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Assessing the urban carbon footprint: An overview

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ABSTRACT

All cities present environmental sustainability issues, above all regarding greenhouse gas (GHG) emissions, and specifically carbon dioxide (CO_2), that directly affect climate change. Consequently, it is very important to quantify and report their Carbon Footprint (CF) for implementing national and international policies/strategies aimed at mitigating and adapting these concerns. The Urban Carbon Footprint (UCF), indeed, has been recognized as the more valuable choice to inform, specifically, decision makers about city environmental sustainability. Several accounting systems and inventory methods have been taken into account to perform UCF, highlighting the complexity of the topic and generating very often confusion among users.

In this context, the authors aim to summarize what has been done and what is going on with UCFs, trying to classify them according to some principal dimensions. Thus, they divide UFCs in two main categories namely: “spatial” or “direct”, with a limited amount of data requested, and “economic” or “life cycle based”, more or less data inclusive according to the accounting systems considered. Furthermore, they observe that there is not a “global agreed-upon protocol” yet, neither is there a specific model shared among researchers, even if some steps have been made towards this direction (Relative Carbon Footprint - RCF, Publicly Available Specification – PAS 2070 and Global Protocol for Community scale - GPC). Consequently, it is necessary to complete and standardize, in the short term, the accounting and reporting frameworks, in order to compare different UCFs for adopting shared climate strategies and actions at global level.

1. Introduction

All cities are characterized by environmental sustainability issues that are expressed in terms of traffic congestion, noise, air quality and Greenhouse Gas (GHG) emissions. Therefore, over the years, a series of international strategies and policies have been aimed at resolving these problems and, specifically, to reduce carbon dioxide (CO_2) emissions, thus directly affecting climate change (IPCC, 2014; Lombardi et al., 2014, 2016).

Urban areas, indeed, although covering only 2% of the Earth's land surface (Balk et al., 2005; Athanassiadis et al., 2015), are the places where more than half of the world's population lives (3.9 billion in 2014), and so where a high level of the consumption of resource's occurs (United Nations, 2014). For instance, in 27 megacities (where more than ten million people live) the total waste production in 2011 was equal to 12.6% of the global value, gasoline use to 9.9%, electricity consumption to 9.3%, energy demand to 6.7%, and water use to 3% (Kennedy et al., 2015). This means that urban agglomerates cause the depletion of natural resources and have a significant environmental impact, such as the GHG emissions mostly associated with the

Abbreviations: AFOLU, Agriculture, Forestry, and Other Land Use; BEET, Balanced Embodied Emission in Trade; BEI, Baseline Emission Inventory; BSI, British Standard Institution; C40, C40 Cities Climate Leadership Group; CBF, Consumption-Based Footprint; CCM, City Carbon Map; CCN, City Carbon Network; CF, Carbon Footprint; CH_4, Methane; CIF, Trans-boundary Community-wide Infrastructure Footprint; CO_2, Carbon dioxide; CO_{2eq}, Carbon dioxide equivalent; CoM, Covenant of Mayors; DPSC, Direct Plus Supply Chain; EC, European Commission; EEBT, Emissions Embodied in Bilateral Trade; EIOA, Environmental Input-Output Analysis; EP, Export of Products; FC, Final Consumption; GHG, Greenhouse Gas; GPC, Global Protocol for Community-Scale; GWP, Global Warming Potential; HFCs, Hydro-fluorocarbons; HPCA, Hybrids of Production and Consumption Approaches; IBA, In-Boundary Accounts; ICLEI, International Council for Local Environmental Initiatives; IEAP, International local government GHG Emissions Analysis Protocol; IIPE, Import of Intermediate Products for Export; IIPFC, Import of Intermediate Products for Final Consumption; IOA, Input-Output Analysis; IP, Import of Products; IPCC, Intergovernmental Panel on Climate Change; IPPU, Industrial Process and Product Use; ISC, International Standard for reporting GHG emissions for Cities; LCA, Life Cycle Assessment; MFA, Material Flow Analysis; MRIO, Multi - Regional Input-Output; MRIOA, Multi - Regional Input-Output Analysis; N_2O, Nitrous oxide; NF_3, Nitrogen trifluoride; PA, Process Analysis; PAS, Publicly Available Specification; PBF, Production-Based Footprint; PCB, Purely Consumption-Based Accounting; PFC, Production for Final Consumption; PFCs, Per-fluorocarbons; PGA, Purely-Geographic Accounting; PGI, Purely-Geographic Inventory; P-IOA, Physical Input-Output Analysis; PPF, Purely Production Footprint; RCF, Relative Carbon Footprint; SEAP, Sustainable Energy Action Plan; SF_6, Sulphur hexafluoride; SO_2, Sulphur dioxide; TBIF, Trans-Boundary Infrastructure Supply Chain Footprint; UCF, Urban Carbon Footprint; UM, Urban Metabolism; UN, United Nations; UNEP, United Nations Environment Programme; UN-H, United Nations – Habitat; WB, World Bank; WBCSD, World Business Council for Sustainable Development; WRI, World Resources Institute

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combustion of fossil fuels for heating houses or commercial/administration activities, for producing electricity, and for the public and private transport of people and goods. Specifically, every year, cities are responsible for 80% of releases of these gases (Kalmykova et al., 2015; Sovacool and Brown, 2010), of which 70% is CO_2 (Lombardi et al., 2016).

In this framework, it is very important to quantify and report GHG emissions for the implementation of the aforementioned international policies/strategies in order to mitigate and to adapt climate change (Bulkeley, 2010; Larsen and Hertwich, 2009; UN-HABITAT, 2011).

The first attempt to assess the level of environmental impact of cities was the application of the Urban Metabolism (UM) concept, elaborated in the 1960's. This allows the analysis of the energy and material flows associated with the production and consumption of human activities, by using different methodologies developed in the last 20 years (Beloin-Saint-Pierre et al., 2016; Chen and Chen, 2015). Among those settled to date, the Urban Carbon Footprint (UCF) represents one of the most significant "outflows" from a city with worldwide consequences (Da Schio and Fagerlund Brekke, 2013). Additionally, it has been recognized as the more valuable choice to inform, specifically, decision makers about urban direct and indirect GHG emissions. Indeed, as reported by Beloin-Saint-Pierre et al. (2016), 91% of reviewed UM studies applied this methodology to provide useful data for mitigation policies (Beloin-Saint-Pierre et al., 2016; Lin et al., 2015).

Nevertheless, UCF calculation is almost complex due to some aspects that have to be considered. Indeed, in recent years, both researchers, and organizations and political leaders have proposed both different accounting systems (to define what emissions should be taken into account) and methods (to gather GHG data for the city-scale inventory). Additionally, various terminologies have been often used to indicate the same meaning, contributing at generating confusion in this field. Consequently, the studies are in continuous development in order to overcome these drawbacks and to identify a standardized framework, which has to be accurate, comparable, and comprehensive.

In this context, the authors aim to summarize what has been done and is going on with UCFs, trying to classify them according to some principal dimensions. Based on the available data, the resulting outline could represent a guide for choosing the more complete and consistent UCF for GHG emission assessment, meeting the needs of final users.

2. Urban carbon footprint: principal elements and accounting systems

The CF was born to measure the overall amount of CO_2 and other GHG emissions linked directly or indirectly with a product (that means both goods and services), along its supply-chain (EC-JRC, 2009). Such releases are all expressed in terms of carbon dioxide equivalent (CO_{2eq}) thanks to the Global Warming Potential (GWP), which indicates the potential climate change effect per kg of a GHG over a fixed period (e.g. 100 years) (IPCC, 2007). The CF studies were then applied at various scales, such as for households, organizations, and corporations, nations and cities that, under climate change mitigation policies, must have a comprehensive tool for implementing specific actions in such fields. There exists a significant difference between national and cities CF since: a) for nations, emissions data are always based on production activities within the territorial spatial boundary; b) for cities, actually, emission data could be based also on spatial relationships with surrounding hinterlands and the global resource web, since the city condition is more complex than that of the country (Ibrahim et al., 2012; Li and Zan, 2016; Zhang et al., 2015a).

In this context, the CF applied to a city has been recognized as a comprehensive view for assessing the GHG emissions arising from an urban system in order to provide a valuable tool for local policy decision-makers (Dhakal and Ruth, 2017; Ohnishi et al., 2017; Lin et al., 2015; Onat et al., 2014; Xi et al., 2011; Hoornweg et al., 2011; Sovacool and Brown, 2010; Dodman, 2009). This term is used in the urban area as a synonym for embodied carbon, carbon content, embedded carbon, carbon flows, virtual carbon, GHG footprint, and climate footprint (Bhoyar et al., 2014; Peters, 2010).

In order to calculate city's carbon footprint the compilation of GHG inventories is necessary. This collecting is very difficult because: 1) there are not always available city-sale data; 2) and there are several existing connections among citizens and economic activities, that make hardly the GHG allocation.

The first important element that has to be considered for the UCF assessment is where the city emissions occur, that means the "*spatial boundary*" considered. Actually, the emissions can take place inside (in-boundary) or outside (out-boundary) the city, therefore generating direct and indirect releases respectively (Ramaswami et al., 2011; Wiedmann and Minx, 2008). In recent years, the definition and inclusion of more indirect emissions have been debated by the academic literature (Dodman, 2009; Hillman and Ramaswami, 2010; Kennedy et al., 2009; Ramaswami et al., 2008) and so different meanings exist.

The second important element is the "*community typology*" (or city) according to its economic structure. Some authors distinguished net producer, net consumer and trade-balanced community. The first typology refers mainly to industrial or resort communities with higher territorial emissions due to the local production; the second concerns suburban towns dominated by homes with higher territorial emissions due to consumption. Lastly, the trade-balanced city is characterized by the equal amount of industries and homes in the hinterland, and so does not have any emission typology prevalence (Chavez et al., 2012; Ramaswami et al., 2011; Yetano Roche et al., 2014). Chavez and Ramaswami (2013) also introduced the concept of embodied emissions associated with export and import activities. If the balance between imports and exports of GHG embodied activities approaches zero, the community has to be considered as trade-balanced; if the difference is largely negative, the city is identified as a net-producer; if positive as a net-consumer. The previous identification of community allows not underestimating or overestimating its GHG emissions since it addresses towards the UFC accounting system closer to the city characteristics.

According to the "spatial boundary" and the "community typology" considered, the combination of approach (system) types and the data collecting methods, a fair classification of UFCs is possible.

The authors decided to label UCFs in: "spatial or direct", since it measures only the territorial GHG emissions; and "economic or life cycle based", since it include all type of releases even those generated by export and import city activities (Fig. 1).

The following sections will explain which are the scopes, the accounting systems and the inventory methods associated to these typologies, describing also all the essential elements, which have brought to this classification.

2.1. Scopes and accounting systems

The scopes are the most used and standardized definitions for classifying the direct and indirect emissions. They were elaborated by the World Business Council for Sustainable Development (WBSCD) and World Resources Institutes (WRI), in 2001, for corporates, and categorised according to three scopes. In 2014, these were extended to city (WBSCD and WRI, 2001; WRI et al., 2014) (Fig. 2).

As depicted in Fig. 2, GHG emissions deriving from local/territorial activities inside the city boundary are classified as direct; they include "scope 1" emissions (e.g. fossil fuel combustion, waste, industrial processes and product use, agriculture, forestry and other land use). If emissions come from the use of energy purchased from the national grid and produced out of city boundary they are called energy indirect emissions; these include "scope 2" emissions (e.g. electricity, heat, steam and/or cooling). In this case, the GHG releases may or may not cross the boundary because of upstream activities of fuel supply chains. Finally, if they derive from upstream and downstream city activities, occurring outside the city boundary, they are named "other indirect

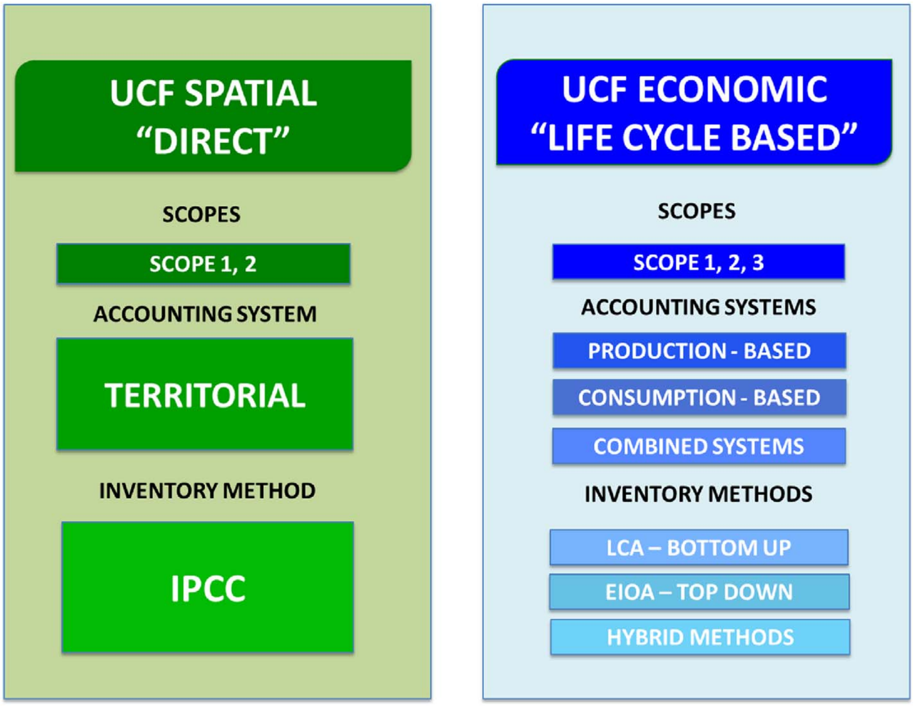

Fig. 1. UCF classification according to the different systems and inventory methods.
(Source: Our elaboration)

emissions"; these include "scope 3" emissions (e.g. waste and wastewater, marine and aviation transport, imported and exported food, water, construction materials, fertilizer/pesticide, manufacture, and upstream of power plants) (WRI et al., 2014).

Consequently, the abovementioned scope classification allows the indirect emissions to be split into trans-boundary (emissions that occurred cross-scale and cross-sectors) and/or embodied emissions (included in food, water, fuels and building materials consumed or exported by the cities). Thus, the urban environmental impact at local, regional and global geographical level can be identified (Ramaswami

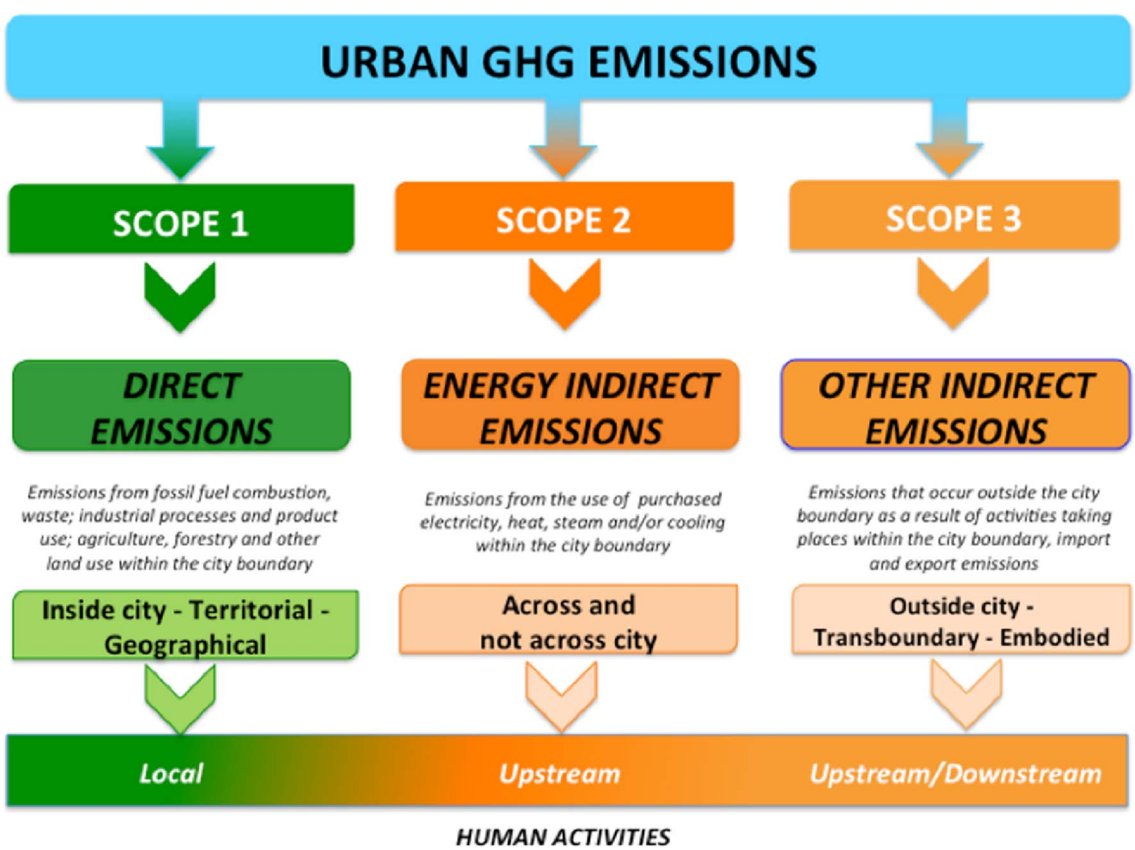

Fig. 2. Definition of urban GHG emissions including scopes.
(Source: Our elaboration on Ramaswami et al., 2011; Ramaswami et al., 2012a, 2012b; WRI and WBSCD, 2013; WRI et al., 2014)

Table 1
Evolution of UFC systems according to the academic literature.

Systems	Typology	Authors
Territorial	Purely-Geographic Inventory (PGI)/In-Boundary Accounts (IB)	Chavez and Ramaswami, 2013
	Purely-Geographic Accounting (PGA)	Lin et al., 2015
Production-based	Purely Geographic Production-based GHG Accounting	Ramaswami et al., 2011
Consumption-based	Purely Consumption-Based Accounting (PCB)	Ramaswami et al., 2011
	Consumption-Based Footprint (CBF)	Chavez et al., 2012
Combined	Demand-centred, hybrid GHG inventory method	Ramaswami et al., 2008
	Geographic-Plus Infrastructure Supply Chain GHG Footprints	Ramaswami et al., 2011
	Trans-Boundary Infrastructure Supply Chain Footprint (TBIF)	Chavez et al., 2012
	Trans-boundary Community-wide Infrastructure Footprint (CIF)	Chavez and Ramaswami, 2013
	Supply Chain	Yetano Roche et al., 2014
	Production-Based Footprint (PBF)	Lin et al., 2015
	Purely Production Footprint (PPF)	Lin et al., 2015

Source: Our elaboration.

et al., 2011; Richter, 2012; Vetőné Mózner, 2013).

According to the "community typology" and the "spatial boundary" considered, there are three main UCF accounting systems (as an alternative also named approaches, models or perspectives). They are the territorial, the production-based and consumption-based system. In some case, to better represent the city-scale environmental impact related to climate change, a combination of them has been used (Chavez and Ramaswami, 2013; Dahal and Niemelä, 2017; EEA, 2013; Erickson et al., 2012; Hu et al., 2017; Lin et al., 2015; Munksgaard et al., 2005; Pandey et al., 2011; Peters et al., 2011; Richter, 2012; Shao et al., 2016; Yetano Roche et al., 2014; USEPA, 2016). At present, the consumption-based system is defined as the more comprehensive option and largely used (Vetőné Mózner, 2013; Wiedmann et al., 2016; WRI et al., 2014).

Territorial System calculates emissions occurring within one's borders and offshore areas falling under the jurisdiction of city, including scope 1 and scope 2 emissions. Initially, this system was born to account for a country or region releases and to define mitigation efforts as established by international environmental law (USEPA, 2016). TS does not reflect city-scale emissions from national and international trade. It is used above all for net-producer community.

Production-Based System includes all emissions from economic activities (production) by resident companies and households in specific sectors regardless of where these take place (also beyond the city's boundaries). For this reason, they include not only the scope 1 and scope 2 but also some of scope 3 emissions. Indeed, PBS takes account of embodied emissions deriving from the export city activities (WRI et al., 2014). It is used above all for net-producer community.

Consumption-Based System calculates the emissions associated with fuels, products and services used by the city (i.e. locally produced and/or imported regardless of where the production of such goods and services occurred); therefore, they include sources that are beyond the boundary (apart from exported products and services). As PBS, this system considers the scope 1 and scope 2 but also some of scope 3 emissions, specifically embodied ones from import city activities. This system covers all emissions resulting from the consumption of local and imported goods and services, and are, therefore, considered more comprehensive calculation methods than production-based and territorial models (Dahal and Niemelä, 2017). It is used above all for net-consumer community.

As said before, in some case, a combination of them could be used. The authors decided to title it as *Combined Production and Consumption System* (CPCS). This measures GHGs within city boundaries, plus indirect emissions deriving from infrastructure (commuter and airline transport, energy supply, water supply, wastewater infrastructures, etc.), and non-infrastructure supply-chains serving the whole community (all goods and services not included in infrastructure supply-chains). This means that all the embodied emissions from import and export activities are included (Chavez and Ramaswami, 2013; Dahal and Niemelä, 2017; ECIS, 2012; Ibrahim et al., 2012; Lin et al., 2013). It is used above all or trade-balanced community.

2.2. Academic literature overview

Since 2008, academic researchers have been dealing with these aspects to define a theoretical backdrop applicable to specific studies, developing several specific systems in order to improve them.

The production-based system has been the most merged in order to overcome both own limitations and those deriving from consumption-based approach, including all the typologies of indirect emissions. The first proposal was elaborated, in 2008, with the life-cycle-based methodology called "demand-centred" applied to Denver city (Colorado, USA). These included indirect GHG emissions associated with the embodied energy of producing key urban materials, together with the direct ones reported in the typical city-scale GHG inventory. In the following years, the same authors tried to improve this model in order to standardize it. In 2011, they developed the "Geographic-Plus Infrastructure Supply Chain GHG Footprints", in 2012, the "Trans-boundary Infrastructure Supply Chain Footprint Method" (TBIF), and in 2013, the "Trans-boundary Community-Wide Infrastructure Footprint" (CIF) (Chavez and Ramaswami, 2013; Chavez et al., 2012; Ramaswami et al., 2011; Ramaswami et al., 2008). Two years later, starting from these previous approaches, other researchers elaborated the "Production-Based Footprint" (PBF) and "Purely Production Footprint" (PPF) that cover emissions embodied in products traded among regions and intra-city sectors, i.e. non-infrastructure supply chains (Lin et al., 2015) (Table 1).

3. Urban carbon footprint: inventory methods

Once the accounting system has been selected, it is necessary to apply a model to collect data in order to conduct a city-scale inventory. Three main basic methods have been identified: the **IPCC**, the **LCA**, and the **EIOA** (Carloni and Green, 2017; Ohnishi et al., 2017; Larsen and Hertwich, 2010a; Lin et al., 2013; Peters, 2010; Ramaswami et al., 2008). As reported by Peters (2010), choosing between these options generally depends on functional unit via scale. On a large scale, i.e. at the national level, studies would use the top-down input-output analysis for gathering emissions data; while at a fine scale, i.e. for a production process, generally, they would apply LCA.

The **IPCC** is a comprehensive method of reporting for the Greenhouse Gas Inventories at the national level (IPCC, 2006). This methodology was created to calculate and report territorial GHG emissions resulting from the six main gases (CO_2; CH_4; N_2O; HFC_s; PFC_s; SF_6), outlined in the Kyoto Protocol. It requires, indeed, only the reporting of direct emissions from sectors and subsectors and can also be applied for city level within its boundaries, regardless of where the output of the production is consumed (Dong et al., 2016; Larsen and Hertwich, 2010a; Richter, 2012). The **IPCC** was the first method adapted for city-scale GHG inventories and so, frequently, used. Nevertheless, as shown in Table 3, it was also applied for the other system typologies since the researchers utilized its emission factors for assessing the UCF of some sectors, such as municipal solid waste. As discussed in the next section, all the international institutional protocols for GHG accounting use principles, approaches, and methodologies provided by the IPCC guidelines. Three modelling approaches (tiers), with an increasing level of complexity, are given by this standard (IPCC, 2006).

Yajie et al. (2014) offered another tool in this direction with the Emission Sources Account (ESA) model, which is a simplified method used to calculate the UCF. ESA adopts the 2006 Guidelines for National Greenhouse Gas Inventories by IPCC to account for only four emission sources: energy consumption, soil and crop, livestock, and solid waste, and it does not require the complex datasets that are used by other approaches (LCA and EI-O analysis).

The **LCA** or **PA** is defined as a bottom-up analysis and mainly used for consumption-based accounting system, according to a life cycle -based prospective. It is a way of reporting potential environmental loads and resources consumed in each step of a product or service supply chain (i.e. extraction of raw materials, production of goods, their use by the end-users, or provision of a service, recycling, energy recovery and final disposal) (ISO, 2006a; ISO, 2006b; Strohbach et al., 2012). As is known, LCA measures the emissions of a specific process and has a greater level of accuracy; it could be a sufficient way of developing a UCF model for a specific case study, performing details and responses to actions well (Heinonen and Junnila, 2010). In a process-based LCA, data are collected for all the processes that have been identified as important to include within the chosen system boundary. For this reason, it has the disadvantage being a subjective evaluation of which processes to include. It is time-consuming and requires a large amount of data, specific software, and specialized analyst skills for fully understanding the outcomes provided by the method (Kalbar et al., 2017). Additionally, the LCA model could be insufficient when it is focussed on municipal services, due to the significant number of services purchased from other cities, governments, or private actors. Therefore, assessing the UCF by LCA is not recommended due to its complexity and no representativeness (Larsen and Hertwich, 2010a, 2010b).

The **IOA** is a top-down model originated by Leontief during the 1940s; it is extremely useful quantifying transactions between the activities measured in monetary units. Its evolution is the **P-IOA** that evaluates, instead, these transactions in physical units, such as kilograms or kWh. The extended advancement is the **EIOA**, a useful choice because the effects of many elementary flows (e.g. pollutant emissions) are converted into few environmental impact indicators for each component; it therefore considers the associated carbon emissions embodied in international trade (import/export) (Feng et al., 2012; Vetőné Mózner, 2013). It could also be used for consumption-based accounting approach such as LCA and it based also on a life cycle based prospective. However, although the EIOA needs less time and labour than LCA, it cannot be used for micro systems (i.e. particular processes, small groups of individual products, etc.). It has been also extended to inter-regional trade analysis generating a new accounting approach for embodied emissions in national trade, namely **Multi-Regional Input-Output Analysis** (**MRIOA**). MRIOA is the most popular tool since it allows analysis at a multi-regional level (intra- or inter-country, intercities, inter-metropolitan areas), thus avoiding the double counting of emissions (Boitier, 2012; Chen et al., 2016; Choi, 2015; Minx et al., 2009; Peters, 2008; Zheng et al., 2016). Specifically, Choi (2015) stated the importance of the MRIO modelling framework as it provides information by assessing the impact of coordinated policy actions among cities connected through supply and demand chains. However, in order to estimate the emission trade balance, the use of this methodology is not always possible, as the existence of such tables is rare (Vetőné Mózner, 2013).

In recent years, in order to overcome the drawbacks of the respective methods for the aforementioned emission inventories, academic researchers proposed their combination (hybrid methods). For example, EIOA/LCA, merging the strength of both, becomes more complete (Kjaer et al., 2015; Onat et al., 2014; Shirley et al., 2012; Wright et al., 2011; Wiedmann and Minx, 2008). Indeed, service and capital good expenses data are provided by EIOA, while the process-based data are added by LCA; this therefore integrates the EIOA model with higher levels of detail (Kjaer et al., 2015). Jayanthakumaran and Liu (2016) proposed the **Emissions Embodied in Bilateral Trade** (**EEBT**), a hybrid method that first uses IPPC formula and then I-O analysis. It focusses on the total exports (among bilateral trading partners) from a territory including intermediate and final products. Furthermore, it takes into account the share of local emissions from the exported products of bilateral partners; it could therefore be considered an advantage over MRIO because it is simpler to use (Jayanthakumaran and Liu, 2016; Wu et al., 2016). This model has been applied only to countries so far; nevertheless, it could also be a valuable tool for UCF. Lin et al. (2015), indeed, have employed a similar approach, the **Balanced Embodied Emission in Trade** (**BEET**) for Xiamen City and so with more uncertain data.

Further typologies are given by combining some UM methodologies, such as MFA and Emergy, with EIOA and LCA (Ramaswami et al., 2008; Pincetl et al., 2012; Chester et al., 2012; Ramaswami et al., 2012a, 2012b; Goldstein et al., 2013). These hybrid models are able to capture the environmental impacts that mass and energy flow analyses do not allow (Beloin-Saint-Pierre et al., 2016; Yetano Roche et al., 2014).

These hybrid methods are still an active area of research and they are increasingly being used in practice. However, the prevailing city-scale model is certainly the EIOA/LCA applied to CBA since it overcomes the lack of city-scale EIOA data. Furthermore, it is able to take into account the different GHG emission intensities inside and outside the city-boundary (Chavez and Ramaswami, 2013; Kjaer et al., 2015; Ramaswami et al., 2008; Vetőné Mózner, 2013) (Table 2).

Some researchers developed a new dynamic concept of UCF, starting from the described city-scale frameworks shown in Table 2. One of these is the **City Carbon Map** (**CCM**), proposed by Wiedmann et al. (2016) and applied to the city of Melbourne. It identifies, using the EIOA and the hybrid approach, the embodied emission flows from industries (origin) to products (destination) in and out the urban area including, consequently, all type of releases (scopes 1, 2 and 3). The CCM could represent a carbon accounting framework at various spatial scales, permitting the elaboration of city, regional, national, and global GHG inventories. Therefore, there is no double counting or ambiguity since all emissions have been allocated to clearly defined and standardized economic sectors. However, since data are obtained by a top-down accounting method, they do not consider the emissions coming from locally specific activities. Thus, in order to improve the GHG emission modelling, bottom-up data should be included (Wiedmann et al., 2016). The possibility of using the combination of a hybrid approach with a hybrid method, not used so far, might represent the best way of assessing the UCF as considering all emission sources.

Another new concept is the **City Carbon Network** (**CCN**), proposed by Chen et al. (2016), which considers the inter-city embodied emission flows, starting from the CCM concept. It reveals, using a MRIO method and the CBA approach, a hierarchy of responsibility for emissions between cities and regions. It is very crucial to monitor and report embodied emissions since omitting these would underestimate the real GHG amount, making mitigation policies ineffective. Therefore, involving trade partners can support the design of broader and more appropriate local government strategies.

3.1. Inventory standards overview

In recent years, governments and international organizations have introduced different kinds of UCF inventory standards (i.e. protocols or

Table 2
GHG emission city-scale methods.

METHODS FOR INVENTORY	SYSTEMS			
	Territorial	Production-based	Consumption-based	Combined
Principal				
IPCC	Lin et al., 2015; Carloni and Green, 2017	Xi et al., 2011	Larsen and Hertwich, 2009; Feng et al., 2015	Chavez et al., 2012
ESA		Yajie et al., 2014		
LCA			Heinonen and Junnila, 2010	Kalbar et al., 2017
EIOA			Munksgaard et al., 2005; Larsen and Hertwich, 2010a; Larsen and Hertwich, 2010b; Zhou et al., 2010; Ramaswami et al., 2011; Larsen and Hertwich, 2011; Erickson et al., 2012; Guo et al., 2012; Ala-Mantila et al., 2013; Chen et al., 2013; Wang et al., 2013; Heinonen et al., 2013, Lazarus et al., 2013; Vause et al., 2013; Ala-Mantila et al., 2014; Dias et al., 2014; Caro et al., 2015; Shao et al., 2016	Chavez and Ramaswami, 2013; Lin et al., 2013; Lin et al., 2015; Wiedmann et al., 2016
MRIO			Peters, 2008; Lenzen and Peters, 2010; Minx et al., 2013; Yao et al., 2013; Feng et al., 2014; Hermannsson and McIntyre, 2014; Choi, 2015; Zhang et al., 2015b; Zheng et al., 2016	Minx et al., 2009; Hu et al., 2016; Chen et al., 2016
Hybrid				
EIOA/LCA			Wiedmann and Minx, 2008; Jones and Kammen, 2011; Jones and Kammen, 2014; Wright et al., 2011; Shirley et al., 2012	Onat et al., 2014; Yetano Roche et al., 2014; Dong et al., 2016; Ohnishi et al., 2017
EEBT and BEET				Jayanthakumaran and Liu, 2016; Lin et al., 2015
MFA/EIOA/LCA				Ramaswami et al., 2008
EMERGY/LCA				Li and Wang, 2009
MFA/LCA				Chester et al., 2012; Pincetl et al., 2012; Ramaswami et al., 2012b; Goldstein et al., 2013

Source: Our elaboration.

Table 3
Major inventory frameworks reviewed of IPCC standards.

	Authors	Inventory framework	Target audience	GHG included
1996/2006 IPCC Guidelines for National GHG Inventories	ICLEI (2009)	**I**nternational local government GHG **E**missions **A**nalysis **P**rotocol (**IEAP**)	Local governments and communities	CO_2; CH_4; N_2O; HFCs; PFCs; SF_6.
	EC – CoM (2010)	**B**aseline **E**mission **I**nventory (**BEI**)	Cities in the EU	CO_2; CH_4; N_2O
	World Bank et al. (2010)	**I**nternational **S**tandard for reporting GHG emissions for **C**ities (**ISC**)	Cities and metropolitan regions	CO_2; CH_4; N_2O; HFCs; PFCs; SF_6
	BSI (2013)	Specification for the assessment of GHG emissions of a city - **PAS 2070**	Cities	CO_2; CH_4; N_2O; HFCs; PFCs; SF_6
	WRI et al. (2014)	**G**lobal **P**rotocol for **C**ommunity scale GHG emissions (**GPC**)	Communities worldwide	CO_2; CH_4; N_2O; HFCs; PFCs; SF_6; NF_3.

Source: Our elaboration.

specifications), for making comparable results of city-scale carbon footprint since, as already shown, there is no uniform methodology, universally accepted (Gao et al., 2014).

In this context, there are different existing institutional protocols, used internationally, for GHG accounting based on different levels of reporting. All GHG inventories for cities derive their principles, approaches, and methodologies from the guidelines of IPCC (2006) (Richter, 2012; World Bank et al., 2010). For example, all reviewed standards generally followed the division of emission sources into four sectors: Energy, Industrial Process and Product Use (IPPU), Waste and Agriculture, Forestry, and other Land Use (AFOLU) (WRI et al., 2014). The authors decided to compare the most important standards, since they have been applied worldwide, as reported in the following Table 3. These inventory methods differ for the sources and number of GHGs involved and for the accounting method of indirect emissions (Wiedmann et al., 2016).

The **International local government GHG Emissions Analysis Protocol** (**IEAP**), launched in 2009 by ICLEI, represented the first guidelines and standards for urban GHG emissions reporting. It provides support for characterizing indirect GHG emissions for local governments based on their degree of control. It considers some GHGs (such as CO_2, N_2O and CH_4) and main economic sectors of the IPCC framework, with the addition of optional community sectors for facilitating decision-making. Furthermore, it relies on the concept of scopes including all emissions from electricity production in scope 2, but not taking into account where the production occurs, and the indirect emissions from waste and wastewater. It is not fully complete because it does not comprise embodied import emissions for food, construction materials and water (WRI et al., 2014; Richter, 2012; ICLEI, 2009).

One year later, the European Commission (EC) published the guidebook for elaborating the Sustainable Energy Action Plan (SEAP), including the **Baseline Emissions Inventory** (**BEI**), addressed to all signatories' of the European cities of Covenant of Mayors' initiative (CoM). The BEI suggests a predominantly production-based approach, according to IPCC framework, but with the inclusion of indirect emissions due to heating, cooling, and electricity production consumed within the geopolitical boundaries. Other important differences are the possibility of reporting one GHG – CO_2; to use either of the standard IPCC default emission factors or an LCA emission factor in their calculations; to report any other GHG emissions separately in an additional category. EC-CoM requires activity data related to the city and discourages estimates based on national averages. According to all these aspects, BEI could not be considered as a comprehensive and complete framework (WRI et al., 2014; Lombardi et al., 2014; Richter, 2012; Covenant of Mayors, 2010). Consequently, the main objective of this document is only to show the economic sectors with the greatest GHG emission amount where mitigation actions have to be implemented.

In the same year, the World Bank (WB) together with the United Nations-Habitat (UN-H) and United Nations Environmental Program (UNEP) issued the **International Standard for Greenhouse Gas for Cities** (**ISC**), a methodology very similar to IEAP. The difference is its specific list of embodied emission sources, intensively used by cities, characterized by both emissions from production and consumption activities (e.g. food). Indeed, it reports emissions from AFOLU and allows the gathering of information with a different degree of precision depending on data availability (such as the IPCC's "Tier 1, Tier 2, and Tier 3" approach). The ISC methodology results in transparency, accessibility, and is available to everyone (World Bank et al., 2010; Richter, 2012; Ibrahim et al., 2012). While indirect emissions are more clearly defined, they are still optional components for accounting and reporting.

In 2013, the British Standard Institution (BSI) elaborated the **PAS** (Publicly Available Specification) **2070**, a document that has standardized the city GHG emission inventory, providing a robust and transparent method. There are two possible methodologies: the direct plus supply chain (DPSC) methodology (i.e. including direct emissions and those indirect associated with infrastructures serving cities), and the consumption-based methodology (i.e. direct and life cycle GHG emissions for all goods and services consumed by residents of a city) (BSI, 2013; WRI et al., 2014; Wiedmann et al., 2016). This must represent an improvement on the previous methodologies.

The latest most recent is the **Global Protocol for Community Scale GHG Emissions** (**GPC**), issued by WRI/C40/ICLEI in December 2014. This accounting framework can also be used for boroughs or wards within a city, towns, districts, counties, prefectures, provinces, and states. There are two distinct but complementary approaches: one focussing on geographically defined emissions from both production and consumption activities; the other on city-induced emissions, depending on where they physically occur. This seems to be more complete than the other four protocols as it suggested the inclusion of all indirect emissions deriving from energy, waste, aviation and marine transport. In 2015, the GPC authors planned for a more detailed guidance to account for scope 3 emissions, not available so far (WRI et al., 2014; Sanna et al., 2014; Wiedmann et al., 2016).

For this reason, Wiedmann et al. (2016) stressed that both PAS 2070 and GPC cannot be considered as "global agreed-upon protocols" because they are relatively incomplete and inconsistent. Indeed, they lack some parts of supply-chain emissions because they consider only certain products or services and, specifically for GPC, scope 3 guidelines have still to be published.

The problem of inconsistency derives instead, from the potential for double counting of emissions allocated to the production activities.

In this context, it is evident that there are still many problems in the application of these standards, because they used different accounting methods (Gao et al., 2014). For this reason, it is necessary to define a unique global city-scale accounting standard to facilitate consistency and comparability among city inventories. This would therefore allow decision makers to identify the proper mitigation efforts and effective adaptation strategies in the reduction of GHG emissions (Radu et al., 2013).

Table 4
Classification of UCF accounting systems according to some dimensions.

Systems				
Dimensions	Territorial	Production-based	Consumption-based	Combined
Spatial boundary	In-boundary	In/out-boundary	In/out-boundary	In/out-boundary
Community	Net-producer	Net-producer	Net-consumer	Trade-balance
Scope	1, 2	1, 2, 3 (embodied export emissions)	1, 2, 3 (embodied import emissions)	1, 2, 3
Inventory method	IPCC	EIOA	LCA	Hybrid
Economic activity[a]	PFC; FC	PFC; IIPE; EP	IIPFC; IP; FC	PFC; IIPE; IIPFC; IP; EP; FC
Double counting	Yes	No	No	No
System user	Citizens; communities	City planners; local government; manufactures	Local government; citizens; communities; manufactures; suppliers	Local government; city planners; manufactures; suppliers; energy, land use, and climate modellers
Standard method	BEI	GPC; IEAP	PAS 2070; ISC; GPC	PAS 2070; ISC; GPC

[a] Legend: Production for Final Consumption (PFC); Import of Intermediate Products for Final Consumption (IIPFC); Import of Intermediate Products for Export (IIPE); Import of Products (IP); Export of Products (EP); Final Consumption (FC).

4. Discussion and conclusion

The present overview highlighted that the UCF methodology currently represents the most appropriate choice to assess the urban sustainability associated with GHG emissions, according to the UM concept. Indeed, it is able to identify the critical economic sectors where policy makers may intervene to implement energy efficiency measures to reduce environmental costs. Some authors, instead, stressed that sometimes UCF cannot be a good environmental sustainability indicator if applied to consumption patterns that take into account several components of city activities. Certainly, its use does not show statistical representativeness for other impact typologies that can occur in a complex model of urban life style (Kalbar et al., 2017).

Additionally, the analysis outlined that there were many UFC studies performed to date, not always homogeneous as they consider different combination of accounting systems and inventory methodologies. Conversely, it was possible to divide UCFs into two main types, namely “spatial”, with a limited amount of data requested, and “economic”, more or less data inclusive according to the accounting systems considered. Consequently, the accounting systems play a fundamental role in the implementation of UCF. For this reason, the authors decided to focus on their categorization.

In this regard, they elaborated of a cross-tabulation including all dimensions attributed to different accounting systems, from spatial boundary to standard methods. They also decided to add a new one, the system users, to identify potential people who should use such systems (Table 4).

As reported in Table 4, the “combined systems” are the most complete for providing supplementary information mainly for energy, land use and climate modellers. Indeed, thanks to the UCF results, these latter could offer detailed long–run knowledge to policy makers to plan a proper urban mitigation and adaptation strategy for climate change. Subsequently, this classification can help final users to individuate the best system that satisfies own request about environmental impacts of the urban activities.

Some other important considerations, deriving from the present overview, have to be stressed. Generally, cities adopt territorial - or production-based rather than consumption-based emissions accounting systems, which means a less comprehensive approach. They find difficult to define a specific emissions' standard, because there are various and not updated data sources. Additionally, they do not have specific indications for well-defining system boundaries sectors that means inappropriate calculations, and exclusion of several important city-induced emissions. Due to all these factors, city emission reductions and climate action comparisons remain challenging (Dahal and Niemelä, 2017).

Consequently, in order to facilitate the comparison among different urban areas, and to allow decision makers to identify similar mitigation strategies and actions in the reduction of GHG emissions, Da Schio and Fagerlund Brekke (2013) proposed the “Relative Carbon Footprint” (RCF). This takes into account the ration between the city's GHG emission level per capita and the corresponding national average level. This standardization considers all factors that affect the UCF outcome (such as city economic development, geographical conditions, social or political factors, or specific public policies linked to the national context), allowing comparison among different UCFs.

The international institutions and organizations also proposed standardized methods. However, the most recent PAS 2070 and GPC cannot be considered as “global agreed-upon protocols” yet, because they are incomplete and inconsistent in some parts, as stressed by Wiedmann et al. (2016). Further improvements, such as more details for the inclusions of scope 3, could be done for making them more comprehensive. Waiting for a “global agreed-upon protocol”, cities themselves might develop methods along with governmental agencies, other municipalities, universities, and research institutions.

Finally, it becomes relevant to monitor the urban GHG emission trends, over time, in order to recognize drivers and key sources for planning the mitigation and adaptation strategy, as well as focussing studies mainly on midsize cities that will certainly have an urban growth.

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