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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