ABSTRACT
To date, many cities have engaged in efforts to become more sustainable. These efforts often are translated into measures to reduce their greenhouse gas (GHG) emissions, leading to a proliferation of standards and methods. Discrepancies exist between these various accounting approaches in terms of the definition of system boundaries, allocation procedures, quality of data, and the reporting and verification of results. This paper examines some of the most important theoretical and practical issues and challenges of urban-related GHG accounting and highlights how existing approaches deal with these. Three different GHG emission accounting standards are compared and critically analysed: the Global Protocol for Community-Scale Greenhouse Gas Emissions (GPC), Bilan Carbone and ISO 14064-1:2018. The Organizational Environmental Footprint (OEF) and a previous analysis about footprinting performed by the European Commission are used as analytical lenses. Based on this analysis, suggestions are made for enhancing comprehensiveness and transparency, and providing guidelines for driving cities towards a more low-carbon path.

PRACTICE RELEVANCE
This critical analysis shows that each method has strong points, but practical issues remain for urban stakeholders undertaking GHG emissions inventories. First, the uniqueness of each urban system needs to be addressed in the goal and scope phase in order to provide meaningful terms of comparison between cities. The creation of different categories to provide similar clusters of cities would enable a more meaningful cross-city comparison as well as a proper formulation of targeted policies. Second, the inclusion of a life-cycle perspective in GHG accounting is essential for avoiding the risk of burden-shifting. Both production and consumption approaches are crucial in supporting the objectives of decarbonisation and the carbon neutrality of cities. If both perspectives are not acknowledged, ‘climate neutral’ targets can be misleading and impact negatively on decision-making and behavioural change of producers and consumers.
1. INTRODUCTION

Many cities have engaged in reducing their greenhouse gas (GHG) emissions in the recent past due to the increasing awareness of climate change and their potential effects on cities. Globally, cities significantly contribute to energy use and related GHG emissions. Although cities occupy only 3% of the global surface area, they are responsible for 67–76% of the overall primary energy consumption and 71–76% of global CO₂ emissions, taking into account a consumption-based perspective (see section 2 below) (Seto et al. 2014). This is driven by the increasing concentration of population in urban areas (estimated to be 66% by 2050, according to the United Nations 2012), and the associated demands for materials and energy resources (Hudeková et al. 2007).

At the same time, cities are increasingly threatened by the effects of climate change and, hence, appropriate climate policies should be part of an overall strategy to enhance their resilience. Today, both national governments and municipal authorities recognise the potential for cities to limit the magnitude of climate change through effective mitigation actions (Van Staden 2014). Many cities have already engaged in the challenge and are participating in dedicated international information-sharing and collaboration networks, e.g. the C40 Cities Climate Leadership Group (2017), Local Governments for Sustainability (ICLEI) (n.d.) and Global Covenant of Mayors for Climate and Energy (2017) (Ibrahim 2015). According to C40 (2019), the network connects 96 of the world’s greatest cities to take bold climate action. EUROCITIES claims that 64% over a total of 80 of its members have already committed to reach carbon neutrality by 2050, and 87.5% have adopted climate-adaptation strategies to adapt to the impact of climate change and protect their citizens. Among them, 12 cities have even committed to reach neutrality before 2040. And climate mitigation is only one side of the coin (EUROCITIES 2019). The Covenant of Mayors was first launched in 2008, and later formally merged with the Compact of Mayors, creating the Global Covenant of Mayors (GCoM) (Global Covenant of Mayors for Climate and Energy 2017). Today, GCoM includes 9261 cities, 8800 of which are located in Europe. According to Alberti et al. (2019), the ambition of cities has risen remarkably to go beyond their national governments’ climate change targets, as the Intergovernmental Panel on Climate Change (IPCC) stressed the insufficiency of nationally determined contributions stated in the Paris Agreement.

Local authorities are the main promoters of this engagement towards a low-carbon future. First, they can set regulations and put forward urban planning principles. Second, they can act as implementers, and the municipal self-governing mode of governance and awareness are key measures for implementing climate action plans (Alberti et al. 2019). Because of their glocal nature (Athanassiadis et al. 2016) they are considered privileged places of interventions against climate change (Lombardi et al. 2017).

Although climate change mitigation has become a top priority in many political agendas, the question of how to reduce urban-related GHG emissions (IPCC 2009) in an effective, economic viable and socially acceptable way remains challenging for many reasons. Indeed, cities are complex and evolving entities, including both static and dynamic aspects, and are therefore difficult to define and model. As bearers of economic, social and cultural values, cities involve tangible (e.g. buildings, transport infrastructures, etc.) and intangible matter (e.g. cultural heritage, social relationships, etc.). In this regard, experts claim for more participation of social sciences and more collaboration among hard and soft disciplines (Victor 2015; Gurney et al. 2015).

In response to demands for clear rules and guidance, the recent decade has seen a proliferation of standards and methods developed by different types of organisations (non-profit, non-governmental organization (NGO), research institutes, etc.). This offers opportunities for both diversity and confusion, especially for urban policy-makers and stakeholders who are surrounded by multiple tools designed to reply to the same target of reducing carbon emissions in cities. Furthermore, various methodological, reporting and communication issues may arise, leading to transparency, comparability and accountability issues. The main issues identified are reported below.

First, the definitions, system boundaries, methods and forms of presentation used by each accounting approach are different. Differences, for example, occur in the allocation of ‘responsibility’ (producers’ or consumers’ perspective), the GHGs accounted for and whether or
not they rely on life-cycle thinking (LCT) (Kennedy et al. 2010). The LCT perspective considers not only direct and local emissions but also indirect emissions and emissions originating from processes outside the city.

Second, most cities lack reliable, comprehensive and comparable data, as well as appropriate expertise and staff. This forces the city authorities, and the experts commissioned by them, to be dependent on data from various sources, affecting data quality. Transparency of data and methods is also crucial to enable comparisons and verification by third parties (Gurney et al. 2015).

Finally, the heterogeneity of reporting and verification steps across the accounting schemes creates additional problems. In this context, political claims such as ‘climate neutral’ can be misleading and even erroneous, and they may hence lose their power for an effective and efficacious change.

The main objective of this paper is to provide an in-depth analysis of how various standards handle the issues described above in order to identify: strong and working points; and which approach is most appropriate for which goal.

The remainder of the paper is structured as follows. First, an exploration and definition of the system under study—the city—is crucial, and therefore is presented (section 2). This is followed by a critical analysis of three widely used standards to assess the carbon footprint of cities and/or organisations and a comparison with the Organizational Environmental Footprint (OEF) of the European Commission (section 3). Finally, the paper discusses how each method can support stakeholders in their goal to account and reduce urban GHG emissions, discussing current advantages and limitations, as well as proposing future outlooks for the next steps forward.

2. WHAT DEFINES A CITY TO TACKLE CLIMATE CHANGE?

Accounting for urban GHG emissions requires a clear definition of urban areas and related system boundaries. Cities are one of the most complex anthropogenic systems ever created (Hoornweg et al. 2011) and the definition of a ‘city’ poses semantic and technical issues. A unique definition of ‘city’ does not exist (UN-Habitat 2011; Kennedy et al. 2010), but several definitions representing different perspectives are possible according to the field of knowledge, i.e. urbanism, geography, economy, sociology, etc. Each definition has a different scope, and this has consequences for the determination of the system boundaries and the subsystems to be included. The definition of ‘city’ in the scope of climate change is not an exception, i.e. the point is not properly addressed when dealing with carbon emissions. Various methods are available to establish the system boundaries of a city or urban area (Seto et al. 2014):

- administrative approach (Hartshorne 1933; Aguilar et al. 2003)
- functional approach (Brown & Holmes 1971; Douglass 2000; Hidle et al. 2009)
- morphological approach (Benediktsson et al. 2003; Rashed et al. 2003)

It is important that the selection of urban-specific system boundaries is based on the concrete targets and policy goals or governance structure (Seto et al. 2014; Liu et al. 2015) as it can have a substantial influence on the results of the analysis. Nowadays, the topic is poorly addressed in accounting methods. When the goal is GHG accounting, the definition of appropriate system boundaries should be acknowledged and the uniqueness of cities should be recognised in the methods because it will give much more clarity to GHG inventories and will drastically reduce the risk of discrepancies between different inventories from different cities.

Once the boundaries of a city are defined, the GHG emissions attributable to the selected area still may be considered from different perspectives. Emissions can be accounted based on its spatially limited geographical boundaries (territorial/production-based approach), or based on a broader consideration that also includes cross-boundary flows and/or indirect emissions (supply chain or consumption-based approach) (Kennedy et al. 2011; Yetano Roche et al. 2014; Balouktsi 2020). The attribution of emissions can furthermore be made based on a producers’ or a consumers’ perspective. In a consumer approach, emissions from the production of a good or service are
allocated to the consumer of that good or service, while in a producer approach, the emissions associated with an activity are allocated to where that activity takes place (Kennedy et al. 2011). Effective policies able to lead measurable and long-term benefits need to consider both dimensions. Ramaswami et al. (2008) combine both approaches, accounting for GHG emissions occurring from all activities (whether producer or consumer). This hybrid approach allows for a fairer and more effective emissions accounting. Paloheimo & Salmi (2013) argue that the national GHG inventories based on the IPCC recommendations should be allocated presenting both production and consumption. According to them, it is only possible to support political claims of carbon neutrality by also including the consumption perspective because consumers should consider the environmental burdens produced outside the city boundaries (see section 3.2). Including the processes occurring outside the city boundaries but serving the citizens and other key city users is essential to avoid burden-shifting beyond the city boundaries. To date, a growing but still limited number of cities apply a consumption-based approach, revealing a need for more detailed and standardised guidelines on how to include indirect emissions (Balouktsi 2020). Furthermore, the relevance of local policy-making can benefit from a certain level of freedom for cities in accounting their emissions. Notwithstanding, a standardised typology of system boundaries should be followed in reporting estimates and targets in order to guarantee the transparency of the process for both measurements and verification (Balouktsi 2020). Once the system boundaries are defined and transboundary emissions allocated appropriately, the city needs to be analysed by considering its key features and sectors. Depending on the scope and approach selected, distinction and identification among the sectors differ. Comprehensive inventories should at least include emissions related to sectors, such as built environment, energy, industrial processes, transportation, waste and water treatment, agriculture, forestry and land use, household consumption (as categorised by Mirabella et al. 2018), or activities such as food, housing, transport, goods, services, government and infrastructure investment, as presented in the ecological footprint.

The resulting resource and emission profiles allow one to categorise cities according to their GHG emission balances. The following urban types are possible: net producers, net consumers and floating producers–consumers. Net producers have higher territorial emissions compared with their consumption-based emissions; the opposite is true for net consumers (Yetano Roche et al. 2014).

3. CRITICAL AND SWOT ANALYSIS OF THE SELECTED STANDARDS

3.1 KEY FEATURES USED TO COMPARE THE STANDARDS

In order to examine the identified bottlenecks and provide insights on how these are tackled in the various approaches and standards, a set of existing methodologies for carbon footprinting is critically screened. For this purpose, recommendations and guidelines provided by the European Commission, Joint Research Center (2011) are taken as a reference. The main intention of this critical analysis is not providing a complete review of such approaches, but rather identifying representative ones and providing support for their selection when climate actions are part of the local agenda. The methods have hence been selected to provide a reasonable range of different characteristics, but with a similar focus, and with the necessary elements to reply to the complex challenges emphasised in the previous section. For completeness, a brief overview of other existing methods is available in Table S1 in the supplemental data online; for a more in-depth description and brief motivation for their selection, see Appendix C online.

The selected standards are:

- Global Protocol for Community-Scale Greenhouse Gas Emission Inventories (GPC) (WRI et al. 2014)
- Bilan Carbone (ADEME 2010)
- ISO 14064-1:2018: Greenhouse gases—Part 1: Specification with guidance at the organization level for quantification and reporting of greenhouse gas emissions and removals (ISO 2018)
- Organization Environmental Footprint (OEF) (European Commission 2012)
The first two methods were selected because they are explicitly designed for urban GHG emissions accounting and they seek to provide an effective guide to policy-makers and stakeholders to account and manage urban-related emissions. The GPC is the outcome of two years of public consultation and testing by pilot cities and it is a collaboration between ICLEI, C40, WRI and the Cities Alliance Joint Work Program (WRI et al. 2014). Bilan Carbone is a methodology designed by the French Agence de l’environnement et de la maîtrise de l’énergie (ADEME) (2010). The standard ISO 14064 is selected because it is developed by the International Standardisation Organization (ISO) (2017). Although it has a wider scope than the GHG Protocol for Cities and Bilan Carbone, as it is intended for application at the organisational level in a broad sense; it is seen as a crucial base for GHG accounting. Finally, the OEF (European Commission 2012) is included in the assessment as a term of comparison and reference with the other carbon-accounting methods. It is an environmental multicriteria assessment methodology intended for high-scale and complex systems based on LCT with a high level of accuracy and comprehensiveness. It can be considered as the method with the highest level of robustness and efficacy to date able to evaluate the overall environmental performance of organisations (European Commission 2012). Its selection—as term of comparison—aims at more easily acknowledging if and how key methodological aspects are accounted for and to what extent.

The identified features used to analyse the methods are:

- availability at city scale
- definition of ‘city’ provided
- LCT approach
- system boundaries used
- functional unit applied
- source of inventory data
- assessment of data quality
- approach/allocation rules used
- identification of the responsible actor
- type of impact assessment and GHGs accounted for
- type of verification and reporting
- existence of ancillary tools

The description and details related to these features are reported in Appendix B in the supplemental data online. The aim is to highlight major points for comparison and reflections for each method and to trace a theoretical and potential line for improvements for an effective and harmonised accounting of GHG emissions at the urban level.

In addition to the critical analysis, a strengths, weaknesses, opportunities and threats (SWOT) analysis is also performed. SWOT is a strategic planning framework used for the evaluation of an organisation, a plan, a project or a business activity (Gürtel & Tat 2017). Its aim is to identify aspects within a company and/or organisation that act effectively and allow for strategic decisions and long-term actions to be taken (The Economist 2009), including a more efficient resources and capabilities allocation according to the operational environment (Gürtel & Tat 2017; Thompson et al. 2007).

### 3.2 RESULTS

#### 3.2.1 Cross-analysis of standards using OEF as reference

The analysis of the key features of the three standards selected is now presented, while a comparison with the OEF methodology is presented in section 3.2.2 and the results of the SWOT analysis are discussed in section 3.2.3. A complete overview of the results for the four methods is provided in Table 1.
Table 1 Key aspects considered in the cross-analysis of the selected standards and comparison with the Organizational Environmental Footprint (OEF)

**Note:** GHG = greenhouse gas; GPC = Global Protocol for Community-Scale Greenhouse Gas Emissions; ISO = International Organization for Standardization.

| FEATURE | GPC | BILAN CARBONE | ISO 14064 | OEF |
|---------|-----|---------------|-----------|-----|
| Availability at the city level | Yes | Yes | No | No |
| Definition of urban system | Geographical entity | Administrative or geographical entity | No | No |
| Life-cycle thinking (LCT) | Not mandatory | Yes | No | Yes |
| Impact assessment and GHGs accounted for | Climate change, GHGs included in the Kyoto Protocol | Climate change, all GHG emissions are according to the present level of scientific knowledge | Climate change, significant GHG emissions for the organisation | Default set of 14 midpoint impact categories and specified impact (for IPCC 2009, 100 years) |
| Functional unit | Not addressed explicitly, supporting information refers to emissions related to yearly city performance | Not addressed explicitly | Not addressed explicitly | Yes |
| System boundaries | Territorial boundaries, flexible, depending on purpose | Territorial or administrative boundaries | Operational or organisational boundaries, control or equity share approach | Fixed, all activities and processes that occur within the organisational boundaries |
| Inventory data | Activity data, national or international statistics; equations are provided for industrial processes, agricultural and waste sectors. Two levels of accounting, BASIC and BASIC+ | Activity data, national or international statistics | Activity data or direct measurement. No quantification methodology specified | Specific sector data or best available generic data for data gaps. Data management plan provided |
| Data quality | Any, but the degree (low, medium, high) should be stated and references provided; guidelines for uncertainty assessment | Only guidelines for uncertainty assessment | Not addressed | Representativeness, completeness and appropriateness and parameter uncertainty are required; data contributing to at least 70% of impacts estimated should be at least ‘good’ |
| Approach | Territorial/production approach plus supply chain | Life-cycle | Production approach plus supply chain limited to electricity. Other indirect emissions optional | Life-cycle, cradle to grave |
| Allocation rules | Specific guidelines for the transportation sector and combined heat and power plants | Mass and energy allocation, specific guidelines for waste | No guidance provided | Subdivision or system expansion; allocation based on a relevant physical relationship (or other if necessary) |
| Identification of responsible actors | Yes, but limited in scope; influenced by inventory rules | Yes; influenced by inventory rules | Yes, but limited in scope; influenced by inventory rules | Yes |
| Reporting | High level of detail for reporting; two possible reporting options (BASIC and BASIC+) | No precise guidelines | High level of detail for reporting | High level of detail for reporting, three plus one (optional) different reports should be provided |
| Verification | On a voluntary basis, self-verification or third-party verification allowed | No precise guidelines | Guidance for internal and external verification | Compulsory, third-party review with a scoring system for reviewer qualification |
| Tools | Spreadsheets for data-gathering and calculations | Spreadsheets for data-gathering, calculations, targets, uncertainty and future projections | Not provided | Specific software (not specified) |
Differently from the other GHG accounting methods, Bilan Carbone uses an LCT approach for every sector considered, including all direct and indirect emissions from both upstream and downstream processes. This guarantees an increased level of comprehensiveness (Kennedy et al. 2010). System boundaries are defined including the ‘ensemble of physical processes that are necessary for the existence of a human organization’ (ADEME 2010), thus taking into account the multiple aspects necessary for cities to sustain their activities. Bilan Carbone includes a comprehensive accounting of GHG emissions, not limited to those included in the scope of the Kyoto Protocol. Moreover, it provides good methodological guidance to the user and includes supporting material.

GPC has a user-friendly approach for cities and policy-makers and follows the IPCC’s recommendations. It has a high degree of flexibility that can encourage neophytes interested in participating in the climate discussion. ISO 14064 benefits from its standard-oriented and loose framework that could be attractive to potential users, but it does not precisely indicate the type of GHGs to be accounted for. Both GPC and ISO 14064 do not strictly rely on LCT, unless scope 3 is included at the user’s discretion. In ISO 14064, direct and (at least part of) indirect emissions are inventoried, but key choices are in charge of the organisation, as well as the selection of the accounting methodology.

Concerning the definition of the urban system, Bilan Carbone considers two perspectives: the authority and the territorial one. This choice can guide cities to consider two different (and sometimes complementary) perspectives already from the early phases of the accounting process. In fact, the authority approach turns out to be very useful for immediate policy interventions because it identifies the carbon burdens of what can be directly controlled by the entity analysed. However, it also hides tricky and misleading aspects, as a limited view could lead to ineffective actions and burden-shifting. The narrow, but targeted, scope of the authority approach can then be extended through the territorial approach, which also includes a rough accounting of food consumption and food waste prevention. This is recognised as a major source of GHG emissions, and a unique attempt to model and account partially household consumption. GPC recognises a city through its geographical boundaries and it relies on the territorial/production and supply-chain based methodology (identified as Scope 1 and 2 emissions), while the accounting of indirect emissions (Scope 3) is encouraged, but not compulsory. This means that emissions coming from ‘net consumers cities’ have more probability to be underestimated and this increases the risk of burden-shifting. The calculation methodology is not fixed a priori, but several and complete guidelines are proposed, covering a wide range of possible cases. Every city should find the most appropriate way to define its GHG inventories according to the purposes, availability of data and consistency with other national inventories. It provides the most detailed guidance on the calculation of emissions and input data and accepts a certain degree of flexibility by provision of its BASIC and BASIC+ accounting and reporting levels.

Finally, regarding verification and reporting, these are not in the scope of the Bilan Carbone method, despite their importance for communication purposes to the stakeholders and ensuring the reliability of the results. GPC is clearly communication oriented and provides guidelines for the editing of a detailed report. Verification is, however, not mandatory in GPC, hence the reliability of studies using this method is not completely guaranteed. ISO 14064 dedicates high attention to reporting and verification procedures.

According to the analysis and the reference to the OEF, Bilan Carbone performs better with regard to the target of an efficacious GHG emission accounting at the urban level for several reasons because it is particularly effective to balance academic research and policy demand. However, it requires higher costs of implementation due to: (1) big and time-consuming life-cycle data gathering; and (2) the level of expertise necessary to manage it and to apply the method as the guide is less user-friendly than the GPC protocol. Furthermore, the issue of data quality should be better addressed in the method because it is important to obtain consistent and robust results.

According to Wilmsen & Gesing (2016), GPC can be classified as a conventional protocol that does not differ significantly from previously developed methodologies of the same category (i.e. it does not recognise the peculiarities and specific needs of urban systems in an integrated way), but
when directly compared, it can be deemed to be the most user-friendly methodology within its category. Despite these working points, GPC can be expected to play an important role in the political future (Wilmsen & Gesing 2016) because it is recommended by or incorporated into a variety of initiatives by city networks and international organisations (e.g. the Compact of Mayors).

Finally, the analysis shows that the application of ISO 14064 allows many key decisions in charge of the organisation. It does not meet the expectations for the purpose of urban GHG accounting because it does not provide specific and clear guidelines to the user, except for the detailed guidelines for reporting and verification.

As a general conclusion, it is important to note that no method provides an in-depth discussion and proposal about the challenge of defining and categorising the urban system in an appropriate way to serve a more efficient assessment and cross-city comparisons.

3.2.2 Comparison with the OEF method

To make the comparative analysis more meaningful, the OEF method is also screened and added to Table 1 as reference methodology. Its beneficial points for improvements related to the reliability, consistency and transparency of urban GHG emissions inventories are listed. This applies to organisational activities as a whole, i.e. to all activities associated with the goods and/or services an organisation uses and provides from a life-cycle perspective. Depending on the use of the OEF method and purpose of the OEF study, the key methodological requirements differ. This allows for flexibility and optimisation of the efforts while excessive subjectivity (as in the case of GPC or ISO 14064) is avoided. Such an approach could be beneficial, and for city GHG accounting too. Indeed, the OEF guidelines strictly follow the LCT approach, including precise guidance on the expected level of data collection and data quality depending on the goal of the study. Finally, third-party verification and reporting are compulsory.

For all these reasons, the OEF method can serve as a basis for a detailed and reliable GHG accounting for cities approach, provided that the method is first adjusted to the specific context of cities. Indeed, the high level of detail and requirements allows for reliability, but it slows the whole process significantly, or it even makes it unfeasible.

3.2.3 SWOT analysis

In order to quantitatively highlight the most important strong and working points, as well as the opportunities and threats of each method analysed, a SWOT analysis is added (Figure 1).

**Figure 1: Strengths, weaknesses, opportunities and threats (SWOT) analysis of the Global Protocol for Community-Scale Greenhouse Gas Emissions (GPC), Bilan Carbon, International Organization for Standardization (ISO) 14064 and Organizational Environmental Footprint (OEF) for their application at the urban scale.**
GPC’s strengths and opportunities lie in its intention to reach a global audience and its user-friendliness. Cities that use this method can be part of a large network (i.e., C40 and ICLEI). Furthermore, it explicitly addresses city leaders and is designed for politics and attracting international funding. This is especially appreciable considering the growing interest and awareness of climate change and in case of future legal compliance or request for funds related to it. Despite these important strong points, the method lacks transparency and comprehensiveness, and is rather weak if it is to be used for comparability studies.

The strong points of Bilan Carbone are that it relies on its LCT approach and attempts to capture emissions from consumption behaviour. The distinction the method makes between the territorial and management approach is useful for policy actions. A major limitation of the Bilan Carbone method is the lack of an international scope and the required high-level of expertise for its application. The method is considerably less attractive and user-friendly (i.e., lack of graphical guidance) compared with the GPC.

ISO 14064 encourages (even if partially) the accounting of both direct and indirect emissions. The degree of freedom (several key choices are not fixed a priori) in the standard, however, does not fit with the claimed purpose of standardisation or comparability studies. Reporting and verification procedures are a strong point of this method.

Finally, the EC OEF method can be considered as a reference methodology for its completeness and transparency, the high level of robustness in terms of approach, data collection and quality, and exhaustive reporting and verification procedures. Furthermore, the methodology is very strict and, if properly refined for cities, it could also support cross-city comparisons. However, it is not intended for the city context and the time-consuming and costly data-gathering, lack of appropriate expertise, and slow process can discourage its future adaptation and use.

Based on what emerged, the methods are qualitatively compared (Figure 2). Relevant criteria useful for policy-making purposes are selected and scored according to authors’ knowledge and outcomes of previous critical analyses. The purpose of this qualitative comparison is to propose a summary of previous cross-analysis, identifying the most efficient and efficacious method, according to the specific possibilities and needs. The qualitative criteria are:

![Figure 2: Qualitative comparison of the selected standards and the Organizational Environmental Footprint (OEF) for applications in the urban context, comparing expected time and costs, communication and networking outreach, accuracy and complexity in their outcomes.](image-url)
time (expected amount to perform the study)
• costs
• network
• communication
• precision and accuracy
• complexity

The criteria are scored from 0 to 3, according to ‘high’ and ‘low’ performance. For instance, high time and costs are scored 2 or 3, while poor communication is scored 0 or 1. As above, the OEF method was included as terms of comparison.

Final overall recommendations for an effective and rigorous urban-related GHG emission accounting are addressed in sections 4 and 5.

4. DISCUSSION

In the context of urban carbon footprinting, each protocol analysed has several strong and working points that city leaders and stakeholders should consider, before selecting one method over another. It is remarkable that some key features are not addressed in depth or univocally defined in the methods, such as the definition of the urban system and its boundaries, its multiple facets (social, economic, environmental), data quality requirements, and verification of the results. Furthermore, none so far seems completely satisfactory or sufficiently rigorous for meaningful cross-city comparisons. In the analysed set, Bilan Carbone (ADEME 2010) provides the most holistic approach. Furthermore, it considers two perspectives, authority and regional, to facilitate policymakers in identifying areas of interventions under their direct or indirect control and defining appropriate mitigation strategies.

Recommendations based on these findings are now briefly presented. First, it is important to recognise that investigating the relation between cities and climate change is a highly interdisciplinary task and requires a specific depth and width of expertise. Indeed, the specificity and uniqueness of each urban system and its inherent dynamism need ad hoc solutions that could be offered more readily by an interdisciplinary ‘taskforce’ composed of economists, social and environmental scientists. Such a taskforce should be able to analyse the local reality and collaborate in order to define the most appropriate settings, the most appropriate goals and scope, and then the most appropriate method to fulfil them.

Second, according to the results presented in section 3, the following recommendations regarding the use of the different methods and studied approaches can be formulated. Net producers of emissions (e.g. mainly secondary economic activities) with limited resources in terms of time, costs and expertise could provide an accurate estimation of their profile by applying the GPC method. Cities categorised as net consumers (e.g. with mainly tertiary economic activities) should also attempt to conduct an inventorying of their emissions beyond their boundaries, with the application Bilan Carbone. Despite the limitations mentioned for ISO 14064, local authorities willing to refer to an international standardised method could benefit from its enhanced use in combination with other internationally agreed methodologies. A successful example is provided by the joint application of ISO 14064 and the 2006 IPCC Guidelines for National Greenhouse Gas Inventories to the Italian Province of Siena, where this combined use supported by environmental policies and strategies was able to lead to GHG emissions reductions at the subnational scale (Bastianoni et al. 2014).

As claimed by Paloheimo & Salmi (2013), both production and consumption approaches are necessary and crucial for supporting the objectives of decarbonisation and carbon neutrality of cities. Athanassiadis et al. (2016) found that urban GHG emissions estimated by the consumption-based approach in Brussels is more than three times higher than local measures indicate.
A hybrid approach, as, for instance, proposed by Ramaswami et al. (2008), may be a good way forward because it provides an overview of the emissions produced within the city, but at the same time provides an overview of the emissions generated by the activities in the city, inside and outside the city boundaries. Such multilayer and complementary analysis could support different and multiple targets under the condition of precise and well-defined allocation rules for a ‘fair accounting’ of responsibilities and environmental burdens. A territorial/production point of view acknowledges and emphasises the emissions under the direct control of the city authorities to set the basis for immediate and short-term effect interventions. The consumption point of view enlarges this horizon and can stimulate a virtuous chain reaction in which positive behavioural and lifestyle changes coupled with top-down dedicated policies lead to long-term environmental benefits. Moreover, the consumption-based approach is the one where the LCT perspective can be represented.

Third, no discussion is presented in any of these standards to acknowledge the typologies or features related to the various cities existing in the world and no guidelines dealing with them are provided. A set of a priori characteristics able to describe the specific city in terms of economic, social, historical and geographical background could be beneficial not only for comparison purposes but also in the goals and scope definition and in the inventory phase for a more strategical and efficient accounting process. Cities could also be clustered according to their level of maturity for climate policies and their experience in this regard. This is particularly relevant if joint strategies and sharing of best practices are persecuted in a second stage.

Gurney et al. (2015) proposed to combine top-down and bottom-up practices to overcome some of the limiting issues in relation to urban GHG emission accounting. They claimed for a collective operation effort to collect reliable and continuous urban carbon flows and the establishment of an independent intergovernmental centre (with regional representation) to ensure standardisation, to generate practical results, tools and carbon-mitigation options, and to provide tailored information.

Finally, municipal stakeholders, especially industries and citizens, should be actively involved in all phases of the process, both upstream (for a more comprehensive accounting and assessment) and downstream (for a long-term engagement and to ensure continuous and stable progresses). Under these conditions, increasing the willingness of citizens and industry to actively provide data is necessary. These problems are intensified especially in smaller cities and/or developing countries because they rarely have a reliable data-collection plan, energy or sustainability committees, or adequate human resources to manage these tasks.

These recommendations are ambitious for several reasons. First, at the local level, they require a high level of interdisciplinary expertise and a more time-consuming process than normally, involving big efforts in terms of energy and costs. Furthermore, a budget should be allocated in the collection of good-quality data with a sufficient level of granularity for an efficient interpretation of the results. Last, but not least, support at an upper level (regional, national, international) is required to assure harmonisation and to avoid further fragmentation. Notwithstanding, these seem still necessary for an enhanced and effective long-term vision able to tackle the urban climate change challenge.

5. CONCLUSIONS

The critical analysis of three current standards—the Global Protocol for Community-Scale Greenhouse Gas Emissions (GPC), Bilan Carbone and International Organization for Standardization (ISO) 14064—shows that the methods differ from each other in terms of the accounting approaches used, as well as their targets and strategies for data collection and management. Judging by these few selected examples, achieving harmonisation in the near future seems to be a hard task. Although each method has particular strengths, there are still important aspects that need to be improved and various practical issues are still open, as detailed in the discussion above section.
Detected future research outlooks are addressed here. First, concerning the identification of appropriate goals and scope, it is important to recognise the uniqueness of each city and that the research field connecting cities and climate change is highly interdisciplinary. Therefore, city climate governance requires the collaboration of experts with different technical knowledge, also including economics and social science. The formation of a ‘taskforce’ representing different types of local stakeholders can be efficacious in supporting the policy-making process and engaging the local community, from the definition of relevant climate targets, to the identification of the more sensitive areas, to the data-gathering, communication and monitoring of the results. The acknowledgement of the uniqueness of each urban system should be integrated (in terms of both background and targets and needs) in order to achieve more coherent and meaningful results and avoid ‘one-fits-all’ solutions. Clustering cities in different categories can make cross-city comparisons in a certain category meaningful. Such city categorisation (typology) could be based on physical/geographical attributes (i.e. location, climate, size, number of residents, etc.), but also on functional ones (i.e. touristic cities, industrial cities, metropolitan cities, etc.). Some of these cities have additional transient stakeholders and users (e.g. touristic cities) who affect the local context and economy. Taking into account these additional city-users and their use of urban spaces could be helpful in defining priorities of interventions and dedicated policies more precisely. In this regard, the concept of a functional unit inherent in life-cycle thinking (LCT) can be very helpful because it could offer an added value to the discussion and provide an objective and quantifiable unit of reference for accounting greenhouse gas (GHG) emissions. The inherent dynamics of each city could be captured by an enhanced functional unit (referring to the population-equivalent concept) that could relate and compare, for instance, total yearly emissions, emissions per capita versus emissions per full-time residents and part-time city-users (Mirabella et al. 2018). This is important especially for cities where larger flows of people move compared with permanent residents (e.g. small cities with high touristic activity).

Second, the inclusion of LCT in GHG accounting is essential to avoid the risk of burden-shifting. Both production and consumption approaches are necessary and crucial in supporting the objectives of decarbonisation and the carbon neutrality of cities. The two approaches efficiently support different and multiple targets, and can be used in a complementary way with regard to identifying responsibilities and environmental burdens, acknowledging the emissions under the direct control of the city authorities (territorial/production approach), and emphasising the influence of urban consumption outside city boundaries.

Third, regarding data collection and management, it is of paramount relevance to pay attention to the quality of the data and provide an adequate level of resolution suitable for the urban context (Mirabella et al. 2018), i.e. distinguishing between economic sectors and services, as this greatly affects the results and, therefore, the accounting and assessment steps. An efficient inventory management is helpful in identifying the hotspots and drivers of the emissions, and therefore the final targets of subsequent policies can be detected more precisely. Combining top-down and bottom-up practices, as suggested by Gurney et al. (2015), can be effective in providing a reliable source of information that can support the accounting step and provide meaningful and informative results.

It is important to acknowledge the limitations of this work, as other research and methods focusing on a larger scope deal with similar research questions, e.g. from urban to transnational scales or energy production at a global scale (Chen et al. 2018; Cheng et al. 2018). Most likely, a more extensive scope and cross-analysis would lead to further insights for achieving global carbon emissions reductions. Nevertheless, this contribution emphasises the current research needs of cities for moving towards a carbon-neutral future.

**COMPETING INTERESTS**

The authors have no competing interests to declare.
SUPPLEMENTAL DATA
Supplemental data can be found at https://doi.org/10.5334/bc.50.s1

AUTHOR AFFILIATIONS
Nadia Mirabella orcid.org/0000-0002-2155-0138
Department of Architecture, Faculty of Engineering Science, KU Leuven, Leuven, BE

Karen Allacker orcid.org/0000-0002-1064-0795
Department of Architecture, Faculty of Engineering Science, KU Leuven, Leuven, BE

REFERENCES
ADEME. (2010). Bilan Carbone®. Companies–Local authorities–Regions. Methodology guide, version 6.1. Objectives and accounting principles, 2010. Agence de l'environnement et de la maîtrise de l'énergie (ADEME). Retrieved from http://associationbilancarbone.fr/sites/default/files/guide_methodologique_v6_evk-v.pdf

Aguilar, A. G., Ward, P. M., & Smith, C. B. (2003). Globalization, regional development, and mega-city expansion in Latin America: Analyzing Mexico City's periurban hinterland. Cities, 20, 3–21. DOI: https://doi.org/10.1016/S0264-2751(02)00092-6

Alberti, J., Brodhag, C., & Fullana-i-Palmer, P. (2019). First steps in life cycle assessments of cities with a sustainability perspective: A proposal for goal, function, functional unit, and reference flow. Science if the Total Environment, 646, 1516–1527. DOI: https://doi.org/10.1016/j.scitotenv.2018.07.377

Anthanassiadis, A., Christis, M., Bouillard, P., Vercalsteren, A., Crawford, R. H., & Khan, A. Z. (2016). Comparing a territorial-based and a consumption-based approach to assess the local and global environmental performance of cities. Journal of Cleaner Production, 173, 112–123. DOI: https://doi.org/10.1016/j.jclepro.2016.10.068

Baloukti, M. (2020). Carbon metrics for cities: Production and consumption implications for policies. Buildings and Cities, 1(1), 233–259. DOI: https://doi.org/10.5334/bc.33

Bastianoni, S., Marchi, M., Caro, D., Casprini, P., & Pulselli, F. M. (2014). The connection between 2006 IPCC GHG inventory methodology and ISO 14064-1 certification standard—A reference point for the environmental policies at sub-national scale. Environmental Science and Policy, 44, 97–107. DOI: https://doi.org/10.1016/j.envsci.2014.07.015

Benediktsson, J. A., Pesaresi, M., & Amason, K. (2003). Classification and feature extraction for remote sensing images from urban areas based on morphological transformations. IEEE Transactions on Geoscience and Remote Sensing, 41, 1940–1949. DOI: https://doi.org/10.1109/TGRS.2003.814625

Brown, L. A., & Holmes, J. (1971). The delimitation of functional regions, nodal regions, and hierarchies by functional distance approaches. Journal of Regional Science, 11, 57–72. DOI: https://doi.org/10.1111/j.1467-9787.1971.tb00240.x

C40 Cities Climate Leadership Group. (n.d.). The world is watching cities, now more than ever. Retrieved February 2017 from http://www.c40.org/

C40. (2019). C40 Cities annual report, 2019. Retrieved from https://c40-production-images.s3.amazonaws.com/other_uploads/images/2574_C40_2019_Annual_Report_original.pdf?1587634742

Chen, Z. M., Ohshita, S., Lenzen, M., Wiedmann, T., Jiborn, M., Chen, B., Lester, L., Guan, D., Meng, J., Xu, S., Chen, G., Zheng, X., Xue, J. J., Alsaedi, A., Hayat, T., & Liu, Z. (2018). Consumption-based greenhouse gas emissions accounting with capital stock changes highlights dynamics of fast-developing countries. Nature Communications, 9. DOI: https://doi.org/10.1038/s41467-018-05905-y

Cheng, Y., Zhang, N., & Kang, C. (2018). Carbon emission flow: From electricity network to multiple energy systems. Global Energy Interconnection, 1, 500–506. DOI: https://doi.org/10.14171/j.2096-5117.gei.2018.04.010

Douglass, M. (2000). Mega-urban regions and world city formation: Globalisation, the economic crisis and urban policy issues in Pacific Asia. Urban Studies, 37, 2315–2335. DOI: https://doi.org/10.1080/00402098020002823

EUROCITIES. (2019). Cities leading the way on climate action. Retrieved from http://nws.eurocities.eu/ MediaShell/media/EUROCITIES_cities_climate_action_2019.pdf

European Commission. (2012). Organization Environmental Footprint Guide (OEF) Deliverable 3 and 48 to the Administrative Arrangement between DG Environment and Joint Research Centre No. N 070307/2009/552517, including Amendment No 1 from December 2010. Retrieved from http://ec.europa.eu/environment/eussd/pdf/footprint/OEF%20Guide_final_July%202012_clean%20version.pdf
European Commission, Joint Research Center. (2011). Analysis of existing environmental footprint methodologies for products and organizations: Recommendations, rationale, and alignment. Publications Office of the European Union. Retrieved from http://ec.europa.eu/environment/eussd/pdf/Deliverable.pdf

Global Covenant of Mayors for Climate and Energy. (2017). Retrieved April 2017 from www.globalcovenantofmayors.org/

Gurney, K. R., Romano-Lanzano, P., Seto, K. C., Hutyra, L. R., Duren, R., Kennedy, C., G., Grimm, N. B., Ehleringer, J. R., Marzuttiuli, P., Hughes, S., Pincetl, S., Chester, M. V., Runfolo, D. M., Fedema, J. J., & Sperling, J. (2015). Climate change: Track urban emissions on a human scale. Nature, 525, 179–181. DOI: https://doi.org/10.1038/s525179a

Gürtel, E., & Tat, M. (2017). SWOT analysis: A theoretical review. Journal of International Social Research, 10(51). Retrieved from https://www.sosyalarastirmalar.com/clrt10/oys51_pdf/pdf2/satis_isletmeemyuqem erlemet.pdf. DOI: https://doi.org/10.17719/jjsr.2017.1832

Hartshorne, R. (1933). Geographic and political boundaries in Upper Silesia. Annals of the Association of American Geographers, 23, 195–228. DOI: https://doi.org/10.1080/00045603309357073

Hidle, K., Farsund, A. A., & Lysgaard, H. K. (2009). Urban–rural flows and the meaning of borders functional and symbolic integration in Norwegian city-regions. European Urban and Regional Studies, 16, 409–421. DOI: https://doi.org/10.1177/0969776409340863

Hoornweg, D., Sugar, L., Trejos Gomez, C. L., & Trejos Gómez, C. L. (2011). Cities and greenhouse gas emissions: Moving forward. Environment and Urbanization, 23, 207–227. DOI: https://doi.org/10.1177/0969776409340863

Hudeková, Z., Krajscovicová, L., Martin, P., Pouditšová, E., & Reháčková, T. (2007). Ecological footprint, climate change and cities—Innovation of ecological footprint calculation and presentation of opportunities to mitigate adverse impacts of climate change in cities. Retrieved from http://ec.europa.eu/environment/life/project/Projects/index.cfm?fuseaction=home.showFile&rep=file&fil=UrbEco_EcologicalFootprint.pdf

Ibrahim, N. (2015). Prioritizing climate action for low-carbon growth in cities (doctoral thesis, University of Toronto).

ICLEI. (n.d.). Our network. Local Governments for Sustainability (ICLEI). Retrieved November 2019 from https://wwwICLEI.org/en/our_network.html

IPCC. (2009). Concept Paper for an IPCC expert meeting on human settlement, water, energy and transport infrastructure—Mitigation and adaptation strategies—Scoping for the IPCC 5th Assessment Report. IPCC-XXX/Doc.16 On Climate Change (6.Iv.2009) Deliverable.pdf

ISO. (2018). ISO 14064-1:2018: Greenhouse gases—Part 1: Specification with guidance at the organization level for quantification and reporting of greenhouse gas emissions and removals. International Organization for Standardization. https://www.iso.org/standard/66453.html

Kennedy, C., Ramaswami, A., Carney, S., & Dhakal, S. (2011). Cities and climate change: Responding to an urgent agenda. DOI: https://doi.org/10.1596/9780821384930_CH02

Kennedy, C., Steinberger, J., Gasson, B., Hansen, Y., Hillman, T., Havraneck, M., Patoki, D., Phdunsilp, A., Ramaswami, A., & Villalba Mendez, G. (2010). Methodology for inventorying greenhouse gas emissions from global cities. Energy Policy, 38, 4828–4837. DOI: https://doi.org/10.1016/j.enpol.2009.08.050

Liu, Z., Feng, K., Hubacek, K., Liang, S., Diaz Anadona, L., Zhang, C., & Guan, D. (2015). Four system boundaries for carbon accounts. Ecological Modelling, 318, 118–125. DOI: https://doi.org/10.1016/j.ecolmodel.2015.02.001

Lombardi, M., Laiola, E., Tricase, C., & Rana, R. (2017). Assessing the urban carbon footprint: An overview. Environmental Impact Assessment Review, 66, 43–52. DOI: https://doi.org/10.1016/j.eiar.2017.06.005

Mirabella, N., Allacker, K., & Sala, S. (2018). Current trends and limitations of life cycle assessments applied to the urban scale: critical analysis and review of selected literature. International Journal of Life Cycle Assessment. DOI: https://doi.org/10.1007/s11367-018-1467-3

Paloheimo, E., & Salmi, O. (2013). Evaluating the carbon emissions of the low carbon city: A novel approach for consumer based allocation. Cities, 30, 233–239. DOI: https://doi.org/10.1016/j.cities.2012.04.003

Ramaswami, A., Hillman, T., Jonson, B., Reiner, M., & Thomas, G. (2008). A demand centered, hybrid life cycle methodology for city-scale greenhouse gas emissions. Environment Science and Technology, 42, 6455–6461. DOI: https://doi.org/10.1021/es702992q

Rashed, T., Weeks, J. R., Roberts, D., Rogan, J., & Powell, R. (2003). Measuring the physical composition of urban morphology using multiple endmember spectral mixture models. Photogrammetric Engineering and Remote Sensing, 69, 1011–1020. DOI: https://doi.org/10.14358/PERS69.9.1011
