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Characterizing the metabolic pattern of urban systems using MuSIASEM: The case of Barcelona

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ABSTRACT

The extreme degree of openness of contemporary urban systems with regard to both economy and population creates a serious challenge for the study of urban energy metabolism. A novel tool based on Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) is proposed to overcome these challenges. It consists of an end-use matrix, a coherent multi-level integrated characterization of the uses of different forms of energy carriers (electricity, heat, fuels) for the various tasks performed in the city, including private and public mobility, tourism, commercial and residential activities. The end-use matrix integrates quantitative data referring to different dimensions (i.e. energy, human activity, land use, value added) and hierarchical (economic sectors and functional elements at lower levels) and spatial scales (i.e. individual buildings, neighborhoods, and the city as a whole). The end-use matrix provides information on both extensive (flows) and intensive variables (flow/fund ratios or benchmarks). Benchmarks are important for policy-making and allow a meaningful comparison of energy performance across hierarchical levels within the urban system, and among different urban systems. The approach is illustrated for Barcelona, a global city characterized by an important service sector.

1. Introduction

Since ancient times cities have been the center of the economy and power of nations (Braudel, 1979). They specialize in consuming goods and services while concentrating the command and control over the rest of the territory, shaping and guiding the process of economic development (Jacobs, 1984). On the flipside, though, this specialization makes cities highly dependent on activities taking place in the near or distant periphery, such as agriculture, mining, and ecological services. Recent globalization has reshaped cities worldwide by generating an international division of labor. Notably global cities in post-industrial societies have almost fully externalized manufacturing (secondary sector) to less developed countries and have become ‘purely dissipative systems’ (Dyke, 1988), expressing activities mainly in the service, government and residential sectors (Sassen, 2010). Due to improved and cheap transport services and global cities being attractors of activities generating high value added, an increasingly large share of urban activities is performed by people living outside the city (Miralles-Guasch and Tulla Pujol, 2012). Thus, globalized cities are not only ‘made of’ residents, but also an important number of commuters and tourists. The extreme degree of openness of contemporary urban systems with regard to both economy and population creates a serious challenge for the study of urban energy metabolism and the development of local energy and climate policies: Who is consuming energy in the city to do what?

From a thermodynamic perspective, cities represent dissipative systems, constantly importing and exporting energy and matter across their boundaries (Dyke, 1988; Prigogine and Nicolis, 1977). A city “can only survive as long as it is a center of inflow of food, fuel and other commodities and sends out products and waste” (Prigogine and Nicolis, 1977, p. 4). The openness of cities and their dependence on processes taking place outside their borders has also been described as ‘entropy debt’ (Dyke, 1988; Straussfogel and Becker, 1996). Therefore, the idea that cities are metabolic systems (Wolman, 1965) is consistent with the thermodynamic perspective. The metabolism of human society is not a new notion. It has been used to characterize the processes of energy and material transformation in society required for its continued existence (Cottrell, 1955; Lotka, 1956, 1922; Ostwald, 1911, 1907; Soddy, 1926; White, 1943; Zipf, 1941). Overviews of the application of the concept have been provided by, among others, Martínez-Alier (1987) and Fischer-Kowalski and Hüttler (1998).

While thermodynamic considerations indisputably provide a sound

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general framework for understanding cities and their evolution, operational representations of urban metabolism and corresponding indicators of sustainability are yet to be developed (Filchakova et al., 2007). A similar concern has been expressed by Zhang et al. (2015): “Practical methods of analysis need to be improved. Future analysis should focus on establishing a multilevel, unified, and standardized system of categories to support the creation of consistent inventory databases”. This challenge requires the exploration of new transdisciplinary approaches, as emphasized by Dijst et al. (2018): “the need to come to a better understanding of the different disciplinary perspectives on urban metabolism through identifying and analyzing the flows and drivers”.

This paper presents the results of an exploratory application of Multi-Scale Integrated Analysis of Societal and Ecosystem Metabolism (MuSIASEM) to urban energy metabolism, using the city of Barcelona as a case. The aim of the work is to show that, despite the challenges posed by the extreme degree of openness of urban systems, it is possible to: (i) generate a coherent multi-level integrated characterization of the uses of different forms of energy carriers for the various tasks performed in the city (i.e. private or public mobility, tourism, commercial activities, residential activities), and (ii) integrate quantitative data referring to different dimensions (i.e. energy, human activity, land use, value added) and hierarchical/spatial scales (i.e. individual apartments, neighborhoods, districts and the city as a whole). We discuss the pros and cons of the proposed approach and illustrate the importance of the analysis for guiding practical decision support and help local governments achieve sustainable development goals.

The contents of this paper are organized as follows. Section 2 provides the theoretical framework of the proposed approach and the description of the construction of the end-use matrix. In Section 3, the end-use matrix is further explored for the case study of Barcelona. The conclusions are presented in Section 4, together with a reflection on further research needs and complementary approaches, as well as policy implications.

2. Methodology

2.1. MuSIASEM and the energy end-use matrix

MuSIASEM has been specifically developed for studying the complex metabolic pattern of social-ecological systems at different hierarchical levels, scales and dimensions of analysis (economic, social, demographic, ecological, etc.) (Giampietro et al., 2013, 2012, 2009, 2006; Giampietro and Mayumi, 2010, 2000, 1997; Pastore et al., 2000; Ramos-Martín et al., 2007). It provides a quantitative representation of the metabolic pattern of the system under study in relation to two non-equivalent views: internal viability (inside view) and external feasibility (outside view). Internal viability refers to the functions (tasks) expressed by the system needing a pertinent combination of structural elements capable of metabolizing specific input flows required to express these tasks. Internal viability is analyzed with the end-use matrix (Velasco-Fernández, 2017; Velasco-Fernández et al., 2018). External feasibility concerns the interaction of the system as a whole with its context. Indeed, the ability to sustain the metabolic pattern of the whole depends on the existence of an adequate supply of inputs (e.g. energy, water, minerals) and an adequate sink capacity for absorbing wastes and emissions. In MuSIASEM, external feasibility is assessed by the ‘environmental pressure matrix’ (requirement of primary sources and primary sinks from the local environment) and ‘externalization matrix’ (the primary sources, primary sinks and end-uses embodied in imports from outside the system boundaries) (Ripa and Giampietro, 2017; Ripoll-Bosch and Giampietro, 2018). We focus here only on the analysis of the end-use matrix.

The energy end-use matrix is a tool for analyzing in a coherent way how different energy carriers (electricity, fuel, process heat) are used to perform different end-uses (e.g. inside the household, industry, transport sectors). In particular, the end-use matrix identifies which types of energy carriers are used, how much, where, when, by whom and to what purpose (why). Besides energy, the end-use matrix considers additional dimensions of analysis, such as human time allocation, land use, and value added, thus providing an integrated characterization (Velasco-Fernández, 2017; Velasco-Fernández et al., 2018). The end-use matrix has previously been studied at the national level (Velasco-Fernández et al., 2018), but not yet at the urban level.

2.2. Construction of the urban end-use matrix: defining constituent components

The identity of the city depends on the specific mix of its functional and structural elements whose maintenance and reproduction is required to preserve ‘the whole’. Therefore, the first step in the construction of the end-use matrix for an urban system is the definition of the city's constituent components associated with the definition of ‘why energy is used’ (‘final causes’). The functions (or categories of socio-economic activities) of the energy transformations are needed for the maintenance and reproduction of the city's constituent components. Constituent components are defined in relational analysis (Rosen, 1991) as the parts that are essential to preserve the identity of a self-producing system (that what has to be reproduced). In MuSIASEM, following Georgescu-Roegen's flow-fund scheme (Giampietro et al., 2012), the size of the constituent components is measured by looking at the size of the fund elements making up the constituent components. The two funds used for this task are: Human Activity (in hours per year) and Area of Built Environment (in square meters).

Human activity relates to the time spent inside the city boundaries. In quantifying this human activity (in hours per year), it is important to not only assess the total hours/year in relation to the chosen categories of functional activity (*what* is done and *how*), but also to further characterize the constituent component: *Who* is allocating these hours? Notably for urban systems, this information is essential to understand the *why*, the final cause of the functional activity. Indeed, because of the extreme openness of urban systems, the elaboration of the end-use matrix at city level introduces a novel feature in the MuSIASEM accounting, that is, the distinction between activity of residents, commuters (people entering the city to work on a daily basis), and tourists (people visiting for short periods).

The second fund element is the controlled area of built environment or ‘useful surface’, defined as available area devoted to end-uses (in m^2). It is composed of ‘land uses’ (e.g. streets, parks, the port) and ‘building uses’ (internal area of buildings). This component allows a spatially explicit analysis in regard to the chosen subdivision. In this particular study, administrative areas (neighborhoods or ‘*barrios*’ in Spanish) have been selected as constituent component.

Note that the decision of how to define constituent components is an exercise that is normative by definition. Hence it would require a co-production process with the users of the analysis (Giampietro, 2018).

2.3. Construction of the urban end-use matrix: functional characterization

The identification of the constituent components is necessarily linked to the functional characterization of the system. In this way we can identify the functions required for their reproduction. We use the definition of categories of human activity expressed inside the system boundaries to identify a taxonomy of functions stabilizing the activities of residents, commuters and tourists and maintaining and reproducing the spatial patterns found in *barrios*. This step involves the translation of the implications of final causes (what a desirable city should be and should do) into the definition of a set of functional elements capable of expressing the required tasks. This is illustrated in Fig. 1 for the city of Barcelona. Note that the primary sector is not included in Fig. 1, it being virtually completely externalized outside the city boundaries—a feature common to all service cities.