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Review

A comparative overview of city-level carbon accounting: Key processes and considerations

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Abstract: As global climate change intensifies, city-level carbon accounting has become increasingly important, as cities are significant sources of carbon emissions. This paper provides an overview of key steps and considerations in city-level carbon accounting methods, with a particular focus on the bottom-up approach that involves defining accounting boundaries, selecting accounting perspectives, identifying emission sources, collecting data, determining calculation methods, and performing calculations and uncertainty analyses. Additionally, the paper introduces the top-down method that uses macro-level data to estimate carbon emissions at the city level and briefly discusses emerging methods for city-level carbon accounting. The strengths and limitations of these approaches are examined. The paper also provides an overview of different databases used for carbon accounting and evaluates their appropriateness for estimating carbon emissions at the city level. It also analyzes key research topics in the literature related to urban carbon accounting. Common challenges in city-level carbon accounting are discussed, along with recommendations for future research in this field.

Keywords: carbon emission; accounting; city; urban; databases

1. Introduction

Governments and international organizations face the urgent challenge of addressing greenhouse gas (GHG) emissions amid global warming and climate change. Carbon accounting has emerged as a crucial tool in monitoring and reducing emissions, enabling accurate quantification that supports effective management and mitigation efforts.

Carbon accounting operates at various levels, including product, organizational, and spatial levels.

Product-level accounting focuses on carbon footprints, while organizational-level accounting addresses both direct and indirect GHG emissions from companies and organizations, aiming to create publicly accessible carbon data platforms. At the spatial level, the Intergovernmental Panel on Climate Change (IPCC) provides guidelines, defining three scopes for accounting and outlining five sectors: energy, industry, agriculture, land-use change, and waste disposal [1]. It also provides detailed calculation methods and emission factors to ensure consistency in reporting.

While much research has focused on national and regional carbon accounting, relatively few studies have specifically addressed carbon accounting at the city-wide level. Cities, as hubs of economic, social, and environmental activity, play a critical role in global carbon emissions. They are home to over half of the world's population, generate the majority of global GDP, and consume vast amounts of resources, all of which contribute significantly to GHG emissions. This makes them a focal point for both mitigation and adaptation strategies, as well as a critical space for implementing effective climate policies.

The original IPCC's accounting methodology is less suitable for cities due to its scale-related limitations. A key challenge in adapting the IPCC accounting methodology to urban contexts lies in its original design for broader spatial scales, such as national or regional evaluations. At these levels, GHG emissions are typically estimated using high-level categories, such as national energy consumption, sectoral industrial outputs, or land-use changes in agriculture. The IPCC guidelines often rely on national statistics and generalized emission factors, which facilitate the aggregation of emissions data across sectors and regions [1]. However, applying the IPCC framework to cities presents limitations due to the omission of local-scale variability. Urban environments exhibit distinct characteristics, such as heterogeneous transportation patterns, localized energy portfolios, and diverse waste management practices, which can significantly influence emission profiles. These localized factors are not adequately captured by methodologies designed for national reporting, leading to potential inaccuracies in urban emission inventories.

Furthermore, cities are characterized by complex, multi-sectoral systems with a wide range of emission sources, including transportation, buildings, waste management, and industrial operations. The intensity of emissions by these sectors can vary substantially between cities [2], depending on factors such as infrastructure, energy sources, and policy frameworks. For instance, a city with extensive public transit and renewable energy integration may exhibit significantly lower per capita emissions than one reliant on private vehicles and fossil fuel-based power. The IPCC's generalized approach does not fully account for this intra-urban heterogeneity. Nevertheless, the IPCC guidelines can serve as a methodological foundation for emissions accounting and may be supplemented with city-specific protocols to improve accuracy.

To address the gap between national methodologies and city-scale needs, local governments, such as those in China, have refined carbon accounting methodologies based on the IPCC's guidelines. China's National Development and Reform Commission (NDRC) developed provincial GHG Inventory Guidelines in 2007 and later introduced city-level guidelines in 2010. In 2013, the World Resources Institute (WRI) released the Guidelines for Urban Greenhouse Gas Accounting Tools, incorporating sectors like residential, commercial, and industrial to improve inter-city carbon trading. In 2014, ICLEI, WRI, and C40 Cities Climate Leadership Group developed the Global Protocol for Community-Scale Greenhouse Gas Emission Inventories (GPC), a simplified framework that allows local governments to adapt methods based on available data, fostering a globally comparable approach to urban carbon emissions [3]. City-level carbon accounting has become an increasingly vital tool for local governments aiming to understand and reduce their carbon footprint while promoting sustainability.

In recent years, scholars have explored city-level carbon accounting. Some have integrated carbon stocks, emissions, and flows into an integrated system for comparative analysis [4], while others have developed urban-specific frameworks addressing sectors like logistics, buildings, and water supply [5–7], allowing for more granular and sector-specific carbon analysis within urban environments. Several reviews of urban carbon accounting have been published. Yin et al. [8] and Zhang et al. [9] provided insights into the evolution and future trends of urban carbon accounting. Xu and Wang [10] explored the classification and basic framework of urban carbon accounting in China. However, these reviews have not specifically elaborated on the overall workflow involved in city-level carbon accounting. To bridge this gap, this study provides an overview of key steps and considerations involved in the commonly used city-level carbon accounting methods, especially the bottom-up method, which allows for a more fine-grained and accurate estimation of city-level carbon emissions. This study also identifies typical challenges faced and future research directions.

2. Urban carbon emissions in general vs. city-level carbon accounting

While extensive research has been conducted on carbon emissions in the context of cities [11,12], relatively few studies have specifically focused on carbon accounting at the city-wide scale. As part of our literature review, we intentionally employed two search criteria, as shown in Figure 1, to identify relevant literature from the Core Collection of the Web of Science (WoS) database using the Advanced Search Query Builder. One criterion focused on studies related to urban carbon emissions in general, using the following query criterion: (TI = (carbon accounting) OR TI = (carbon emission) OR TI = (CO_2 accounting) OR TI = (CO_2 emission) OR TI = (GHG accounting) OR TI = (GHG emission) OR TI = (GHG inventory)) AND (TS = (city-level)) AND (TI = (city) OR TI = (urban)). Over the period from 2011 to 2024, more than 700 articles have explored carbon emissions in urban areas. China is identified as the largest contributor to these publications, followed by the United States, the United Kingdom, Japan, and other countries. While this initial search yielded an excessive number of articles on carbon emissions in the city context, many did not directly address city-level carbon emission accounting.

The other literature search specifically targeted city-level carbon accounting using the following query criterion: (TI = (carbon accounting) OR TI = (CO_2 accounting) OR TI = (GHG accounting) OR TI = (carbon inventory) OR TI = (CO_2 inventory) OR TI = (GHG inventory)) AND (TI = (city) OR TI = (urban)). This led to 69 articles, which were then screened based on their bibliographic data and abstracts. As a result, only 38 articles were deemed to have explicitly addressed the carbon accounting of entire cities. In our review, the city-level carbon accounting methods discussed are primarily drawn from these selected articles, with additional relevant literature referenced where appropriate.

In terms of carbon emission–related studies in the city context, the literature co-citation network graph (shown in Figure 2) from CiteSpace suggests a broad spectrum of topics. These topics include, but are not limited to, economic development, urban form, energy, transportation, policy, epidemics' impact, and region-specific studies. Existing research primarily covers topics such as emission sources across different cities, the relationship between carbon emissions and economic development, policy impacts, and energy consumption models. These studies provide valuable data on the components and influencing factors of urban carbon emissions. However, city-level carbon accounting goes beyond analyzing individual emission sources and requires integrating various types of emissions within the broader context of the entire city. Developing an accounting model that covers all emission sources and accounts for sectoral interrelationships adds another layer of complexity. This type of research demands expertise from multiple fields, such as environmental science, economics, and urban planning, and relies heavily on large amounts of local data, some of which may be real-time data. As such, while research on urban carbon emissions is abundant, cross-disciplinary and systematic studies capable of achieving comprehensive accounting are still in the early stages.

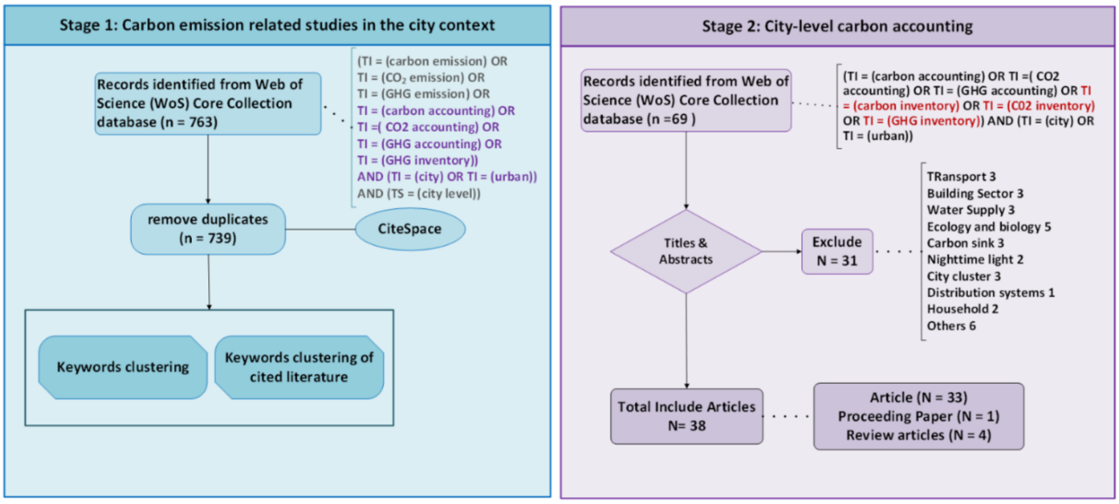

Figure 1. Literature search criteria.

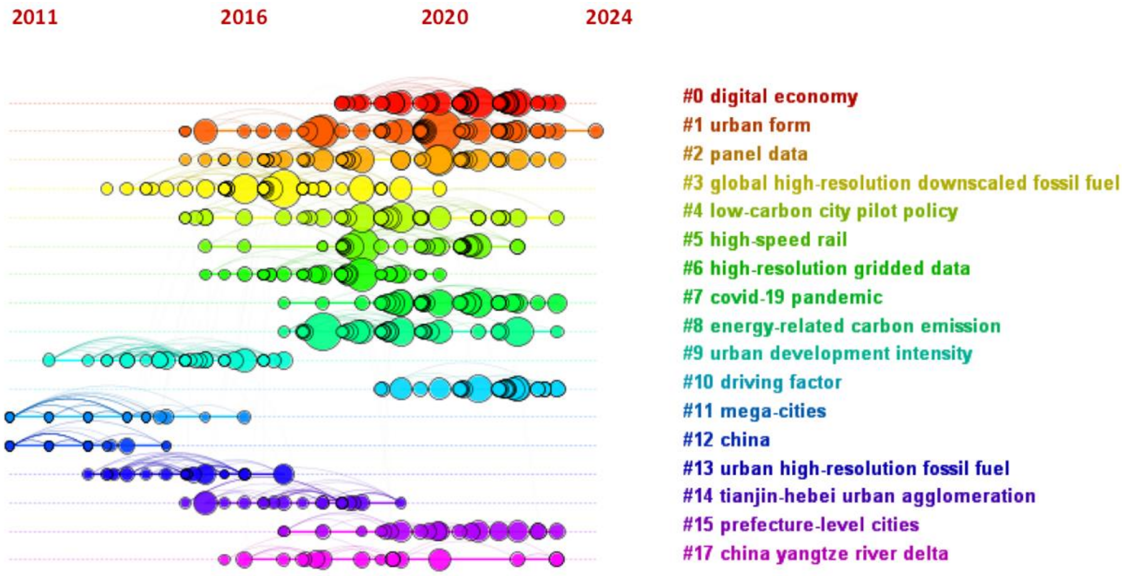

Figure 2. Literature co-citation network of carbon emission studies in the urban context.

The keyword "high-resolution" in terms "high-resolution gridded data", "global high-resolution downscaled fossil fuel", and "urban high-resolution fossil fuel", identified in the co-citation network graph of Figure 2, indicates that research is increasingly using detailed, high-resolution data to more accurately estimate urban carbon emissions. This aids in identifying and quantifying emission disparities across different cities. Given the growing availability of high-resolution, high-quality data from modern technologies (such as remote sensing, the internet of things, and advanced data recording practices), this trend is expected to continue in future studies.

3. International protocols for city-level carbon accounting

Numerous international protocols and guidelines have been developed to systematically assess and report GHG emissions at the city level. One widely used protocol is the IPCC Guidelines [1], which provides a globally accepted framework for emission accounting, categorizing emissions into five sectors: Energy activities, industrial processes, agriculture, forestry and land use, and waste disposal. This multilevel framework, ranging from Tier 1 (basic) to Tier 3 (detailed), allows for both rough estimations and detailed analyses, with the Fifth Assessment Report incorporating a dedicated chapter on urban emissions. Building on the IPCC framework, the International Standard for Determining Greenhouse Gas Emissions for Cities (ISDGC) [13] refines the accounting of energy activities, industrial processes, agriculture, and waste disposal, organizing emissions into Scope 1 (direct), Scope 2 (indirect from purchased energy), and Scope 3 (other indirect emissions). ISDGC also includes supplementary estimates for emissions from goods and materials purchased outside a city when specific data are unavailable.

Another widely used protocol is the GPC [14], which provides a comprehensive approach for accounting energy emissions, transport activities, and land use, categorized by source (e.g., stationary sources, transport, waste disposal). It emphasizes disaggregating emissions by gas type and industry before aggregating totals, offering detailed guidance across five primary sectors. Built on GPC, specialized methodologies such as the Direct Plus Supply Chain (DPSC) methodology extend the GPC framework by covering a broader range of indirect GHG emissions, capturing territorial GHG emissions as well as those linked to the largest supply chains supporting cities [15].

An increasing number of studies now use the IPCC and GPC guidelines, often in combination, reflecting the growing global demand for standardized frameworks. While the IPCC serves as the methodological foundation, the GPC enhances accuracy by refining city-specific boundaries and emission types. Other protocols for city-level GHG emission accounting also exist, such as Publicly Available Specification 2070 (PAS 2070) [15].

4. City boundaries

Defining city boundaries for the purposes of city-level carbon accounting is essential but challenging, given the diverse definitions employed in different studies. The boundaries chosen to delineate a city's spatial extent significantly influence the accuracy and comparability of carbon emission estimates. Typically, a city is defined as a densely populated urban area. However, in certain countries, the term "city" refers to administrative units that may extend into rural, agricultural, or forested zones, which complicates the task of accurately capturing urban emissions. In these cases, focusing on urban areas, rather than administrative boundaries, offers more accurate accounting by excluding areas with low emissions density [15–17].

The question of how to delineate city boundaries for carbon accounting remains a central issue in urban emissions research. This debate is closely tied to the various methods used to classify urban areas, each of which carries implications for how emissions are quantified and attributed. Cities may be defined according to geographical, jurisdictional, functional, or demographic criteria, with each classification influencing the scope and accuracy of emission assessments. A summary of different city boundary definitions is provided in Table 1.

Geographical boundaries typically correspond to the physical extent of a city, including its core urban areas and adjacent suburbs. These are often used in urban carbon inventories due to their apparent alignment with the spatial distribution of emission sources. However, this approach presents challenges, particularly in rapidly urbanizing regions where expansion of the urban footprint can lead to the exclusion of emissions from newly developed zones. In such contexts, urban sprawl may distort emission estimates by omitting areas that are functionally urban but fall outside established boundaries [18].

Table 1. Features and limitations of different city boundary definitions.

Boundary type	Main features	Limitations
Geographical	Based on physical extent (urban core + suburbs); aligns with spatial distribution of emissions; satellite-based carbon accounting	May exclude newly urbanized zones; can misrepresent emissions in areas of urban sprawl
Jurisdictional	Defined by administrative/governmental boundaries; facilitates policy-aligned implementation	May not match actual urban activities or emission sources; misses out regional dependencies
Functional urban area	Based on socio-economic interactions (e.g., commuting, mobility); captures emission flows and metropolitan integration	Requires complex data; may be less aligned with administrative capabilities
Demographic	Uses population size/density thresholds; often aligned with urban intensity (transport, energy use)	Lacks spatial or functional extent; needs to be combined with other metrics for accuracy

To improve the spatial precision of urban definitions, satellite-based methods have been proposed. These utilize remote sensing data to delineate urban areas based on observable characteristics such as night-time light intensity, land cover types, and the extent of impervious surfaces. For example, Park et al. (2021) introduced a method for detecting urban CO_2 enhancements using satellite observations [19]. Such techniques are particularly valuable in settings where administrative records lag behind real-time land use changes, offering an objective and scalable means to define urban extents.

In contrast, jurisdictional boundaries reflect the territories under the governance of municipal or regional authorities. While administratively convenient and aligned with policy implementation, this approach introduces its own set of complications. Jurisdictional boundaries may not coincide with the actual spatial distribution of urban activities or emission sources. Facilities located within the geographical boundaries of a city may fall outside the legal jurisdiction of the city's government, and vice versa, creating inconsistencies in emission reporting [18]. This misalignment reveals the limitations of relying solely on jurisdictional definitions in carbon accounting frameworks.

To address these challenges, more dynamic and functionally oriented methods have been developed. The functional urban area (FUA) approach, for example, defines urban boundaries based on patterns of socio-economic interaction, such as commuting flows, economic interdependencies, and the continuity of the built environment. This method is particularly effective for metropolitan and transboundary regions, where administrative borders do not reflect the integrated nature of urban systems [20]. By accounting for the functional reach of urban activities, the FUA framework offers a more representative basis for emission accounting.

Another city categorization perspective distinguishes between "producer" and "consumer" cities, depending on whether emissions are predominantly generated through local production processes or through the consumption of imported, carbon-intensive goods and services. Although not a spatial classification, this conceptual framing informs the choice between production-based and consumption-based accounting approaches and highlights the shortcomings of purely territorial definitions [21,22].

In addition to function-based definitions, demographic indicators, particularly population density, also play a role in defining urban boundaries [23]. Densely populated areas often exhibit elevated emissions per unit area due to the intensity of transportation networks, industrial operations, and energy demand. When combined with satellite-derived and functional data, population density metrics can contribute to hybrid boundary definitions, enhancing both the spatial and contextual accuracy of urban carbon inventories.

5. Bottom-up approach for city-level carbon accounting

The bottom-up method, outlined in Figure 3, calculates emissions from individual city sources such as building energy use, traffic, industrial production, and waste management. It offers a detailed analysis, identifying specific emission sources and reduction opportunities. However, it requires comprehensive and accurate data, making it resource-intensive and costly to implement. Despite its complexity, it is especially useful for high-accuracy carbon accounting.

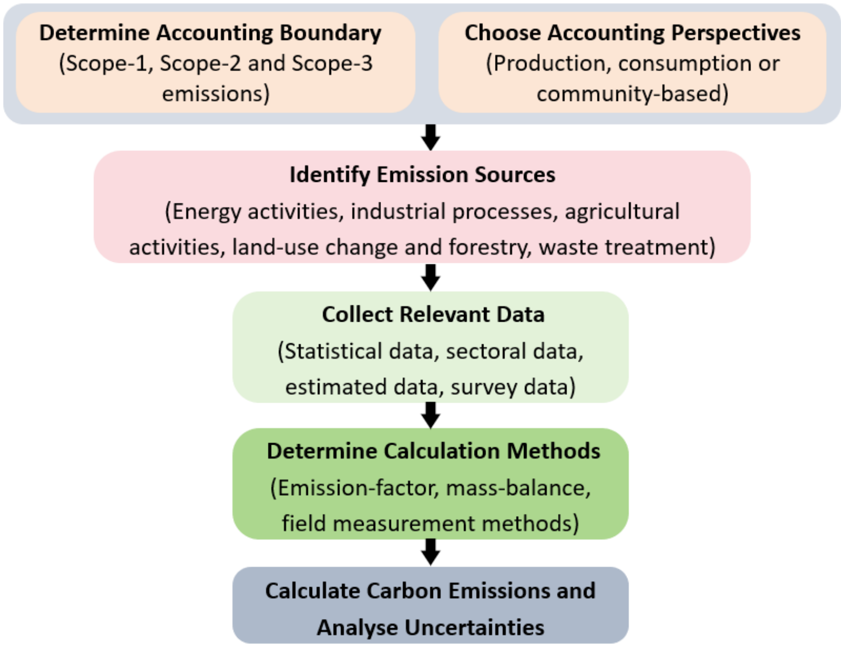

Figure 3. Key steps in the bottom-up approach.

5.1. Determining accounting boundaries

City-level carbon accounting boundaries are categorized by direct and indirect emissions and further delineated into Scope 1, 2, or 3 emissions [24]. Direct emissions originate within the city's jurisdiction, covering activities like fossil fuel consumption, industrial processes, and waste management. In contrast, indirect emissions arise from activities within the city but that are produced outside its jurisdiction, such as those from energy production and utilities.

Scope 1 covers all direct emissions from within the city boundary, also referred to as the geographic inventory. These include emissions from energy use in industry activities, transportation, and buildings, among others, which can be calculated using the IPCC's National Greenhouse Gas Emissions Accounting Framework.

Scope 2 includes indirect emissions from energy consumed within the city but produced outside its boundaries, such as electricity, heating, or cooling purchased from external providers. Despite being generated outside the city, these emissions are included in the city's carbon accounting since the energy is consumed within the city. This inclusion is supported by various city accounting protocols, such as GPC, the International Local Government GHG Emissions Analysis Protocol (IEAP), and PAS 2070 [25].

Scope 3 emissions represent other indirect emissions related to activities within the city but originating outside its boundaries, such as emissions from the production, transport, use, and disposal of goods purchased by the city from external sources [26].

A main challenge in city-level carbon accounting is establishing appropriate boundaries, especially for Scope 3 emissions. Many cities rely on external goods, resulting in significant Scope 3 emissions that are frequently overlooked or underreported. Neglecting these emissions can greatly underestimate urban GHG emissions [3,26]. Therefore, addressing transboundary emissions is crucial to ensure that the carbon accounting framework accurately represents the emissions associated with urban activities.

5.2. Choosing accounting perspectives

City-level carbon accounting is generally approached through three main perspectives: production-based, consumption-based, and hybrid. Each offers a distinct lens through which to view and manage GHG emissions, and the choice among them carries significant implications for policy-making and intercity comparisons.

The production-based approach attributes GHG emissions to the location where they are physically released into the atmosphere. This includes emissions from local industrial activity, transportation, residential energy use, and waste management, corresponding primarily to Scope 1 emissions [27]. Aligned with traditional territorial GHG inventories and consistent with national and international frameworks such as those of the IPCC, this approach enables cities to quantify and control emissions within their borders. It is particularly useful for designing localized mitigation strategies and regulatory policies. However, a key limitation is its exclusion of emissions embodied in imported goods and services, a category that can be substantial, especially in affluent, consumption-driven cities with minimal local production [28,29]. As a result, this approach may significantly underrepresent the total climate impact of such urban areas.

In contrast, the consumption-based approach reallocates responsibility for emissions to the point of final consumption rather than the point of origin. It accounts for Scope 2 and 3 emissions, including those from externally generated electricity and heat, as well as upstream emissions embedded in global supply chains. This methodology offers a more comprehensive carbon footprint by linking emissions to end-user demand, highlighting the critical role of consumer choices and urban lifestyles in shaping global emissions [30–32]. Typically implemented using multi-regional input-output (MRIO) models, this approach traces emissions across complex international trade flows [31,32]. While it demands more detailed data and computational resources, the consumption-based perspective supports policies aimed at encouraging sustainable consumption, circular economies, and ethical procurement. Nonetheless, its practical adoption at the city level remains limited due to difficulties in acquiring granular supply chain data and accurately attributing upstream emissions to specific urban populations [29,32].

The hybrid perspective combines elements of both production-based and consumption-based accounting, aiming to provide a more holistic picture of urban carbon emissions. This perspective seeks to balance control-based responsibilities (what a city can manage directly) with demand-based accountability (what a city drives through consumption). Hybrid approaches can, for example, include direct emissions from within the city, emissions from imported electricity, and selected upstream emissions associated with key goods and services consumed locally [33]. They are particularly well-suited for cities seeking to engage in transboundary climate governance, as they recognize both territorial and trans-territorial climate impacts [22,34]. Although promising, hybrid methods face methodological challenges such as potential double counting, particularly when emissions are simultaneously accounted for under both production and consumption categories.

Overall, the production-based approach remains dominant due to its relative simplicity and policy alignment, but the consumption-based and hybrid approaches are gaining traction for their ability to address the broader environmental impacts of urban economies.

5.3. Identifying emission sources

The definition of emission sources for city-level carbon accounting mainly draws from the IPCC and GPC guidelines. According to IPCC, energy activities, industrial processes, agricultural activities, and waste treatment are considered sources, while land-use change and forestry can act as both sources and sinks. GPC follows a similar categorization with six main sectors: stationary energy, transportation, waste, industrial processes and product use (IPPU), agriculture, forestry, and other land use (AFOLU), and other Scope 3 emissions. While both IPCC and GPC include energy activities as a major source, GPC further distinguishes between stationary and mobile sources, providing more details on energy consumption. Certain emission sources, such as AFOLU and low-emission fuels, are often excluded due to quantification challenges or minimal contributions to overall emissions. However, such omissions can bias accounting, especially in cities where these sources are significant [35].

Despite the comprehensive nature of the IPCC and GPC methods, challenges arise when accounting for cross-border energy procurement or external industrial activities, as traditional methods may fail to provide full coverage. Recent research has focused on accounting for Scope 3 and cross-border emissions, using techniques like environmental input-output analysis (EIO) to capture the broader carbon flows within and outside the city [26]. This approach offers a more complete picture of urban carbon emissions and the external activities influencing them.

5.4. Data collection

Data collection is a critical component of city-level carbon accounting, with activity-level data often sourced from statistical, sectoral, and research databases as well as yearbooks [36]. Institutions such as the International Energy Agency (IEA), the European Commission's Joint Research Centre (JRC), the U.S. Energy Information Administration (EIA), the World Bank, and WRI provide widely referenced global emissions data. City-specific carbon emissions data can be categorized into two main types. The first type includes those from city-level accounting databases like the China Emission Accounts and Datasets [37], the Carbon Disclosure Project [38], and the C40 Cities Climate Leadership Group [39]. These databases offer emissions data at the city level. The second type relies on spatial data provided by databases such as the Emission Database for Global Atmospheric Research (EDGAR) [40], the Carbon Dioxide Information Analysis Centre (CDIAC) [41], the Fossil Fuel Data Assimilation System (FFADS) [42], and the Open-Source Data Inventory of Anthropogenic CO_2 Emissions (ODIAC) [43]. A comparison of typical databases is presented in Table 2, illustrating their respective characteristics and suitability in supporting urban carbon accounting.

Table 2. Databases for city-level carbon accounting, ranked by their suitability for city-level carbon accounting.

Database	Coverage	Update frequency	Spatial scale	Spatial resolution	Emission sectors	City-level suitability
C40 Cities Climate Leadership Group	Global	Varies	City-level	City-level	Energy, buildings, waste, transportation, land use	**Very high** (focuses explicitly on city-level)
Multi-resolution Emission Inventory for China (MEIC)	China	Annually	City-level, provincial, national	High resolution (0.25° or 25 km; finer for city-level studies)	Energy, industry, residential, transport, agriculture	**High** (designed for detailed city-level accounting)
Carbon Disclosure Project (CDP)	Global	Annually	City-level, corporate, regional	Varies (self-reported data)	Energy, industry, waste, transport, land use	**High** (city-reported emissions data)
China Emission Accounts and Datasets (CEADs)	China	Varies	City-level, provincial, national	Varies (detailed for cities)	Energy, industry, cement, agriculture, trade	**High** (urban-level data for China)
Environmental Protection Agency (EPA)	United States	Annually	National, sub-national	Varies (sector-specific)	Energy, transportation, industry, agriculture, land use, forestry, waste, residential	**High** (sub-national details allowing for city-level analysis in the U.S.)
Carbon Monitor	Global	Near real-time	Global, regional, national	Varies (country and regional levels)	Energy, transport, industry, residential, aviation	**Moderate** (limited city-level resolution; real-time trends for monitoring)
Emissions Database for Global Atmospheric Research (EDGAR)	Global	Annually	Global, regional, national	0.1° × 0.1° (10 km)	Energy, industry, transport, agriculture, waste, land use	**Moderate** (limited details for specific cities)
European Commission's Joint Research Centre (JRC)	Global, EU focus	Varies (sector-specific)	Global, regional, national	Varies (10 km for specific datasets)	Energy, industry, transport, agriculture, waste	**Moderate** (regional focus with some urban cases)

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Database	Coverage	Update frequency	Spatial scale	Spatial resolution	Emission sectors	City-level suitability
U.S. Energy Information Administration (EIA)	United States	Annually	National, sub-national	State and regional levels	Energy, transport, industry, residential	**Moderate** (some datasets useful for city-level energy-related emissions)
World Resources Institute (WRI)	Global	Varies	Country-level	Country-level (aggregated)	Energy, land use, waste, industry, agriculture, forestry	**Low** (data aggregated at country level)
International Energy Agency (IEA)	Global	Annually	Country-level, sectoral	Country-level (aggregated)	Energy, transport, industry, residential	**Low** (designed for the energy sector at the country level)
United Nations framework Convention on Climate Change (UNFCCC)	Global (UNFCCC Parties)	Annually (developed nations); periodic	National	Country-level	Energy, industry, transport, agriculture, land use, forestry, waste	**Low** (mainly on national reporting)
Global Carbon Budget (GCB)	Global	Annually	Global, regional, national	1° × 1° (100 km) or coarser	Fossil fuels, land use, cement, oceans, natural sinks	**Low** (coarse global and regional resolution)

5.5. Determining calculation methods

The choice of calculation methods for city-level carbon emissions depends on emission sources, data availability, and accounting objectives. Commonly used methods include the emission-factor, mass-balance, and direct measurement methods. Among these, the emission-factor approach is the most widely employed, particularly for estimating emissions from energy consumption and industrial processes [21,44,45]. The applicability of carbon accounting scopes (Scopes 1–3) to emission-factor, mass-balance, and direct measurement methods is summarized in Table 3 and detailed in this section.

Table 3. Applicability of carbon accounting scopes (Scopes 1–3) to emission-factor, mass-balance, and direct measurement methods.

Method	Scope 1	Scope 2	Scope 3
Emission-factor	Widely used	Widely used	Limited but possible
Mass-balance	Selectively used	Rarely used	Possible for specific sectors
Direct measurement	Selectively used	Not suitable	Not suitable

The emission-factor method, first proposed by the IPCC, constructs activity data and emission factors for each emission source, with the product of these two variables used to estimate the total emissions: $\text{Emission} = \text{Activity Data} \times \text{Emssion Factor}$. Here, activity data refer to the amount of a specific resource used, while the emission factor indicates the amount of GHG released per unit of activity. Activity data typically come from national statistics, surveys, and monitoring data, while emission factors are provided by international organizations such as the IPCC or national standards. Emission factors are chosen based on the city's specific sectors and energy types for more accurate calculations. After initial emission estimates are made, the results are refined by considering local characteristics, such as energy structure, industrial layout, and traffic patterns.

The emission-factor method is particularly well-suited for estimating Scope 1 emissions and is also widely used for Scope 2 emissions. The strength of this method lies in its structured, data-driven approach, making it highly effective when reliable energy consumption data and standardized emission factors are available. While it may be extended to Scope 3 emissions, its effectiveness decreases significantly. Scope 3 sources, such as the production of imported goods, upstream transportation, and external waste treatment, are complex and often lack transparent data. This makes it difficult to quantify them due to fragmented supply chains and uncertainties in emission attribution.

The mass-balance approach focuses on tracking the flow of carbon through a system, which is often used as a secondary method, particularly for waste treatment and large-scale chemical processes [46]. It estimates net emissions by analyzing carbon inputs (e.g., fuel, raw materials), outputs (e.g., emissions, waste), and storage (e.g., forests or urban green spaces), requiring detailed data on material flows and the carbon content of materials. Although comprehensive, this method demands technical expertise, intensive information, and complex calculations, limiting its applicability at the city level.

The mass-balance method is effective for Scope 1 emissions in controlled environments where carbon inputs and outputs can be clearly tracked, such as industrial facilities or waste treatment plants. By monitoring fuel consumption, raw material input, product output, and carbon storage (e.g., in landfills or biomass), the method provides a holistic view of emissions within a closed system. Its application to Scope 2 emissions is rare because it deals with material flows rather than energy. However, it can occasionally support Scope 3 analysis, especially in tracking carbon embedded in materials crossing city boundaries.

The direct measurement method involves the use of specialized instruments to measure emissions directly from carbon sources. While it provides highly accurate data, it is generally applied to large industrial facilities or fuel combustion sources that have the necessary on-site monitoring facilities [47]. However, its applicability is limited by the availability of such facilities, highlighting the need for financial and technical support to facilitate the deployment of sensing technologies and the Internet of Things (IoT). Additionally, it is not always feasible for widespread use, particularly for mobile or scattered sources. Despite these limitations, direct measurement offers valuable data for monitoring major emitters within a city, supplementing city-level carbon accounting, and potentially validating results derived from the emission-factor method.

The direct measurement method is effective in quantifying Scope 1 emissions from large, stationary sources like power plants and industrial facilities, where monitoring infrastructure is available. Its precision makes it particularly valuable for validating estimates from other methods or for closely tracking emissions from major polluters. However, it is largely unsuitable for Scope 2 and 3 emissions, as it cannot capture indirect or geographically dispersed sources outside the city.

5.6. Calculation and uncertainty analyses

By following the steps stated in Sections 5.1–5.5, carbon emissions can readily be estimated. This process usually results in a comprehensive carbon emission inventory, detailing the total emissions for each sector, source, and type (Scopes 1–3).

However, emission estimates derived from activity data and emission factors inherently involve uncertainties, which can impact the accuracy of carbon accounting. Cross-referencing the results with existing sources, such as national emission inventories or data from comparable cities, is an effective way to assess the consistency and reliability of the calculated outcomes.

In addition, uncertainty analyses are essential for improving the accuracy of emission estimates. The IPCC guidelines provide standardized methods for preparing GHG inventories and conducting uncertainty analyses to minimize such discrepancies [48]. These methods are also incorporated into the GPC guidelines. Furthermore, techniques such as error transfer methods and Monte Carlo simulations have been employed to simulate uncertainties and generate a comprehensive uncertainty estimate [49–51]. Despite these attempts, many studies fail to adequately address uncertainties in carbon accounting [52].

6. Top-down methods for city-level carbon accounting

Top-down methods for city-level carbon accounting follow international standards, such as those outlined by the IPCC, and primarily rely on national or regional data sources such as those listed in Table 2. The main steps involved in the top-down process are illustrated in Figure 4. Initially, macro data, such as energy balances [37], input-output tables from input-output analysis (IOA) or multi-region input-output (MRIO) models, national or regional statistics (e.g., population size, GDP, industrial structure), and emission factor databases (e.g., IPCC guidelines), are collected. These data are then scaled down to the city level using disaggregation techniques such as proportional allocation or extrapolation techniques. Allocation weights are determined based on city-specific factors, such as population, economic activity, energy consumption, or industrial structure, with proportional allocation methods applied [53]. For example, if a city's economic activity accounts for 5% of national output, it is assumed that the city's carbon emissions also represent about 5% of the national total.

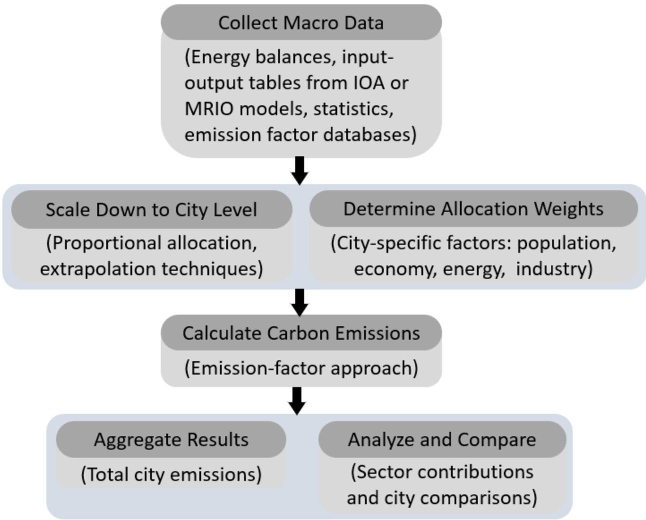

Figure 4. Key steps in the top-down approach.

Carbon emissions are then calculated using the emission-factor approach, and the final results are aggregated to determine the total carbon emissions of the city. Further analyses are conducted to examine the structural characteristics of emissions, such as the contribution of energy, industry, transport, and other sectors. Additionally, trends in carbon emissions can be assessed and compared to those of other cities [54].

The top-down method is computationally efficient, allowing for quick estimates of city-level carbon emissions, even when detailed local data are unavailable. It is useful for cross-city comparisons and macro-level trend projections. However, the top-down approach may fail to accurately capture local emission details, as it overlooks city-specific characteristics such as industrial structure, energy consumption patterns, and other unique factors. This limits its usefulness for designing detailed emission reduction strategies by local policymakers.

7. Discussion

This study explores two primary approaches to city-level carbon accounting: the top-down and bottom-up methods, each with distinct advantages and limitations. The top-down approach is often used for preliminary carbon emission accounting at the city level, as reliable city-specific data are often difficult to access and process. It depends heavily on macro-level data, such as national energy balance sheets and emission factor databases. However, these data may have limited accuracy or be incomplete, particularly in developing regions or areas with inadequate data collection, which can compromise the accuracy of city-level carbon accounting. Additionally, emission factors often reflect broad averages that may not account for a city's unique energy mix or patterns, potentially introducing biases. In contrast, the bottom-up approach calculates emissions from individual city sources and can produce more accurate estimates. However, it requires comprehensive and accurate data, making it resource-intensive and costly to implement. In addition, accounting for Scope 3 emissions is sometimes considered optional, and excluding it undermines the overall accuracy of carbon accounting for a city, especially when the city relies on external products and services with high carbon footprints. Integrating the top-down and bottom-up approaches presents challenges, as the former relies on broad estimates, while the latter provides more detailed source-level data. These differing approaches can yield conflicting results, and developing an effective method to combine them for a more consistent and comprehensive carbon accounting system remains a key focus for future research.

In addition to traditional carbon accounting methods, new approaches have also been introduced. One prominent example is the global multi-region input-output (GMRIO) model, which captures implicit carbon emissions embedded in inter-city trade and supply chains [21]. This model evaluates the distribution of a city's carbon footprint, including Scope 3 emissions, and the transfer of emissions between cities [26]. Similarly, the environmental input-output analysis framework (EIO-LCA) addresses gaps in traditional Scope 3 accounting by examining carbon emissions in both upstream and downstream urban economic activities and global supply chains. For example, Wang and Chen found that upstream supply chain emissions accounted for 70%–80% of total emissions in most manufacturing sectors using this framework [3]. Building on EIO-LCA, Wiedmann et al. proposed a "city carbon map" framework that integrates direct and indirect emissions, which was successfully applied in Melbourne, Australia [55]. Researchers have suggested redefining accounting scopes, including internal emissions, core external emissions, and non-core emissions, for refined analyses [56]. Hao et al. introduced a unified framework for urban carbon cycle accounting, integrating carbon stocks, emissions, inputs, and outputs for comparative analyses [4]. These methods collectively enhance the accuracy and applicability of city-level carbon accounting, supporting better policy development and climate action planning.

Future research should prioritize delivering actionable solutions for carbon management across various types of cities. To enhance practicality, carbon accounting methods must be adapted to reflect the unique size and functions of each city, ensuring both accuracy and usability. For example, the "urban form" identified in the co-citation network graph in Figure 2 highlights how the spatial structure and functions of cities play a significant role in shaping carbon emissions.

Additionally, the development of city-specific approaches that integrate techniques such as artificial intelligence (e.g., machine/deep learning techniques, discipline-specific foundation models) [57], Internet of Things sensors [58], remote sensing technology, and semantic segmentation [59,60] is essential to improve the efficiency and accuracy of carbon accounting processes. This requires support from the government in the form of policy initiatives and potential financial assistance. At the same time, the industry and academic communities can play a crucial role in driving technical advancements in this area.

8. Conclusions

This study suggests that although extensive research has been conducted on carbon emissions in the context of cities, relatively few studies have specifically focused on carbon accounting at the scale of an entire city. This paper briefly analyzes hot research topics in urban carbon accounting. It provides an overview of the key steps and considerations involved in city-level carbon accounting methods, with a primary focus on the bottom-up approach, which estimates carbon emissions at the city level through a hierarchical process. It also briefly introduces the top-down approach and discusses emerging methodologies in the field of city-level carbon accounting. Additionally, the paper highlights commonly used databases in this field, discussing their applicability and suitability for city-level carbon accounting. It also identifies areas for improvement, and recommends developing city-specific carbon accounting frameworks and tools to support low-carbon initiatives for cities and address global climate change.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in creating content in this article, but have used AI tools for enhancing the English language.

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Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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