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

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A B S T R A C T

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 nonequivalent 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 socioeconomic 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 coproduction 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.
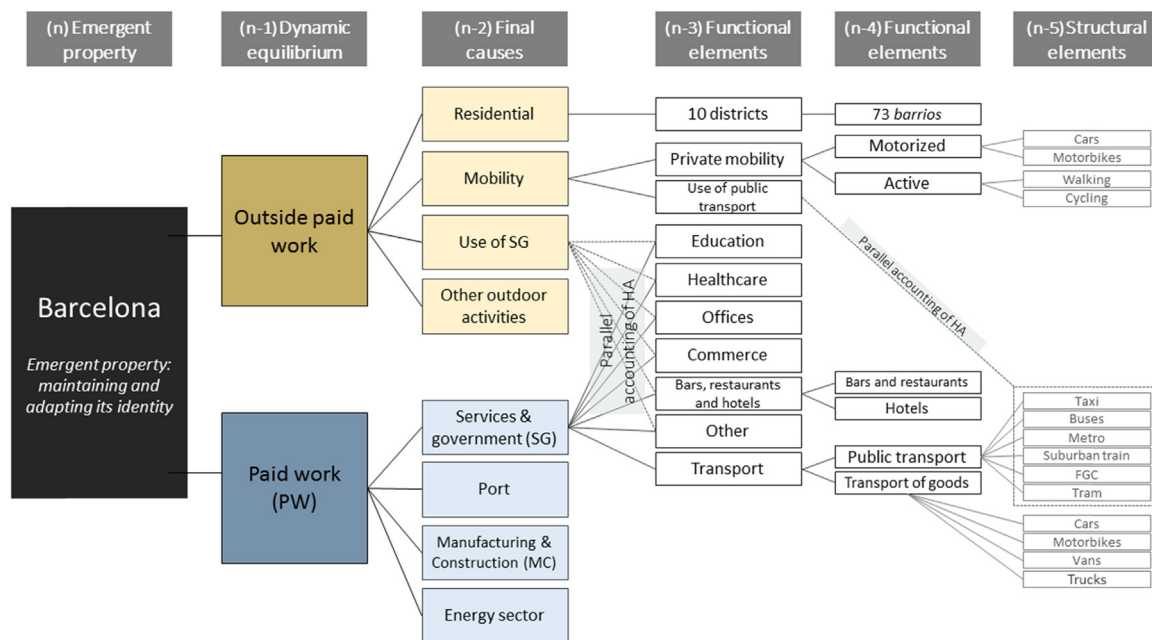
Fig. 1. Dendrogram of functional categories across hierarchical levels for the Barcelona case study.

Table 1
Data array used in the analysis. Variables are defined in Table 2.

Ext. var.		Intensive variables								Extensive variables			
HA	US	EMR_{elec}	EMR_{heat}	EMR_{fuel}	EJP	EMD_{elec}	EMD_{heat}	EMD_{fuel}	EUSP	ET_{elec}	ET_{heat}	ET_{fuel}	GVA
Funds		Flow/Fund								Flow			

As shown in Fig. 1, the function 'Services and Government' maps onto eight functional elements (education, healthcare, offices, commerce, bars, restaurants & hotels, transport, other). Hence, at the level of functional elements we identify typologies of processes associated to specific tasks. Note that in order to express the expected tasks, functional elements must be linked to structural types, that is, typologies of organized structures needed to express the task. For example, the functional element 'transport', defined at hierarchical level n-3, can be further sub-divided into functional elements at level n-4. These lower-level functional elements (e.g. private mobility) in turn map, at level n-5, onto structural elements (e.g. cars, motorbikes, vans, trucks, buses).

A parallel accounting of the profile of allocation of human activity in the service sector is introduced in the end-use matrix. This represents another important novelty compared to earlier work. Indeed, for many of the activities taking place in the service sector there is a simultaneous requirement of human activity both on the supply side (e.g. people working in a restaurant or bus drivers) and the demand side (e.g. customers of the restaurant or passengers riding on the bus). Changes in human activity may entail a non-linear change in the feasibility of the dynamic equilibrium between the human activity needed to consume goods and services and that required for the production of goods and services (Zipf, 1941). Therefore, at the urban level, we analyze the simultaneous investment of two distinct types of human activity: 'Outside paid work' (e.g. passengers in a bus, customers having lunch in a restaurant, or taking a guided tour) and 'Paid work' (e.g. workers as bus drivers, waiters, tour guides). These two sets of accounting categories are shown in Fig. 1. The category 'Outside paid work' is further sub-divided into: Residential, Mobility, Use of services and government (henceforth Use of SG), and Other outdoor activities. The category 'Paid Work' is split into: Services and Government (SG), Port, Construction and Manufacturing (CM), Energy Sector.

This novelty allows the simultaneous characterization of unpaid

human activities in the economy (e.g. residential, use of services, part of the mobility) and the hours of human activity related to a service (the hours of the worker and the users). This is illustrated in Fig. 1. It is important to note that, human activity being a fund, the accounting of the hours of human activity must preserve closure across hierarchical levels of analysis: the size of the system (expressed in hours) must remain the same when accounted across different categories of human activity referring to different levels of analysis (from n to n − 4).

2.4. Construction of the urban end-use matrix: data arrays, extensive and intensive variables

Each element in the dendrogram of functional and structural elements illustrated in Fig. 1 is associated with a data array that is shown in Table 1. The data array consists of extensive variables (funds and flows) and intensive variables (flow/fund rations). Variables are defined in Table 2. The two fund coordinates (human activity and useful surface) are used to map the size of constituent components introduced in Section 2.2, and as external referents to contextualize the assessment of flows. That is, energy flows are expressed in relation to a specific category of human activity.

In this study, four different flows are considered; three relate to energy carriers (Giampietro and Sorman, 2012) and one to monetary flows, following the classification by Velasco-Fernández et al. (2018): (i) energy throughput electricity; (ii) energy throughput heat; (iii) energy throughput fuels; (iv) gross value added.

In the accounting any flow of energy carrier (a quantity per year in MJ or kWh) or money must always be associated with a defined size of fund element metabolizing it. In this way the intensive metabolic characteristics of the fund element can be defined, namely the pace (e.g. MJ of fuels per hour of human activity) and the density of the flows (e.g. kWh of electricity per m^2 of useful surface). The use of

Table 2

Description of the variables used in the analysis (intensive variables are averages per year).

Indicator		Definition	Unit
HA	Human Activity	time invested in the end-use per year	h
US	Useful Surfaces	quantity of area devoted to the end-use	km^2
EMR$_i$	Exosomatic Metabolic Rate	ET$_i$/HA: amount of energy carrier i metabolized per hour of work allocated to the end-use	kWh/h or MJ/h
EJP	Economic Job Productivity	GVA/HA: value added per hour invested in the end-use	€/h
EMD$_i$	Exosomatic Metabolic Density	ET$_i$/US: amount of energy carrier i metabolized per quantity of area devoted to the end-use	kWh/m^2 or MJ/m^2
EUSP	Economic Useful Surfaces Productivity	GVA/US: value added per area of end-use	€/m^2
ET$_i$	Energy Throughput	Amount of energy throughput metabolized in the form of energy carrier i (electricity, heat or fuel) by the end-use.	kWh/year or MJ/year
GVA	Gross Value Added	Value of goods and services produced by the end-use	€/year

intensive variables is essential to establish an accounting scheme *across* different hierarchical levels. These ratios can not only be used to compare qualitative aspects of the metabolic pattern among hierarchical levels of a given city, but also to compare different cities or evaluate the performance of an activity against reference values (benchmarks). Regarding the calculation of benchmarks (e.g. consumption of energy carriers per hour of a service) we can either consider the metabolic rate in relation to the human activity of the workers or that of the users, thus generating a more detailed characterization of its performance.

2.5. Data sources

Data from a large number of diverse sources are needed to implement the end-use matrix, including throughput of energy carriers, value added, useful surfaces and human activity. Generally, these data come from distinct disciplines, often using different classifications, definitions and units of analysis, and are often not sufficiently disaggregated to fit the defined organization of the system. This poses a serious challenge to transdisciplinary analysis but, at the same time, is an indispensable step to analyze the urban system in all its complexity. Intensive variables can be calculated from extensive variables (top-down assessment). However, where data on extensive variables are difficult to obtain, benchmarks for intensive variables from similar systems or elements can be used to estimate extensive variables (bottom-up estimation).

The sources of data for this exploratory analysis were diverse and involved meetings with relevant actors in the city administration of Barcelona. General socio-economic data, value added and useful surface data were obtained mainly from the statistical office of the city council (Ajuntament de Barcelona, 2016, 2012). The Local Energy Agency of Barcelona provided valuable data on energy carriers for households, services and mobility, which were then complemented with energy data from other sources. Human activity data were derived from two distinct sources: the time use survey of Catalunya (IDESCAT, 2012) and the statistics on number of workers (Ajuntament de Barcelona, 2012). A detailed list of sources and an explanation of the calculations is available in Giampietro et al. (2018).

3. Results and discussion

3.1. Disclaimer

In this section we validate the energy end-use matrix for the city of Barcelona. It is important to realize that the main purpose of this paper is the exploration of a new approach to operationalize the concept of urban metabolism. We do not pretend providing robust numerical results for actual use in local policy making. At present, the sole goal of this work is to illustrate the possibility of organizing, in a coherent way, the various pieces of quantitative (including spatially explicit) information required to characterize, monitor and control urban energy performance. Generation of data useful for decision-making would require the fulfillment of three additional conditions: (i) construction of

the end-use matrix in a participatory way, involving the users of the analysis in the choice of final causes and the corresponding relevant categories for the functional and structural elements; (ii) involvement of local experts to double check the robustness of data and assumptions; (iii) carrying out the analysis in an iterative way, starting with a preliminary set of results where the numbers included in the multilevel end-use matrix should be considered place-holders and then going through the activities described in the previous two points to improve the robustness and the quality of the analysis.

3.2. Description of the urban system and system boundaries

Barcelona is the second most populated city in Spain (after Madrid) and the capital of the region Catalonia. With a population of 1.6 million inhabitants in 2012 and occupying 102 km^2, it is also one of the most densely populated cities in Europe.

Barcelona is divided in 10 administrative districts and 73 neighborhoods or *barrios* (Ajuntament de Barcelona, 2012). *Barrios* are heterogeneous in size, age, type of construction, availability of services, demography, income and other characteristics. The city of Barcelona is in turn part of a larger administrative unit, the metropolitan area of Barcelona (AMB), which besides Barcelona includes also the urban agglomerations around the city. The AMB had 3.3 million inhabitants in 2012 (Àrea Metropolitana de Barcelona, 2012). The system boundary chosen for the validation of the end-use matrix is the administrative domain of the city of Barcelona and the reference year is 2012.

The main economic sector of Barcelona is the service sector both in monetary terms (88,7% of the value added) and in number of workers (84,5%) (Ajuntament de Barcelona, 2012). The manufacturing subsector is progressively losing importance in the economy of the city (Barceló and Solà, 2014). Logistics has a strategic importance, with the port of Barcelona being one of the most important ports in Spain and the Mediterranean Sea, both in terms of passengers and volume of goods. Relying on its natural gas import facilities, the port houses a combined cycle power plant (850 MW), which is the only large-scale electricity generation plant inside the boundaries of the city. Fishery is not a significant economic activity (Port de Barcelona, 2012).

3.3. Human activity

The fact that Barcelona is surrounded by other smaller urban agglomerations, a characteristic shared by many cities, poses serious land constraints and creates an intense daily commuting between municipalities (see Table 3). Indeed, tourists and commuters play an important role in shaping the identity of Barcelona and its economy. Their roles are expressed in their contribution to the overall human activity in the city, as shown in Fig. 2. For example, the paid work in Barcelona is equally distributed between residents and commuters, and a significant share of services (leisure, commerce and education) is used by tourists (22%).

Table 3
Million trips (one way) made in a working day inside Barcelona and from or to Barcelona (IERMB, 2013).

Trips (one way)	Internal	From or to Barcelona
Active (walking, bike)	2.85	0.07
Public transport	1.45	0.88
Private transport	0.66	0.77

3.4. Energy end-use matrix of Barcelona

In Fig. 3 we first show a simplified energy end-use matrix for Barcelona. On the other hand, Fig. 4 represents the complete energy end use matrix, including US, VA and the corresponding flow/fund ratios. As described in Section 2.4, the information in the end-use matrix is organized in the form of data arrays, with each row describing the profile of inputs required to express a specific function. The top-row refers to Barcelona as a whole (level n), whereas the other rows describe lower-level functional compartments (levels n-1 and n-2). As shown in Fig. 3, the largest share of 'paid work' activity in Barcelona is allocated to the 'services & government' (SG) sector: 1.5×10^9 h compared to 0.3×10^9 h allocated to 'manufacturing & construction' (MC). The SG sector presents the highest metabolic rate for electricity (EMR_{el}) compared to the other 'paid work' sectors, thereby making SG the dominant electricity (ET_{el}) consumer in absolute terms, but the lowest for heat. Indeed, despite the large share of human activity in SG, the ES and MC sectors are the largest overall heat consumers (ET_{heat}). Comparing the EMRs of Barcelona's MC sector (EMR_{el} = 1.7 kWh/h, EMR_{heat} = 24 MJ/h, EMR_{fuel} = 0 MJ/h) with the average of Europe (EMR_{el} = 16 kWh/h, EMR_{heat} = 103 MJ/h, EMR_{fuel} = 7.1 MJ/h) (Velasco-Fernández, 2017), we may conclude that the city is doing relatively well. However, the relatively low rate of energy carrier consumption is due to the specific composition of Barcelona's MC sector, consisting mainly of construction (which is characterized by the lowest EMRs in the MC sector) and manufacturing of vehicles (mainly assembling).F

In the specific case of Barcelona, the port deserves attention. It exhibits relatively high metabolic rates (EMRs) and high economic job productivity, due to the use of heavy machinery and relatively low requirement of human labor typical of logistic ports (compared to ports with shipyards). The relevance of this infrastructure for the city is difficult to assess both in monetary and biophysical terms since it carries out international shipping both for exports and imports of energy, food

and products, providing benefits and services to the whole foreland and hinterland. All the same, as the port is an important node of an international transport network it is an essential component of the city of Barcelona, facilitating the externalization of the functions of the primary and secondary sectors at worldwide scale.

As concerns the energy sector, the port houses the only relevant power plant (a combined cycle thermoelectric plant) producing electricity. The plant is used as a peak producer, and relies on imported natural gas. Other large power plants are located outside the city boundaries and local photovoltaics produce only a mere 0.2% of electricity (Observatori de l'Energia de Barcelona, 2013). Considering that the plant consumes all of the heat energy consumed in Barcelona's energy sector (11.8×10^3 TJ) and has an efficiency of 58%, it produces 1896 GWh or approximately 25% of the total electricity consumed in the city.

3.5. Example of lower-level analysis

An example of lower-level analysis is shown in Fig. 5 for the Services and Government sector. It describes the metabolic pattern of its immediate lower-level (level n-3) elements: education, healthcare, offices, commerce, hotels, bars and restaurants, transport and other. At this level we can define the characteristics of functional and structural elements in relation to more specific definitions of activities developed inside the sub-sector. As we have already seen, the SG sector, including both services to people and companies, is the largest sector in Barcelona in terms of ET_{elec}, ET_{fuel}, value added (VA) and HA. As shown in Fig. 5, 'Offices' is its main subsector in terms of HA and VA, and also has the highest EJP (except transport) and EUSP (value added per area of end-use). However, it has relatively low EMRs compared to the other sub-sectors.

The Barcelona city council has presented a strategic plan that aims at further boosting its transformation in global city. The 22@ area, formerly an industrial area is projected to become "*a system of innovation- cutting edge companies, universities and training centres, and centres of research and transfer of technology*" (Ajuntament de Barcelona, 2018) with the final aim of making Barcelona the "capital of innovation" (Europa Press, 2017). The creation of new office buildings, increasing economic activity, recruiting unemployed people and/or attracting more workers to the city (no substitution of economic activities, but net increase), will increase energy consumption no matter how efficient new infrastructures will be. The effect on the urban energy metabolism of replacing an abandoned industrial area with services can be
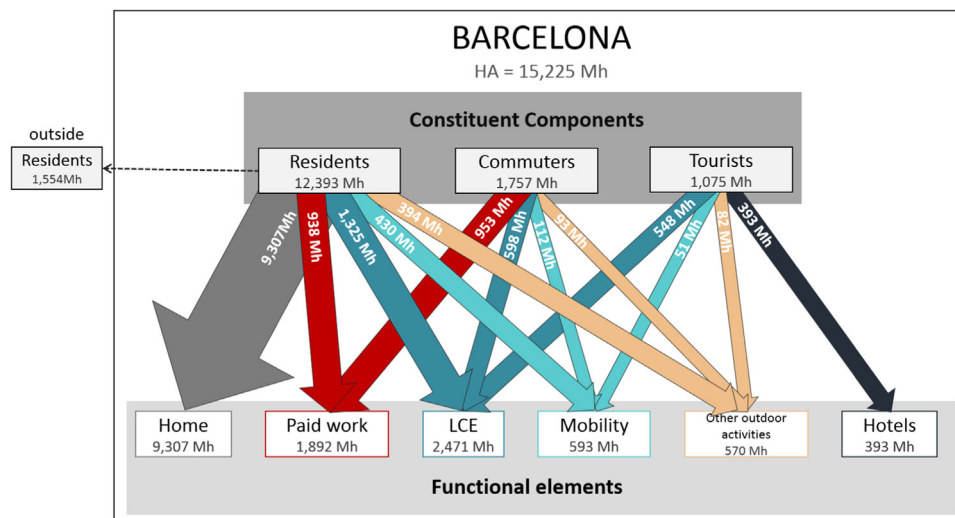

Fig. 2. Tracking the amount of investment of human activity (in hours) of the constituent components. LCE = leisure, commerce and education. LCE + hotels = Use of SG.
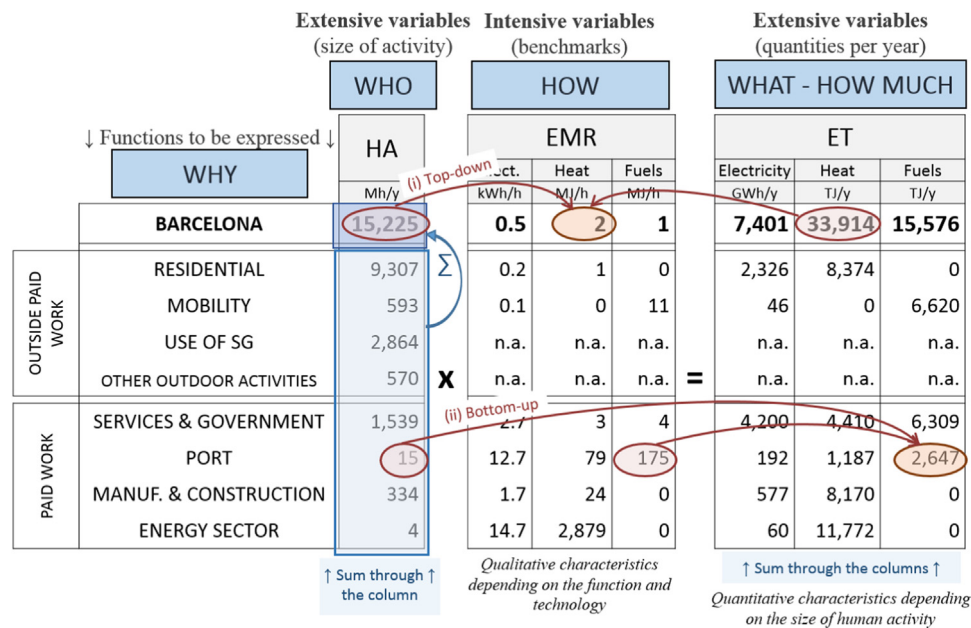
	Extensive variables (size of activity) WHO	Intensive variables (benchmarks) HOW			Extensive variables (quantities per year) WHAT - HOW MUCH		
↓ Functions to be expressed ↓ WHY	HA	EMR			ET		
	Mh/y	Elect. kWh/h	Heat MJ/h	Fuels MJ/h	Electricity GWh/y	Heat TJ/y	Fuels TJ/y
BARCELONA	15,225	0.5	2	1	7,401	33,914	15,576
OUTSIDE PAID WORK							
RESIDENTIAL	9,307	0.2	1	0	2,326	8,374	0
MOBILITY	593	0.1	0	11	46	0	6,620
USE OF SG	2,864	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
OTHER OUTDOOR ACTIVITIES	570	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
PAID WORK							
SERVICES & GOVERNMENT	1,539	2.7	3	4	4,200	4,410	6,309
PORT	15	12.7	79	175	192	1,187	2,647
MANUF. & CONSTRUCTION	334	1.7	24	0	577	8,170	0
ENERGY SECTOR	4	14.7	2,879	0	60	11,772	0

Fig. 3. Simplified end-use matrix characterizing each function with the Energy Throughput (ET), hours of Human Activity (HA) and their metabolic ratios (EMR).

	HA	US	EMR			EJP	EMD			EUSP	ET			VA
			Elect.	Heat	Fuels		Elect.	Heat	Fuels		Elect.	Heat	Fuels	
	Mh	km²	kWh/h	MJ/h	MJ/h	€/h	kWh/m²	MJ/m²	MJ/m²	€/m²	GWh	TJ	TJ	M€
TOTAL:	15225	147	0.5	2.2	1.0	5	50	231	106	501	7401	33914	15576	73441
OUTSIDE PAID WORK	13333	101	0.2	0.6	0.5	0	24	83	66	0	2372	8374	6620	0
Residential	9307	51	0.2	0.9	0.0	0	46	164	0	0	2326	8374	0	0
Mobility	593	21	0.1	0.0	11.2	0	2	0	322	0	46	0	6620	0
Use of Services & Gov.	2864	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Other outdoor act.	570	29	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
PAID WORK	1892	46	2.7	13.5	4.7	39	110	558	196	1603	5029	25539	8956	73441
Services & Government	1539	32	2.7	2.9	4.1	39	132	139	198	1884	4200	4410	6309	59956
Port	15	8	12.7	78.5	175.1	96	25	152	339	186	192	1187	2647	1450
Manufacturing & Const.	334	6	1.7	24.5	0.0	34	101	1436	0	2021	577	8170	0	11497
Energy sector	4	0	14.7	2879.2	0.0	132	127	24851	0	1136	60	11772	0	538

Fig. 4. Energy end-use matrix of the levels n, n-1 and n-2 of Barcelona.

	HA	US	EMR			EJP	EMD			EUSP	ET			VA
			Elect.	Heat	Fuels		Elect.	Heat	Fuels		Elect.	Heat	Fuels	
	Mh	km²	kWh/h	MJ/h	MJ/h	€/h	kWh/m²	MJ/m²	MJ/m²	€/m²	GWh	TJ	TJ	M€
SERVICES & GOV.	1539	31.8	2.7	2.9	4.1	39	132	139	198	1884	4200	4410	6309	59956
Education	101	3.6	1.3	6.3	0.0	35	38	177	0	986	135	637	0	3542
Healthcare	157	1.9	1.4	1.3	0.0	22	116	104	0	1805	223	201	0	3477
Offices	641	7.0	1.9	1.2	0.0	45	177	112	0	4075	1246	792	0	28697
Commerce	321	8.3	4.1	5.4	0.0	35	156	208	0	1337	1300	1730	0	11114
Hotels, bars & restaurants	135	2.0	2.2	2.0	0.0	37	149	133	0	2467	304	270	0	5031
Other	119	3.7	5.9	3.0	0.0	33	190	99	0	1063	696	360	0	3881
Transport	65	5.3	4.6	6.5	97.6	65	56	80	1199	800	296	419	6309	4212

Fig. 5. Example of an end-use matrix from the Services and Government Sector of Barcelona.

anticipated by an analysis based on the end use matrix.

3.6. Digging deeper into the end-use matrix: consumption versus production in the service sector

Another important feature of the end-use matrix is that the functional categories can be expanded depending on the need for detail in relation to decision-making. For example, when dealing with transport (mobility) (Fig. 6) we can further distinguish between 'Private Mobility'

and 'Public Transport' (see Fig. 1). All the same, the effect of policies aimed at reducing private mobility in favor of public transport (a redistribution of human activity across the two subcategories) must be studied in relation to changes in the generic function 'Mobility', both in the paid work sector (service provision) and outside of the paid work sector (service consumption). The latter is illustrated in Fig. 6.

Indeed, for the service sector the amount of human activity of the users (e.g. bus passengers) is as important as that of the workers providing the service (e.g. bus drivers). For this reason, we have

	HA (user)	EMR			ET			Distance
		Elect.	Heat	Fuels	Elect.	Heat	Fuels	
	Mh	kWh/h	MJ/h	MJ/h	GWh	TJ	TJ	Gm
MOBILITY	**593**	**0.6**	**0.7**	**15.9**	**342**	**419**	**9,434**	**8,990**
PRIVATE MOBILITY	401	0	0	17	46	0	6,620	4,884
Active	289	0	0	0	15	0	0	1,588
Private motorized	112	0.3	0	59.3	31	0	6,620	3,296
PUBLIC TRANSPORT	192	1.5	2.2	14.6	296	419	2,814	4,105
Collective pub. transp.	180	1.6	2.3	7.2	291	419	1,293	3,598
Taxis	12	0.4	0	124.8	5	0	1,521	507

Fig. 6. Special End-use Matrix describing the metabolic pattern associated with the final cause "Mobility" using categories of Human Activity defined in Outside Paid Work".

established a parallel accounting of the hours of human activity allocated to services including the human activity of both users (in the outside paid work sector) and workers (paid work sector) (see Fig. 1). This parallel accounting permits a comprehensive evaluation of the services not only in terms of labor force and capitalization (e.g. the power capacity and the type of devices required for providing the services based on the energy consumed per hour of paid work), but also in relation to the quality of the service (i.e. time spent by in using the service). The same rationale can be applied to other types of services. For instance, the analysis of the number of hours of paid work per user is a useful indicator for analyzing the quality of caring services (e.g. hospitals, nursing homes) and education (e.g. schools). In this way it becomes possible to generate diverse indicators of material standard of living for the city.

Returning to mobility, an assessment of distances (shown in Fig. 6) is another interesting feature. In the specific case of Barcelona, private motorized mobility consumes about two thirds of the total fuels in mobility. Active modes of transport (walking or cycling) are those where most time is spent, but less kilometers are covered (after taxis).

3.7. Spatially explicit analysis—neighborhoods

For the residential sector (subsector of the Outside Paid Work sector—see Fig. 1), a spatially explicit analysis by *barrios* was explored through the construction of an end-use matrix characterizing the residential sector for each barrio (a total of 73 *barrios* in Barcelona). Preliminary results are shown in Fig. 7, showing graphs exploring correlations of EMR and EMD with four variables (e.g. family income, building use per inhabitant, multi-story index, and year of construction) characterizing the *barrios*. While *barrios* are heterogeneous among each other, they are internally sufficiently homogeneous in terms of socio-economic conditions and built environment to assume that their average characteristics enable an identification of factors affecting energy use. Note that for this analysis the assessment of energy end-use is calculated as the thermal equivalent of the overall gross energy requirement using the partial substitution method (Giampietro and Sorman, 2012). This is a reasonable step given that, according to the data provided by Local Agency of Energy of the city, the relative contribution of heat and electricity to the total energy consumption is almost the same in all *barrios*. In the residential sector, EMR (the overall rate of energy consumption) may be assumed to be a proxy of the material standard of living as it reflects the number of appliances metabolizing energy inside the dwellings. EMD (the density of overall energy consumption in residential useful surfaces) is a variable already in use in technical assessments of energy efficiency of buildings. It indicates the actual energy carrier consumption per m^2 of the house (Building Use, BU).

The results in Fig. 7 show that in our specific case of Barcelona the EMR is correlated with Building Use per inhabitant and family income. The shapes of the two graphs are similar as these two variables are correlated among each other (wealthy people having bigger homes).

However, there is no evident relation between these two variables and EMD. In addition to family income and area per capita, two other variables have been considered: (i) year of construction of the buildings; (ii) the multi-story index of residential buildings (MSI) reflecting the number of floors of the residential buildings. While our exploration shows some trend for the majority of barrios there is a considerable number of outliers having high EMD at low building use per inhabitant, low family income and low MSI. These outliers, possibly due to the low density of buildings, represent a low share of the population. Indeed, there are many other factors that have to be considered in a spatially explicit analysis of EMR_i and EMD_i.

This brief exploration of energy use in the residential sector by barrios shows the possibility of incorporating spatially explicit analysis in our approach, thus providing a holistic view of the different functional compartments defined in the end-use matrix. Further multivariate analyses are required for specific case studies in order to provide robust information for policy-making. Also, in order to better visualize results, further work is need to develop user-friendly maps and graphs.

4. Conclusion and policy implications

Proper accounting of urban energy metabolism is of paramount importance for policy making. Cities are open systems and heavily rely on trade for their energy and food security and on flows of commuters and tourists. This makes any analysis of urban energy metabolism extremely complex. We have shown for the city of Barcelona that the various forms of energy carriers (electricity, heat, fuels) are used in different combinations and at different rates for different purposes. This multi-level analysis is useful for identifying the relevant factors that determine the energy metabolism of the city: What activity is the largest consumer of what type of energy carrier? Is this consumption necessary and why? How does Barcelona express this function compared to other cities? Is there room for improvement?

Achieving the general target of a 40% reduction of greenhouse gas emissions by 2030, as proposed by the Covenant of Mayors (https://www.covenantofmayors.eu/en/), is a major challenge for cities. Strategies toward reaching this general target must necessarily be city-specific and carefully consider the potential implications on the delicate equilibrium of the many different functions carried out in the city (residences, economic sectors, etc.) as well as the city's dependence on trade (mining, agriculture, industry, transport) and movements of people (e.g. tourists, commuters, immigrants). The quality of specific technological solutions (energy performance) can only be assessed in relation to an identified function or task (e.g. private mobility, residential, public mobility, construction). The more we move the analysis of the metabolic pattern to a lower level of analysis, the better we can identify benchmarks that allow comparing 'apples with apples and oranges with oranges' when studying the performance of different cities. On the other hand, general targets set for technical processes (e.g. efficiency of buildings) or economic sectors (e.g. transport efficiency in terms of kWh/ton-km) not necessarily reflect the impact of energy
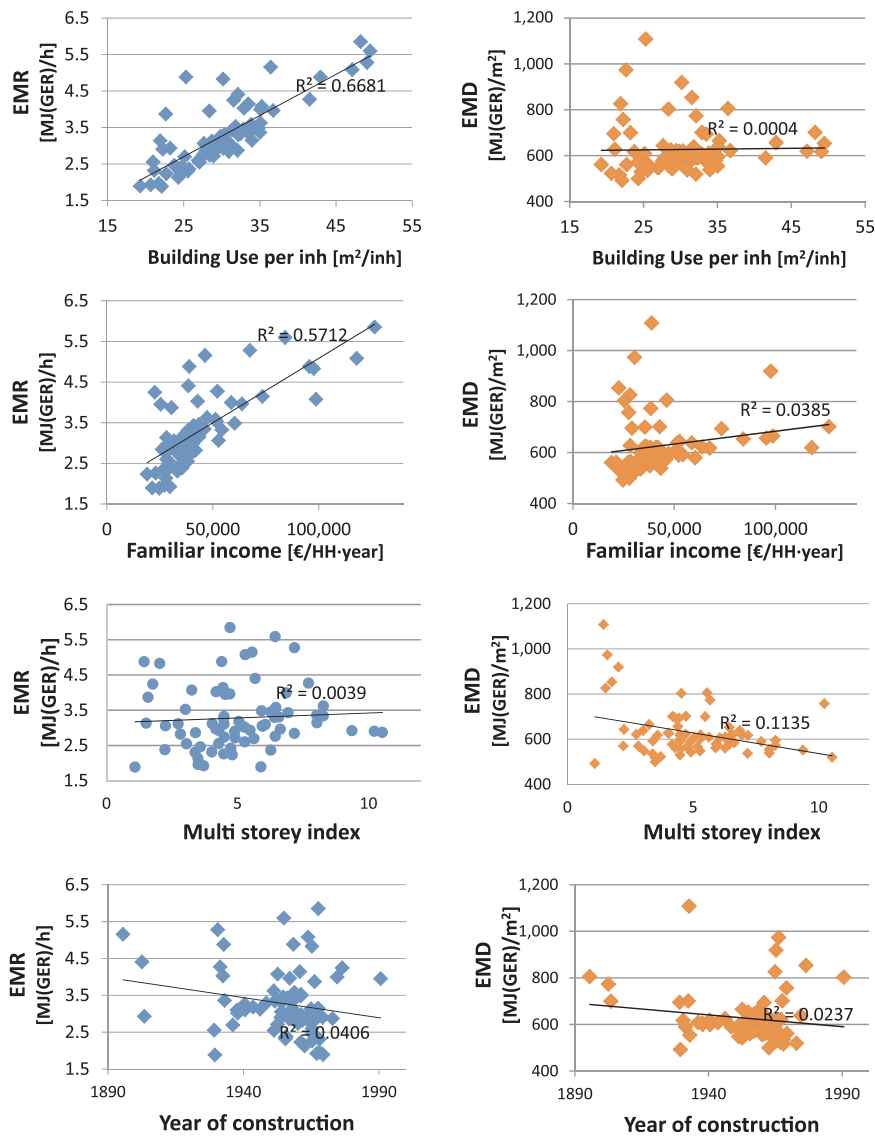
Fig. 7. Exploring the effect of different factors on the metabolic characteristics of the residential sector at level n-5 (73 barrios).

savings at the local (sectoral) level on city-level performance. Different cities express different functions, in different ways, using different types of technologies and different mixes of primary energy sources. Policies based on assessments or comparisons of aggregate levels of energy consumption or emission risk missing this diversity.

A second important point to consider is that transformations of energy in a city are complex. It is essential to acknowledge that not all joules are the same. Energy carriers have different qualitative characteristics (electricity vs fuels) and this difference must be maintained in the accounting. In addition, an integrated analysis of the metabolic pattern must include other dimensions beyond energy: global and local emissions, economic cost reduction, labor requirement, effects on citizens' life quality, etc. Without considering all these dimensions, it is easy to fall into a trap of flawed monitoring schemes, where an unplanned collapse in economic activity may be interpreted as a successful environmental policy reducing emissions or where targets are achieved through "externalization" of energy intensive activities

This work is a step toward establishing a comprehensive multi-level system of integrated accounting in the form of the end-use matrix to provide standards and guidance that will help local governments in developing strategies toward reduction of emissions. Constituent components of the urban system and their size are defined using two fund coordinates: (i) human activity (residents, commuters and tourists); and

(ii) useful surfaces (classified by area of neighborhoods). The metabolic characteristics of the main sectors of the system (Paid Work: services and government, port, manufacturing and construction, energy sector; Outside Paid Work: residential sector, mobility, use of SG, other activities) are defined in the form of benchmarks. Detailed analyses can be performed at lower levels (sub-sectors), as has been shown for the services and government sector of Barcelona. As regards mobility, the accounting scheme also covers an assessment of the human activity of the users of services, the identification of structural elements (private cars, public transport, etc.) and other variables such as distance covered. The analysis of the residential sector, carried out at the level of *barrios*, includes relevant factors affecting energy consumption, such as family income, housing area, multi-store index and year of construction.

In conclusion, the end-use matrix represents a promising analytical tool for overcoming the limits of conventional quantitative analysis by: (i) moving away from a mono-scale, mono-dimensional quantitative analysis toward a multi-scale multidimensional quantitative analysis; (ii) moving away from predicative representations (deterministic results) toward impredicative representations (contingent results); (iii) Moving away from analytical models providing representations chosen by the analysts/experts, toward analytical tool-kits designed for co-production of information with the users of the analyses. Indeed, a

meaningful analysis of urban energy metabolism must necessarily be based on a complex information space, linking diverse aspects at different scales and levels. The multi-level analysis provided by the end-use matrix can bridge the analysis of structural elements at the lower levels, characterized by technical aspects, to the analysis of the performance of functional elements defined at the upper-hierarchical level of the metropolitan area.

As regards the impredicative nature of the assessment, the definition of the semantic structure of accounting and the set of logical rules identifying functional and structural components is necessarily the result of a process of learning by doing. Starting out with available data the consistency of the quantitative results can be checked against the structure of accounting and expected relations. An iterative procedure then helps achieving a sound crunching of numbers in the quantitative analysis in two ways: (i) by identifying external referents—potential sources of available data which refer to measurements of attributes and/or characteristics of processes taking place in the city across different dimensions and levels of analysis; (ii) by generating redundancy in the information space (generation of mutual information in the data set). The various layers of relations across quantitative values thus generate a "sudoku effect" in the data array that is useful to verify its robustness (Giampietro and Bukkens, 2015). "Triangulations" in the sudoku can also be used to estimate the value of a same variable from different sources of data across different expected relations. In this way it becomes possible to fill empty cells in the multi-layered matrix where reliable data are missing or double check the robustness of estimated data or rough statistics.

As regards co-production of information, societal multi-criteria evaluation (SMCE) would lend itself particularly well for structuring and organizing a participatory discussion with various stakeholders on the quality of the assessment process and the policy relevance of the results of the end-use matrix (Munda, 2004). In this process it is important to keep in mind that the representation of desirability found in institutions (a procedural definition of desirability) is always a sub-set of the virtually infinite universe of perceptions of desirability. Especially in relation to the analysis of roles and responsibilities, it is essential to discuss who decides what is relevant when assessing benchmarks and targets, and how this was decided.

Future work is aimed at integrating the urban energy end-use matrix with an analysis of the environmental pressure matrix (inputs produced and wastes dumped within the boundaries of the urban system) and an externalization matrix (inputs imported from and wastes exported outside the city boundaries) to visualize the dependence of urban energy consumption and emissions on trade (import) and reduce the risk of incentivizing cost-shifting strategies (externalization). In addition, a detailed analysis of household metabolism to characterize metabolic patterns of household types is underway, as well as an extension of the analysis to include also other elements of the urban energy-food-water nexus.

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