

Full length article

A multi-level framework for metabolism in urban energy systems from an ecological perspective

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ARTICLE INFO

Keywords:

Urban metabolism
Multilevel organization
Metabolic theory of ecology
Regulation
Urban energy systems

ABSTRACT

Cities have become the main centres of consumption and transformation of resources. As cities are still growing in terms of physical size, number of inhabitants and total energy consumption, unique challenges present themselves in order to safeguard a healthy urban living environment, while preventing resource shortages and pollution. The concept of urban metabolism may contribute to sustainable growth of cities as it can be used to understand emergent patterns in flows of energy and materials in the urban environment. The concept of urban metabolism draws upon an analogy with the biological meaning of metabolism, as it occurs in organisms and ecosystems. Here we present a review of the interpretation of urban metabolism in the context of urban energy dynamics and assess the validity of the proposed analogy with biology. Based on this analogy, we propose a conceptual framework for the role of urban metabolism in urban energy systems. Our review highlights that urban energy systems show a hierarchical organization comparable to ecological systems. However, the emergent patterns that result from the dynamics within urban systems differ from those occurring within ecological systems. We suggest that, in contrast to biological systems, urban energy systems lack energetic constraints at the lowest level of organisation that could enable the resource-efficient regulation of energy requirements at larger scales. The proposed framework highlights that low-level resource supply regulations may contribute to introduce scale-dependent relationships that increase energy use efficiency as cities grow.

1. Introduction

Cities have become the key centres of consumption and transformation of resources. Nowadays, cities consume approximately 75% of global material resources and 80% of the global energy supply while generating approximately 50% of the world's waste and 75% of total carbon emissions (Gladek and Van Odijk, 2014; Swilling and Annecke, 2012). Urban living is becoming the dominant life style globally: since 2007 more people are living in cities than outside them and their number is still increasing (Swilling and Annecke, 2012). It is expected that 90% of the global population is living in cities by the year 2100 (Fragkias et al., 2013). Owing to the high economic and industrial activity in cities, this development brings about unique challenges to safeguard a healthy urban living environment while preventing resource shortages and pollution. In order to understand which processes regulate this potentially effective resource use, scientific methods and techniques are required to analyse social and economic interactions that occur within cities and relate them to their aggregated impact on the environment. By analogy with biological systems, the concept of

Urban Metabolism provides a promising model for analysing and steering these interactions towards sustainability (Kennedy et al., 2011). Here we present a review on urban system dynamics and, based on analogies with ecological systems, propose a conceptual framework for the use of Urban Metabolism to achieve an efficient use of resources in cities.

In the context of our analyses, when discussing energy use, we refer to both direct energy and indirect energy use. Cities are considered complex systems characterized by the interactions between system components. Such interactions are derived from the necessity of cities to fulfil a variety of social and economic functionalities such as provision of habitat, products and services as well as political control (Lane et al., 2009). Social and economic activities in cities are closely supported by energy services (Rutter and Keirstead, 2012). Hence, the link between social and economic activities occurring within cities and energy services exemplified by the definition of urban energy systems proposed by Rutter and Keirstead (2012),¹ provides a potential mechanistic relationship to analyse the environmental impact of the city as a whole. Therefore, dynamics of urban energy systems may

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¹ An urban energy systems is “the combined processes of acquiring and using energy to meet the energy services demand of an urban population...” (Rutter and Keirstead, 2012).

explain urban interactions and yield insight in connections between environmental and socio-economic processes that occur in cities.

2. Ecological origin of urban metabolism

Urban metabolism is a widely adopted concept that is used to describe how interactions within cities impact the use of resources and energy (see Kennedy et al., 2011). The idea of urban metabolism as an analogy to the view that ecosystems interact with their environment as a single ‘super organism’ originated from the field of systems ecology (Odum, 1959; Patten and Odum, 1981). According to this view, ecosystems were analysed as functioning entities by describing the dynamics of energy and nutrient flow (Conan, 2000). More recently, the metabolic theory of ecology postulates that the metabolic rate of individual organisms is a function of an organism’s body mass and body temperature and controls ecological processes at all levels of organization from individuals to the biosphere (Brown et al., 2004). Based on this theory, sub linear (allometric) scaling relationships between variables such body mass and metabolic rate at the organism level, were extended to other variables at higher levels such as population growth, population density or standing stock of biomass (Brown et al., 2004) (see Box 1). These relationships indicate that individual energy efficiency increases when organisms and systems become larger. Hence, the natural foundation of this theory provides a potential solution to mitigate the increasing energy use and its effect on the use of energy that sustain other socio economic functionalities of the city in growing cities. In that way, we would be able to characterize aspects of the cities with the potential to shift patterns of energy consumption from linear or super linear models to models describing sub linear relations as it occurs in ecological systems with body size (Fig. 1).

In the urban context, the concept of metabolism was adopted to develop theory on networks and material flows within cities by analogy with the way organisms use resources and energy in order to survive (Camaren and Swilling, 2012; Rapoport, 2011; Swilling and Annecke, 2012). Seminal studies focused on accounting material inputs and outputs of cities such as energy, water, food and nutrients (Newcombe et al., 1978; Wolman, 1965). According to Kennedy et al. (2011), there are two different accounting methods that have been implemented for urban metabolism studies: solar energy equivalents (recently termed as energy) and Material Flow Analysis (MFA).

Box 1

Examples of scaling relationships shown in Fig. 1.

Inverse scaling: $\beta < 0$

Ecological scaling relationships between the average population density (Y) and the average body size of a species (X) exhibit inverse scaling (with the exponent $\beta < 0$), for example for mammal primary consumers ($\beta = -0.75$) (Damuth, 1981) and an Amazonian bird community ($\beta = -0.22$) (Russo et al., 2003). In a similar way, the equilibrium number of individuals or carrying capacity is predicted to vary inversely to body size (Brown et al., 2004).

Sub linear scaling: $0 < \beta < 1$

A classic sub linear ecological scaling relationship (with $0 < \beta < 1$) is identified between the energy use (or metabolic rate) of an organism (Y) and its body mass (X), which typically reveals an scaling exponent $\beta = 3/4$ (Kleiber, 1947; West and Brown, 2005). A similar sub linear scaling relationship exists between the total biomass and body size (Brown et al., 2004).

Linear scaling: $\beta = 1$

Individual-based human development indicators (Y) typically scale linearly with city size (X) (with $\beta = 1$), for example the total housing in the US ($\beta = 1.00$), household electrical consumption in Germany ($\beta = 1.00$) and household water consumption in China ($\beta = 1.01$) (see Bettencourt et al., 2007 for details).

Super linear scaling: $\beta > 1$

Wages, income, growth domestic product, bank deposits as innovation-based development indicators (i.e. new patents) (Y) show super linear scaling relationships with city size (X) (with $\beta > 1$), for example the number of new patents in the US ($\beta = 1.27$), R & D employment in China ($\beta = 1.26$) and EU GDP ($\beta = 1.26$) (see Bettencourt et al., 2007 for details). Such super linear scaling is not expected to hold across wider ranges of organisms sizes owing to the fundamental constraints of body size on the energy supply network (West and Brown, 2005).

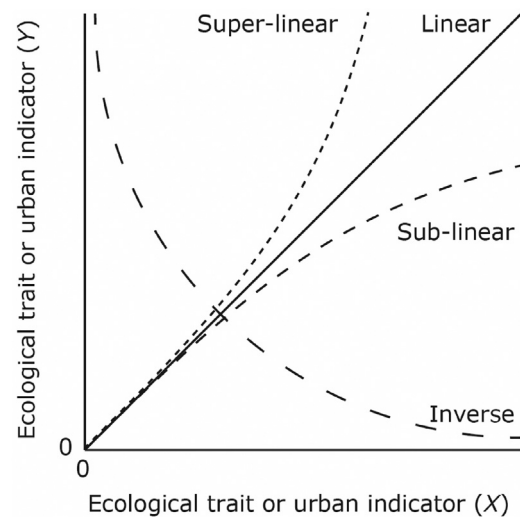


Fig. 1. Examples of Allometric scaling relationships between ecological traits or urban indicators X (e.g. body size, the number of inhabitants, number of firms, physical size of the city) and the subsequent energy consumption Y , generalized to depict the allometric scaling relationship $Y \propto X^\beta$. A linear scaling relationship implies no economy of scale, while sub-linear scaling implies economies of scale that allow for more efficient energy use with an increase in the body size of an organism, or the city size. Super linear scaling implies the presence of diseconomies of scale in terms of energy consumption. Inverse relationships depict a decline of the trait of indicator Y with an increase of the trait or indicator X .

Application of the concept of urban metabolism based on these accounting methods conceives the city as a single ecosystem that should emulate the cyclical and the efficient nature of biological processes envisioned by system ecologists (Rapoport, 2011). Owing to the implied cyclicity of resource use in ecological ecosystems, these methods challenge the linearity of consumption patterns and waste production of cities (Golubiewski, 2012; Rapoport, 2011). However, the applicability of urban metabolism is limited to urban and industrial ecology with the main purpose of describing flows of materials and energy as an accounting method with no practical implications in the way resources should be used or distributed across the city. Yet, expansion of the concept of urban metabolism into the social and political realm, as proposed by (Rapoport, 2011), may help to intervene in politics, power

relations or normative recommendations that guide the use of resources through an efficient pathway similar to nature.

Here we review the analogies that are drawn between urban metabolism and metabolism in ecological systems. We thereby specifically focus on the properties of cities as complex adaptive systems (Batty, 2012, 2009; Chapin et al., 2011; Lane et al., 2009; Levin, 1998). The aim of this paper is to develop parallel conceptual frameworks of metabolism in the context of (biological) ecosystem and metabolism in urban energy systems. As a basic for testing the analogies and develop the conceptual frameworks, we focus on system dynamics and metabolism in ecological systems and the role of metabolism in such dynamics in chapter 3. In chapter 4 we focus on system dynamics and metabolism in urban energy systems. Here we also identify socio-economic interactions that relate to the use of energy in cities and propose how mechanisms from ecological systems can be incorporated in the concept of urban metabolism. The validity of the analogies between metabolism in ecological systems and urban energy systems are discussed in chapter 5. Final conclusions are drawn in chapter 6.

3. Ecological systems

3.1. System dynamics

System dynamics describe the patterns of behaviour of a system, the system components, and the interactions between system components that contribute to the emergence of such patterns (Meadows, 2008). The study of system dynamics needs to be framed by the spatial and the temporal scales at which the system is observed (Turner, 1990). As a result, emerging patterns are derived from interactions between the system components across spatial and temporal scales (Gunderson, 2001).

We analyse the dynamics of ecological systems across four levels of organization (i.e. organism, population, ecosystem and landscape). These levels are determined by the spatial and the temporal extension of the interactions that occur among the system components (Fig. 2). The temporal scale ranges from hours to millennia whereas the spatial scale ranges from individual to global. System components group themselves to form particular subsystems nested in a hierarchical organization of ecological systems (Lane, 2006). This type of nested organization relates to an increase in the level of complexity of the ecological system (Carroll, 2001). For example, at the organism level,

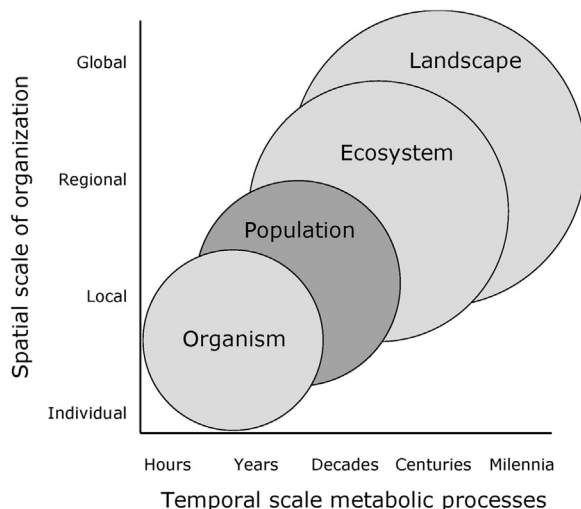


Fig. 2. Spatial and temporal scales of the key levels of interaction that occur within ecological systems are linked so that larger processes act at longer time scales. This framework considers four levels of interaction, including (i) the individual organism, (2) the population that consists of multiple organisms of the same species, (ii) the ecosystem that consists of interacting organisms of multiple species, and (iv) the landscape that can host multiple ecosystems.

interactions occur between genes, cells or organs, while at the population level interactions occur among organisms. At the larger ecosystem level, interactions happen among populations of different species, while at the landscape level, interactions occur between different ecosystems.

Interactions between system components are influenced by specific environmental conditions present at each organizational level. Environmental factors such as climate, potential biota, topography and parental material determine system dynamics at the largest spatial and temporal scales that may lead to the evolution of landscapes (Leopold, 1994; Sharp, 1982). In turn, these large scale dynamics determine processes that occur at lower organisational levels, for example the formation of soil and changes in disturbance regimes (Chapin et al., 2011; Jenny, 1941). As a result, large-scale ecosystem dynamics portray the structure and functioning of the ecosystem through emergent patterns at lower organisational levels. Changes in birth and death rates are the most prominent examples of dynamics that occur at the population level. Here, the life cycle of individuals is a pattern that emerges at the organism level responding to conditions at the population level such as species density that regulate the availability of food for each individual. The occurrence of such patterns shows a top-down effect in the dynamics of the system imposed by conditions at the larger levels of the system organization.

3.2. Metabolism in ecological systems

The metabolic theory of ecology (Brown et al., 2004; Enquist et al., 2003; West et al., 1997) provides the starting point for our review of the role of metabolism in the dynamics of ecological systems. According to the metabolic theory of ecology, metabolic rates of organisms govern most of the observed patterns in ecology. Metabolism therefore forms the link between the physiology of individual organisms and the ecology of populations (Brown et al., 2004; Savage et al., 2004a,b; West et al., 1997). Specifically, the metabolic theory of ecology postulates that metabolic rates at the organism level can be approximated as a general function of body size and temperature (Brown and Gillooly, 2003; Gillooly et al., 2002, 2001). Based on this relationship, the theory predicts the emergence of patterns at the organism level in which several biological traits scale allometrically to the quarter-power with body mass (Enquist et al., 1998; Gillooly et al., 2001; Savage et al., 2004a,b; West et al., 1997, 1999). These biological traits are variables that characterize different aspects of the life cycle of organisms. Examples of these variables are: i) structural variables such as cross-sectional areas of blood vessels, ii) transformational variables such as physiological rates iii) allocation variables such as nutrient transportation and biological times. The relation between such biological traits and body mass shows how metabolism is responsible for regulating the use of resources of individual organisms throughout their life cycle. Moreover, these relationships give flexibility to the system to adapt to changing environmental conditions.

The metabolic theory of ecology further postulates that metabolism operates through fractal design networks and the kinetic energy of reactions. This theory considers the organism, population and ecosystem as key levels of organization of dynamic ecological systems (Fig. 3). Fractal design networks specifically allow for an efficient use of body mass through volume/area preserving networks. These networks optimize the exchange and distribution of energy and resources and likely evolved in organisms to minimize internal transport distances (Gillooly et al., 2001; West et al., 1999). The kinetic energy of reactions produces a general acceleration of metabolic rates with an increase in temperature and body mass (Gillooly et al., 2001).

The emergence of patterns at higher levels of the ecological organization crucially depends on constraints related to the availability of resources via a trade-off between population size and organism size. As a result, equilibrium population size scales inversely with individual body size (Enquist et al., 1998; Savage et al., 2004a,b). The metabolic theory of ecology therefore predicts emergent patterns at the popula-

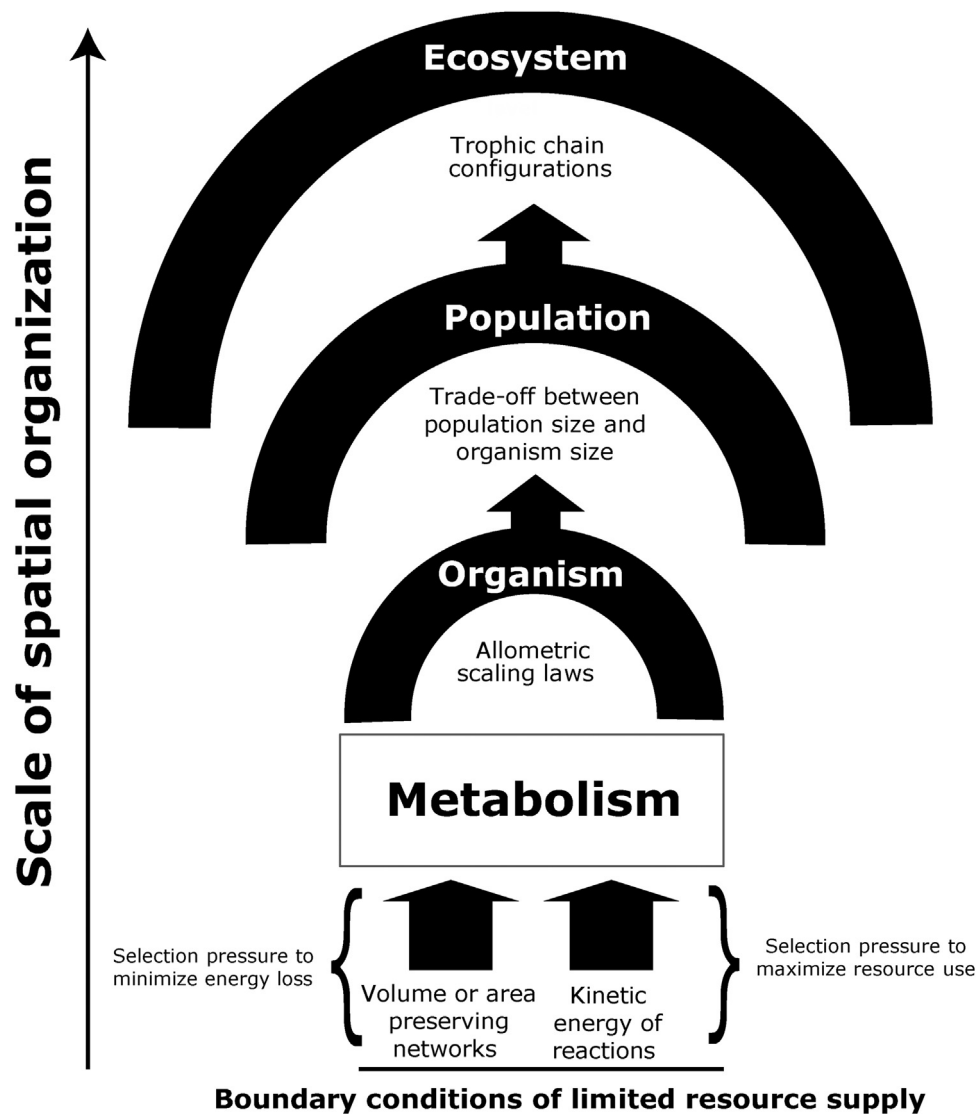


Fig. 3. Conceptual framework for metabolism in ecological systems based on the metabolic theory of ecology (West et al., 1997). This conceptual framework considers the organism, population and ecosystem as key levels of organization. Critical concepts that allow to explain the association between metabolism and the dynamics of ecological systems are: (i) the boundary conditions that act as outside forces on the ecological system, (ii) the levels of organization of the ecological system, (iii) the variables representing the stocks and flows of the system, and (iv) the emergent patterns that result from system interactions, such as allometric scaling laws, relationships between population size and organisms size, and configurations of trophic chains.

tion level in which variables such as population growth (Peters, 1986) and carrying capacity (Damuth, 1987) scale allometrically with body size. These patterns relate to the energy equivalence rule in which (Damuth, 1981) postulates that the amount of energy used by one specie population is independent of its body size.

At the ecosystem level, populations are organized by the relationships between producers and consumers that form trophic chains along which energy and materials flow through the ecosystem (Chapin et al., 2011). These trophic chains display an energy pyramid configuration where productivity at each subsequent level depends on the productivity at the preceding one in accordance with the laws of thermodynamics and conservation of energy, see for example Brown et al. (2004). The energy pyramid configuration denotes the influence on variables that relate preys and predators and, as a result, reveals emergent patterns such as allometric relationships between the weights of predators and their prey (Cohen, 1991). This association across levels has relevant implications for the structure of the trophic chain as less energy is available at higher trophic levels (Chapin et al., 2011). The emergence of these patterns across levels shows how metabolism at the organism level produces emergent patterns at higher levels by regulating

individual functions.

4. Urban systems

4.1. System dynamics

Like ecological systems, urban systems can be described as a multilevel complex organization (Lane et al., 2009). Interactions among system components occur at particular spatial and temporal scales. Therefore, we suggest organising urban systems in four main levels arranged along a spatial and a temporal scale (Fig. 4). The four levels range from individuals (micro), through the single city (meso) to the level of a system of multiple cities (macro) (Lane et al., 2009). The aggregated level is positioned between the meso and micro level and corresponds to the population level in the organization of ecological systems. This level groups single components from the micro level and provides a disaggregated view of the city. The proposed arrangement shows different subsystems nested in a hierarchical organization of urban systems that compare with the organism, the population, the ecosystem and the landscape levels in the ecological system organiza-

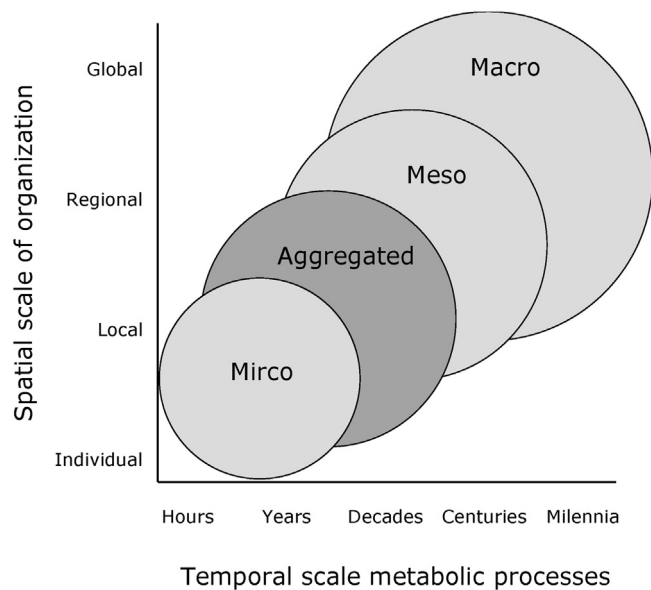


Fig. 4. Spatial and temporal scales of the key levels of interaction that occur within urban systems are linked so that larger processes act at longer time scales. This conceptual framework considers four levels of organization: (i) the macro level as an ensemble of multiple cities that interact under a unified control (e.g. national political territory or global economic network), (ii) the meso level where this city acts as a geographical entity, (iii) the aggregated level which corresponds to the population level in the organization of ecological systems, and (iii) the micro level that represents elementary units (i.e. households, urban citizens, firms, institutions) living together in a city (Lane et al., 2009).

tion (c.f. Fig. 2).

Dynamics in urban systems is seen as a set of interactions between components across the four levels of organization. Such interactions are influenced by socio-economic factors that operate at each level, emerging in different patterns of behaviour. At the macro level, factors such as historical path dependency and patterns of settlement influence dynamics in the system of cities evolving in a hierarchical pattern (Lane et al., 2009). This pattern generates a differentiation of city sizes followed by a differentiation in urban functions. As a result, asymmetries may develop in the interactions between cities. At the meso level differences in economic specialization, social composition, cultural features and urban landscapes can be considered emergent patterns that result from internal dynamics. In response to these dynamics, patterns emerge also at the aggregated level, for example as reflected by differences in supply chains and socio-economic stratifications. These patterns show relations between aggregations within the cities that also determine the behaviour of individual components and produce emergent patterns at the micro level such as consumption habits, purchasing power or self-actualizations.

We take the case of urban sprawl versus compact cities as an example of occurring dynamics within urban energy systems (Dieleman and Wegener, 2004). While a city is conditioned by energy resources, it can still expand because there is the possibility of importing energy from outside the system. This pattern will occur as long as there is available imported energy. This is different to what occurs in natural ecosystems where the use of energy is regulated since there is limited energy availability. However, a compact city is the result of an urban planning and design concept. Being a concept, there is an implicit regulation (as it occurs with natural ecosystems), namely, the idea of a high-density urban settlement with specific services. Eidlin (2010), shows that high-density areas in the United States have lower emission in transportation in contrast to low-density settlements which -typically- have private transport as the main commuting mode. High-density settlements, if properly planned, could use less energy than sprawling settlements.

Table 1

Types of elements identified in Urban Energy Systems.

Levels of Organization	Perspectives	
	Urban elements	
	Behavioural	Structural
Micro level	Households, Firms	Buildings (houses)
Aggregated level	Urban land uses	Squares or Neighbourhoods, Groups of buildings
Meso level	Economic sectors ^a	Urban districts
Macro level	Economic sectors, Cities	Cities ^b

^a Economic sector is an urban element determined at the meso and the macro level. At the meso level, it refers to the sectors that interact within a single city (i.e. domestic, industrial, financial etc.). At the macro level, it refers to interactions among cities when they are specialized in particular functions (i.e. financial cities, manufacturing cities etc.).

^b City is found in both the structural and the behavioural perspective. In one sense, city is seen as the ensemble of infrastructural organizations and networks housing urban citizens. On the other side, it is also seen as the group of people that inhabit the space together with the institutions and the social organizations conformed by them.

4.2. Metabolism in urban energy systems

Characterization of dynamics in urban systems depends on the type of urban elements interacting at each level of the system organization. The definition of these elements depends on the interpretation given to urban energy systems considering that an element can be either structural or behavioural (Table 1). The structural perspective contemplates architectural infrastructures, metropolitan spaces and territorial and administrative areas as determinants of urban interactions. This perspective refers to pure physical and spatial traits of the energy system that is defined in terms of i) buildings, ii) urban squares or neighbourhoods, iii) groups of buildings, iv) districts and v) cities. The behavioural perspective refers to elements that connect people and energy needs. This is based on the idea that the energy system responds to human activities and therefore, is characterized by the different types of uses given to energy. Hence, this perspective is defined in terms of i) households, ii) firms, iii) urban land uses, iv) economic sectors and v) cities. This perspective places human activities at the basis of the energy system and acknowledges that the socio-economic activities determine urban energy dynamics.

Energy flows generated by socio-economic activities and energy efficiency of urban energy systems can be analyzed by methods already developed within the field of energy systems analysis. Grubler et al. (2012), distinguish two main approaches. First Law analysis highlights the difference of defining efficiency as the relationship between energy output-input. Second Law analysis (or exergy analysis) considers quality differences in energy forms. Considering the structural and behavioural elements identified in urban energy systems, we have developed a conceptual framework for urban metabolism in the context of urban energy systems by analogy with ecological systems.

4.3. Relationships within the urban energy system

The analysis of relationships between energy consumption patterns and urban elements can contribute to understanding of the dynamic responses of the urban energy system. As Table 1 shows, urban energy systems are organized in levels. The different urban elements contained within each level can be related to energy use. At the micro level, Hong et al. (2009) identified a relation between thermal comfort and energy efficiency. Liu et al. (2005) describe the relation among household size and energy consumption per capita. Stenzel and Frenzel (2008), show that strategic and managerial decisions of energy companies affect the urban energy system. For example, the adoption of new technologies and prioritize certain energy carriers, energy resources and energy uses

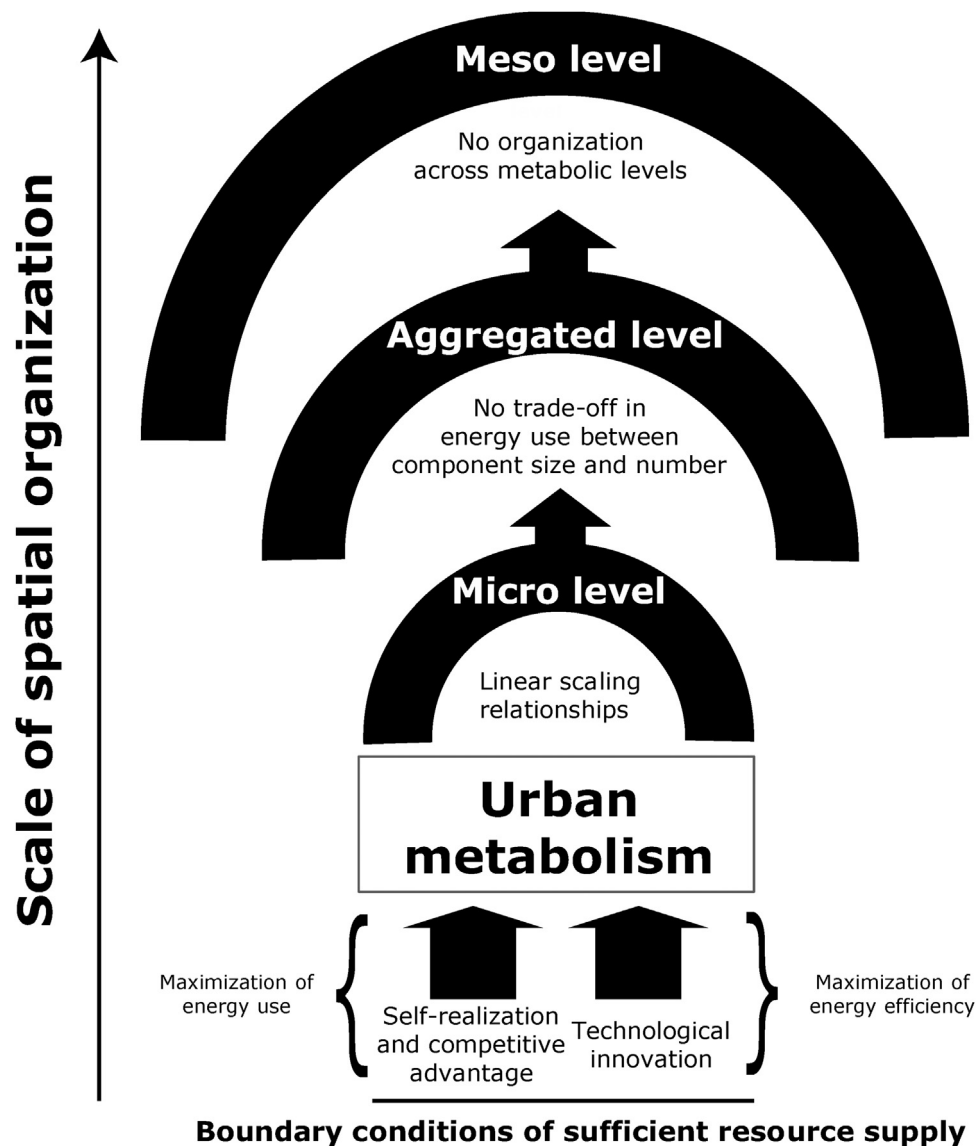


Fig. 5. Conceptual framework for metabolism in urban systems based on the dynamics of energy systems. Key components of the framework are: (i) the boundary conditions that act as outside forces on the urban energy system, (ii) the levels of organization of the urban energy system, (iii) the variables representing the stocks and flows of the system, and (iv) the potential emergent patterns that result from system interactions, such as allometric relationships between city traits and energy use, the potential trade-off between the size and number of city elements and the potential of organization across metabolic levels. Owing to the lack of constraining boundary conditions in terms of resource supply, no emergent patterns are currently observed across organizational levels in urban energy systems.

in cities. Energy use is also related to design parameters (Aksoy and Inalli, 2006; Jo et al., 2010a). All these relations emerge in patterns of linear or super linear scaling relationships where energy variables respond proportionally, and sometimes over proportionally, to variables characterizing urban elements (Fig. 5). These patterns differ from the sub linear (allometric scaling) relationships observed in ecological systems where organisms adjust themselves to regulate internal requirements to the external availability of resources. In urban systems, households, firms and buildings do not exhibit internal adjustments on energy requirements having as a consequence a non-regulated behaviour in energy consumption patterns.

Grouped elements at the micro level produce a collective behaviour at the aggregated level. As a result, variables at the micro level relate to variables at the aggregated level evidencing emergent patterns characterized by linear relationships as well. For example, while designing a house, energy calculations are based on an assumed household structure and composition. If household size and occupancy patterns change significantly, these changes should be reflected in energy requirements and layouts of larger urban areas (Kämpf and Robinson,

2007; Weber et al., 2010). Moreover, potential of renewable energy is directly related to particular uses and corporate strategies in the energy supply sector (Pillai and Banerjee, 2007; Stenzel and Frenzel, 2008). Furthermore, energy consumption in urban squares or any other type of urban area relate to parameters of building design such as insolation, cooling loads, heat gains, heat storage or heat island energy cost (Assimakopoulos et al., 2007; Jo et al., 2010a,b; Yezioro et al., 2006). These relations between elements at the micro and the aggregated level exhibit a difference from interactions as predicted by the metabolic theory of ecology. According to this theory, there is a trade-off between the organism and the population level where individual body size and equilibrium population size, adjust to each other with the purpose of creating a balance of energy use and productivity in ecological populations (Brown et al., 2004; Enquist et al., 1998; Savage et al., 2004a,b). In urban energy systems however, the aggregated level performs without limitations in the energy budget due to the absence of internal regulation in energy consumption at the micro level (Fig. 5).

The meso level of the urban organisation is characterized by elements that reflect different energy uses in a city. For example, the

growth of the population of cities relates to an increase of energy flows (Decker et al., 2000; Grubler et al., 2012) via the expansion of socio-economic activities (Decker et al., 2000). In the same manner, cities with high population density but low automobile dependency relate to lower transport energy use (Grubler et al., 2012). These examples show how urban planning is related to urban energy use. Hence, the configuration and the design of the city are key elements that need to be considered for the optimization of energy use in cities. Urban planning should define self-sufficient areas or making spatial arrangements that organize human activities and technologies that complement each other across the city. However, there is no evidence that cities organise themselves to cope with inefficiencies in energy transfer as ecological systems do so by organising into trophic chains.

Analysing energy requirements of a city by studying subsystems could allow to formulate alternatives for energy efficient use at different levels of the system. The Second Law or Exergy analysis, can be helpful for this as it involves the evaluation of energy quality along the urban energy system as well as the examination of where the largest losses lie. Exergy analysis for urban systems could help to identify areas of where further design, planning and optimisation will be of most value and the scope of improvements of energy use (Creutzig et al., 2015; Grubler et al., 2012).

4.4. Energy consumption patterns in urban metabolism

We propose that urban metabolism operates through mechanisms that explain energy consumption patterns at the micro level and while the consequences of these mechanisms emerge at the higher levels of organisation (Fig. 5). There are two main drivers that can explain the emergence of such energy consumption patterns. The first driver pertains to the maximization of energy use that reflects modern consumption patterns, specifically the consumption of new goods and services (Rutter and Keirstead, 2012; Stenzel and Frenzel, 2008). In ecological systems, the rate of resource use is proportional to the supply rate of resources available (Enquist et al., 2003, 1998). However, in the urban context, there is no evidence that energy use patterns at the micro level are dependent on the energy supply to individuals. The key difference between ecological and urban systems therefore lies in the ability of urban systems to import additional energy, if needed.

The second driver is maximisation of energy efficiency that operates through technological innovations to increase resource use efficiency while meeting consumer demands. The efficiency gains can result in lower costs or increased added value (Grubler et al., 2012). This second driver can be considered an analogue to the evolutionary pressure to minimize energy losses in ecological systems (West et al., 1999). In urban energy systems however, there is no evidence of a particular arrangement that reflects optimal connectivity between urban elements and individuals. As a result, energy demand in growing urban centres normally follows rather than leads urban expansion (Grubler et al., 2012; Seto and Shepherd, 2009).

5. The biological analogy

5.1. Differences between metabolism in urban and ecological systems

This review has analysed ecological and urban systems in terms of their properties as multilevel dynamical systems. Within ecological systems, metabolism is seen as a factor that operates at the organism level and determines many aspects at the population and ecosystem levels. Drivers and mechanisms guiding ecological metabolism regulate the use of resources in accordance with resource supply that may result in sub linear allometric scaling relationships between organism size and energy use. In analogy, urban metabolism also operates at the micro level and explains the energy consumption patterns throughout the different levels of the system organization. However, in contrast, the emerging relationships describing the energy consumption patterns in

urban systems scale linearly or super-linearly (Bettencourt et al., 2007). Hence, we suggest that the regulatory function of resource limitation, as occurs in biological metabolism, constitutes an important difference with the general lack of such limitation in urban system.

Crucial for appreciating the difference between metabolism in urban and ecological systems is the central role that body size plays in biological metabolism. The body size of organisms strongly determines life history traits such as the heart cycle, breath cycle, incubation, gestation periods and life span (Calder, 2001). Owing to the cross-scale relationships between organism size and population size (Enquist et al., 1998; Savage et al., 2004a,b), the availability of resources in a specific unit of habitat therefore constrains the size of the population as well as the specific life history traits of the individual in the population (Calder, 2001). In the context of urban metabolism, the size of a city (measured as population size) has been related to different socio economic indicators. Although city size may be related to the socio economic activities of its inhabitants (Decker et al., 2000), the urban indicators that pertain to individual energy use scale linearly to city size (Bettencourt et al., 2007). As a result, the size of a city does not determine the needs and activities of individuals.

5.2. Regulatory implications of urban metabolism

Despite the limited analogy between allometry in scaling relationships in urban and ecological systems, the efficient use of resources in ecological systems may still provide inspiration of regulation of urban energy systems. In order to emulate the regulation of ecological dynamics in urban energy system we need to consider five essential aspects of urban metabolism. First, urban energy systems need to be characterized in terms of elements that communicate dynamics throughout the system. These elements should be able to perceive and respond to changes across the different levels of the organization. Depending on its interpretation, the resulting adaptive behaviour of the system can be provided by technological innovations (structural perspective), or by intervening on individual behaviour (behavioural perspective). However, this adaptive character needs to be shown by patterns describing sub linear scaling relations instead of relations that produce constant and proportional effects in energy expenditures across levels as described in Section 4.3.

Second, dynamics of urban energy systems need to be constructed based on the interactions among elements at the lower level of the system. The individual role at the micro level is highlighted as the most relevant for the dynamics of the system especially because it determines the individual needs and particular activities to fulfil. Based on this, the interactions among elements at the micro level produce the patterns that emerge at the higher levels of the system organization.

Third, planning for urban energy systems should consider the availability of resources at their disposal. (Kennedy et al., 2014) show that managing energy is especially critical for megacities. There is a trade-off between providing urban energy services and, consequently, increasing energy use and the decrease of energy use in order to diminish associated environmental burdens. Energy management plays a crucial role because the resources and the capabilities to use them are finite. In the current analysis of urban energy systems (Fig. 5), there are no boundary conditions that delimitate the availability of resources. We argue that for urban metabolism to operate in a regulatory way, it is crucial to denote a limitation of resources at every level of the system organization. This means that the study of urban systems needs to include the analysis of energy sources that fuel cities, or shift into a self-sufficiency model in which every level of the system organization supplies its own energy.

Fourth, the regulation of the system requires a trade-off between elements at micro and aggregated levels. So, external limitation of resources gives rise to an emergent pattern at the aggregated level enabling energy savings. The emergence of such pattern at higher levels of organisation is only possible through individual adjustments of

energy consumption at the micro level. As a result, each individual unit compensates its energy requirements by sharing uses with others in the group. This aligns the principles of the emergent properties attributed to complex systems in which system components self-organize (Bar-Yam, 2011).

Fifth, regulation of urban energy systems needs to address mechanisms to tackle internal motivations, lifestyles and habits at the micro level. Addressing these mechanisms can help to regulate energy consumption throughout the urban system. We propose to use the concept of energy services to describe the city in terms of the uses that people make out of energy in order to fulfil their needs (Haas et al., 2008). Thereby, characterization of the city in terms of energy flows can be shifted to describing the services fulfilled with the transformation of energy resource (Haas et al., 2008). Mapping the energy services of a city might help to provide information about the different uses given to energy and how they are supplied across the different levels of organization. This approach could facilitate the collaboration across levels that compensate individual adjustments at the micro level by stimulating a particular behaviour at the aggregated level. Through this collaboration, the management of energy services at the higher levels could optimise the energy use by individuals and reduce energy inputs for the whole system. The urban energy system could then exhibit emergent behaviour characterized by sub linear allometric relationships between population size and energy consumption. This perspective opens space for intelligent management of energy supply and supports the analogy with ecological metabolism that regulates the use of resources and contributes to the sustainability of cities.

6. Conclusion

This study reviewed the system dynamics of ecological and urban energy systems by analysing how interactions between internal elements operate to produce emergent patterns of behaviour and how they are related to ecological and urban metabolism. Our findings show that metabolism in ecological systems helps to regulate the use of resources in ecological systems by emerging patterns characterized by sub linear allometric scaling relationships with organism size. In contrast, urban energy systems exhibit emergent patterns described by linear relationships that explain energy consumption across the system organization. Hence, urban energy systems do not exhibit the behaviour performed by ecological systems that permits the regulation of resources throughout the different levels of the system organization. We consider urban metabolism to be a process that regulates the flows of energy and material along the different organizational levels of an urban system. As current urban systems are key centers for energy use, there is a need to transit from an energy use driven by linear relationships (i.e. exponential growth), to an energy use characterized by sub linear functions (i.e. convergence to a stable level for indefinite period). Mechanisms helping to this transition need to be the result of a trans disciplinary approach where (natural and social) scientists, politicians and civil society develop a better understanding of how urban energy (and material) flows relate to social well being and environmental stewardship. We used the example of urban sprawl as an illustrative example of the use of the developed framework (see 4.1). Crucially, urban energy systems need to be described by elements that facilitate system dynamics so those changes in boundary conditions and individual behaviour, produce emergent behaviours at higher levels of aggregation. Reduction of energy inputs at the higher levels of the urban system might derive from sharing or redistributing services at the micro level, reflecting similar patterns of behaviour as those referred to by the metabolic theory of ecology. Our framework highlights that in order to achieve a sustainable use of energy in cities (as it occurs in nature) regulations at the micro level (derived from limited conditions of resource supply) may contribute to introduce scale-dependent relationships between urban elements and energy use.

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