published after 2019 (figure 1a), underscoring a growing interest in applying the scaling framework to urban energy and environmental systems. Overall, among the 655 studies screened, 92 studies met the general inclusion criteria, and 27 provided extractable scaling exponent values that are used in this meta-analysis. Table S1 summarizes the extracted data and their corresponding references.

3. Results

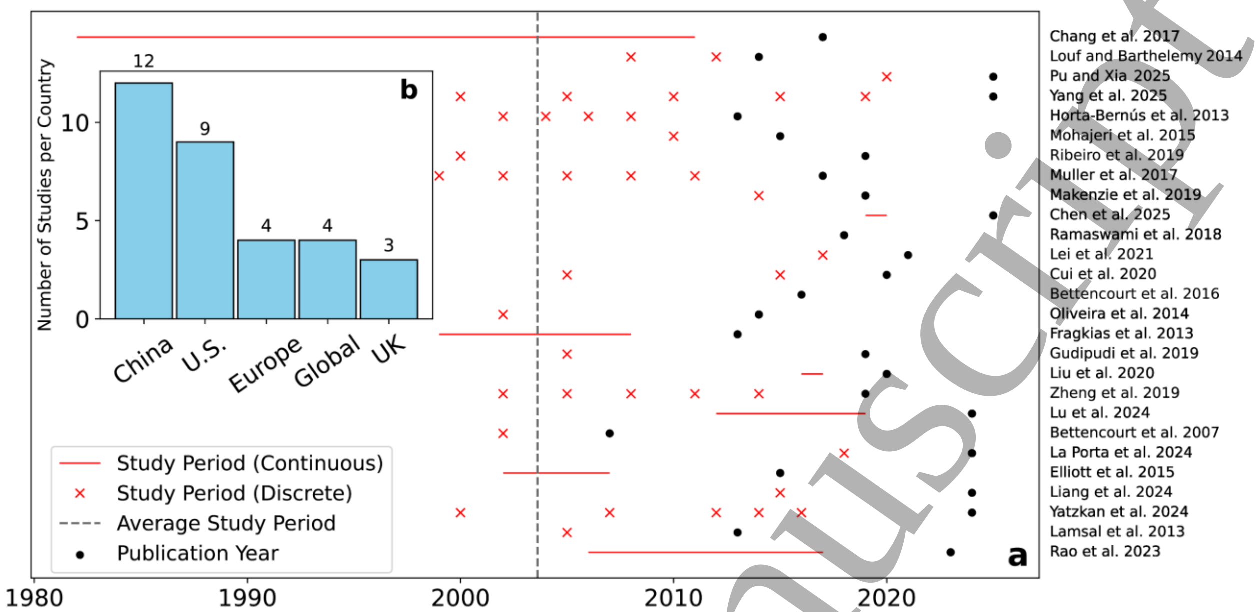

Figure 1. Summary of studies included in the meta-analysis on urban energy consumption and pollutant emission scaling. (a) Temporal distribution of the 27 studies analyzed. The dashed gray line indicates the mean publication year of approximately 2004. Red cross symbols represent studies using discrete years for their scaling analysis, while solid red lines denote continuous study periods. Black dots mark the year of publication. (b) Geographic distribution of studies by country. Countries represented by fewer than three studies are excluded from the figure.

Our meta-analysis includes 362 unique urban scaling exponents (β), including 18 global-scale values, 17 continental-scale values, 312 country-level values, and 15 regional or sub-regional values. Most studies on urban energy and pollution scaling were conducted in China (n = 12), the USA (n = 9), and Europe (n = 4), respectively (figure 1b). The mean and median year used to derive scaling relationships across the 27 studies was 2004 and 2005 respectively (figure 1a)—nearly two decades ago. This temporal gap highlights an important limitation: most urban scaling analyses rely on pre-2020 datasets. This reflects both the lag in availability of consistent city-level energy and emissions data and the relatively slow evolution of key structural features of cities, such as infrastructure networks and urban form. While recent changes in urban energy systems and mobility patterns, including temporary disruptions associated with the COVID-19 pandemic, may have influenced absolute levels of energy use and emissions, the underlying drivers of scaling relationships, particularly interaction dynamics mediated by infrastructure and spatial organization, tend to evolve over longer, often decadal, timescales. Therefore, previously reported scaling relationships still remain informative for understanding long-term urban dynamics. This also highlights the importance of updated datasets to reassess scaling behavior under contemporary conditions. In terms of methodology, the majority of these studies estimate scaling relationships using cross-sectional analyses across cities, typically by fitting log–log regressions between urban indicators (e.g., energy use, emissions) and population size. In contrast, longitudinal analyses that examine how scaling relationships evolve over time within individual cities remain comparatively limited (see section 3.3). This imbalance underscores the need for longitudinal analyses to more rigorously evaluate how urban metabolism responds to evolving socioeconomic, infrastructural, and environmental conditions.

3.1 Scaling of urban energy consumption

Urban energy consumption reflects the aggregation of diverse energy flows that sustain production, transportation, and residential activities. These flows have been studied within the framework of urban metabolism to understand environmental impacts associated with energy consumption, waste production, and material throughput (Kennedy *et al* 2007, 2011). Energy consumption is strongly correlated with economic metrics such as GDP (Kennedy *et al* 2015, Yu *et al* 2024), and often serves as an indicator of a city's economic advancement (Dalgaard and Strulik 2011, Liu *et al* 2021). This coupling between energy use and economic growth is reflected in urban scaling laws. For example, previous studies reported that residential electricity sales scale linearly with population, while total electricity sales scale superlinearly (Kennedy et al. 2015; Bettencourt et al. 2007; Bettencourt 2013). Superlinear scaling of energy-related indicators has been observed in several countries, particularly for gas consumption and supply (Yatzkan *et al* 2024, Liu and Zou 2020, Lei *et al* 2022, Ramaswami *et al* 2018, Bettencourt *et al* 2007).

Indeed, across all studies included in our meta-analysis, the distribution of electricity, gas, and transportation fuel scaling exponents predominantly exhibit superlinear scaling with population (figure 2a), with 58.3%, 76.9%, and 100% of reported exponents exceeding 1, respectively. The reported median scaling exponent is 1.06 [25th percentile: 0.94, 75th percentile: 1.13] for electricity, 1.18 [1.05, 1.34] for gas, and 1.22 [1.19, 1.27] for congestion-related transportation fuel. Particularly for gas and transportation fuel, our results imply that demand for these urban properties intensify faster than population growth. When aggregated by country, China produced the largest number of energy-related scaling exponents (figures 2 and

3), reflecting the country's rapid urbanization, economic development, and the availability of extensive urban data (Lu *et al* 2024, Rao *et al* 2023, Cui *et al* 2020). Our analysis specifically identifies gas as an energy variable exclusively examined in China, where it exhibits a superlinear scaling pattern (figure 2b). In comparison, transportation fuel scaling exponents are largely derived from a single study in the U.S. (figure 2d).

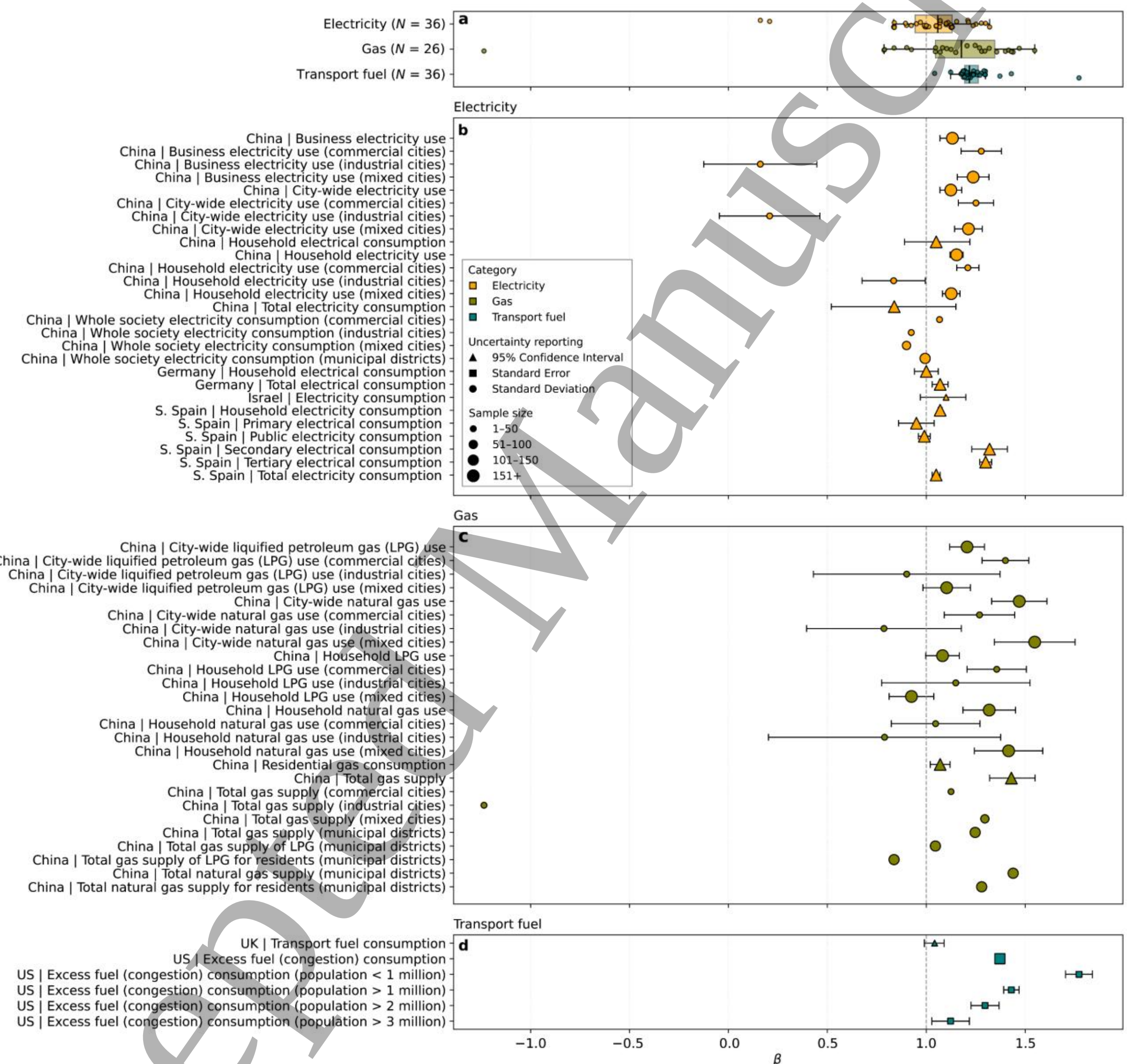

Figure 2. Urban scaling exponents (β) for energy-related attributes. (a) Combined results for all energy-related studies. (b–d) Scaling exponents grouped by energy type: electricity, gas (e.g., natural gas), and transportation fuel, respectively. The dashed vertical line marks $\beta = 1$, indicating linear scaling; values of $\beta > 1$ and $\beta < 1$ correspond to superlinear and sublinear relationships, respectively. Each data point represents an individual scaling exponent. Marker

size denotes the sample size, while solid black horizontal bars indicate the reported uncertainty range. Triangles represent 95% confidence intervals, squares represent standard errors, and circles represent standard deviations. Note that for studies reporting time-series of scaling exponents, only the most recent year or the aggregated exponent is included in panels (b–d).

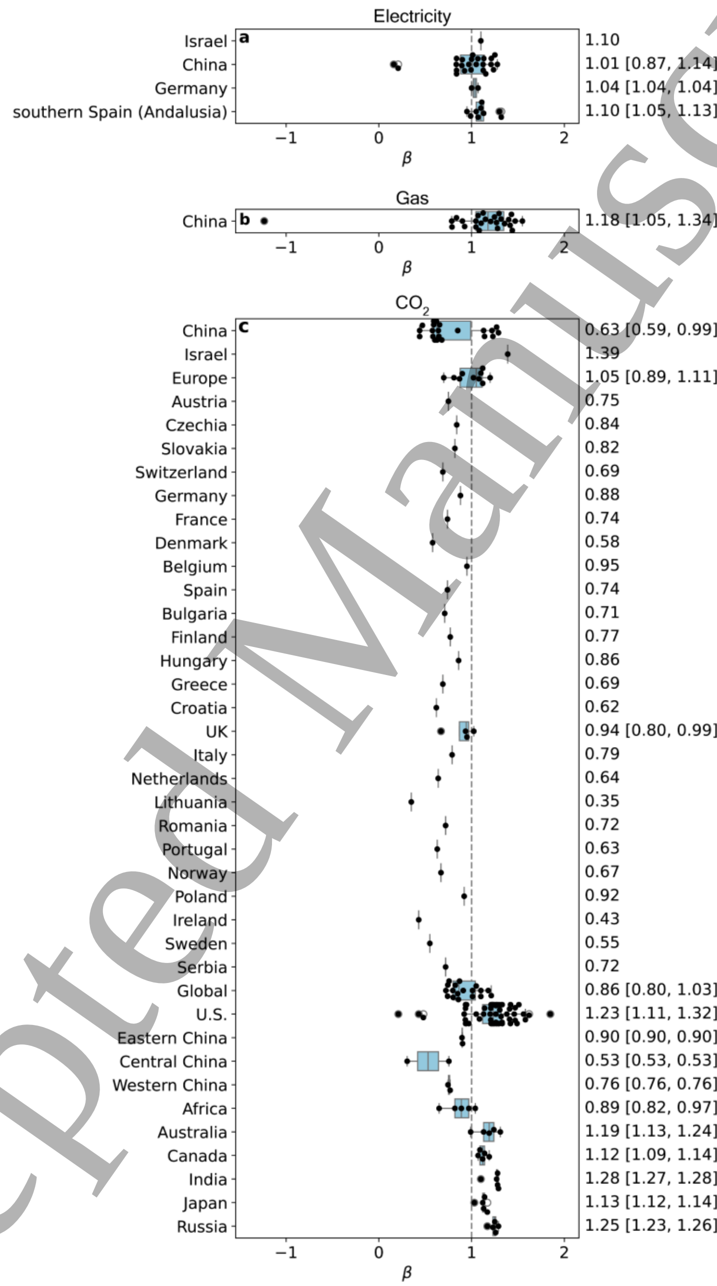

Figure 3. Distribution of urban scaling exponents (β) for electricity, gas, and CO_2 emissions by country. The dashed gray line marks $\beta = 1$, indicating linear scaling; values of $\beta > 1$ and $\beta < 1$ correspond to superlinear and sublinear relationships, respectively. Boxes show the interquartile

range (IQR) of β values between the upper and lower quartiles, whiskers extend to 1.5 × IQR, and points beyond the whiskers denote outliers. Each dot represents an individual β value extracted from the reviewed studies. Numbers on the right show the median [25th percentile, 75th percentile] for each country/region; single-exponent cases display the reported value.

Our synthesis here contrasts with earlier individual studies that found sublinear or linear scaling of urban energy use and electricity (Kennedy *et al* 2015, Bettencourt *et al* 2007, Bettencourt 2013, Liu and Zou 2020, Lei *et al* 2022, Ramaswami *et al* 2018, Bristow and Kennedy 2015, Gudipudi *et al* 2019a, Liu and Zou 2020, Dalgaard and Strulik 2011). These discrepancies can be attributed to the different study scales used (e.g., global vs. country-level). Regardless, a universal scaling relationship for urban energy consumption remains elusive, partly due to the challenges of obtaining consistent and comparable energy data across countries and regions (Facchini *et al* 2017).

3.2 Scaling of urban pollutant emissions

Pollutant emissions are tightly coupled with urban energy consumption, especially in sectors such as transportation, industry, and construction (Hou *et al* 2024, Bettencourt and West 2010, Li *et al* 2024, Keleş *et al* 2022, MacKenzie *et al* 2019, Louf and Barthelemy 2014a). Combustion of fossil fuels is primarily responsible for CO_2, NO_2, and SO_2 emissions, which also contributes substantially to other pollutants such as $PM_{2.5}$ and CO, alongside emissions from industrial activities and agricultural processes (Liang *et al* 2024). Because urbanization and human settlement processes are complex (Batty 2008, Louf and Barthelemy 2014a, Ribeiro *et al* 2019), their impacts on pollutant emissions are multifaceted and often spatially heterogeneous (Wang and Komonpipat 2020, Muller 2016).

Like many other urban attributes, pollutant emissions exhibit empirical scaling behavior (Gudipudi *et al* 2019a, Cui *et al* 2020, Li *et al* 2021b, Yatzkan *et al* 2024, Muller 2016, MacKenzie *et al* 2019). While larger, denser cities are often assumed to be less environmentally intense due to shared infrastructures (Bettencourt and West 2010, Bettencourt *et al* 2007, Kumar and Sen 2025), empirical findings remain inconclusive (Fragkias *et al* 2013, Oliveira *et al* 2014, Louf and Barthelemy 2014a). Multiple studies have shown superlinear scaling of pollutant emissions, indicating that larger cities generate disproportionately higher emissions per capita (Lamsal *et al* 2013, Yatzkan *et al* 2024, Liang *et al* 2024, Bettencourt and Lobo 2016, Li *et al*

2021b, Oliveira *et al* 2014), raising the possibility that larger cities might not have a smaller per-capita environmental footprint. For example, in our meta-analysis, while the median scaling exponent for CO_2 emission at the global scale is 0.86 [0.80, 1.05], that for the U.S. is 1.23 [1.11, 1.32], which tends to be superlinear (figure 3c).

Across all studies compiled in our meta-analysis, pollutant emissions generally scale sublinearly with population. This indicates that most urban air pollutant emissions tend to increase more slowly than population size. Specifically, the median scaling exponents for SO_2, CO_2, NO_x, PM_{10}, $PM_{2.5}$, and CO are 0.58 [0.32, 0.96], 1.06 [0.78, 1.24], 0.96 [0.60, 1.06], 0.74 [0.74, 0.74], 0.69 [0.59, 0.75], and 0.77 [0.76, 0.85], respectively. Superlinear scaling exponents are reported only for SO_2, CO_2, and NO_x, accounting for 33.3%, 54.3%, and 45.5% of their respective samples. These three pollutants also exhibit broad distributions of reported exponents, suggesting substantial variability across studies. CO_2, in particular, shows a roughly balanced mix of superlinear and sublinear scaling exponents, ranging from markedly sublinear to strongly superlinear across studies and yielding a median slightly above 1. This wide dispersion likely reflects heterogeneity in methodological choices, such as city definitions (see section 4), national contexts, and stages of socioeconomic development. Consequently, the scaling behavior of these pollutant emissions appears not to follow a universal relationship but instead depends on structural, geographic, and developmental differences across study settings.

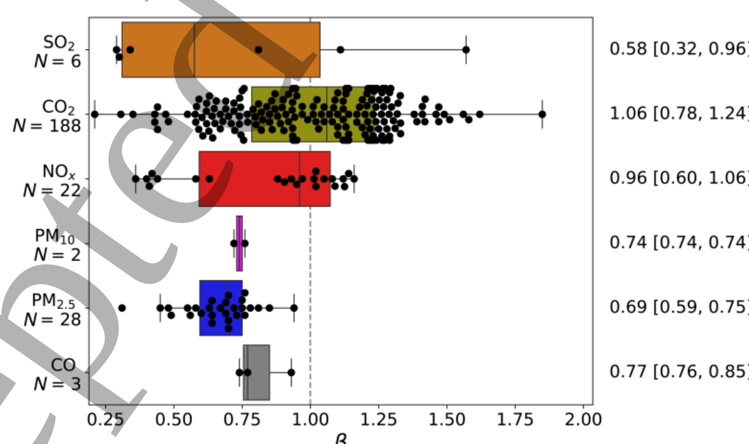

Figure 4. Distribution of urban scaling exponents (β) for pollutant emissions. The dashed gray line marks $\beta = 1$, indicating linear scaling; values of $\beta > 1$ and $\beta < 1$ correspond to superlinear and sublinear relationships, respectively. Boxes show the interquartile range (IQR) of β values between the upper and lower quartiles, whiskers extend to 1.5 × IQR, and points beyond the

whiskers denote outliers. Each dot represents an individual β value extracted from the reviewed studies. Numbers on the right show the median [25th percentile, 75th percentile] for each country/region; single-exponent cases display the reported value.

The geographical variation in pollutant emissions scaling indeed reveals contrasting trajectories (figures 3 and S1). Because of China's rapid urbanization and economic growth over the last two decades, Chinese cities are often viewed as environmentally unfriendly (Cui *et al* 2020, Chen *et al* 2025). However, our meta-analysis suggests that Chinese cities tend to have sublinear scaling of CO_2 emissions, indicating improved emission efficiency with city size (figure 3c). In contrast, urban CO_2 emissions in the U.S., Europe, Australia, Canada, India, Japan, and Russia tend to scale superlinearly, as suggested by the median values, which means larger cities in these regions remain more carbon intensive. This contrast implies that differences in urban infrastructure and energy mix might play a more significant role than city size alone in determining environmental outcomes. Such differences could point toward a quantifiable need to incorporate a higher mix of renewable energy generation to offset the environmental impact of larger city population. Other pollutants, such as $PM_{2.5}$, NO_x, SO_2, and CO, scale sublinearly across most countries (figure S1), with the notable exception of NO_x emissions in the UK and Israel, which tend to scale linearly or superlinearly.

3.3 Temporal evolution of the urban scaling law

Eight studies in our meta-analysis reported time-varying urban scaling exponents, yielding a total of 18 unique β time series that capture the temporal evolution of scaling relationships (figure S2) (Chang *et al* 2017, Yang *et al* 2025, Horta-Bernús and Rosas-Casals 2015, Muller and Jha 2017, Fragkias *et al* 2013, Lu *et al* 2024, Elliott *et al* 2015, Rao *et al* 2023). These studies represent a small but growing body of work studying whether scaling behavior remains stable or evolves as cities and their energy systems further develop.

From the limited time series available, we find that CO_2 scaling exponents have generally increased over time with regional disparities. However, this apparent upward trend is from a single long-term analysis (Yang *et al* 2025), suggesting the need for caution in generalizing this finding. Nearly all studies examined post-2000 periods, with the exception of Chang *et al* (2017), which analyzed data extending back to 1982. Overall, the lack of time-series analyses in our meta-analysis underscores the short temporal coverage and the limited number of studies addressing how scaling exponents evolve through time. Moreover, several of the reported β values have substantial uncertainty, as indicated by the wide confidence intervals.

4. Discussion

The scaling law provides a coarse-grained framework to quantify how urban systems evolve with size. However, the results synthesized here highlight several fundamental limitations in how these relationships are defined, interpreted, and applied. In particular, variations in city definition, data construction, and study design introduce substantial uncertainty in reported scaling exponents. One of the most important factors is the inconsistent definition of a city/urban area, which remains a major source of variation in reported scaling exponents (Yang *et al* 2025, Louf and Barthelemy 2014a, Decker *et al* 2007, Gudipudi *et al* 2016, 2019a, Kumar and Sen 2025, La Porta and Zapperi 2024, Lu *et al* 2024, Cottineau *et al* 2017). As illustrated in figure 5, the same urban attribute can have vastly different scaling behavior depending on how a study's city boundaries are defined. This definitional heterogeneity directly influences whether cities appear to be more or less resource-efficient. Even within the same country, city boundaries are often ambiguous, especially when neighboring metropolitan areas share some functional and socioeconomic characteristics that would otherwise differentiate a city from its surrounding area (Kumar and Sen 2025, Decker *et al* 2007). Intermediate-sized cities may also play an outsized role in shaping national energy flows and emissions but are frequently underrepresented in global analyses (Bahers *et al* 2019).

Furthermore, inconsistencies in urban inventory data, especially for energy consumption in commercial buildings (Kontokosta 2015) and indirect resource flows that occur outside city boundaries (Ramaswami *et al* 2012) can further influence the derived scaling relationships. This issue is particularly important for sectors involving cross-boundary flows, such as electricity and air pollutants, where production and consumption can be spatially decoupled. Such decoupling provides a plausible explanation for the contrasting scaling patterns identified in this study: while energy consumption reflects demand concentrated within cities, emissions (especially CO_2) may be displaced outside city boundaries through regional energy production, industrial relocation, or supply-chain dynamics. As a result, emissions associated with urban consumption may not scale proportionally with population within administrative city boundaries, contributing to the sublinear behavior observed for many pollutants. In such cases, scaling relationships may reflect differences in accounting conventions (e.g., production-based vs. consumption-based) as much as underlying urban processes. In addition, spatial heterogeneity within cities is often overlooked: studies using finer-resolution spatial data show that intra-urban scaling relationships may differ from city-level aggregates (Li *et al* 2017, Huang and Lu 2025), highlighting the need to consider both boundary definitions and internal spatial structure in scaling analyses.

Another key uncertainty/knowledge gap is the temporal stability and generalizability of the urban scaling law. A key distinction is whether scaling relationships are derived from cross-sectional comparisons across cities or from longitudinal analyses within cities over time, as these approaches may yield different interpretations of scaling behavior (Molinero and Thurner 2021, Keuschnigg 2019). There have been very few comprehensive studies of whether scaling exponents remain constant over time (Burghardt *et al* 2024, Balta-Ozkan *et al* 2015, Liu *et al* 2022, Zhao *et al* 2018, Rybski *et al* 2017), despite early formulations of urban scaling often being interpreted as implying universality (Bettencourt 2013, Bettencourt *et al* 2020, West 2017). Temporal variations in scaling exponents may arise from heterogeneous growth rates across cities of different sizes, which can systematically shift aggregate scaling relationships over time (Li *et al* 2021a). Though, some studies do suggest that scaling exponents remain stable over time (Lei *et al* 2022, Zünd and Bettencourt 2019, Bettencourt *et al* 2010, Zhao *et al* 2018). However, these studies typically cover short time spans and have small samples of cities and/or small sets of urban attributes (Liu and Zou 2020, Zhao *et al* 2018, Lei *et al* 2022, Zünd and Bettencourt 2019, Pumain 2025). This raises the question of whether observed scaling exponents represent intrinsic, stable properties of urban systems or instead reflect context-dependent outcomes that evolve over time.

The generalization of existing studies is further limited by both spatial and sectoral biases. While disentangling the specific mechanisms underlying these differences is beyond what can be inferred from a synthesis of reported scaling exponents, prior studies suggest that factors such as environmental policy, infrastructure systems, and economic structure can significantly influence observed scaling relationships (e.g., Muller and Jha 2017). For example, while most urban CO_2 scaling studies originate from the U.S. (figure 3), there are surprisingly few analyses of other urban energy consumption and pollutant emissions variables for U.S. cities. This gap is notable given the country's combination of high population, low urban density, and heavy dependence on private vehicles, all of which likely influence the scaling of energy use and emissions in distinct ways. This gap largely reflects the limited public availability of consistent city-level energy and non-CO_2 emission data. Part of this data unavailability can be attributed to fragmented data governance, as local/regional utility companies and independent authorities often restrict access to energy and emissions data (Gocke 2023, Cao 2024, Kontokosta 2015). Particularly in the U.S., the decentralized role of utility providers further contributes to reliance on alternative data sources such as the Vulcan Project (Fragkias et al. 2013) and satellite observations (Lamsal et al. 2013), and coarse-resolution governmental datasets such as the Environmental Protection Agency's National Emissions Inventory (Muller and Jha 2017). In addition to data sources, the use of population as the primary scaling variable in existing studies may obscure the influence of urban density, spatial structure, and land-use patterns, which are known to shape energy use and emissions but are not explicitly represented in standard scaling formulations (Ribeiro and Rybski 2023). As a result, widely reported scaling relationships may reflect aggregate effects of population size without fully capturing the underlying heterogeneity, and may not generalize consistently across different socioeconomic and infrastructural contexts.

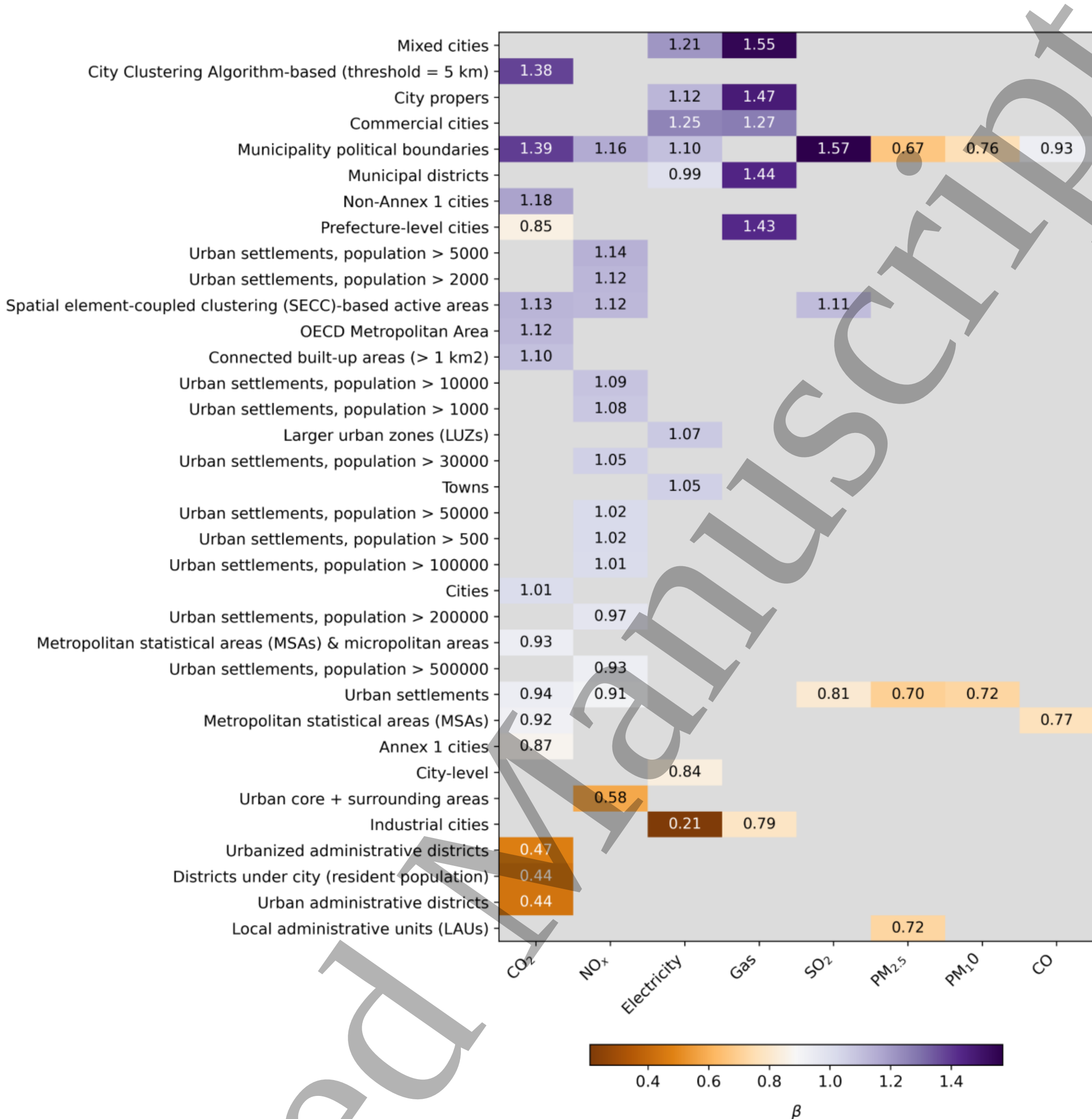

Figure 5. Heat map illustrating how different city definitions influence the calculated urban scaling exponents (β) for total emission/consumption. The color scale is centered over $\beta = 1$, representing linear scaling. Darker shades indicate $\beta > 1$ (superlinear scaling), whereas lighter shades indicate $\beta < 1$ (sublinear scaling). Each filled cell shows a representative β value with the corresponding city definition. When multiple years are reported, only the most recent or aggregated value is used. When both global and regional values are available, only global values are shown. When the same attribute is reported across multiple regions, a single representative value is selected.

All these challenges are closely linked to underlying data limitations. Addressing them will require the development of integrated, gap-free, and long-term datasets suitable for large-scale and temporally resolved urban scaling analyses (e.g., Wang *et al* 2024, Cao 2024, Xu *et al* 2024). Existing datasets often suffer from inconsistent boundary definitions, incomplete sectoral coverage, and temporal gaps due to irregular reporting or changes in administrative delineations. These inconsistencies are especially evident in energy use and emissions, where data are frequently aggregated at coarse regional levels, which can limit their usefulness for city-level scaling analyses. In addition, the inherent lag in many urban energy and emissions datasets further constrain the ability to evaluate how scaling relationships evolve under changing urban conditions, especially for countries undergoing rapid urbanization. At the same time, heterogeneity and incomplete reporting of statistical information across included studies (e.g., missing uncertainties, inconsistent definitions, and varying estimation methods) also limit the application of formal meta-analysis techniques, such as effect-size weighting or publication bias testing. It is noteworthy that scaling analysis represents only one of several approaches used to examine urban energy use and emissions. Alternative frameworks, including bottom-up inventories, process-based modeling, and high-resolution observational or remote sensing approaches, can provide more mechanistic and spatially explicit insights into urban systems. While model-based reconstructions and downscaling methods can help fill these gaps, they may introduce additional structural uncertainty and may not fully capture local urban dynamics. A promising pathway to improve scaling analyses is to ground them in observationally constrained simulations that integrate models, measurements, and administrative data, leveraging the complementary strengths of these approaches. The integration of such datasets with harmonized definitions of urban boundaries would enable consistent cross-country comparisons and time-series analyses of the urban scaling law.

These limitations also raise a broader question about the intended role of urban scaling analyses in advancing understanding of urban systems. Despite extensive empirical evidence documenting scaling relationships across a wide range of urban indicators, the interpretation and application of these relationships remain varied. This emerges as a central challenge emerging from the present synthesis. In the literature, scaling relationships have been used both as descriptive summaries of cross-city variation and as a framework for generating hypothesis-informed interpretations about underlying mechanisms, but rarely as rigorously tested mechanistic or predictive frameworks. For example, sublinear scaling of infrastructure-related quantities is often interpreted as a consequence of economies of scale in spatially embedded networks, whereas superlinear scaling of socioeconomic indicators is linked to increased interaction rates, knowledge exchange, and information flow in larger urban populations (West 2017, Ribeiro and Rybski 2023). In practice, most studies of urban energy use and emissions, including many included in this synthesis, primarily report cross-sectional scaling exponents. As a result, mechanistic explanations are often invoked, and observed exponents are often interpreted as signatures of efficiency or intensification, even though similar scaling behavior may arise from multiple underlying processes and may be sensitive to city definitions, data construction, and study design. This disconnection limits mechanistic interpretation and partially explains why reported exponents vary across regions and sectors. Future work would benefit from integrating scaling analyses with process-based representations of urban systems, including infrastructure networks, urban form, governance, and energy-system structure, so that scaling exponents can be interpreted not only as empirical summaries but also as tests of hypotheses. Such a shift would be essential if urban scaling is to move from a descriptive framework toward a predictive and explanatory science of cities.

5. Conclusion

This meta-analysis synthesizes evidence on how urban energy use and pollutant emissions scale with population across cities. By compiling 362 scaling exponents from 27 studies, we show that energy-related quantities such as electricity, gas, and transportation fuel predominantly exhibit superlinear scaling. This result implies that energy demand tends to increase faster than population growth. In contrast, most air pollutants scale sublinearly, which suggests per-capita emission efficiencies tend to improve with city size. A notable exception is superlinear scaling of CO_2 emissions in U.S. cities, which contrasts with the sublinear scaling of CO_2 emissions in Chinese cities and global-scale studies. Such discrepancies are likely a result of differences in energy structure, technology, and policy interventions. More broadly, the contrasting scaling behavior between energy consumption and pollutant emissions may also reflect the spatial decoupling of production and consumption, whereby emissions associated with urban energy demand are often generated outside city boundaries, weakening the direct linkage between population size and locally accounted emissions.

Despite growing use of the urban scaling framework, this synthesis reveals several important limitations in the current literature. The existing literature synthesized here is geographically uneven, with a strong concentration of studies from China and the U.S. and much more limited coverage of rapidly urbanizing regions such as Africa and Latin America. This imbalance reflects the availability of existing studies. Variations in city definitions and data completeness also continue to produce inconsistent scaling exponents and limit cross-regional and country comparability. In addition, the scarcity of long-term, high-resolution datasets and a lack of temporal analyses limit our understanding of how scaling relationships evolve over time across cities. More fundamentally, the literature remains largely descriptive: many studies report scaling exponents without explicitly examining the mechanisms that give rise to these relationships or testing theoretical predictions. As a result, similar scaling behavior may be interpreted as evidence of efficiency or intensification, even though it may result from various underlying processes and can be sensitive to data construction and study design.

These limitations have important implications for applications of scaling in practice. Urban planners and decision-makers should interpret scaling relationships with caution, recognizing that inferred trends may depend strongly on data sources, methodological choices, and city definitions. Addressing these challenges will require more geographically diverse, standardized, integrated, and temporally resolved urban energy and emission datasets across sectors, countries, and continents. Expanding urban scaling studies in underrepresented regions will be particularly important for building a more complete empirical basis for comparison. Moreover, improving interpretability requires linking observed scaling relationships to underlying physical, socioeconomic, and infrastructural mechanisms, as well as developing theoretical frameworks that can generate testable predictions. Such efforts would enable more reliable scaling analyses, advance understanding of the dynamics of urban metabolism, and better inform the design of sustainable, low-carbon cities in a rapidly urbanizing world.

Data availability statement

All data that support the findings of this study are included within the article and its supplementary file.

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References

Ascione F, Bianco N, Mauro G M and Napolitano D F 2021 Knowledge and energy retrofitting of neighborhoods and districts. A comprehensive approach coupling geographical information systems, building simulations and optimization engines *Energy Convers. Manag.* **230** 113786

Bahers J-B, Barles S and Durand M 2019 Urban metabolism of intermediate cities: The material flow analysis, hinterlands and the logistics-hub function of Rennes and Le Mans (France) *J. Ind. Ecol.* **23** 686–98

Balta-Ozkan N, Watson T and Mocca E 2015 Spatially uneven development and low carbon transitions: Insights from urban and regional planning *Energy Policy* **85** 500–10

Batty M 2008 The size, scale, and shape of cities *Science* **319** 769–71

Bettencourt L M A 2013 The origins of scaling in cities *Science* **340** 1438–41

Bettencourt L M A and Lobo J 2016 Urban scaling in Europe *J. R. Soc. Interface* **13** 20160005

Bettencourt L M A, Lobo J, Helbing D, Kühnert C and West G B 2007 Growth, innovation, scaling, and the pace of life in cities *Proc. Natl. Acad. Sci. U S A* **104** 7301–6

Bettencourt L M A, Lobo J, Strumsky D and West G B 2010 Urban scaling and its deviations: Revealing the structure of wealth, innovation and crime across cities *PLoS ONE* **5** e13541

Bettencourt L M A, Yang V C, Lobo J, Kempes C P, Rybski D and Hamilton M J 2020 The interpretation of urban scaling analysis in time *J. R. Soc. Interface* **17** 20190846

Bettencourt L M and West G B 2011 Bigger cities do more with less. *Sci. Am.* **305** 52–3

Bettencourt L and West G 2010 A unified theory of urban living *Nature* **467** 912–3

Brelsford C, Coon E T, Moran V E and Allen-Dumas M 2020 Urban scaling as validation for predictions of imperviousness from population *Geophys. Res. Lett.* **47** e2020GL089742

Bristow D and Kennedy C 2015 Why do cities grow? Insights from Nonequilibrium thermodynamics at the urban and global scales *J. Ind. Ecol.* **19** 211–21

Burghardt K, Uhl J H, Lerman K and Leyk S 2024 Analyzing urban scaling laws in the United States over 115 years *Environ. Plan. B* **51** 2249–63

Cao C 2024 Integration of ten years of daily weather, traffic, and air pollution data from Norway's six largest cities *Sci. Data* **11** 744

Carozzi F and Roth S 2023 Dirty density: Air quality and the density of American cities *J. Environ. Econ. Manag.* **118** 102767

Castells-Quintana D, Dienesch E and Krause M 2021 Air pollution in an urban world: A global view on density, cities and emissions *Ecol. Econ.* **189** 107153

Chang Y S, Lee Y J and Choi S S B 2017 Is there more traffic congestion in larger cities? Scaling analysis of the 101 largest U.S. urban centers *Transp. Policy* **59** 54–63

Chen C, Zhang X and Webster C 2025 Scaling of urban environmental performance in Chinese cities *Environ. Plan. B* 23998083251324765

Conticelli E, Falcioni S, Marzani G, Morini G L and Tondelli S 2024 Assessing energy efficiency at urban scale through the use of energy performance certificates: An application in the Emilia-Romagna region, Italy *Cities* **145** 104728

Cottineau C, Hatna E, Arcaute E and Batty M 2017 Diverse cities or the systematic paradox of urban scaling laws *Comput. Environ. Urban Syst.* **63** 80–94

Creutzig F, Baiocchi G, Bierkandt R, Pichler P-P and Seto K C 2015 Global typology of urban energy use and potentials for an urbanization mitigation wedge *Proc. Natl. Acad. Sci. U S A* **112** 6283–8

Cui C, Cai B, Bin G and Wang Z 2020 Decennary spatial pattern changes and scaling effects of CO_2 emissions of urban agglomerations in China *Cities* **105** 102818

Dalgaard C-J and Strulik H 2011 Energy distribution and economic growth *Resour. Energy Econ.* **33** 782–97

Decker E H, Kerkhoff A J and Moses M E 2007 Global patterns of city size distributions and their fundamental drivers *PLoS ONE* **2** e934

Elliott R J R, Sun P and Xu Q 2015 Energy distribution and economic growth: An empirical test for China *Energy Econ.* **48** 24–31

Facchini A, Kennedy C, Stewart I and Mele R 2017 The energy metabolism of megacities *Appl. Energy* **186** 86–95

Fragkias M, Lobo J, Strumsky D and Seto K C 2013 Does size matter? Scaling of CO_2 emissions and U.S. urban areas *PLoS ONE* **8** e64727

Gocke A 2023 Public utility's potential *Yale LJ* **133** 2773

Gudipudi R, Fluschnik T, Ros A G C, Walther C and Kropp J P 2016 City density and CO_2 efficiency *Energy Policy* **91** 352–61

Gudipudi R, Rybski D, Lüdeke M K B, Zhou B, Liu Z and Kropp J P 2019a The efficient, the intensive, and the productive: Insights from urban Kaya scaling *Appl. Energy* **236** 155–62

Gudipudi R, Rybski D, Lüdeke M K and Kropp J P 2019b Urban emission scaling — Research insights and a way forward *Environ. Plan. B* **46** 1678–83

Güneralp B, Zhou Y, Ürge-Vorsatz D, Gupta M, Yu S, Patel P L, Fragkias M, Li X and Seto K C 2017 Global scenarios of urban density and its impacts on building energy use through 2050 *Proc. Natl. Acad. Sci. U S A* **114** 8945–50

Horta-Bernús R and Rosas-Casals M 2015 Obsolescence in urban energy infrastructures: The influence of scaling laws on consumption forecasting *J. Urban Technol.* **22** 3–17

Hou M, Cui X, Chu L, Wang H, Xi Z and Deng Y 2024 Nonlinear effects of environmental regulation on $PM_{2.5}$ and CO_2 in China: Evidence from a quantile-on-quantile approach *Energy* **292** 130456

Huang K and Lu M 2025 Nested economies of scale in global city mass *ArXiv Prepr. ArXiv250703960*

Jung M C, Wang T, Kang M, Dyson K, Dawwas E B and Alberti M 2024 Urban landscape affects scaling of transportation carbon emissions across geographic scales *Sustain. Cities Soc.* **113** 105656

Keleş A E, Önen ,Ecem and and Górecki J 2022 Make saving crucial again: building energy efficiency awareness of people living in urban areas *Adv. Build. Energy Res.* **16** 371–84

Kennedy C A, Stewart I, Facchini A, Cersosimo I, Mele R, Chen B, Uda M, Kansal A, Chiu A, Kim K, Dubeux C, Lebre La Rovere E, Cunha B, Pincetl S, Keirstead J, Barles S, Pusaka S, Gunawan J, Adegbile M, Nazariha M, Hoque S, Marcotullio P J, González Otharán F, Genena T, Ibrahim N, Farooqui R, Cervantes G and Sahin A D 2015 Energy and material flows of megacities *Proc. Natl. Acad. Sci. U S A* **112** 5985–90

Kennedy C, Cuddihy J and Engel-Yan J 2007 The changing metabolism of cities *J. Ind. Ecol.* **11** 43–59

Kennedy C, Pincetl S and Bunje P 2011 The study of urban metabolism and its applications to urban planning and design *Environ. Pollut.* **159** 1965–73

Keuschnigg M 2019 Scaling trajectories of cities *Proc. Natl. Acad. Sci. U S A* **116** 13759–61

Kontokosta C E 2015 A market-specific methodology for a commercial building energy performance index *J. Real Estate Finance Econ.* **51** 288–316

Kontokosta C E and Jain R K 2015 Modeling the determinants of large-scale building water use: Implications for data-driven urban sustainability policy *Sustain. Cities Soc.* **18** 44–55

Kumar S and Sen R 2025 Are larger or denser cities more emission efficient? Exploring the nexus between urban household carbon emission, population size and density *Appl. Energy* **377** 124500

La Porta C A M and Zapperi S 2024 Urban scaling functions: Emission, pollution and health *J. Urban Health* **101** 752–63

Lamsal L N, Martin R V, Parrish D D and Krotkov N A 2013 Scaling relationship for NO_2 pollution and urban population size: a satellite perspective *Environ. Sci. Technol.* **47** 7855–61

Larson W and Yezer A 2015 The energy implications of city size and density *J. Urban Econ.* **90** 35–49

Leffel J, Wang C, Hu X M, Feron S, Henry S 2025 Cities as hotspots of compound heat and fine particulate matter pollution: A 23-year urban–rural comparison across the United States. *Environ. Res.* **285** 122508

Lei W, Jiao L, Xu G and Zhou Z 2022 Urban scaling in rapidly urbanising China *Urban Stud.* **59** 1889–908

Lengyel B, Bokányi E, Di Clemente R, Kertész J and González M C 2020 The role of geography in the complex diffusion of innovations *Sci. Rep.* **10** 15065

Li G, Fang C and He S 2020 The influence of environmental efficiency on $PM_{2.5}$ pollution: Evidence from 283 Chinese prefecture-level cities *Sci. Total Environ.* **748** 141549

Li J, Wang P and Ma S 2024 The impact of different transportation infrastructures on urban carbon emissions: Evidence from China *Energy* **295** 131041

Li R, Dong L, Zhang J, Wang X, Wang W X, Di Z and Stanley H E 2017 Simple spatial scaling rules behind complex cities *Nat. Commun.* **8** 1841

Li R, Lu L, Cui T, Gu W, Ma S, Xu G and Stanley H E 2021a Assessing the attraction of cities on venture capital from a scaling law perspective *IEEE Access* **9** 48052–63

Li Y, Shen J, Xia C, Xiang M, Cao Y and Yang J 2021b The impact of urban scale on carbon metabolism -- a case study of Hangzhou, China *J. Clean. Prod.* **292** 126055

Liang S, Zhang J, Cai B, Wang K, Zhang S and Li Y 2024 How to perceive and map the synergy between CO_2 and air pollutants: Observation, measurement, and validation from a case study of China *J. Environ. Manage.* **351** 119825

Liu G and Wu M 2024 Thermodynamic-based ecological scaling theory in urban metabolic framework: a review *Front. Environ. Sci. Eng.* **19** 4

Liu N, Zhang Y and Fath B D 2021 The material metabolism characteristics and growth patterns of the central cities of China's Beijing-Tianjin-Hebei region *Ecol. Model.* **448** 109532

Liu X and Zou Z 2020 Analysis on urban scaling characteristics of China's relatively developed cities *PLoS ONE* **15** e0236593

Liu Z, Liu H, Lang W, Fang S, Chu C and He F 2022 Scaling law reveals unbalanced urban development in China *Sustain. Cities Soc.* **87** 104157

Louf R and Barthelemy M 2014a How congestion shapes cities: from mobility patterns to scaling *Sci. Rep.* **4** 5561

Louf R and Barthelemy M 2014b Scaling: Lost in the smog *Environ. Plan. B Plan. Des.* **41** 767–9

Lu M, Zhou C, Wang C, Jackson R B and Kempes C P 2024 Worldwide scaling of waste generation in urban systems *Nat. Cities* **1** 126–35

MacKenzie A R, Whyatt J D, Barnes M J, Davies G and Hewitt C N 2019 Urban form strongly mediates the allometric scaling of airshed pollution concentrations *Environ. Res. Lett.* **14** 124078

Mohajeri N, Gudmundsson A and French J R 2015 CO_2 emissions in relation to street-network configuration and city size *Transp. Res. Part Transp. Environ.* **35** 116–29

Molinero C and Thurner S 2021 How the geometry of cities determines urban scaling laws *J. R. Soc. Interface* **18** 20200705 Online: https://doi.org/10.1098/rsif.2020.0705

Muller N Z 2016 Power Laws and air pollution *Environ. Model. Assess.* **21** 31–52

Muller N Z and Jha A 2017 Does environmental policy affect scaling laws between population and pollution? Evidence from American metropolitan areas *PLoS ONE* **12** e0181407

Nlend B, Reimuth A, Yang L E, Jampani M, Cristiano E, Dewals B, Boyer E, Daloglu Cetinkaya I, Diémé L P, Dutta R, Feng W, Grossi G, Nasr W B, Obaitor O S, Ololade A O, Panchanathann A, Rab G, Sharma S, Wang C, Warter M M, Welty C and Tetzlaff D 2025 Building resilient urban water systems: emerging opportunities for solving long-lasting challenges. *Hydrol. Sci. J.* **70** 2003–15

Oliveira E A, Andrade J S and Makse H A 2014 Large cities are less green *Sci. Rep.* **4** 4235

Pu J and Xia F 2025 Exploring the relationship between city size and carbon emissions: An integrated population-land framework *Appl. Geogr.* **177** 103571

Pumain D 2025 How scaling laws challenge the geographical theories of urban systems *Netw. Spat. Econ.* **25** 887–906

Ramaswami A, Jiang D, Tong K and Zhao J 2018 Impact of the economic structure of cities on urban scaling factors: Implications for urban material and energy flows in China *J. Ind. Ecol.* **22** 392–405

Ramaswami A, Weible C, Main D, Heikkila T, Siddiki S, Duvall A, Pattison A and Bernard M 2012 A Social-Ecological-Infrastructural Systems Framework for Interdisciplinary Study of Sustainable City Systems *J. Ind. Ecol.* **16** 801–13

Rao Y, Zhong Y and He Q 2023 Evaluation of carbon emission efficiency based on urban scaling law: take 308 cities in China as an example *Environ. Sci. Pollut. Res.* **30** 105166–80

Riahi K, van Vuuren D P, Kriegler E, Edmonds J, O'Neill B C, Fujimori S, Bauer N, Calvin K, Dellink R, Fricko O, Lutz W, Popp A, Cuaresma J C, Kc S, Leimbach M, Jiang L, Kram T, Rao S, Emmerling J, Ebi K, Hasegawa T, Havlik P, Humpenöder F, Da Silva L A, Smith S, Stehfest E, Bosetti V, Eom J, Gernaat D, Masui T, Rogelj J, Strefler J, Drouet L, Krey V, Luderer G, Harmsen M, Takahashi K, Baumstark L, Doelman J C, Kainuma M, Klimont Z, Marangoni G, Lotze-Campen H, Obersteiner M, Tabeau A and Tavoni M 2017 The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview *Glob. Environ. Change* **42** 153–68

Ribeiro F L and Rybski D 2023 Mathematical models to explain the origin of urban scaling laws *Phys. Rep.* **1012** 1–39

Ribeiro H V, Rybski D and Kropp J P 2019 Effects of changing population or density on urban carbon dioxide emissions *Nat. Commun.* **10** 3204

Ríos-Ocampo J P and Gary M S 2025 Urban growth strategy in Greater Sydney leads to unintended social and environmental challenges *Nat. Cities* **2** 223–33

Rybski D, Reusser D E, Winz A-L, Fichtner C, Sterzel T and Kropp J P 2017 Cities as nuclei of sustainability? *Environ. Plan. B* **44** 425–40

Shen J, Yi P, Zhang X, Yang Y, Fang J and Chi Y 2023 Can water conservation and energy conservation be promoted simultaneously in China? *Energy* **278** 127893

Sugar L and Kennedy C 2020 Thermodynamics of urban growth revealed by city scaling *Phys. Stat. Mech. Its Appl.* **557** 124971

Sugar L and Kennedy C 2021 Urban scaling and the benefits of living in cities *Sustain. Cities Soc.* **66** 102617

Wang C, Deng C, Horsey H, Reyna J L, Liu D, Feron S, Cordero R R, Song J and Jackson R B 2024 CHUWD-H v1.0: a comprehensive historical hourly weather database for U.S. urban energy system modeling *Sci. Data* **11** 1383

Wang C, Song J, Shi D, Reyna J L, Horsey H, Feron S, Zhou Y, Ouyang Z, Li Y and Jackson R B 2023 Impacts of climate change, population growth, and power sector decarbonization on urban building energy use. *Nat. Commun.* **14** 6434

Wang C and Wang Z-H 2017 Projecting population growth as a dynamic measure of regional urban warming *Sustain. Cities Soc.* **32** 357–65

Wang Y and Komonpipat S 2020 Revisiting the environmental Kuznets curve of PM2.5 concentration: evidence from prefecture-level and above cities of China *Environ. Sci. Pollut. Res.* **27** 9336–48

West G 2017 *Scale: The Universal Laws of Life, Growth, and Death in Organisms, Cities, and Companies* (East Rutherford: Penguin Publishing Group)

Xu X, Zheng Z, Hu Z, Feng K and Ma W 2024 A unified dataset for the city-scale traffic assignment model in 20 U.S. cities *Sci. Data* **11** 325

Yang Z, Wu J, Shang X, Fu R, Xie L and Ge Q 2025 Scaling laws of CO_2 emissions during global urban expansion *npj Urban Sustain.* **5** 3

Yatzkan O, Omer I and Burg D 2024 Urban scaling of air pollutants in Israel *Environ. Dev. Sustain.* **28** 9225–46

Yu P, Wei Y, Ma L, Wang B, Yung E H K and Chen Y 2024 Urbanization and the urban critical zone *Earth Crit. Zone* **1** 100011

Zhao S, Liu S, Xu C, Yuan W, Sun Y, Yan W, Zhao M, Henebry G M and Fang J 2018 Contemporary evolution and scaling of 32 major cities in China *Ecol. Appl.* **28** 1655–68

Zhou C, Gong M, Xu Z and Qu S 2022 Urban scaling patterns for sustainable development goals related to water, energy, infrastructure, and society in China *Resour. Conserv. Recycl.* **185** 106443

Zünd D and Bettencourt L M 2019 Growth and development in prefecture-level cities in China *PLoS ONE* **14** e0221017