

SYNTHESIS

Carbon metrics for cities: production and consumption implications for policies

Maria Balouktsi¹**Abstract**

The estimated cities' contribution to climate change varies depending on the methods chosen by a given city for compiling its greenhouse gas (GHG) emission inventory. This study provides an interpretative synthesis of existing research to explore the differences of three emerging approaches to city-level GHG emissions accounting, based on methodological dimensions: boundary-setting, the categorisation of emissions and the type of emissions. The policy relevance and implications of selecting different system boundaries are explored: each approach can reveal important information which the others fail to identify. This suggests the value of using different and complementary approaches to address as many policy questions and relevant actors possible in climate action planning. Next, key methodological considerations that arise in target-setting approaches involving bringing the emissions balance to zero are presented. An analysis of actual 'net-zero emission' concepts used by eight cities reveals that their precise meaning and applicability remain ambiguous. Finally, to improve both the transparency about such metrics and their usability for policy and decision-making, this paper synthesises all key considerations occurring from the analysis of inventorying approaches and net-zero targets into a reporting and communication framework.

Policy relevance

Many cities are assuming responsibility for measures to mitigate climate change, but they need greater clarity on 'climate neutral' or 'net-zero' approaches. Each city's intended purpose needs careful alignment with a choice of methods. The diverse accounting and target-setting landscape and the associated policy implications are elucidated. This can empower more cities to select appropriate methods and set ambitious targets. Calculation of a GHG emission balance is a means to an end and not the end itself. Its purpose is to show the options for action and measure success. Non-transparent methods involve reputational and ethical risks for city governments. A framework to improve transparency is presented. Dual-accounting approaches involving both production and consumption are now the new trend. Individual actors must be able to identify their influence and potential action scope for mitigating climate change. Agreement is needed on how to approach consumption-based accounting and create more city-specific data.

Keywords: accounting methods; cities; climate change; consumption-based accounting; greenhouse gas emissions; mitigation; net zero; public policy; target-setting

1. Introduction

The recently released special report on *Global Warming of 1.5°C* (2018) by the Intergovernmental Panel on Climate Change (IPCC) signifies that achieving the global target of limiting the temperature increase to 1.5°C above pre-industrial levels requires the necessary drastic greenhouse gas (GHG) emissions reduction to happen much faster than previously thought. Decarbonisation of the economy in the upcoming decades continues to be one of the biggest challenges facing nations, and it will largely depend on cities (UN-Habitat 2016: 87). Although cities occupy only a tiny proportion of the total global surface area (around 3%), over 70% of global CO₂ emissions associated with final energy use can be attributed to them by some accounts (IEA 2008; Seto *et al.* 2014). If GHG emissions associated with products consumed by urban residents are included, this share would be even larger (Hoornweg, Sugar, & Trejos Gómez 2011). If accounting is based on where emissions are caused, the respective proportion would be about 30% lower (Seto *et al.* 2014). While

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much contestation remains about the exact emission shares attributed to cities (Dodman 2009; Satterthwaite 2008), it is widely acknowledged that in the absence of action, cities' contribution to climate change will be further raised because of the projected rise of the global urban population by 2.5 billion by 2050 (Heilig 2012).

The 'city' is not only an important object of assessment and level to act, but also a dense network of actors and agents of change (Lützkendorf & Balouktsi 2019), with social actors, comprised of individual users (*i.e.* households and businesses within a city), infrastructure designers and operators (*i.e.* cross-scale actors responsible for design, construction, operation, maintenance and dismantling of the infrastructures) and policy actors (*i.e.* civil government officials, special-interest groups and other groups involved in governance) as the primary ones (Ramaswami *et al.* 2012). Given the urgency for GHG reductions, the global recognition of cities as sites for addressing this issue (Bulkeley 2010), and the leading role of local governments in urban climate governance (Hölscher *et al.* 2019), city governments need to increase their ambition and strive to limit their cities' emissions as close to zero as possible by or before 2050. Achieving aspiring climate targets by sustainable means can also yield various synergies with Sustainable Development Goals (SDGs) other than climate action (SDG 13), such as affordable and clean energy goal (SDG 7), responsible consumption and production (SDG 12), health and well-being (SDG 3), and the goal to make cities and human settlements inclusive, safe, resilient and sustainable (SDG 11) (Creutzig *et al.* 2018; Lützkendorf & Balouktsi 2019).

Owing to their smaller spatial scale, the IPCC national source-based accounting is not readily applicable to cities (Chen *et al.* 2019). This is why, over the last decade, leading organisations and city networks have developed different accounting and reporting protocols that focus on cities and go far beyond source-based activities. All these approaches now include electricity use that is supplied from power plants located outside a city's geographical boundary; most include waste; and the newest ones, *e.g.* the Global Protocol for Community-Scale Greenhouse Gas Emission Inventories (GPC) (WRI *et al.* 2014) and the US Community Protocol (ICLEI—Local Governments for Sustainability USA 2019), additionally include transport fuels and construction materials, among others (see the Appendix for details). It can be assumed that this trend was motivated by earlier research addressing supply chains of key infrastructure sectors (Chavez *et al.* 2012; Hillman & Ramaswami 2010; Kennedy *et al.* 2009; Ramaswami *et al.* 2008). Consumption-based approaches have also started being increasingly explored in both reporting protocols (BSI 2013; ICLEI—Local Governments for Sustainability USA 2019) and the academic literature (*e.g.* Chavez & Ramaswami 2013; Chen *et al.* 2016; Feng *et al.* 2014; Mi *et al.* 2016; Millward-Hopkins *et al.* 2017).

However, a high-quality GHG inventory does not guarantee practical GHG reductions; amongst others, concrete and accountable target-setting is also needed (Haarstad 2020). However, no matter how intensive cities' reduction efforts are, some GHG emissions are unavoidable, and this is where net-zero concepts come into play. Rogelj *et al.* (2015) define 'net-zero GHG emissions' as the status when any remaining tonne of CO₂e is balanced by negative emissions of CO₂ (*i.e.* CO₂ removals from biomass regrowth and/or CO₂ capture and permanent geological storage). In city-level 'net-zero' targets, however, a sort of 'financial' balancing often also applies through the purchase of offset credits, in addition to physical balancing (Lützkendorf & Balouktsi 2019). The application of this concept to cities has, therefore, more flexible boundaries.

Clarifying methodological considerations in city-level carbon accounting and subsequent target-setting is more important than ever (Chavez & Ramaswami 2013). The different emerging accounting approaches involve various subsets of city activities leading to different mitigation strategies; various terminologies used to express similar concepts add to the overall confusion in the field (Lombardi *et al.* 2017). Targets that appear to be ostensibly the same, as is the case with net-zero emission targets, vary considerably in their details (Lützkendorf & Balouktsi 2019). While these issues are well known to experts and practitioners in the field, they may limit the usability of the results in policy- and decision-making (Heinonen *et al.* 2020). Elucidating the diverse accounting and target-setting landscape and the associated policy implications can also support the currently under-preparation IPCC special report for cities to be included in its seventh assessment cycle that will empower more cities to set ambitious targets and explore the possibilities and advantages of consumption-based inventories (Priour-Richard *et al.* 2018: 12).

The present paper synthesises what is already known about the variations in both city-level GHG emission accounting and how a net-zero balance is achieved. Seven principal methodological dimensions are examined: three in relation to emission inventorying/accounting (boundary-setting, categorisation of emissions and type of emissions) and four in relation to target-setting (reference unit, use of scenarios, target year and treatment of residual emissions). Based on this analysis, the final outcome of this paper is a 'net-zero' minimum reporting and communication framework that improves transparency regarding such metrics, without thereby reducing local relevance. Transparency is a precondition for achieving the desired consistency in future GHG emission assessment at the city level, as well as the basis for traceability, credibility and trust (Aldy 2014; Haarstad 2020). Parts of the present paper are built on a previous conference paper by Lützkendorf & Balouktsi (2019).

Environmental performance assessments at any spatial scale should address not only climate change but also other environmental problems, *e.g.* depletion of natural resources, fine particulate matter pollution, land use, water use, *etc.* The focus on a single indicator (*i.e.* global warming potential—GWP) brings the risk of burden-shifting when GHG emission reductions are obtained to the detriment of increasing in other environmental impacts (Laurent, Olsen & Hauschild 2012). However, climate mitigation is a good place to start. Similar considerations as those discussed here are valid for cities when assessing and setting targets for other environmental indicators, *e.g.* water, energy, materials and land. Net-zero concepts and targets are not restricted to emissions/carbon (Terblanche 2019).

2. Synthesis method

The present synthesis paper addresses one central research question: How the net-zero emission balance is defined across cities, and what are the associated policy implications? The creation of net-zero targets is built on two interlinked processes undertaken by cities, namely GHG accounting (or inventorying) that establishes the baseline emissions of a city; and target-setting that establishes the quantifiable performance expectations and the timeframe. For the first process (GHG accounting), two complementary search strategies were applied to identify relevant articles and studies: (1) snowballing, where an initial set of review articles was selected based on the author's experience and the trail of references was then followed; and (2) open search in Scopus, where papers published over the last decade up to February 2020 were included. The criteria for consideration of papers as a basis for extracting lessons learned and elucidating key differences in accounting approaches were: (1) peer-reviewed journal articles or book chapters published in English; and (2) a focused discussion on system boundaries, as well as the types and categories of emissions included in inventories. The latter points of variation in accounting approaches were selected as a starting point based on the author's previous work oriented towards identifying system boundary variations of 'net-zero' targets (Lützkendorf & Balouktsi 2019), as well as a review of the existing city-carbon-accounting and -reporting protocols and guidelines (briefly presented in the Appendix). For the second process (target-setting) the paper reviewed actual climate action plans and feasibility studies of cities adopting a 'net-zero emission' target/ambition. A limitation of this study is the lack of interviews with city representatives to understand the rationale behind certain target-setting choices.

3. GHG inventories for cities: current state and trends

3.1 Treatment of the boundary challenge

3.1.1 Main boundary-setting methods for city-scale GHG accounting

To identify the different sources of GHG emissions tied to a city, a clear definition and system boundary-setting of 'city' is essential (Lützkendorf & Balouktsi 2019). Specifying a spatial delineation of a city is a complicated task because there is as yet no universally applicable definition of what constitutes a city (Kennedy *et al.* 2010; Moran *et al.* 2018; UN-Habitat 2011). Cities have administrative boundaries, which most likely are the easiest to understand by the relevant stakeholders. However, the boundary delineation can also be, among others, density based, *i.e.* limits are defined based on the continuity of the population density, or service based, *i.e.* limits are defined based on the services induced by a city (Albertí *et al.* 2019a). All these system boundary definitions represent different perspectives and exist side by side. The selection of the most appropriate ones depends on the specific targets and purposes of the emission accounting (Liu *et al.* 2015; Mi *et al.* 2019).

Defining the boundary of a city is one aspect; allocating the GHG emissions to this city generated by an activity to determine its share of responsibility for climate mitigation is the other. The question of how to allocate GHG emissions to nations and regions in view of gaining useful insights for climate policy is commonly made between two approaches (Afionis *et al.* 2017; Peters 2008; Peters & Hertwich 2008):

- *Production-based approach (PBA)*, also known as a 'territorial approach' (Chavez & Sperling 2017) or a 'pure geographic approach' (Chen *et al.* 2019). It quantifies GHG emissions being produced within geographical boundaries, *i.e.* emissions are accounted for at source point.
- *Consumption-based approach (CBA)*, also often referred to as a 'carbon footprint' (Chen *et al.* 2019; Larsen & Hertwich 2009) or a 'GHG footprint' (Pichler *et al.* 2017). This quantifies GHG emissions generated as a result of actors' consumption of goods and services, *i.e.* emissions are accounted for at the end-user point.

These two different views of how GHGs may be attributed to a spatially defined area have also been adopted by city-level accounting systems and are linked to the capacity and responsibility of different groups of actors to act on limiting the sources and activities that cause the greatest impact (Satterthwaite 2008; Wright *et al.* 2011; Yetano Roche *et al.* 2014). In PBAs, responsibility is assigned to the 'producers' of emissions, while in CBAs, responsibility is assigned to the final 'consumers' of goods and services irrespective of where they are produced (emissions are associated with their manufacture and transport) (Dodman 2009; Wright *et al.* 2011).

Other methodologies exist to support infrastructure designers and operators in city-level emission accounting, the so-called community-wide infrastructure footprint approach (CIFA) (Chavez & Ramaswami 2013; Ramaswami *et al.* 2008). This approach was first introduced by Ramaswami *et al.* (2008) and has so far been applied to cities in the United States, India and China (Chavez *et al.* 2012; Hillman & Ramaswami 2010; Tong *et al.* 2016). CIFA accounts for both direct (territorial) and transboundary GHG emissions associated with key infrastructure sectors by combining PBAs for the first one and economic input-output life cycle assessment (EIO-LCA) or process-based LCA (or a combination of the latter two into a hybrid EIO-LCA) for the second one (Chavez & Ramaswami 2013; Ramaswami *et al.* 2008). Some researchers refer to it as the 'hybrid approach' (Chavez & Ramaswami 2013; Lin *et al.* 2013), others as the 'supply-chain approach' (Yetano Roche *et al.* 2014) or the 'expanded territorial/production' approach (Chavez & Sperling 2017). In clarifying CIFA, Chavez & Ramaswami (2013) propose that an infrastructure is considered essential when it supports the basic needs and well-being of a city's residents and/or highly correlates with a city's economic productivity while being produced sparsely across cities. These key infrastructure systems are energy supply, transportation and connectivity,

water supply, wastewater treatment, building/shelter materials supply, green/public spaces, and food provisioning (Ramaswami *et al.* 2016).

Covering the full supply chain of essential infrastructures, in CIFAs responsibility is allocated to both 'producers' and 'consumers'. Therefore, it moves beyond the traditional producer/consumer dichotomy and takes a systems perspective that can describe activities that cannot clearly be allocated to either production or consumption, such as energy storage (the concurrent production and consumption associated with actors generating renewable energy has also given rise to the emerging concept of a 'prosumer'; Espe, Potdar, & Chang 2018). CIFA can also be viewed as a method strongly contributing to SDG 12, which aims at promoting sustainable production together with sustainable consumption patterns.

Figure 1 summarises the different approaches and illustrates their differences, similarities and overlapping areas, whereas the mathematical relationships among these three methods were elucidated by Chavez & Ramaswami (2013) to characterise North American cities based on their emission profile. It only represents a simplified decomposition of the different methods, since cities can be engaged in complicated trades, *e.g.* exports from a city may be imported back into the city (Fry *et al.* 2018).

In terms of practical application, as shown by a recent review, PBAs and CIFAs are the most widely adopted methods for city carbon accounting (Chen *et al.* 2019). These two methods (with some adaptations) are also the prevalent ones in the different reporting standards and their requirements for the calculation of embodied emissions, although the value of CBA as a complementary approach has started being increasingly acknowledged (see the Appendix). The reasons behind the slower adoption of CBA may be the considerable time, effort and speculation required to reconcile incompatible bottom-up and top-down data sources, *i.e.* survey-based consumer expenditure data and national input–output (IO) tables, and/or the additional simplifying assumptions, and therefore uncertainties, associated with IO accounts in general (Pichler *et al.* 2017). A recent review by Heinonen *et al.* (2020) on consumption-based assessments at different spatial scales summarises, among others, the commonly acknowledged weaknesses or sources of uncertainty in IO-based assessments, including:

- the aggregation error (multiple actual sectors with varying emission profiles are aggregated into one IO model sector);
- assumptions on linearity of scale and product homogeneity;
- assumption of imports production using domestic technology; and
- data age.

Although there has been some development towards addressing these weaknesses (see Heinonen *et al.* 2020 for a detailed discussion), the field is still relatively young.

However, the exact level of uncertainty associated with local consumption when using IO models cannot be known without matching economic flows with physical flows (Chen *et al.* 2020). No study so far has undertaken such explorations (Chen, Hadjikakou, & Wiedmann 2017). To reduce difficulties associated with the matching of specific local data to the expenditure amounts and categories in IO models, several authors propose supplementing IO models with

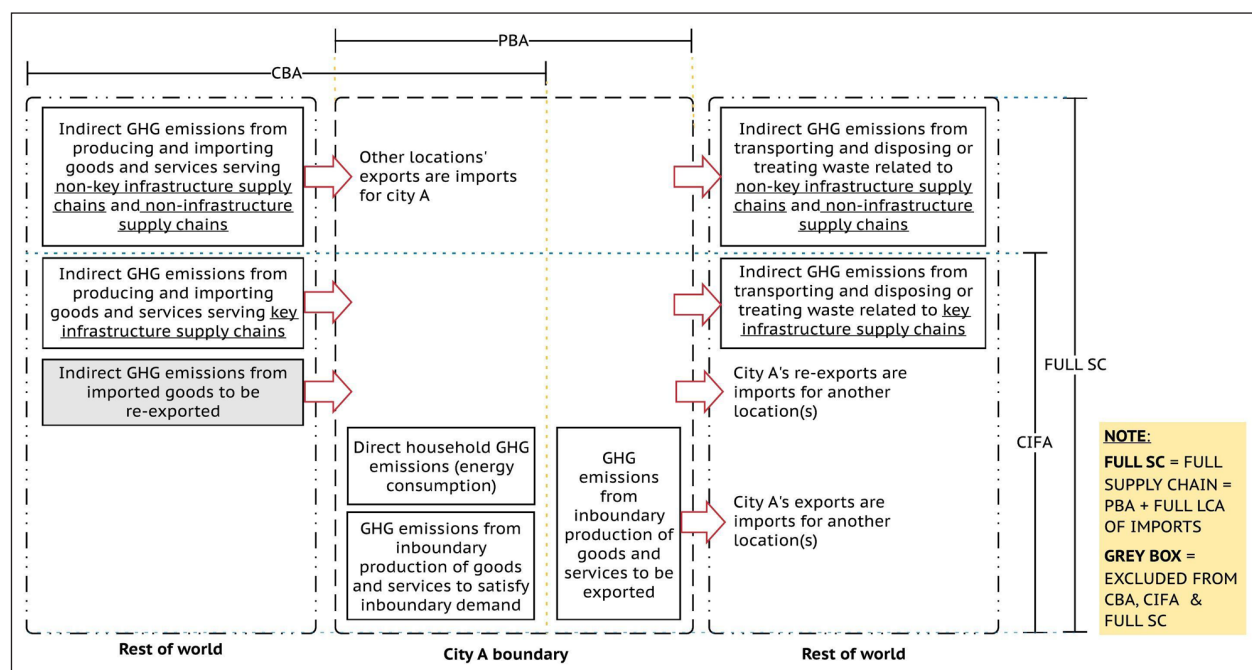


Figure 1: Simple decomposition of the three methods.

Sources: Based on Chavez & Ramaswami (2013) and Lützkendorf & Balouktsi (2019).

process-based life cycle inventory (LCI) data in a hybrid LCA approach (Heinonen & Junnila 2011; Larsen & Hertwich 2009). However, the construction of a CBA inventory fully based on process-based LCA is not considered practical at the city scale (Broekhoff, Erickson, & Piggot 2019). Perhaps such an exercise would only be feasible at smaller scales, such as neighbourhoods, where surveys coverage could reach 100%, as well as for limited consumption categories. In this context, many researchers have highlighted that PBAs are much more developed than CBAs, and therefore investment into the development of the latter and its underlying databases is necessary (Dahal & Niemelä 2017; Fry *et al.* 2018; Millward-Hopkins *et al.* 2017; Ottelin *et al.* 2019).

Substantial differences in quantitative terms between these three approaches for city-scale GHG emissions accounting have been demonstrated by several studies. Those differences are well-justified since PBA, CIFA and CBA include different subsets of activities. For example, on the basis of comparisons between PBA and CBA accounts for certain cities, several researchers have warned against a narrow focus on PBAs—especially in the case of developed countries (and their cities) as primarily net importers of GHG emissions because of their high-consumption urban lifestyles. PBAs lead to substantial proportions of cities' GHG emissions being absent from their local emissions inventories and reduction targets (Larsen & Hertwich 2009; Millward-Hopkins *et al.* 2017; Minx *et al.* 2013; Sudmant *et al.* 2018). This proportion can be twice or thrice as high as a city's direct emissions (Broekhoff, Erickson & Piggot 2019; Kennedy *et al.* 2009; Moran *et al.* 2018; Ramaswami *et al.* 2008). CBAs are becoming increasingly important for cities in the developing world that are currently shifting from producer to consumer city status (Sudmant *et al.* 2018). However, net production is not unique to cities in the developing world (Baynes *et al.* 2011; Chavez & Ramaswami 2013; Sudmant *et al.* 2018). A shift is not improbable for cities in highly developed nations currently finding themselves as net exporters. As Erickson, Chandler, & Lazarus (2012) stress, leaving future increases in consumption unchecked could offset decreases in direct emissions. Similar conclusions are drawn by studies that compared PBA and CIFA accounts for particular cities, showing that the latter method can produce close to 50% more emissions than the former one for net consumer cities (Hillman & Ramaswami 2010).

For comparisons between CIFAs and CBAs, Chavez & Ramaswami (2013) showed that for trade-balanced cities their difference is negligible, but for highly net-consuming cities CIFA results in a decreased footprint by about one-quarter compared with CBA. Despite the practical benefits of infrastructure-based approaches, they risk underestimating the overall contribution of highly consuming or highly producing cities to climate change because they do not account for the full spectrum of imports in the first case and exports in the second (Wheeler, Jones, & Kammen 2018).

3.1.2 Relationship between PBA, CBA, CIFA and the scopes framework

Three different scopes of urban GHG emissions are commonly accepted (WRI *et al.* 2014; Mi *et al.* 2019):

- *Scope 1* covers the direct emissions from sources located within the city boundary, and therefore the territorial emissions.
- *Scope 2* includes the indirect emissions that occur as a result of the use of grid-supplied or purchased electricity, heat, steam and/or cooling within the city boundary.
- *Scope 3* includes all other indirect emissions.

To link the three emerging accounting methods to Scopes 1–3, one must disaggregate them into their constituent elements. **Table 1** does this in a more actor-specific way, where three broad categories of local actors living and operating within a city's geographical boundaries are recognised, *i.e.* households, government, and businesses and industries. All categories are infrastructure end-users, while the latter two may also be infrastructure owners and operators. Although not seen as local actors in the sense of participating in a way or another at local decision-making, 'visitors' are also served by city infrastructures and should be accounted for from an infrastructure-centred perspective. Therefore, they are also acknowledged in **Table 1** where necessary.

Table 1 also draws the relationship of the different methods and the scopes framework. As can be seen, both CBA and CIFA include Scope 3 emissions from upstream processes. There are three main differences between these two methods: (1) in-boundary production emissions that serve exports, *i.e.* Scope 1F emissions, are excluded from CBA, while CIFA quantifies both imports and exports of selected goods and services (Chavez & Ramaswami 2013; Chen *et al.* 2019); (2) CBA excludes any emissions due to waste landfilled or treated within a city's boundary, *i.e.* Scope 1G emissions, if this is induced by another city; and (3) CBA provides a more complete picture of imports than CIFA (**Figure 1**). Concerning the difference between PBA and CBA, the former includes exports and excludes imports, whereas the latter includes imports and emissions embodied in trade, but excludes exports. Finally, the direct emissions of land use and land-use change, *i.e.* Scope 1H emissions, form only part of PBA and CIFA; CBA may only cover the indirect part of this type of emissions as part of 'food and beverages' consumption category. However, this category is one of the most complex to account for, especially when it comes to connecting it to IO model categories, and therefore only a minor share of related studies seems to include it (Heinonen *et al.* 2020; WRI *et al.* 2014).

Table 1 shows seven different system boundary types to city-level carbon accounting can occur. This seven 'system boundaries' concept differs from the 'four system boundaries' approach proposed by Liu *et al.* (2015) and redefined by

Table 1: Relationship analysis between the three accounting methods—a production-based approach (PBA), a consumption-based approach (CBA) and a community-wide infrastructure footprint approach (CIFA) – and Scopes 1–3, and the definition of functional system boundaries (SB) 1–7.

Items in Scope 1–3 emissions		SB1: PBA	SB2: PBA plus imported electricity	SB3: SB2 plus waste	SB4: CBA (only households) ^b	SB5: CBA (all) ^b	SB6: CIFA	SB7: Complete (full Scope 1–3)
Indirect upstream (geographically out-boundary)								
Scope 3	A: Upstream electricity (transmission and losses)	–	–	–	✓	✓	✓	✓
	B: UEE in products and services consumed by households (key infrastructure SC)	–	–	–	✓	✓	✓	✓
	C: Same as for B for non-key infrastructure and non-infrastructure SC	–	–	–	✓	✓	–	✓
	D: UEE in products and services consumed by businesses and industries (key infrastructure SC)	–	–	–	–	✓	✓	✓
	E: Same as for D for non-key infrastructure and non-infrastructure SC	–	–	–	–	✓	–	✓
	F: UEE in products and services consumed by the city government (key infrastructure SC)	–	–	–	–	✓	✓	✓
	G: Same as for F for non-key infrastructure and non-infrastructure SC	–	–	–	–	✓	–	✓
Scope 2 ^a	A: Electricity use in privately owned buildings and cars (households)	–	✓	✓	✓	✓	✓	✓
	B: Electricity use in privately owned buildings and cars (businesses and industries)	–	✓	✓	–	✓	✓	✓
	C: Electricity use in city-owned buildings, spaces and cars (government)	–	✓	✓	–	✓	✓	✓
Direct (geographically in-boundary)								
Scope 1	A: Direct household emissions (i.e. buildings and transport)	✓	✓	✓	✓	✓	✓	✓
	B: Direct city government emissions (i.e. buildings and transport)	✓	✓	✓	–	✓	✓	✓
	C: Direct commercial emissions (i.e. buildings and transport)	✓	✓	✓	–	✓	✓	✓
	D: Direct visitor emissions (i.e. transport)	✓	✓	✓	–	–	✓	✓
	E: Direct emissions from in-boundary production of goods and services to satisfy in-boundary demand	✓	✓	✓	✓	✓	✓	✓
	F: Direct emissions from in-boundary production of goods and services to be exported	✓	✓	✓	–	–	✓	✓
	G: Direct emissions from in-boundary landfill/treatment of waste	✓	✓	✓	–	–	✓	✓
	H: Direct emissions from in-boundary land use, land-use change and forestry (LULUCF)	✓	✓	✓	–	–	✓	✓
Indirect downstream (geographically out-boundary)								
Scope 3	H: DEE in products and services consumed by households (key infrastructure SC)	–	–	✓	o	o	✓	✓

(Contd.)

Items in Scope 1–3 emissions	SB1: PBA	SB2: PBA plus imported electricity	SB3: SB2 plus waste	SB4: CBA (only households) ^b	SB5: CBA (all) ^b	SB6: CIFA	SB7: Complete (full Scope 1–3)
I: Same as for H for non-key infrastructure and non-infrastructure SC	–	–	✓	o	o	–	✓
J: DEE in products and services consumed by businesses and industries (key infrastructure SC)	–	–	✓	–	o	✓	✓
K: Same as for J for non-key infrastructure and non-infrastructure SC	–	–	✓	–	o	–	✓
L: DEE in products and services consumed by city government (key infrastructure SC)	–	–	✓	–	o	✓	✓
M: Same as for L for non-key infrastructure and non-key infrastructure SC	–	–	✓	–	o	–	✓

Notes: ^a Grid-supplied energy may or may not cross city boundaries.

^b Additional system boundaries to SB4 and SB5 could be derived for CBA if a distinction is also made between key and non-key consumption sectors. To avoid an impractical enlargement of the table, this was not done.

DEE, downstream embodied emissions; SB, system boundary; SC, supply chains; UEE, upstream embodied emissions. An 'o' denotes that the inclusion highly depends on whether this component forms part of the product data.

Murakami *et al.* (2020). System boundary type 1 (SB1) is identical to PBA and Scope 1 emissions, while system boundary type 2 (SB2) amounts to the sum of Scopes 1 and 2 emissions and can be seen as a simplified version of CIFA. The latter is the most applied system boundary by cities (Nangini *et al.* 2019) and is the one required in some of the 'older' city-level carbon accounting protocols, as shown in the Appendix. System boundary type 3 (SB3) additionally includes Scope 3 emissions related to waste, which is a mandatory option in basic reporting of the GPC (WRI *et al.* 2014). Indeed, many cities already have bottom-up activity data on waste (*e.g.* tonnes of waste sent to landfill, recycling treatment facilities, *etc.*) obtained through waste audits (Broekhoff, Erickson & Piggot 2019).

System boundary type 4 (SB4) and type 5 (SB5) represent two different kinds of CBA. The former exclusively focuses on consumption-based emissions caused by households or residents of the city under consideration. The latter covers the total final consumption irrespective of who are the consumers, *i.e.* households, government or capital formation (see also section 3.2). As pointed out by Ottelin *et al.* (2019) and Heinonen *et al.* (2020), these two types of consumption-based accounts, respectively referred to as 'personal carbon footprint' and 'aerial carbon footprint' by these authors, differ significantly in their scope, although they are often reported under the same label. Specifically, the magnitude of personal carbon footprint can be lower by around 10–50% compared with aerial carbon footprint, with the higher percentages being reported for developing countries because of increased construction activities accompanying economic and population growth (Heinonen *et al.* 2020). Finally, system boundary type 6 (SB6) is identical to CIFA, while system boundary type 7 (SB7) equals the sum of all scopes—therefore, the sum of SB2 emissions and the life cycle emissions (up- and downstream) of all net imports (infrastructure and non-infrastructure).

When the goal of a GHG emission inventory is to identify as many emission 'sources' and 'inducers' as possible, except for SB7, no accounting system boundary is shown to be automatically more comprehensive; they are complementary, since they cover different—albeit overlapping—energy and material flows, and therefore inform different mitigation policies. However, for 'newcomer' cities without any prior history in regular GHG inventorying, perhaps simplicity, and a focus on the core emission categories a city has direct control over, are more favourable attributes of an accounting system boundary than completeness. This is also argued by Erickson & Morgenstern (2016), who suggest that cities should put more emphasis on relevance in their GHG accounting than anything else.

3.1.3 Evaluation of policy relevance

Each of the GHG accounting methodologies and system boundaries has strengths and weaknesses that complement each other when it comes to informing mitigation policy. They are also associated with different levels of effort for conducting them. **Table 2** summarises the degree of relevance of the various system boundaries (*i.e.* those presented in **Table 1**) for selected local policy interests/purposes. Some were discussed in previous studies (*e.g.* Broekhoff, Erickson & Piggot 2019; Chavez & Ramaswami 2011, 2013; Ramaswami *et al.* 2011; Chen *et al.* 2019; Ottelin *et al.* 2019; Yetano Roche *et al.* 2014). These are worthy of further exploration within the context of the seven SBs, the increasing policy interest to develop local carbon budgets aligned with the global carbon budget for the 1.5 or 2°C scenarios (Arup & C40 2016: 29), and the traditional policy interest in identifying the most economical strategies due to budget constraints which, surprisingly, is not mentioned in the related literature.

In short, it can be concluded that SB1 is the easiest to apply due to the higher degree of data availability compared with the other SBs and for tracking emissions over time based on local policy outcomes. Despite possible problems with

Table 2: Relevance analysis of the seven types of system boundaries for carbon accounting to common cities' policy interests.

Policy interest	SB1	SB2 and SB3	SB4 and SB5	SB6	SB7
Prevents burden-shifting from within the city boundary to the outside boundary	✓ Shifts the burden to the producing cities	✓ Same as for SB1 to a lower degree	✓✓ Shifts the burden to consuming cities in the case of considerable exports	✓✓✓ High relevance	✓✓✓ High relevance
Tracks the impacts of infrastructure development/transitions and links local and regional actions (<i>i.e.</i> multilevel planning and policy)	✓ Most infrastructures exceed beyond the city boundaries	✓✓ Limited transboundary focus, only energy supply and/or waste	✓ Leaves out infrastructure serving exporting industries	✓✓✓ High relevance	✓✓✓ High relevance
Links in-boundary-occurring greenhouse gas emissions to local air pollution, urban heat islands and local public health impacts	✓✓✓ High relevance	✓✓✓ High relevance	✓ Consumption-based allocation, not location based	✓✓ Use-based allocation, not location based	✓✓ Same as for SB6
Is relevant to urban planning for whole communities and the design of circular economy strategies	✓✓ Considers only producers	✓✓ Same as for SB1 to a lower degree	✓✓ Considers only consumers	✓✓✓ High relevance	✓✓✓ High relevance
Makes transboundary supply chain risks/vulnerabilities visible	✓ Most infrastructures exceed beyond the city boundaries	✓✓ Limited transboundary focus	✓ Allocates emissions after consumption occurs	✓✓✓ High relevance	✓✓✓ High relevance
Enables using per economic output metrics	✓ Most infrastructures exceed beyond the city boundaries	✓✓ Limited transboundary focus	n.a. Per economic output metric is falsely applied	✓✓✓ High relevance	✓✓✓ High relevance
Enables using per capita metrics to inform residents and households and engage them in climate action	n.a. Per capita metric is falsely applied	n.a. Per capita metric is falsely applied	✓✓✓ High relevance	✓ Per capita metric is not fully suitable	✓ Per capita metric is not fully suitable
Enables fair carbon budgeting based on the global carbon budgets	n.a. Per capita metric is not applicable	n.a. Per capita metric is not applicable	✓✓✓ High relevance	✓ Per capita metric is not fully suitable	✓ Per capita metric is not fully suitable
Facilitates public communication	✓ Economic activity metrics do not highlight the impacts of a citizen's lifestyle	✓ Same as for SB1	✓✓✓ High relevance	✓✓ Matches adequately the major activities in carbon calculators for individuals	✓✓✓ High relevance
Directs at strategies resulting in cheaper and quicker solutions to reduce emissions	✓ Targeting territorial emissions is less economic than targeting consumer behaviour	✓✓ Directs only to some consumption-reducing strategies	✓✓✓ High relevance	✓✓ Directs only to some consumption-reducing strategies	✓✓✓ High relevance

(Contd.)

Policy interest	SB1	SB2 and SB3	SB4 and SB5	SB6	SB7
Avoids double counting of emissions (therefore, also of reductions) if multiple cities' emissions are aggregated	Yes	No, multiple cities' emissions cannot be simply aggregated	Yes	No, multiple cities' emissions cannot be simply aggregated	No, same as for SB6
Data quality and availability, less uncertainty	✓✓✓ High relevance	✓✓ Electricity use data often are protected	✓ Often based on downscaled input-output data	✓✓ Same as for SB2 and SB3	✓✓ Same as for SB2 and SB3
Aligns well with existing international reporting standards	✓✓✓ Aligns well with IPCC national inventory	✓✓✓ Aligns well with the GPC Basic	✓ Aligns well with PAS 2070	✓✓✓ Aligns well with GPC Basic+	n.a. No such standard exists yet

Notes: ✓✓✓, high relevance; ✓✓, medium relevance; ✓, low relevance; and n.a., not applicable; explanations are provided where necessary.

GPC, Global Protocol for Community-Scale Greenhouse Gas Emission Inventories; IPCC, Intergovernmental Panel on Climate Change; PAS, Publicly Available Specifications.

Sources: The table synthesises conclusions from Broekhoff, Erickson & Piggot (2019), Chavez & Ramaswami *et al.* (2011, 2013), Ramaswami *et al.* (2019, 2020), Ottelin *et al.* (2019) and Yetano Roche *et al.* (2014), organised and complemented according to the present author's understanding of the key messages.

collecting primary energy use and transport data due to confidentiality issues and the high cost of processing, among others (Yetano Roche *et al.* 2014), it is nowadays becoming increasingly possible to measure even low CO₂ concentrations with high-resolution measurements with the help of remote sensing—a valuable opportunity, particularly for cities in the Global South, to tackle data scarcity (Creutzig *et al.* 2019). Moreover, it provides the best platform to demonstrate the direct contributions of climate policy to tackle local impacts such as air pollution, microclimatic and health effects, in addition to the intended emission reductions (Chavez & Ramaswami 2013; Yetano Roche *et al.* 2014). This is important not only in terms of delivering multiple benefits at once in a cost-effective way, but also clearly showing the added value to citizens and civil actors (who are inclined to care more about visible and local issues) and motivating them to actively participate in climate action (Balouktsi & Lützkendorf 2020). An additional benefit of SB1-based GHG inventories is that they are compatible with IPCC-based national accounts (Chen *et al.* 2019), which means that cities can evaluate how they perform compared with the normalised national emission values without performing significant adjustments in their inventories as well as consistently inform the nationally determined contribution (NDC) with the provision of high-resolution local data.

Finally, SB1 also avoids the risk of double counting (Chen *et al.* 2020; Yetano Roche *et al.* 2014), whereas most other SBs do not. In general, if GHG emissions reporting is not combined with other cities, the issue of double counting becomes trivial for any SB. However, if data from multiple cities are aggregated into greater spatial scales, *e.g.* a region, and double counting of inter-city carbon flows cannot be prevented, then the actual GHG emissions of this region could end up being greater than the reported aggregated achievement of these cities (Schneider *et al.* 2019). As Chen *et al.* (2020) show in their quantitative assessment of the effects of double counting induced by the bilateral trade between four Chinese megacities, the effect is amplified and becomes worthy of caution with an increasing number of cities.

SB4 and SB5 are more appropriate for engaging individuals and households directly in climate action process, as the impacts of their lifestyle are highlighted. These approaches avoid burden-shifting from the direct emissions to embodied emissions which are out of sight in SB1. For example, the significant proportion of embodied emissions in construction materials used in high energy-efficient retrofitting of the old building stock or building new net-zero buildings stays 'hidden' (Röck *et al.* 2020). These two policy interests are also satisfied by SB7, and partly by SB6 as household consumption of the seven key sectors can still inform households and encourage action on these sectors. However, SB4, SB5 and SB7 are the only methods that can provide information to the citizens on the impacts of the goods they regularly consume, such as clothing, furnishing and household equipment (which, in some regions, are shown to be more important than, for instance, private transport from a CBA perspective; C40 Cities 2018). SB4 and SB5 also provide a sound base for fairly sharing out the global GHG emissions budgets; it is a well-known fact that consumption-based emissions of all wealthy cities of the Global North are at least twice as high as the global average, and therefore these cities should take more responsibility for mitigating global climate change (Broekhoff, Erickson & Piggot 2019).

SB6 and SB7 (and partly SB2 and SB3) are most useful for informing infrastructure planners as they address the community as a whole—both producers and consumers—allowing for cross-infrastructure and cross-regional strategies (*e.g.* circular economy strategies). They also illustrate several sustainability co-benefits and trade-offs associated with the full infrastructure supply chain, including future vulnerabilities (Chavez & Ramaswami 2013; Chen *et al.* 2019). The demonstration of the lower (in overall) environmental and social costs of low carbon infrastructure to public and private infrastructure investors, which can compensate the higher upfront costs than its environmentally damaging alternatives, is particularly important for cities/regions with budgetary constraints (Granoff, Hogarth, & Miller 2016). In terms of global cross-city comparisons SB2, SB3 and SB6 align well with existing reporting standards, while consumption-based approaches are far less standardised (see the Appendix). However, it is important to highlight that for meaningful cross-city comparisons of mitigation efforts the application of the same system boundaries, methodologies and reporting standards is not adequate (Balouktsi & Lützkendorf 2020). This is further discussed in section 6.3.

On the whole, no single city-level carbon accounting method can take every possible uncertainty and unforeseeable event into consideration (Chavez & Ramaswami 2013; Chen *et al.* 2019). Chen *et al.* (2019) stress: to assist policy-makers to choose the right method for their intended purpose, it is necessary to clearly communicate not only what the different methods measure but also what their particular focus is. **Table 2** can serve as a starting point in this direction. If the primary objectives of climate action plans are to address as many policy questions/interests and relevant actors as possible, then several methods should be used in parallel.

3.2 Categorisation of emissions

In addition to the decision of how to define system boundaries and which sources to include in an inventory, the breakdown itself, here referred to as 'categorisation', can also be a source of uncertainty (Wattenbach *et al.* 2015). For example, two cities may use the same GPC reporting levels, but allocate their mixed-use buildings in different subsector categories, since GPC only distinguishes between 'residential buildings' and 'commercial and institutional buildings and facilities'.

So far, there is no uniform and generally accepted typology of sources or consumer needs in the form of an International Organization for Standardization (ISO) standard that cities may turn to for guidance. However, for sector-based structures, GPC can now be considered as a form of 'international protocol'. This is the reporting standard recommended by the Global Covenant of Mayors for Climate and Energy, as well as by ISO 37120 (2018) as a 'multi-stakeholder consensus-based protocol for developing international recognised and accepted community-scale GHG accounting and reporting'. Influenced by ISO's recommendation, sustainability assessment standards for cities, such as CASBEE-City, already suggest the use of the GPC to calculate GHG emissions (Kawakubo *et al.* 2018). As the Carbon

Disclosure Project (CDP) database reveals, many leading cities are also increasingly shifting towards the GPC standard (CDP 2019). This may be due to cities' membership in particular networks supporting this standard (*e.g.* C40 Cities report their emission data according to this standard), but also because they recognise GPC as a better-formulated emissions accounting scheme than the national calculation methods in place, which are often outdated (Dahal & Niemelä 2017).

No single prescribed way exists for categorising emissions in CBA-based inventories (Broekhoff, Erickson & Piggot 2019), neither as a universal standard nor as a widely accepted protocol. Only some national standards exist such as Publicly Available Specifications (PAS) 2070 (BSI 2013) and the US Community Protocol (ICLEI—Local Governments for Sustainability USA 2019) (see the Appendix). In practice, various groupings of consumption categories can be an obstacle for aggregating consumption-based inventories at subnational and national levels. Moreover, standardised methods or reporting formats help local governments to verify their claims which is important as part of international or national climate-linked funding (Haarstad 2020). Therefore, what categorisation of emissions will be most useful for identifying and developing policy actions is still questionable.

Many cities account for only the household consumption in their CBAs (Ottelin *et al.* 2019). Therefore, the city's per capita GHG emissions is equal to the average individual carbon footprint. However, the other two key consumers need to be included: local government itself, and business investment in capital formation (Broekhoff, Erickson & Piggot 2019), *i.e.* investment in physical assets such as infrastructure and building construction (C40 Cities 2018). For example, the recently published C40 report explored the situation on a relative basis and showed that capital formation is most significant for cities in East and Southeast Asia, while government services are important in most regions (C40 Cities 2018).

A separate treatment of the emissions induced by these three categories of 'consumers' is especially useful for identifying actor-specific mitigation options. For instance, government purchasing decisions that support markets for sustainable goods and services can decrease consumption and also serve as a role model influencing other actors (Broekhoff, Erickson & Piggot 2019). Likewise, controlling capital investment can have an unparalleled potential to reshape urban consumption (Li *et al.* 2018). This applies to both the replacement of existing infrastructures and the provision of new ones particularly in Global South (Ramaswami *et al.* 2016; Sebi *et al.* 2019; WEF 2016: 12). The investments in new construction and infrastructure are important when studying the impacts of urbanisation on a city's carbon footprint (Ottelin *et al.* 2019). For example, building contractors' use of cement is arguably a consumer choice that ultimately leads to emissions associated with the latter (C40 Cities 2018). Therefore, the separation of these consumers can help to identify additional policy actions that would otherwise stay invisible.

When these three categories are combined into one per capita value, as is usually the case in CBA accounts, methodological complexities regarding how to allocate government consumption and capital investment to 'residents' exist. To better understand the effects of business and government investments on emissions, and the related allocation issues, Chen *et al.* (2018) highlight the need for further studies. Currently, most studies follow a simplified solution, which is to give equal shares of investments and government consumption to all residents of the urban area, since there are usually no data available for more personalised allocation (Heinonen *et al.* 2020; Ottelin *et al.* 2019).

Urban policy-makers can also benefit from knowing the geographical locations of upstream emissions and therefore how global their supply chains are (Pichler *et al.* 2017). Such a detailed spatial analysis of carbon flows can help cities have a better understanding of optimisation possibilities of their upstream supply chains (Chen *et al.* 2020). For examples of such supply-chain tracing exercises, see Pichler *et al.* (2017) and Chen *et al.* (2020).

3.3. Coverage of GHG species

Different reporting standards require the reporting of different GHGs (see the Appendix). This has generated confusion regarding which GHGs to include or exclude from the emissions accounting and reporting (Wright, Kemp & Williams 2011). As revealed in a recently developed global data set of data related to emissions for hundreds of cities (built upon data reported on the CDP and the carbon *n* Climate Registry among others), a significant proportion of cities reported only the CO₂ emissions from fossil fuels and cement manufacturing processes (process-based emissions) and neglected other non-CO₂ GHGs (Nangini *et al.* 2019). The reason for this can often be attributed to the non-inclusion of these types of emissions in the different available accounting tools (Lützkendorf & Balouktsi 2019). For example, the baseline emission inventory (BEI) by EU-COM (2010) only requires the reporting of CO₂ (see the Appendix).

However, non-CO₂ GHGs cause up to 40% of global GHG emissions depending on the activities included in an inventory and should therefore not be omitted from inventarisation, target-setting and mitigation strategies (BBSR & BBR 2017). A common policy implication of neglecting non-CO₂ GHG emissions is that the importance of certain emission-inducing activities may stay unseen. For example, the importance of food production and consumption activities in the overall emissions highly depends on whether nitrous oxide (N₂O) and methane (CH₄) are considered (Heinonen *et al.* 2020). Given the significant impact of non-CO₂ GHGs, the challenges faced during data complication cannot be used as an excuse for excluding emissions from climate change indicators, since data availability will improve over time (Moss, Lambert, & Rennie 2008). Against expectations, many cities do not account for all legislatively controlled GHGs under the Kyoto Protocol (Nangini *et al.* 2019), despite the inclusion of these gases in most existing GHG accounting and reporting standards. Instead, most cities adopt a middle-road approach, accounting only for CO₂, N₂O and CH₄ (Nangini *et al.* 2019). Examples are Swedish and Finish municipalities (Dahal & Niemelä 2017).

There is currently an interest from policy-makers in reducing emissions of short-lived climate pollutants (SLCP) (Stohl *et al.* 2015), and even more after the clear statement in the IPCC (2018) special report on *Global Warming of 1.5°C* that

emissions of CH₄ and black carbon (BC) need to be reduced by 35% or more by 2050 if warming is to be kept <1.5°C. However, the Kyoto basket of seven gases—i.e. CO₂, CH₄, N₂O, hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), SF₆ and NF₃—does not cover BC. The latter is mainly a local and regional air pollutant with a much stronger global warming potential (GWP) compared with CO₂, but a very short atmospheric lifetime (about a week). There is presently no consensus regarding the most appropriate accounting metrics to use for BC, and the typical CO₂-equivalent metric used for GHGs is not easily applied (Chavez & Ramaswami 2012). Indeed, the Science Advisory Panel of the Clean Air and Climate Coalition (CCAC) recommends avoiding integrating BC and CO₂ into the same metric since these two gases influence climate on different time and spatial scales, and through different physical mechanisms (CCAC 2018). Therefore, reductions in near- and long-term climate change pollutants should be preferably considered as separate issues with separate mitigation approaches that are complementary.

The emissions of BC need to be addressed not only in relation to their role in affecting air quality and human health (*e.g.* Janssen *et al.* 2011; Meng *et al.* 2016), but also for their role in climate change. Future GHG accounting protocols require an additional indicator for the quantity of BC emissions to GWP100 (or GWP20, since it is an indicator already examined by some cities, *e.g.* New York City; City of New York 2017).

4. Target-setting approaches to achieve net-zero emissions

Once a GHG inventory is defined, the next question that arises is how to establish time-bound, ambitious yet achievable and robust GHG-emission reduction targets to assess the city's progress in achieving them. According to the CNCA (2014) the GHG (or carbon/CO₂) emissions reduction target is the most important concept around which cities share somewhat different views and terms. **Tables 3** and **4** provide essential details of the methodologies behind the net-zero targets adopted by some cities, to illustrate their differences. To the extent possible, the cities are drawn from different continents. Specifically, **Table 3** analyses the carbon metrics behind the targets, while **Table 4** examines the target elements that are independent of the inventorying process. Part of the information was taken by the official action plans (or technical background reports) of the cities, and others by the CDP platform.

Of course, methodological differences in inventories automatically cause variations in targets, even when they seem to be outwardly the same. However, notwithstanding that the 'inventory scope' strongly influences the 'target scope', these two scopes are not and should not necessarily be identical. Although the city authorities are responsible for the generation of the GHG inventory, they are not exclusively responsible for all the emissions reported; some sources can only be influenced on a national level. For example, some cities are dominated by emissions from large point sources, such as industrial facilities and power plants (usually serving demands far beyond the city boundary), over which they have little influence. Therefore, regardless of the inventorying standard used, when it comes to target-setting, emission targets are sometimes not set for the entire suite of emission sources (activities in a city) represented and accounted in the GHG inventory, but only for the ones over which the city governments have the greatest direct influence. While setting goals over all (or nearly all) emissions makes sense at national level as part of the intended nationally determined contributions (INDCs) submitted under the Paris Agreement, this may be counter-productive for city-scale GHG inventories (Erickson & Morgenstern 2016).

This approach is particularly favoured in the case of 'net-zero emission' or 'climate neutrality' targets (or conceptually similar targets such as 'carbon neutrality', 'energy independence' and '100% fossil-fuel free'). For city examples with such targets, see Lützkendorf & Balouktsi (2019). Many cities follow a step-by-step approach. They often start from the target of establishing a 'GHG neutral' city administration and therefore concentrate their efforts on first achieving a balance for the municipality operations (**Table 3**, *e.g.* Melbourne's scope of emissions). However, cities should initially exclude such emissions only from the balance, and not from the list of necessary actions. Influencing direct emissions caused by industry is also essential for reducing impacts to local environment, in addition to GHGs.

In relation to Scopes 1–3, cities striving for net-zero emissions or neutrality typically include Scopes 1 and 2 emissions in their target scope, with some partly extending into Scope 3. However, some cities have begun to experiment with consumption-based inventories as complementary accounts and include them in their plan together with related actions, *e.g.* City of Seattle, but without including these emissions in their carbon neutral scenario analysis (Lazarus *et al.* 2011). Other cities, such as New York City, declare such an intention in their plan for future updates (City of New York 2017). These are good examples of a dual strategy to exploit all possibilities for action, showing that the 'action scope' should always be larger than the 'target scope'. The inclusion of Scope 3 emissions either as a complementary target-setting package according to the 'community-wide infrastructure approach' or 'consumer-based' approach or only as part of the recommended actions is also useful for bringing citizens and local stakeholders 'on board' as end-users and encouraging them to assume responsibility, since the share of emissions caused directly by municipality often is rather small. As highlighted by Lützkendorf & Balouktsi (2019) the time is ripe for using additional accounting approaches in city-level target-setting as the window of opportunity to influence consumption patterns is huge.

4.1 Choice of reference unit

In the context of net-zero emission targets, the necessary emission reductions are usually expressed in total emissions (**Table 4**). However, the emission quantities can be expressed using different units and/or methods of normalisation. The most common ones are per capita and per gross city product (GCP) or gross domestic product (GDP). In general,

Table 3: Description of the carbon metrics behind the conceptual targets of selected cities.

Examples of cities	Population (as of 2018)	Launch date	Target statement	Carbon metric behind the target		
				Type of greenhouse gas (GHG)	Scope of emissions	Emission sources
Bristol	671,000	2020	'Carbon neutral' and climate resilient by 2030 (Bristol One City 2020)	CO ₂ , CH ₄ , N ₂ O, HFCs, PFCs, SF ₆ , NF ₃	Scopes 1 and 2/SB2 CBA accounts are in place to support separate carbon neutral 2030 objectives for 'all public service organisations' and 'all businesses and organisations'	Energy, transport, waste
Cape Town	3.8 million	2018	'Carbon neutral' by 2050 (Davis 2019)	CO ₂ , CH ₄ , N ₂ O	Scopes 1–3 (as per GPC Basic+)/SB6 CBA accounts are also in place; unclear whether it is part of the target	Buildings, transport, waste CBA structure: COICOP: classification of individual consumption according to purpose
Copenhagen	633,021	2012	'Carbon neutral' by 2025 (City of Copenhagen 2012)	CO ₂	Scopes 1 and 2/SB2	Energy consumption, energy production, mobility, city administration initiatives
Helsinki	1.2 million	2018	'Carbon neutral' by 2035 (City of Helsinki 2018)	CO ₂ , CH ₄ , N ₂ O	Scope 1 and 2/SB2	Electricity, heating, traffic, waste management, industry and machinery, agriculture
London	8.9 million	2018	'Zero carbon' by 2050 (GLA 2018)	CO ₂ , CH ₄ , N ₂ O	Scope 1 and 2(excluding waste)/SB2(excluding Scope 1C). Although waste-related full life cycle emissions (Scopes 1–3) are not included in the pathway to zero carbon, their accounting, as well as related action, are integrated into London's circular approach to waste	Buildings (residential and non-residential), transport (river, road, rail, aviation)
Melbourne	4.9 million	2016	'Carbon neutral' by 2020/21 (City of Melbourne 2016)	CO ₂ , CH ₄ , N ₂ O	Scopes 1 and 2 (only municipal operations), Scope 3 (calculated emissions as obtained by the suppliers of the city government)/SB6 (excluding Scope 1A, 1C–G, 2A–B, 3B, D, H, J)	Municipal buildings, streetlights, energy supply. Scope 3 structure: unclear
New York City (NYC)	8.4 million	2017	'Carbon neutral' by 2050 (City of New York 2017)	CO ₂ (distinction between fossil and biogenic), CH ₄ , N ₂ O. GWP20 is also calculated	Scopes 1–3 only waste (as per GPC Basic)/SB3 (excluding Scope 1H). The city intends to include consumption-based accounting in future, without a clear statement on whether this could be also translated into a target	Two inventories: city-wide inventory (follows GPC Basic), city government inventory (follows the Local Government Operations Protocol—LGOP)
Seattle	724,745	2011	'Carbon neutral' by 2050' (Lazarus <i>et al.</i> 2011)	CO ₂ , CH ₄ , SF ₆	Scopes 1 and 2/SB2 (excluding Scope 1H). Scope 3 emissions are measured, and related actions are recommended, but are not part of the target	Transportation (road), building energy (residential and commercial), waste Scope 3 structure: raw materials, manufacturing, transportation, retail, product use and disposal

Table 4: Description of elements specific to the targets of selected cities.

Examples of cities	Reference unit	Baseline year	Target-specific elements			Removals and compensations/offsets
			Use of scenarios	(a) Target year (b) Intermittent targets/budgets		
Bristol	tonnes CO ₂ e	2017	Baseline (BAU) scenario: unclear	2030		Assumed residual emissions level: unclear. Treatment: unclear in terms of the specific measure; the timing of offsetting will be close to 2030 to avoid shifting the focus from the actual reductions
Cape Town	tonnes CO ₂ e	2012	Baseline (BAU) scenario: unclear. Existing national/regional actions are shown as a separate trajectory	(a) 2050 (b) 2030		Assumed residual emissions level: unclear. Treatment: unclear
Copenhagen	tonnes CO ₂	2005	Baseline (BAU) scenario: unclear	(a) 2050 Climate neutral (b) 2025 Carbon neutral		Assumed residual emissions level: 20%. Treatment: provision of excess wind power to the electricity grid
Helsinki	tonnes CO ₂ e and per capita tonnes CO ₂ e	1990	Baseline (BAU) scenario: population growth plus employment growth plus traffic growth plus changes in heating demand plus existing political measures and actions	(a) 2035 (b) 2030		Assumed residual emissions level: 20%. Treatment: no concrete plan, two possibilities are discussed: implementation of emission reductions outside the city or increase in carbon sinks
Melbourne	tonnes CO ₂ e	2010	Baseline (BAU) scenario: unclear	2020/21		Assumed residual emissions level: 20%. Treatment: purchase of offsets in line with Australia's National Carbon Offset Standard (NCOS)
London	tonnes CO ₂ e	1990	Baseline (BAU) scenario: population growth plus existing policies driving emissions reduction at a national and city level Additional scenario to baseline: grid electricity decarbonisation in line with policies to achieve national carbon budgets	(a) 2050 (b) Five-year carbon budgets for the period 2018–32		Assumed residual emissions level: 10%. Treatment: no concrete plan, only general statement 'These will need to be offset through negative emissions technologies such as carbon capture and storage or tree planting'
New York City (NYC)	tonnes CO ₂ e. 'Per capita' and 'per gross city product' metrics are also used in the inventory	2005	Baseline (BAU) scenario: population growth plus gross city product development	(a) 2050 (b) 2030		Assumed residual emissions level: 15%. Treatment: inclined towards biological carbon removal from forestry or agriculture. A precondition is that residual emissions will be reserved for facilities/processes where the technology for full elimination of carbon is still commercially unavailable
Seattle	Per capita tonnes CO ₂ e	2008	Baseline (BAU) scenario: population growth plus income growth plus number of households plus employment growth plus vehicle-miles travelled plus changes in vehicle fuel economy plus existing local actions plus changes in energy use intensity plus trends in fuel switching (buildings) plus others	(a) 2050 (b) 2030		Assumed residual emissions level: 10%. Treatment: different options are abstractly discussed, such as broadening and deepening the suite of reduction strategies, taking credit for emissions reductions (or sequestration) occurring outside of the city, generating and selling 'excess' low-carbon electricity not needed in the city, or purchasing GHG offsets

Note: BAU, business-as-usual.

the indicator GHG emissions per capita and year is becoming central in the global debate and has already been adopted by several cities regardless of the accounting method used to yield a city's aggregate GHG account. Indeed, ISO 37120 (2018) proposes that GHG emissions of cities are measured on a per capita basis to compare mostly source-based (Scopes 1 plus 2) inventories.

Several challenges are associated with using per capita metrics for PBA- or CIFA-based inventories and targets (*i.e.* all SBs in **Table 1** other than SB4 and SB5). For example, Ramaswami & Chavez (2013), who modelled 20 US cities, found that cities with low commercial–industrial activity reported $\text{GHG}^{\text{CIFA}}/\text{capita}$ emissions much lower than the national average, despite not being more efficient than others based on local transportation or buildings energy intensity benchmarks. Instead, they found that $\text{GHG}^{\text{CIFA}}/\text{unit GDP}$ was highly correlated with urban energy intensity features (Ramaswami & Chavez 2013). A shift to dual methods (CIFA and CBA) is now proposed by different reporting protocols (*e.g.* ICLEI—Local Governments for Sustainability USA 2019; BSI 2013) (see the Appendix). Different organisations such as C40 Cities (2018) use this approach and it is expected to be officially adopted in the future by several cities (*e.g.* NYC) (**Table 3**). The use of different normalising metrics is necessary to accompany the different methods for GHG accounting. Having two widely different numbers for the same city, both expressed in per capita emissions, will complicate public understanding. For example, two different studies conducted for Delhi in India, one following the infrastructure-based method (Chavez *et al.* 2012) and the other the consumption-based method (Pichler *et al.* 2017), resulted in two different GHG footprints of 2.4 and 1.9 $\text{tCO}_2\text{e}/\text{cap*year}$, respectively.

Given all the above, the present paper supports the recommendation by Ramaswami & Chavez (2013) to use:

- per capita metrics for CBA-based inventories/targets because they are shown to be the metric best representing expenditure variations; and
- economic activity metrics for CIFA-based ones because they are shown to be the most suitable metric to track urban energy/carbon efficiency variations.

It would also be useful to track carbon efficiency per individual sector (and therefore have sector-specific metrics) (Ramaswami & Chavez 2013) to support sector-specific carbon neutrality targets.

4.2 Treatment of temporal aspects

4.2.1 Use of scenarios

Basing climate action planning on a long-term target requires understanding the baseline emissions scenario(s), also referred to as business-as-usual (BAU) emissions scenarios. BAU represents the future emissions with the highest probability of occurrence in the absence of a mitigation target. The development of a realistic BAU trajectory requires a wide variety of inputs, such as historical data on critical GHG emission drivers, assumptions about how these drivers are expected to change, and information on sector-specific policies already in place that may cause these changes (Levin *et al.* 2014, Lützkendorf & Balouktsi 2019). As seen in **Table 4**, some cities restrict themselves to the essentials; they only consider the projected changes in population and economic development for the city to the target year. However, current best practice also incorporates 'sector-specific trends and considerations, appropriate to the local context', such as the anticipated changes in sectoral energy intensity as well as the carbon intensity of the electricity grid (NYC Mayor's Office of Sustainability & C40 Cities 2019). Additionally, instead of mixing all factors into one BAU trajectory, it would be beneficial to separate external factors from internal factors. External factors capture uncertainties emerging from events outside the control of the city authority (demographic, economic and technological developments, as well as national policies). Internal factors (future developments of existing local policies and programmes) reflect the city's own power to achieve emission reductions (Lützkendorf & Balouktsi 2019). Given the fundamental uncertainties in predicting or forecasting the distant future (*i.e.* especially for target horizons longer than 10 years), multiple BAU scenarios are needed to guide the formulation of robust targets and policies—instead of a single BAU scenario which is currently the common practice.

A target scenario represents the cities' estimated impacts on future GHG emissions caused by existing and planned actions (depending on whether action planning precedes or follows target-setting), and thus it shows the reduction pathway. The distance between a city's BAU and target scenario equals the emissions savings. The establishment of a robust BAU trajectory and a GHG emissions reduction trajectory (or carbon budget) enable cities to determine the level of residual emissions that will need to be addressed by the target year in order to reach a carbon neutrality target (NYC Mayor's Office of Sustainability & C40 Cities 2019). Scenario development as a process can also serve another purpose: to support and stimulate larger scale discussions with non-experts and enlarge the circle of decision-making through workshops (Lützkendorf & Balouktsi 2019).

4.2.2 Target year

Another question that arises when formulating targets is how to decide upon the calendar year in which the end target, *e.g.* net-zero emissions, needs to be achieved. The most typical target year is 2050 (**Table 4**). However, a shift from 2050 to 2030 is called for because the problem of climate change is becoming more pressing (*e.g.* Bristol recently declared climate emergency and shifted its 2050 carbon neutral target to 2030; Bristol One City 2020). Details of this are shown in **Table 4**. Perhaps this could also imply a form of competition among cities regarding which one will be the first to achieve the 'carbon neutral' status.

Interim targets as near-future milestones are needed to support the longer time frames with an overarching target (Lützkendorf & Balouktsi 2019). Interim milestones increase the particularity and practicality of the climate plan, as well as the sense of urgency, responsibility and political commitment (*i.e.* shows clear intention to do more, sooner and not wait to dramatically reduce emissions). This enhances the overall credibility of the 'reduction path' (Kramers *et al.* 2013). Indeed, **Table 4** shows that most of the cities with targets beyond 2025 have also interim targets in place. Lützkendorf & Balouktsi (2019) provide more city examples.

The target year and interim milestones also define the timing of the carbon offsetting or negative emissions deployment (*i.e.* the treatment of the negative part of the net-zero balance). This is often less transparently presented, if not at all, in cities' action plans (**Table 4**). Depending on the financial, regulatory, sociocultural and physical context within which they operate, cities may decide to start addressing residual emissions ahead of their target year or wait until close to the target year before doing so (NYC Mayor's Office of Sustainability & C40 Cities 2019). The potential benefits and disadvantages or risks to both timing approaches were presented in the recently published guideline on how to manage residual emissions within carbon neutrality by the NYC Mayor's Office of Sustainability & C40 Cities (2019). In sum, treating residual emissions too early involves the risk of shifting attention away from mitigation and of draining its dedicated resources, whereas waiting until the very last moment, especially in the case of carbon removal, involves time constraints to test the effectiveness of solutions (McLaren *et al.* 2019; NYC Mayor's Office of Sustainability & C40 Cities 2019). Technologies found to be ineffective too late can lead to reputational and ethical issues, as the consequences are to be borne by future generations (NYC Mayor's Office of Sustainability & C40 Cities 2019).

4.3 Treatment of residual emissions

The aspiration to achieve the status of 'carbon neutrality' often involves commitments on 'carbon removal' (natural, technological or combined) or 'carbon offsetting/compensation'. In the local climate action plans where such commitments are absent, cities define 'carbon neutral' or 'climate neutral' as the achievement of a certain 'carbon budget', *e.g.* Berlin (Hirschl & Harnisch 2016) and Munich (Kenkmann *et al.* 2017). Carbon removal may involve projects enhancing the natural carbon sinks (*e.g.* afforestation, green roofs and use of mass timber in construction) or projects deploying carbon capture and storage (CCS) technologies. Carbon offsetting may involve onsite offset projects, such as the production of excess green energy (*e.g.* Copenhagen planned to offset part of its CO₂ emissions in such a way; **Table 4**) or purchase of carbon credits from a third party (*e.g.* Melbourne follows this approach; **Table 4**). Lazarus *et al.* (2011) briefly explored the pros and cons of different options for addressing a city's remaining emissions. If 'carbon neutrality' is achieved using offsets, it is not a physical achievement or transformation, but depends upon an accounting procedure. Which approach cities will follow depends on local interests, economic and technical feasibility of the available solutions, and sometimes guidance provided by national government (*e.g.* Australia has a National Carbon Offsets Standard (NCOS) to enhance the credibility of claims of carbon neutrality). **Table 4** shows that several cities intend to adopt such approaches as an option to fulfil their total carbon-reduction targets; however, specific measures are not always clearly articulated. Most cities vaguely list all the possible options without communicating the rationale for the use of each option on the path to carbon neutrality.

It is important to place restrictions on offsetting the unavoidable emissions in order to ensure that the focus is not shifted from overall emission reductions. In addition to the fact that offsets may represent projects that may well have happened anyway, lack of such restrictions may tempt cities to take a politically or economically easier path to carbon neutrality (McLaren *et al.* 2019). This means that cities must work on their own mitigation strategies to reach the optimum level of technically feasible emission reductions before using the offset possibilities as a means to compensate the remaining emissions. Detailed international guidance is needed on the types of offset allowed and for evaluating the credibility of the offset provider. As mentioned above, the recent guidance document by the NYC Mayor's Office of Sustainability & C40 Cities (2019) is, to the author's knowledge, a first attempt towards this direction.

5. A proposed reporting and communication framework

Despite the existence of some definitions in literature, 'net-zero emission' or 'neutrality' concepts remain unstandardised. System boundaries, calculation and assessment rules vary across cities, and are often vague with respect to the negative part of the balance (**Tables 3 and 4**). Variations in ways of thinking about these concepts can influence urban development (Lützkendorf & Balouktsi 2019), as different target interpretations may lead to different responses. In this regard, operationalisation is required if they are to be adopted as a goal for the future development of cities (Lützkendorf & Balouktsi 2019). Currently, an international agreement is unlikely on harmonised methods and procedures for the net-zero GHG emissions approach in cities in the form of one international standard. It is more likely that an even greater number of approaches will continue to be pursued in parallel. In this context, an essential first step is to reach a more global consensus on a set of minimum information to be reported when municipal climate protection concepts are published (Lützkendorf & Balouktsi 2019).

Table 5 synthesises the considerations explored in the previous sections. It provides a minimum reporting and communication framework for different versions of 'net zero' that can be used as a first step towards improving

Table 5: Overview of the dimensions needed for the clarification for net-zero emission and similar targets on city level.

Type of emissions	Carbon metric			Reduction targets			Proof of climate neutrality
	Scope of emissions	Emission sources (source-based approach)	Emission inducers (consumer-based approach)	Reference unit	Use of scenarios	Target year	
Only CO ₂ OR CO ₂ , CH ₄ and N ₂ O OR GHGs covered by the Kyoto Protocol OR GHGs covered by the IPCC	Scope 1: direct emissions from sources located within the city boundary AND/OR Scope 2: indirect emissions from the use of grid-supplied electricity, heat, steam and cooling within the city boundary AND/OR Scope 3: all other indirect emissions that occur outside of the city boundary due to in-boundary activities	Stationary energy AND/OR Transportation AND/OR Waste management AND/OR Industrial processes and product use AND/OR Agriculture and forestry	Households: ^a housing, mobility, nutrition, private consumption AND/OR Government: ^a public buildings, public infrastructure, public energy plants, public transport, public construction, other goods/services AND/OR Business capital: ^a buildings, infrastructure, transport, <i>etc.</i>	Tonnes of CO ₂ /CO ₂ e AND/OR tonnes of CO ₂ /CO ₂ e per capita AND/OR tonnes of CO ₂ /CO ₂ e per household AND/OR tonnes of CO ₂ /CO ₂ e per product output AND/OR Land use (hectares as part of an ecological footprint) per capita	No scenario modelling OR External factors: ^a migration (inter-) national economic developments, national policies, energy price development, technological advancements, consumer behaviour, <i>etc.</i> AND/OR Internal factors: ^a other planned large-scaled investments in the city, new organisations take lead, <i>etc.</i>	2050 OR 2040 OR 2035 OR 2030 OR 2025	Credits for green procurement AND/OR Counting of recycling benefits AND/OR Purchase of carbon credits AND/OR Sale of excess energy production AND/OR Natural carbon sinks (e.g. forests/parks) AND/OR Carbon capture and storage OR No compensation or offset ^b

Notes: Under each aspect/dimension, the items are listed, to the extent possible, from the most basic choice to make when establishing such targets (top) to most advanced (bottom). 'OR' and 'AND/OR' are used to distinguish whether a list of items is 'single choice' or 'multiple choice'. ^a 'AND/OR' also applies to the listed subitems.

^b This option can be considered as the most advanced, only in the case an absolute zero emissions target is strived for.

Source: Adapted from Lützkendorf & Balouktsi (2019).

transparency. The items at the top of each list represent those included in the most basic approaches. The further one moves from the top, the more advanced the 'net-zero' approach becomes. This proposal is meant as a way of standardising minimum information requirements and not harmonising 'net-zero' concepts. This framework can also help cities to identify opportunities beyond best practice. If cities follow similar reporting structures, knowledge from pioneer cities can be more easily disseminated to other cities and regions. Finally, the approach proposed here can be certainly upscaled for regions, as well as under certain circumstances, be scaled down to neighbourhoods/districts.

6. Discussion

6.1 Data, resources and technical capability

The availability of data, resources and technical capability is an important consideration when undertaking an emissions inventory (Broekhoff, Erickson & Piggot 2019). Nowadays, it is acknowledged that effective policy-making needs to consider consumption-based approaches as complementary to production-based and supply chain approaches (*e.g.* Hult & Larsson 2016; Ramaswami et al. 2012; Scott & Barret 2015). To start exploring this possibility, a city should first assess whether there are pre-existing regional or national IO data and models that can be used to construct such an inventory. Technical capacity to create or update a consumption-based inventory is a consideration in decision-making. Cities should be cautious about consuming excessive time and resources trying to generate precise (in the sense of local specificity) consumption estimates at the expense of implementing policies that actually reduce consumption emissions (Broekhoff, Erickson & Piggot 2019). Therefore, when city governments are faced with limited resources, it may be wiser to use a 'relatively simple inventory approach to identify key sources of emissions, and then select a few key indicators to track consumption patterns' (Broekhoff, Erickson & Piggot 2019).

Another solution to overcome resource and capability limitations (regardless of the accounting method used) could be several neighbouring municipalities combining their resources and capabilities to produce regional-scale accounts with municipal resolution. Danish municipalities act as an example (Damso, Kjaer, & Christensen 2016). This approach is not only cost-effective but also can improve the completeness, consistency and comparability of local accounts.

6.2 Engagement with citizens and non-government stakeholders

The role of citizens as both direct and indirect sources of emissions is not thoroughly considered within current inventory frameworks and reporting mechanisms, as well as carbon neutrality targets, especially those that only focus on Scopes 1 and 2 emissions. Indeed, the inclusion of a wide range of Scope 3 emissions can help cities explore the role of citizens in carbon management and how city initiatives can facilitate their engagement. Engagement with citizens is also critical because they are the main victims of local environmental issues connected to emission-intensive activities such as poor air quality.

The role of citizens as source of information is often underemphasised. Engagement with citizens and other important stakeholders can create advantages for the data collection itself (Lützkendorf & Balouktsi 2017). In deregulated energy markets, there is hardly any governmental institution/body collecting all energy consumption-related data within a municipality (Lützkendorf & Balouktsi 2019). This type of data is usually subject to data protection laws, which forces city authorities and the experts commissioned by them to be reliant on the analysis of (partial) data from different sources (Brander, Carstairs, & Topp 2013; Lützkendorf & Balouktsi 2017). Under these circumstances, cities should develop mechanisms to actively involve industries and citizens in the provision of the necessary data to ensure a more comprehensive accounting and assessment, especially of indirect emissions, besides their necessary involvement in action planning and implementation.

6.3 Cross-city comparisons and standardisation

As mentioned in section 5, it is unlikely that there will soon be an international standard to harmonise net-zero GHG emissions approach in cities. In the medium term, the development of a standard is possible: providing adequate leeway for adaptation to the local situation, supporting a transparent declaration of current GHG accounting methods and system boundaries and generating a basic typology of cities. The profile indicators according to ISO 37120 (2018) already provide a good basis for the latter: the definition of cities' profiles for the purpose of fairer cross-city comparisons. To avoid a long list of indicators to characterise a city's profile, one could focus on key well-researched and acknowledged city attributes that determine urban GHG emissions, or environmental performance in a broader sense (Balouktsi & Lützkendorf 2020), or use common indexes, such as the city prosperity index (CPI) as part of a city's functional equivalent/unit (Albertí, Brodhag, & Fullana-i-Palmer 2019b). A simpler solution could be that comparisons should only be allowed between a city's GHG emission level per capita and the corresponding national average level, or perhaps cities within the same country so as to 'neutralise' most factors that affect emissions (such as geographical conditions, city economic development, socio-political factors or specific national policies).

7. Conclusions

Over the last decade, the city-scale GHG emission inventory methods have evolved from the Intergovernmental Panel on Climate Change's (IPCC) territorial-based metric to more complex consumption-based estimates of city-induced emissions. However, although the latest accounting protocols include consumption-based accounting, most cities still limit their accounting to Scopes 1 and 2 emissions. Although the increasing exploration of community-wide infrastructure footprint approaches (CIFAs) and consumption-based approaches (CBAs) in the different protocols points to a new trend, the limited number of cities currently undertaking such inventories reveals a need for more detailed and standardised guidelines on how to include Scope 3 emissions, or strengthening the workability of the existing ones. Regardless, cities should not wait for a global agreed-upon methodology. Nor should they consume time and resources to obtain harmonised and precise estimates at the cost of achieving actual emission reductions.

Variations are found in the inventorying methods as well as in ways of thinking about 'carbon neutrality' or 'climate neutrality' or 'net-zero emission' concepts. The former also influences the latter, since target-setting largely depends on what has been reported in an inventory. Despite the lack of a shared understanding of such concepts, several leading cities around the world claim to be on the path to net-zero greenhouse gas (GHG) emissions. Based on selected cities with target statements, this paper has illustrated what typically underpins such claims from a methodological point of view. If the net-zero carbon goal is to be widely adopted by cities, then operationalisation and clear guidance is required. This especially applies to the currently much-debated issue of how residual GHG emissions should be defined, cancelled out or removed in order to achieve carbon neutrality.

The heterogeneity of methods and protocols to compile a GHG emission inventory, as well as of target-setting approaches involving bringing the emissions balance to zero, shows the many paths that cities can take to address climate change. Although cities should be allowed a certain level of freedom to account for emissions in ways that increase the relevance for local policy-making, an essential requirement will be for cities to systematically report their estimates and targets following a standardised typology of system boundaries and other dimensions. The transparency of the process is vital for measurement and verification. In future, the development of minimum reporting requirements in the form of an international standard should be a priority in order to support the verification of emissions and emissions reductions to meet the reduction targets established by the Paris Agreement. The broad framework presented here provides the basis for further work in this direction.

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Appendix A: City carbon accounting and reporting protocols and guidelines

The first city greenhouse gas (GHG) emissions accounting and reporting protocol, the International Local Greenhouse Gas Analysis Protocol (IEAP), was published in 2009 by the International Council for Local Environmental Initiatives (ICLEI). Since then, several other organisations have developed standards and guidelines to enable cities to prepare their GHG emissions inventories (see Table A1 below—the characteristics of the latest Intergovernmental Panel on Climate Change (IPCC) guideline for national governments are also shown since they may have an influence on future city standards). Already one year later, the protocols of the Baseline Emissions Inventory (BEI) were published by the European Covenant of Mayors (EU-COM 2010), as well as the International Standard for Determining Greenhouse Gas Emissions for Cities (ISDGC) occurred as a product of the United Nations Environment Programme (UNEP), UN-Habitat and World Bank (World Bank *et al.* 2010).

A consumption-based methodology was not completely presented in city accounting until the publication of the British standard Publicly Available Specifications (PAS) 2070 in 2013. Specifically, this standard proposes two methods: The direct plus supply chain (DPSC) method that can be considered equivalent to the Global Protocol for Community-Scale Greenhouse Gas Emission Inventories (GPC) Basic+, and the 'consumption-based' method which uses IO tables to determine the consumption of goods and services. In the same year, ICLEI developed the US community protocol for cities which categorises emissions into 'sources' and 'activities'. The GPC, launched in 2014 through a collaboration of the publishers of IEAP and ISDGC with World Resources Institute (WRI), is the latest and most globally recognised protocol used by cities (WRI *et al.* 2014). The GPC currently offers two reporting levels for city GHG emissions, Basic and Basic+, in order to accommodate city limitations in data availability and technical capability. Arioli *et al.* (2020) argue that reporting levels before the Basic report level of the GPC may be necessary, since, although more than four years have passed after GPC's release, elaborations of such inventories are hardly seen in the academic literature. This reveals a certain distance between research and practice, since the Carbon Disclosure Project (CDP) database reveals that cities are increasingly shifting towards the GPC despite the complexity of this protocol (CDP 2019).

To conclude, although many reporting protocols have been developed to facilitate city carbon accounting, they include different requirements of accounting (Table A1) that can lead to different results, even for the same city (Chen *et al.* 2019). Especially for out-of-boundary emissions, reliable guidelines are still lacking. Hence, the provision of details of how to account out-of-boundary emissions in these protocols is necessary.

Table A1: Main characteristics of city-level greenhouse gas (GHG) emissions-accounting frameworks.

Protocol/guideline	Latest version (previous)	Publisher(s)	Level of application (in theory)	Type of system boundary ^a	Activities	GHGs covered	Notable applications
IPCC: Guidelines for National Greenhouse Gas Inventories	2019 (2006)	IPCC	National level	SB1	Energy; AFOLU; IPPU; waste; others	Net CO ₂ , CH ₄ , N ₂ O, HFCs, PFCs, SF ₆ , NF ₃ , other halogenated gases in the 5AR ^b	All countries as part of their intended nationally determined contributions (INDCs)
IEAP: International Local Government GHG Analysis Protocol	2009	ICLEI	City level plus neighbourhood level (only within determined sectors, e.g. transportation)	SB2	Buildings; transport; industry; waste; AFOLU; land-use change	CO ₂ , CH ₄ , N ₂ O, HFCs, PFCs, SF ₆	No, soon replaced by the GPC
IPCC: International standard for Determining GHG Emissions for Cities	2010	UNEP, UN-Habitat, World Bank, IPCC	City level	SB3	Energy; AFOLU; IPPU; waste; others	CO ₂ , CH ₄ , N ₂ O, HFCs, PFCs, SF ₆	No, soon replaced by the GPC
BEI: Baseline Emission Inventory	2018 (2010)	EU-COM	City level	SB2, SB3 (optional)	Buildings; transportation; energy production; others	CO ₂ , CH ₄ , N ₂ O (last two are optional)	Used by many European cities along other national tools
GPC: Global Protocol for Community-Scale Greenhouse Gas Emission Inventories	2014	WRI, ICLEI, C40	City level plus neighbourhood level	SB3 (Basic); SB6 (Basic+)	Stationary energy; transportation; waste; IPPU; AFOLU; other out-boundary emissions	CO ₂ , CH ₄ , N ₂ O, HFCs, PFCs, SF ₆ , NF ₃	Mandatory for compact of mayors; recommended by the Global Covenant of Mayors, ISO 37120 and CASBEE-Cities
PAS 2070: Publicly Available Specification 2070	2013	BSI	City level	SB6 (DPSC: direct plus supply chain method); SB5 (CB method: optional)	DPSC-method: stationary energy; transportation; waste; IPPU; AFOLU; other goods and services. CB-method: food and drink; utility services; household; transport services; private services; other goods and services	CO ₂ , CH ₄ , N ₂ O, HFCs, PFCs, SF ₆	Was used by London (GLA 2014); was used by C40 Cities (2018) to assess the consumption-based emissions of its 79 members
US Community Protocol for Accounting and Reporting of GHG Emissions	2019 (2013)	ICLEI USA	City level	SB4 and SB5 (CB-method); SB6 (community-wide method)	Built environment; transportation; solid waste; wastewater and water; agricultural livestock; forests and lands; upstream impacts of community-wide activities. CB-method: household consumption; government consumption; life cycle emissions of community businesses	CO ₂ , CH ₄ , N ₂ O, HFCs, PFCs, SF ₆	Used by several US cities

Notes: ^a As defined in Table 1.

^b Requirement to report other emissions without the conversion into CO₂ equivalents.

5AR, *Fifth Assessment Report* (Edenhofer *et al.* 2014); AFOLU, agriculture, forestry and other land use; IPPU, industrial processes and product use.

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