The behaviour of cities:

Theoretical framework for Urban Metabolism from an ecological perspective

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SUMMARY

In order to cope with the global pressure for natural resources due to the urban development, cities need to be approached as systems. Urban metabolism popularizes as a concept to analogise ecological to urban systems so, links and connections operating in cities could be explained from an ecological perspective. This research develops a conceptual framework to analyse the role of metabolism in ecological dynamics and paralleled it with the urban dynamics, in order to set the theoretical basis for urban metabolism. The relation between metabolism and dynamics in ecological systems was based on a review of the metabolic theory of ecology. This was illustrated by characterizing different categories such as levels of organization, patterns, variables, mechanisms and drivers. Qualitative data from urban energy systems was analysed upon these categories with the purpose of contrasting urban and ecological dynamics. Implications for the regulation of dynamics as well as for the conceptualization of urban metabolism were drawn by integrating knowledge from both fields. In ecological systems, metabolism was found to perform a regulatory process in which constraints at the organism level gives rises to the higher levels of the organization upon conditions of limited resource supply. In the urban context, there was no evidence of such regulatory process. Flexibility of the components that describe the system as well as communication across levels, are fundamentals for the regulation of the dynamics in urban systems. In addition, the acknowledgment of conditions of limited resource supply might stimulate strategies for constraining the use of energy and for the shift in the perception of energy from a materialistic view to a more services oriented one. Then, urban metabolism considers a multilevel approach of cities in which regulation at the individual level unleashes different patterns at the higher levels. This gives the possibility to create an emergent behaviour along which less resource is required as the system enlarges. This proposes a change in the current trends of "*using more for more*" or "*doing more with less*" to a different philosophy of "*using less for more*".

1. INTRODUCTION

Cities have become very significant centres of consumption and transformation of resources. Nowadays, cities use around 75% of resources and 80% of global energy supply, and produce about 50% of world waste and 75% of total carbon emissions (Gladek & Van Odijk, 2014; Swilling & Annecke, 2012). In the last decade, cities have been growing particularly fast: after 2007 there were in the world more people living in cities than outside them (Swilling & Annecke, 2012), and this number is expected to reach 66% in 2050 (United Nations, Department of Economic and Social Affaris, Population Division, 2015) and 90% in 2100 (Fragkias, Lobo, Strumsky, & Seto, 2013). This trend will continuously increase the global pressure for natural resources and waste disposal, which appears to increase proportionally in accordance with the size of the cities (Fragkias et al., 2013). This situation can compromise the maintenance of urban populations and therefore, threaten other functionalities that cities provide to the entire world (Bettencourt, Lobo, Helbing, Kühnert, & West, 2007).

There are a large number of components that intervene on a city to produce a determined behaviour. Approaching cities as systems, enable the analysis of relevant components, interactions and resulting patterns of behaviour that all together can be referred as system dynamics. The understanding the dynamics of cities might help to identify root causes of problems and see new opportunities to tackle current trends in urban systems (Meadows, 2008). Then, knowing the way cities operate can help to expand interventions beyond technological and infrastructural transformations that guide cities through an efficiency pathway aimed at lowering their environmental footprints (Swilling & Annecke, 2012).

One of the fundamental resources that nourish cities is the energy supply. This is one the services on which cities rely upon to fulfil a wide range of functionalities. So, services such as water supply, treatment and disposal, transport and communication systems, food and materials, influence the way energy is distributed across the city. On the other hand, energy supply also affects the way the city develops (i.e. spatial organization or socio-economic arrangements within the city). This means that the energy system of a city is connected throughout a variety of elements that operate at different levels in the urban space. Therefore, understanding the dynamics of urban energy systems might contribute to explain a large part of the urban behaviour, yielding significant insight about the existing connections between environmental and socio-economic factors of cities.

A widely spread alternative to describe the dynamics of cities is the concept of urban metabolism. This concept emerged from the field of systems ecology with the purpose of studying an entire ecosystem as a unit (Odum, 1971). This was based on the analogy of ecosystems envisioned as "super organisms" that interact with their environment to support life (Patten & Odum, 1981). In the urban context, the concept was initially adopted as a way of theorizing and describing networks and flows in cities (Camaren & Swilling, 2012; Rapoport, 2011; Swilling & Annecke, 2012). Then, preliminary studies focused on input-output material flows (using a black box or a sub systemic approach) (Golubiewski, 2012) in which ecological categories, such as compartments and pathways, were meant to describe complex interactions of components within cities (Y. Zhang, Yang, & Fath, 2010; Y. Zhang, Yang, & Yu, 2009a, 2009b). According to C. Kennedy, Pincetl, & Bunje (2011), there have been also implemented different accounting methods (mass balance and solar energy equivalents) to quantify energy, nutrients, foods and water flows across different cities (Hong Kong, Tokyo, Canada, Vienna). Proponents of these methods conceive that cities need to emulate the cyclical and efficient nature of biological processes envisioned by system ecologists (Rapoport, 2011). They assert that the material accounting of urban metabolism makes explicit the pressure for resources and therefore, challenges the linearity of consumption patterns and waste production of cities (Golubiewski, 2012; Rapoport, 2011) .

Further attempts to expand the use of urban metabolism as an integrative concept, have included different parameters that attempt to describe the processes of transformation, consumption and waste production that sustains the economic activities of cities (Golubiewski, 2012). That is the case of metabolic rates linked to consumption rates, wealth and other liveability measures such as health, employment, income, education and leisure. More recent studies have associated urban metabolism to economies of scale for urban infrastructure, greenhouse emissions (L. Zhang, Liu, & Qin, 2014) and macroeconomic models (Fung & Kennedy, 2005). All these studies on urban metabolism have attempted to develop comprehensive methods from a city perspective, but none of them have challenged the concept itself and the way it has been interpreted for using the analogy from the ecology field. In consequence, the widely spread implementation of the concept as an accounting method says little about the internal dynamics that shape cities, and therefore, provides no sound base to formulate and implement sustainable strategies to transform the urban space (Golubiewski, 2012).

The appealing of the concept of urban metabolism derives from the idea that it draws a parallel between cities and ecosystems. In ecological systems, large part of the relations and interactions between organisms and their environment is explained by metabolism in accordance with the "Metabolic Theory of Ecology" (Brown, Gillooly, Allen, Savage, & West, 2004). This convergence is useful to examine how links and connections that operate in cities can be explained by using urban metabolism from an ecological perspective. It requires a thorough examination of how dynamics in ecosystems and cities can be compared: this includes to investigate how concepts from ecology can be implemented so they reflect the socio-economic arrangements of cities, and theorize how such arrangements contribute to the functioning of the city with respect to the utilization of resources.

For that reason, a system analysis of the relation between metabolism and ecological dynamics might be useful to provide a framework for comparing the implementation of the concept in the urban context. Therefore, the aim of this research is to develop a conceptual framework for urban metabolism with special focus on energy systems, by analysing how mechanisms that regulate dynamics in natural systems can be applied to the urban context. This framework will reveal information about the behaviour of cities and will set the basis for further implementation of urban metabolism as an indicator for the dynamics of cities. This might enable policy makers to build strategies contributing to the sustainable pathway of cities illuminating crucial points of intervention (Rapoport, 2011). Then, the central research question is: ***How can the concept of urban metabolism be conceptualised from an ecological perspective so, it provides insight about regulation of urban energy dynamics?.*** Then, this research is guided through the following sub questions:

- *S.Q. 1: How to draw a parallel between dynamics of ecological and urban systems?*
- *S.Q. 2: How does the metabolic theory in the ecology field explain the regulation of system dynamics in ecological systems?*
- *S.Q. 3: How dynamics of urban energy systems fit in the conceptual framework developed for ecological systems?*
- *S.Q. 4: How concepts from metabolism in ecological systems can be integrated to the regulation of dynamics of urban energy dynamics?*

The roadmap for this report proceeds as follows: Chapter 2 contains a theoretical review that draws a parallel between ecosystems and cities as complex systems with special focus on the levels of dynamic processes. Chapter 3 describes a qualitative method composed by three main steps. First, exploration of metabolism in the ecology field, second, contrasting that information against findings from the urban field and third, integrates information from both fields. Chapter 4 presents the conceptual framework that illustrates how metabolism regulates dynamics in ecological systems. Chapter 5 presents an overview of the results from dynamics in urban energy systems and approaches some considerations for the conceptualization of urban metabolism. Chapter 6 discusses the implications of implementing the concept of urban metabolism from the ecological perspective and provide some insight for further research in the topic. Chapter 7 summarizes main findings and draws main conclusions concerning the research question. Then, final chapters are appendixes, references list and acknowledgements.

2. NATURE AND CITIES AS COMPLEX SYSTEMS

A complex system can be interpreted as a collection of things that are coherently organised and interconnected. This organization allows a system to achieve an overall purpose. This purpose – or goal- produces a pattern of behaviour. The elements are organised in a structural way so they affect each other and together produce an effect that differs from the added effect of each individual element on its own. However, systems can also be organised hierarchically in subsystems at different levels that operate based on particular purposes or sub-purposes. Sub-purposes and overall purposes can come into conflict or instead they can work in harmony, creating multiple interconnections and redundancies that enhance stability leading to persistent behaviours.

There is a wide range of scales in which complex systems are represented in nature. Individual living organisms can be considered complex systems so they perform several functionalities aimed to survive, that is their ultimately purpose. An individual organism is usually organised (with a more or less level of complexity) in a structural way in which subgroups (subsystems or organs) are interconnected and perform sub functionalities that all together contribute to the same purpose in reaction to internal or external factors. In a larger scale, ecosystems can be also recognized as complex systems where a group of biotic components are linked between them and to other abiotic components on which they depend in order to pursue survival. Alongside these interactions there might be identified separated entities such as functional types taxonomic groups or niches, that individually display their own functions, but at the same time, contribute to preservation of the overall function of the ecosystem.

The ability of nature to perform harmoniously with the internal rules that govern individual components, and the external factors that influence them, discloses the evolutionary character of natural systems through adaptation, largely discussed since the publication of "The origin of species" from Charles Darwin in 1859. In parallel, a societal organization such as a city is recognized to evolve dynamically following a path dependency alongside changeable features that continuously emerge. Such features are consequences from the aggregated behaviour among components or individual agents (in the urban organization) considered as objects of adaptation and referred by Andersson, as units of selection (2005). In that sense, both ecosystems and cities can be compared as evolving adaptive systems.

As referred to by Levin (1998), John Holland describes four properties for ecosystems as complex adaptive systems. The first one is *aggregation*, which recognizes the formation of groups producing self-organization patterns that emerge from dependency or coordination between subsystems or components. Some patterns have been extensively investigated in nature such as the way species organize themselves (bees, wasps) or the way they move (crawls) (Camazine, 2003) as well as patterns of ecological succession of vegetation or fire dispersion (Solé & Bascompte, 2006). Other patterns of self-organization involving different species have been unveiled based on specific relations between prey-predator or parasite-host less as well as emergence of particular ecological networks (food webs) (Solé & Bascompte, 2006). On the other hand, recent theories consider cities as evolving systems in which urban structures are produced partly through design and planning, and partly through self-organization (Lane et al., 2009), originating a variety of infrastructural or socio-economic types of networks (Grubler et al., 2012).

The second property is *diversity*. This occurs throughout the whole range of species in an ecosystem and the genetic variation within single species, that provides certain degree of buffering and homeostasis for the system (Pascual & Dunne, 2005). In food webs, possible interactions among functional groups are calculated from the relation between species richness and connectance, which also gives insight into the balance of complexity and stability of ecosystems (Pascual & Dunne, 2005). Thus, this property contributes to resiliency of ecosystems (Levin, 1998), constituting the breeding ground for the selective forces of adaptation. In the urban context, diversity can be recognized by the broad array of individual agents´ actions. These actions differ in intentionality and power, through which negotiation of terms, unleashes assorted types of interactions that all together determine the evolutionary pathway of the urban systems (Lane et al., 2009).

The third property is the presence of *flows* that connect components of systems components integrating them as a whole. In the case of ecological food webs, interactions between species of different trophic levels are defined by energy and material flows (Pascual & Dunne, 2005). In the urban context, definition of flows might not be a straightforward conception because it depends on the urban system we approach and with it, the particular functionality that we want to explore. For example, transportation system can be analysed in terms of transportation lines to investigate transport efficiency across the city, or in terms of economic flows to analyse the relation cost-benefit of the system. These are two different ways of observing one type of urban system: as an spatial arrangement or as a socio-economic structure (Lane et al., 2009).

The fourth property is *non-linearity.* This explains how changes are reinforced by random events operating at the individual level and transforming the way system evolves and develops. This characteristic recognizes the changeable nature of ecosystems and the influence of forces that produce dynamic patterns displaying no single stable equilibrium (Chapin III, Matson, & Vitousek, 2011). Evidences of this behaviour have been analysed in complex fluctuations of populations that oscillated within certain range as in a limit cycle (periodic system) instead of going directly to one attractor (equilibrium state) (Solé & Bascompte, 2006). Several factors have been discussed as responsible for the cycles such as food supply, dispersal, genetic mechanisms, predators, parasites and diseases (Solé & Bascompte, 2006). In cities, non-linear property analysis has been recently encouraged by dynamics that occur in mobility patterns such as chaos, catastrophes and bifurcations ("Mike Batty at the NESS Policy Conference," n.d.).

This appraisal has provided a common ground to analyse and elicit what happens in cities compared to ecosystems by looking at them as complex adaptive systems. The discussion above has presented ecosystems and cities as changeable entities that evolve through abrupt and transformational adaptations displaying unpredictable dynamics towards multiple and indefinite states (Gunderson, 2001). Therefore, what makes relevant this comparison is to analyse the way fundamental principles operate to produce emergent and aggregated patterns of behaviour in nature, and how they can be paralleled in cities. In that way, a deeper understanding of how components interact among them and across levels, may help to identify driving factors and alternative pathways which constitutes the core of dynamic studies (Meadows, 2008).

Furthermore, given the complex nature of cities and ecosystems, future patterns can be only predicted under the influence of a certain array of factors, some of which are randomly defined or originate from other levels of the system. However, capturing the inherent dynamics of the system across levels may guide where changes must come from and what aspects (components, interconnections or purposes (Meadows, 2008)) should be intervened in order to modify an undesired behaviour (Holland, 1992). In the context of cities, understanding urban dynamics offers the possibility to explain the speed and direction of changes as well as the volatility of cities (Batty, 2009) and so, guiding through possible points of intervention.

2.1. Levels of dynamics in ecological systems

In nature, a variety of dynamic processes can be identified: ocean circulation, forest succession, nutrient fluxes, relations between diversity-productivity, prey-predator relationships or ontological growth are some examples. These dynamics are recognized as patterns of behaviour of the system that emerge as a result of interactions among all components that compose it. The occurrence of such dynamics is delineated by the spatial and temporal boundaries that define the system itself. This means that patterns are derived from interactions between slow-moving and fast-moving processes, and between processes that have large spatial reach and others relatively localized (Gunderson, 2001). Such interactions determine the overall functioning of the system (Levin, 1998; Meadows, 2008). Figure 1 proposes four different scales for analysing dynamics in nature: landscape, ecosystem, pool and individual.

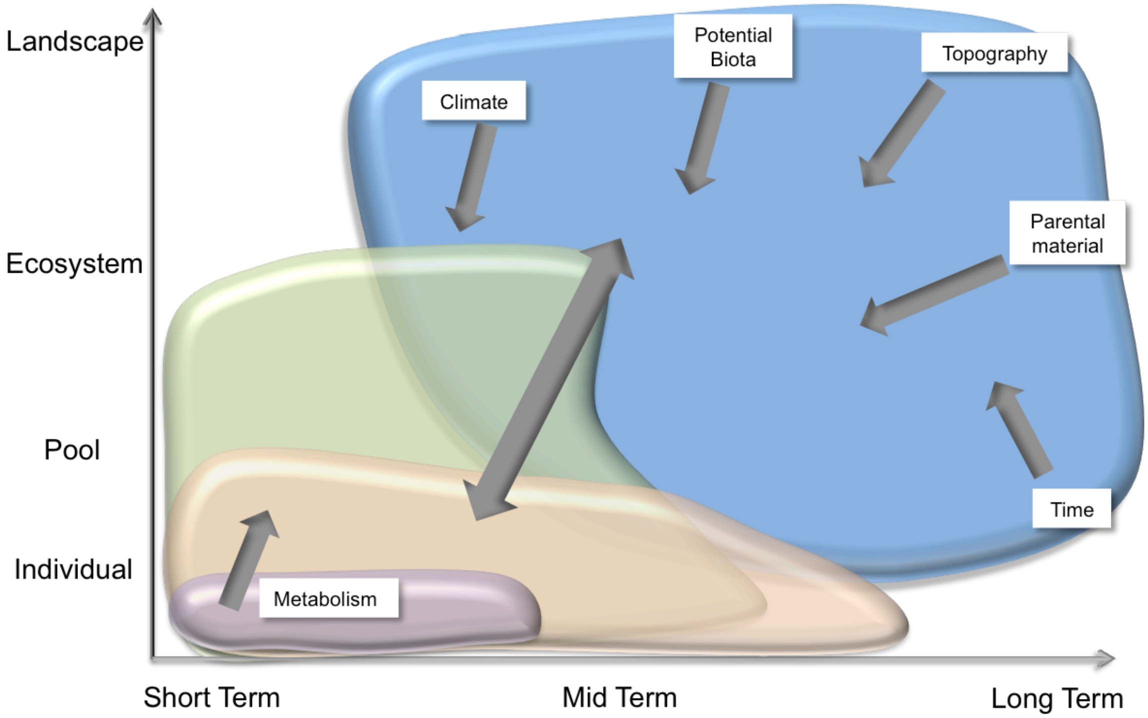


Figure 1 Controls and interactions influencing dynamics in nature at different levels. Adapted from (Chapin III et al., 2011)

From the highest to the lowest scale, the landscape level (blue area) (Figure 1) encompasses dynamics occurring relatively slow in time and producing effects at large scale. In absence of humans, relevant factors of influence are: climate, potential biota, topography, parental material and time (Jenny, 1941). Several patterns of behaviour result from the influence of such factors such as atmospheric and ocean circulation, spatial distribution of land and types and diversity of organisms. The occurrence of these patterns influence dynamic processes at a lower scale: the ecosystem (green area) (Chapin III et al., 2011).

In ecosystems, dynamic processes are determined by interactions among biotic and abiotic pools. These interactions are basically relations among aggregations of plants and animals and stocks of resources (water, nutrients, air etc.) which are ultimately influenced by the factors operating at the landscape level (Chapin III et al., 2011). The resultant patterns of such interactions can be portrayed by the supply of resources, microenvironment (e.g., temperature, pH), disturbance regime (specific events: fire, winds, hurricanes, floods) and biotic community (type of species, relative abundances) that define the structure and functioning of the ecosystem (Chapin III et al., 2011). The occurrence of these patterns causes fluctuations of variables that not only respond to, but also modify, the way factors influence dynamics at a lower level: the pool (orange area). At this level, dynamic processes can be recognized as patterns of mortality and birth of populations as well as abundance of resources. Fluctuations of variables derived from such patterns, determine the way factors influence dynamics at the individual level. For example, reproductive rates or ontological growth are patterns of behaviour at the individual level (purple area) responding to conditions established at the pool level (i.e. abundance of specific resources or competitors presence).

The effect of factors influences changes in a system across scales. These scales are nothing else levels of organization of the system that differentiate in the spatial and temporal dimensions. So, different dynamics are produced throughout the system and therefore, distinctive patterns of behaviour appear at every scale. In addition, the occurrence of such patterns determine fluctuations of particular variables that, at the same time, respond to the factor but also influence the way it affects other levels. This means that there is a dynamic interaction between the system and the factor that is playing a role, in which patterns and variables are constantly adjusting themselves across scales. In that sense, factors are not fixed parameters that apply static forces but, on the contrary, they are mechanisms guided by a set or rules or principles that vary in accordance with the behaviour of the system and so, provides it with flexibility. This effect can partly explain the non-linearity of complex systems mentioned in section 2.1. Understanding the way factors operate throughout the system is fundamental for the analysis of the dynamics.

With respect to metabolism, we postulate it as a factor that operate at the lowest level and exert control at the higher levels of the system. Metabolism determines the way individuals transform energy and materials and exchange them with the environment (Gillooly, Brown, West, Savage, & Charnov, 2001). In consequence, it determines patterns occurring at the population level and therefore, at the ecosystem level, which is the fundamental basis of the Metabolic Theory of Ecology (Brown et al., 2004). This makes the study of metabolism pertinent for the analysis of the dynamics of a natural system. Nonetheless it is important to mention that the evolutionary scale of metabolism (phenotypic and genotypic variations) is beyond the scope of this research, since we are more interested in an operational scale of metabolism.

2.2. Scales of dynamics in urban systems

In the urban field, Bretagnolle and co-authors proposed a theory of organization of systems of cities as multilevel networks (Lane et al., 2009). According to them, emergent properties can be consequence of dynamics occurring at different scales, which resembles the previous arrangement discussed for nature. Thus, organization of urban systems is proposed to occur over three main scales (Figure 2): macro level that is defined as the system of cities built upon a large number of towns and cities that interact under an unified control (e.g. national political territory or global economic network); the meso level (the city itself as a consistent geographical entity) and the micro level representing elementary units or individual agents (individual people, firms, institutions) that live together in a city, (Lane et al., 2009).

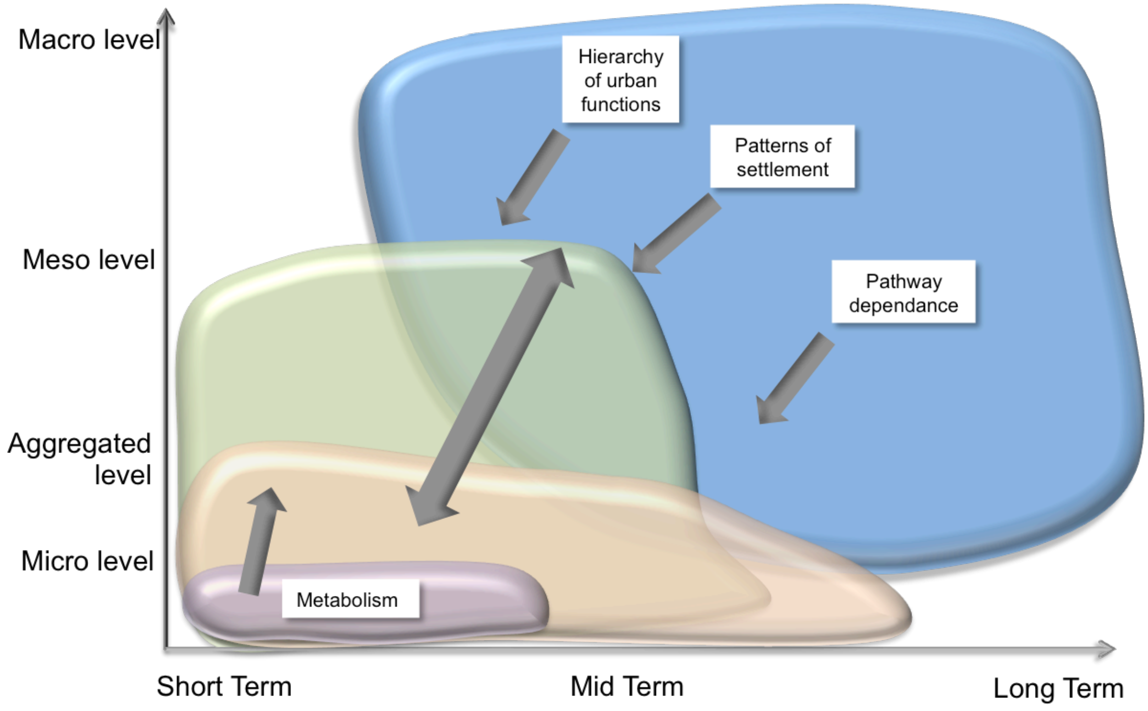


Figure 2 Controls and interactions influencing dynamics in cities at different levels. Adapted from (Lane et al., 2009)

The macro level or system of cities (blue area), develops alongside interactions with other cities throughout a variety of networks such as roads, railways, airlines or capital and information (Lane et al., 2009). Under this perspective, some authors consider that cities evolve through historical times conforming subsets of cities that expand control over wider territories assumed by national or supranational actors. So, system of cities evolves in a hierarchical pattern of city sizes due to the influence of factors such as historical path dependency, settlement features or specialization of urban functions (Lane et al., 2009). Those authors assert that this pattern generates asymmetric exchanges between interconnected cities producing a variety of quantitative and qualitative differences at the city level.

Dynamics occurring at the city level (green area) display other patterns such as economic specialization, social composition, cultural features and urban landscape that respond to, and influence, the city development (i.e. position within its own network). We suggest that this influence makes visible the existence of aggregations within the city, or what was called for nature as the pool level, claiming for a disaggregated view of the city. According to Lane et al., aggregations of individuals uncover the direction of change more clearly than individual agents because the latter exhibit larger variability and random behaviour (2009). Some patterns at the city level already recognise the presence of aggregated organizations such as: supply chains or socio-economic stratification. Factors operating at the pool level are, of course, influencing the individual level as well (e.g. urban citizens, firms and institutions) (purple area). In consequence, paralleling the role of metabolism in nature to cities, we conjecture that the metabolism of a city should be conceptualised as a factor that controls the urban system operating at the individual level, in the similar that metabolism does that for ecosystems.

3. METHOD

This research was aimed at providing a theoretical basis for the conceptualization of urban metabolism based on the role that metabolism plays in regulating dynamics of ecological systems for this, in chapter 2 systems were described in terms of components, interactions and aggregations that all together characterize system dynamics. The core of this research was building up a conceptual framework based on ecological systems to be paralleled with urban systems. The comparison between these two systems provided cornerstones for the conceptualization of urban metabolism. This understanding contributes to the formulation and implementation of strategies aimed at the sustainability of cities, giving relevant insight into city's dynamics and forces that operate within urban systems.

This was a qualitative research that implemented the knowledge integration among the ecology and the urban fields (Figure 3). This integration was based on the systems theory using it as the stand for the comparative analysis of system dynamics as in ecological as in urban systems. In step 1 the metabolic theory of ecology was put in perspective with reference to their contributions to the dynamics in ecological systems, as described in Section 3.1. In step 2, qualitative information from the urban energy field was analysed in the light of the systems dynamics as detailed in Section 3.2. In step 3 information was contrasted and compared in order to identify relevant features from ecology that endow urban systems with the ability of regulation as described in section 3.3. An overview of this method is presented in Figure 4.

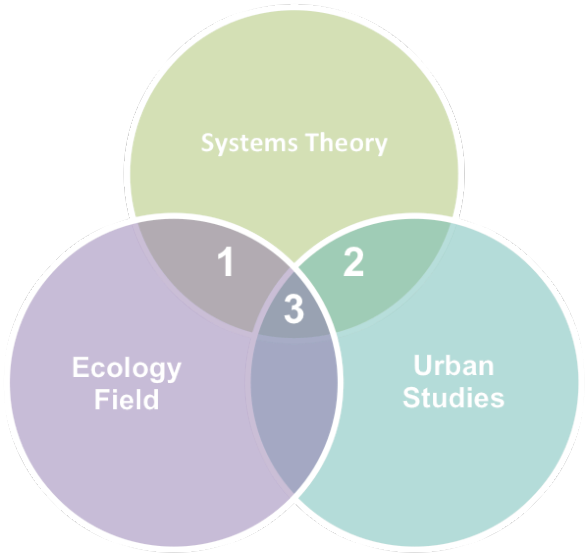


Figure 3 Knowledge integration in the research process

3.1. The role of metabolism in dynamics of ecological systems

This step consisted of a theoretical review of biological theories on metabolism and its implications for dynamics of ecological systems. This information was scrutinised upon the perspective of systems theory identifying key concepts and relations that associated metabolism to dynamics. From these concepts, relevant categories were defined as foundations for building up the conceptual framework for ecological systems. These categories were defined as: levels of organization, patterns, variables, factor, mechanisms and drivers. Some reflections on the application of these categories to the urban context were presented at the end of each section. The end product of this step is the conceptual framework that presented an overview of the concepts, ideas and relationships to describe system dynamics in ecological systems. This framework guided the following steps in the research process.

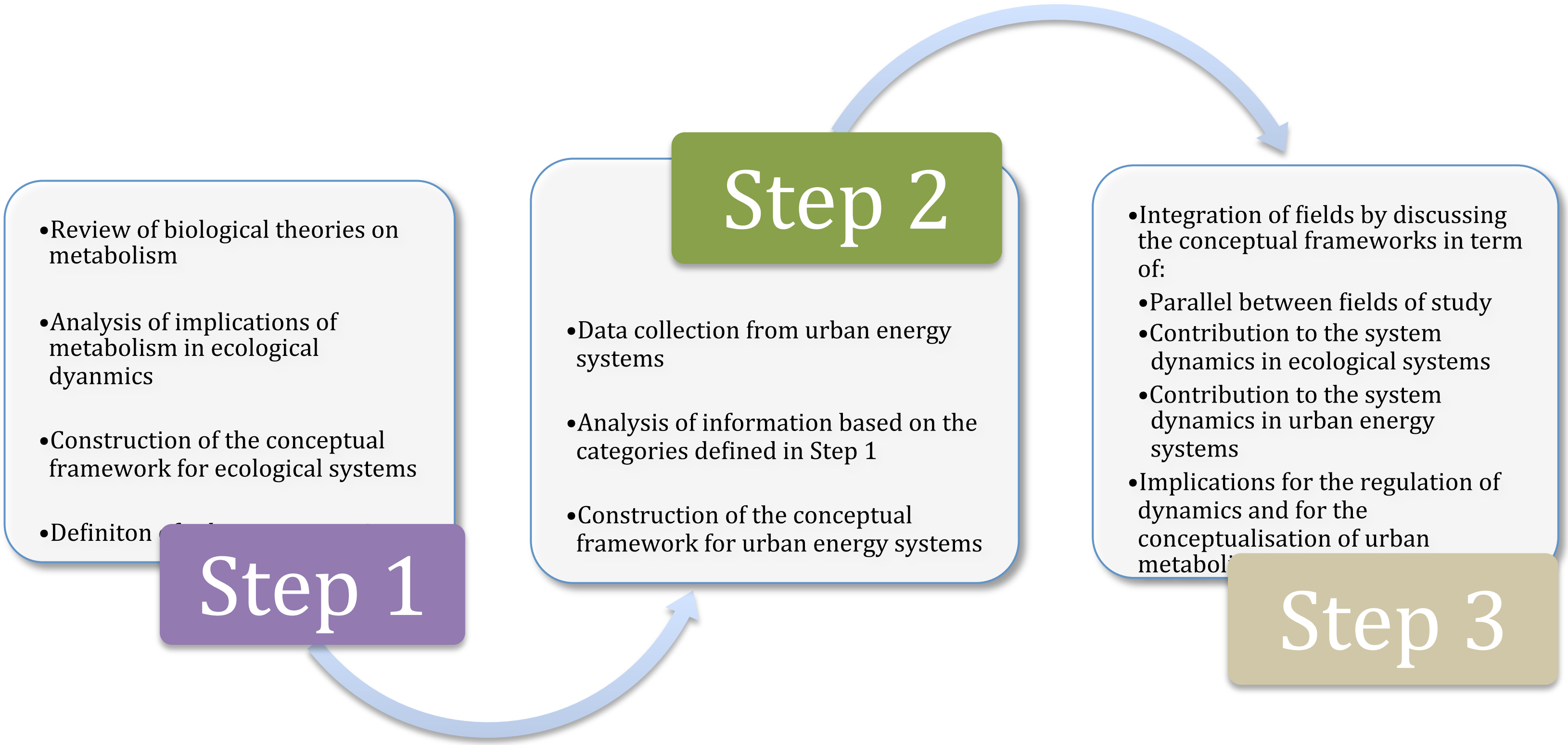
3.2. System dynamics of urban energy systems

In this phase qualitative data from literature on urban systems was collected and analysed. Information was narrowed to urban energy systems with focus on direct energy use. Bearing in mind that virtually all of urban processes directly or indirectly depend on energy (Grubler et al., 2012), means that the analysis of dynamics in urban energy systems provides a significant basis for the conceptualization of urban metabolism.

An extensive review of information on urban energy systems was done, gathering data from scientific journals and specialized books. Collected information was analysed upon the categories defined for ecological systems. Hence, information from energy systems was characterized in term of levels of organization, patterns, variables, drivers and mechanisms that apply to the urban context. All this information was condensed in a conceptual framework for urban energy systems.

3.3. Integration of urban metabolism into urban energy dynamics

In this step, system dynamics in ecological and urban systems was contrasted and discussed in the light of the structure of both conceptual frameworks. First, the applicability of the conceptual framework to parallel dynamics in ecological and urban systems was discussed. Second, the ability of the conceptual framework to explain the regulatory role of metabolism in ecological systems was examined, identifying advantages and disadvantages of this approach. Third, findings from literature on urban energy were discussed based on their practical implementation on the conceptual framework. Based on that, there were drawn several implications for the regulation of dynamics in urban energy systems. This information helped to outline the concept of urban metabolism demarcating its practical limitations and suggestions for further research. Fourth, additional concepts from ecological systems were revised with the purpose of filling gaps or inconsistencies for the conceptualization of urban metabolism.



- Review of biological theories on metabolism
- Analysis of implications of metabolism in ecological dyanmics
- Construction of the conceptual framework for ecological systems
- Definiton

Step 1

Step 2

- Data collection from urban energy systems
- Analysis of information based on the categories defined in Step 1
- Construction of the conceptual framework for urban energy systems

- Integration of fields by discussing the conceptual frameworks in term of:
  - Parallel between fields of study
  - Contribution to the system dynamics in ecological systems
  - Contribution to the system dynamics in urban energy systems
- Implications for the regulation of dynamics and for the conceptualisation of urban metaboli

Step 3

Figure 4 Description of steps of the research method

4. THE ROLE OF METABOLISM IN DYNAMICS OF ECOLOGICAL SYSTEMS

This chapter proposes a framework to examine the role of metabolism in ecological dynamics and delineates its further applicability into the urban context. To do that, the metabolic theory of ecology is scrutinized with the purpose of identifying fundamental principles and mechanisms that contribute to dynamic patterns in ecosystems. By doing that, it can be explained how mechanisms that control metabolic variations produce emergent features at higher levels of organization. This information is summarized in a conceptual framework that shows relevant categories and relations between them, in order to provide the cornerstones for the analysis of dynamics in the urban context.

The metabolic theory of ecology links the performance of individual organisms to the ecology of populations (Brown et al., 2004; V. M. Savage et al., 2004). According to this, ecological systems depict a hierarchical organization along three different levels: organism, population and community as shown by the conceptual framework (Figure 5). Different patterns of behaviour emerge at each level of the organization as a consequence of metabolism. Such patterns relate to particular variables that constantly respond to changes but also influence the occurrence of patterns at other levels. Section 4.1. describes the fundamentals of metabolism at the organism level, and sections 4.2. and 4.3. explain their implications at the population and ecosystem level respectively.

4.1. Organism level

At the organism level, there has been widely recognised that metabolic rates can be approximated as a general function of body size and temperature (Brown & Gillooly, 2003; Gillooly et al., 2001; Gillooly, Charnov, West, Savage, & Brown, 2002). This unleashes well known patterns in which many biological features exhibit a quarter-power allometric scaling law with body mass (Enquist, Brown, & West, 1998; V. M. Savage et al., 2004; West, Brown, & Enquist, 1997, 1999) and respond to temperature rising (Gillooly et al., 2001). This derives from the fact that metabolism dictates how organisms use a limited amount of resources to sustain life, through the processes of growing, developing and reproducing, affecting several features of organisms during their cycle of life (Gillooly et al., 2001). At this level, metabolism regulates energy uptake, transformation and allocation reactions (Brown et al., 2004; V. M. Savage et al., 2004).

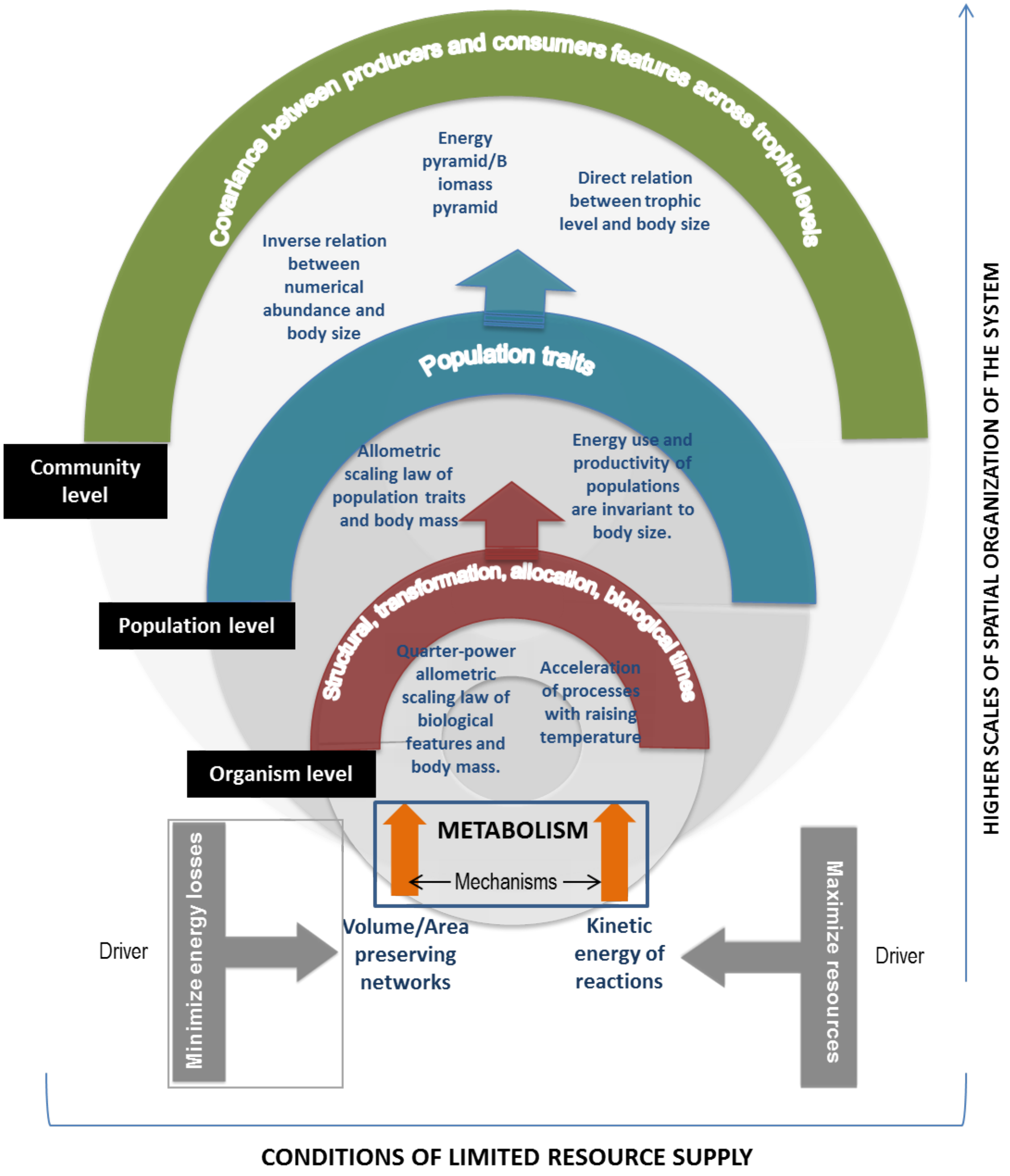


Figure 5 Conceptual framework for ecological systems

Metabolism operates through two mechanisms (Figure 5): fractal design networks and kinetic energy of reactions. The first one has to do with the optimization of the body through the volume/area-preserving networks for exchange and distribution, that evolved in plants and animals, to minimize transport distances and times (e.g. vascular system, circulatory system) (Gillooly et al., 2001; West et al., 1999). This mechanism operates as a constraining effect that increases internal efficiency of organisms driven by minimization of energy losses as illustrated by the driver in Figure 5. Three main properties have been proposed for such networks: (1) they branch hierarchically to supply all parts of three dimensional organisms; (2) they have terminal units, such as capillaries (or petioles), that do not vary with body size; and (3) natural selection has optimized hydrodynamic flow through the network so that the work required to distribute resources has been minimized (V. M. Savage et al., 2004). The second mechanism (Figure 5) has to do with the increase of kinetic energy of reactions that produces a general acceleration of metabolic rates (Gillooly et al., 2001). This mechanism produces a stimulating effect in which organisms respond positively to external stimuli (such as temperature) driven by the maximization of the use of available resources.

These two mechanisms operate at the same time led by two drivers that interact upon a limited resource supply environment. The first one is basically minimizing energy losses whereas the second is accelerating the use of resource. This reveals a fundamental character of metabolism as a regulatory process that creates a balance between internal needs of organisms and availability of resources. Resultant patterns of behaviour at the organisms level, evidence this effect by relations among variables that determine important aspects of organisms life:

- *Structural variables*: exhibit designs that show how areas or volumes are optimized while organisms get bigger e.g. cross-sectional areas of mammalian aortas and tree trunks that scale as $M^{3/4}$ (West et al., 1997).

- *Transformational variables:* Metabolic rates indicate how fast are the processes by which organisms break down nutrients into smaller units to build up structures and to release energy. These rates show bigger organisms exhibit lower metabolic rates in comparison to smaller ones, reducing resource demands as they increase their body size i.e. metabolic rates of entire organisms scale as $M^{3/4}$. This happens with other metabolic rates (i.e. mass-specific metabolic rates scales as $M^{-1/4}$ (V. M. Savage et al., 2004)) and also physiological rates (i.e. heart rate and respiratory rates scale as $M^{-1/4}$ (V. M. Savage et al., 2004)).

- *Allocation variables:* show that the rate at which nutrients and energy are distributed among organs decreases with body size (Enquist & Niklas, 2002). This means that bigger organisms have less requirements that smaller ones, and also denotes which functionalities are prioritized at some particular moment (i.e. maintenance over reproduction) (V. M. Savage et al., 2004).

- *Biological times*: are reciprocals of biological rates per unit of mass. This means that organisms with higher metabolic rates tend to show shorter times such as life-spans or developmental times (Gillooly et al., 2001).

In short, metabolism determines most of the important events of the organism´s life history (birth, growth, maintenance, reproduction and death). It sets the demand for environmental resources and their allocation for survival, growth and reproduction at the organisms level (Van M. Savage, Gillooly, Brown, West, & Charnov, 2004; West et al., 1997). Such effects derive consequences at the population level. In the context of urban systems, this highlights the role of the micro level (section 2.2.) to endure such type of regulatory processes. Thereby, it is important to identify organizations at this micro level, able to modify variables from which emergent patterns can be evidenced at the higher level of organization (aggregated level) as depicted between organisms and populations.

4.2. Population level

An evident trend at this level is a trade-off between populations and organisms (Enquist et al., 1998; Van M. Savage et al., 2004). In that sense, population equilibrium size decreases with individual body size (Van M. Savage et al., 2004). This means that the metabolic regulations of individuals (i.e. resource uptake scaling as $M^{3/4}$), reflect on the scaling of variables at the population level (Enquist et al., 1998).

There are two related patterns identified at this level. The first one shows that traits such as population growth (Peters, 1986) and carrying capacity (Damuth, 1987) scale with body size. The second reveals that energy use and productivity of a population are estimated to be invariant with body size. This situation brings out relevance to the energy equivalence rule in which Damuth hypothesizes that the amount of energy used by one specie population in a community is independent of its body size (1981). Vegetal studies have shown that the rate of resource use per unit area is product of the population density and the rate of resource use per individual, which are both influenced by body size, meaning that the net effect of body size is zero. Then, the total energy use or productivity of plants species is predicted to be invariant with respect to body size (Enquist et al., 1998).

This produces a regulatory effect in which energy requirements at the population vary according to the number of individuals and their individual energy requirements. This also produces implications on the structure at the community level. In the urban context, this suggests that the regulatory process should describe a balance between the micro level (whatever they are) and the aggregated level (whatever it is) with further implications in resource use. The connection between these two levels also might contribute to the organization of the city at the higher level.

4.3. Community level

At the higher level, communities are organised throughout producer-consumer relationships among populations. It displays trophic chains that show energy and materials flowing from preys to predators linked by a consumption process (Brown et al., 2004). Organisms that obtain their energy through the same number of transfers belong to the same trophic level (Chapin III et al., 2011).

Some authors have identified connections between trophic levels, body size and abundances in ecological communities (Brown et al., 2004; Joel E. Cohen, Jonsson, & Carpenter, 2003). For example, in marine and freshwater ecosystems, empirical analysis show how species with small average body mass occur low in the food web while larger-bodied species occur higher in the food web and are numerically rare (Joel E. Cohen et al., 2003). This has been connected to the fact that total standing biomass is invariant with body size (Brown et al., 2004; Damuth, 1981). As a result, there is a general pattern that shows an energy pyramid configuration along which the production at each level depends on the production at the preceding. In terrestrial ecosystems, energy pyramid is associated to biomass pyramid, while in some pelagic and freshwater ecosystems there can be an inverted biomass pyramid (Chapin III et al., 2011).

The occurrence of this pattern influences variables that relate preys and predators e.g. covariance in weights of predator-prey pairs is reported as an allometric relation between predator weight and prey weight (JOEL E. Cohen, 1991). This has relevant implications for the structure of the community. For example, in trophic chains each level has less energy available, therefore, species at a higher position has less energy available than the previous one (Chapin III et al., 2011). On the other hand, covariance existing between average size of prey and predators limits the spectrum of food that certain consumer is able to consume (Brown et al., 2004; JOEL E. Cohen, 1991). This shows how metabolism has influences on the structure of a community by regulating at the organisms level. Paralleling this with urban systems, it suggests that the regulatory process at the micro level, produces consequences in the structure of the organization at the higher levels of the urban system.

In short, this appraisal has provided a link between metabolism and regulation of dynamics in ecological systems, as well as, outlined its possible implementation in the urban context. Then, the structure of this conceptual framework (Figure 5) distinguishes some relevant categories for the description of system dynamics characterized as follows:

- **Levels of organization**: It defines the different levels to analyse dynamics in a system.
- **Patterns**: It makes reference to widespread behaviours at each level that evidence the way factors influence the system.
- **Variables**: represent stocks that vary as a result of the dynamic patterns but also influence mechanisms to cause variations at other levels. These cause connections across levels.
- **Factor**: A process that cause an influence throughout the system. In this case, metabolism is defined as a factor that operates at the individual level but regulates the system at higher levels of organization.
- **Mechanisms**: Instruments through which metabolism operates.
- **Drivers**: Forces that mobilise mechanisms.

5. DYNAMICS OF URBAN ENERGY SYSTEMS

In Chapter 4 we presented a framework that explains how metabolism regulates dynamics in natural ecosystems. Based on that, we proposed a set of categories and illustrated some links according to what we found relevant for examining the dynamics of systems. In this chapter, the framework is used as a fingerprint to urban energy systems. This chapter is divided into two sections. Section 5.1. presents a general definition of urban energy systems. Section 5.2. intends to fit information from urban energy systems into the categories defined in the conceptual framework for ecological systems. The resultant information is presented in a conceptual framework for urban energy systems (Figure 6). The chapter ends by outlining main differences between ecological and urban systems and drawing some considerations for the regulation of the system dynamics on each case.

5.1. Urban Energy Systems

According to Grubler et al. (2012), urban energy system **comprises all components related to the use and provision of energy services associated with a functional urban system, irrespective where the associated energy use and conversion are located in space, such as power plants and transport fuel requirements both locally and internationally**. This definition focuses on the existence of components that all together accomplish the function of providing energy to the urban system. However, this definition seems to focus more on the existence of the physical infrastructure than on the function of providing energy to the urban system.

A more comprehensive definition was given by Rutter & Keirstead (2012) who defined energy systems as the **combined processes of acquiring and using energy to meet the energy service demands of an urban population**. This definition focuses more on the function of the system, identifying three features of the energy use in cities (Keirstead, Jennings, & Sivakumar, 2012):

- "**The combined processes..**": Resource extraction, refining, transportation, storage, and conversion to end service.
- **"..of acquiring and using energy.."**: Energy systems represent a balance between supply and demand-
- **"...in a given society or economy"**: the energy system is a socio-technical system that comprises more than just pipelines, fuels, and engineering equipment; so, markets, institutions, consumer behaviours and other factors affect the way technical infrastructures are constructed and operated as well.

In that sense, the second definition acknowledges a physical separation between the urban environment and the processes of production and transformation of energy. At the same time, it implies that acquisition and use of energy are connected through a supply/demand relation or what Grubler et al. (2012) pointed as " *'production' and 'consumption' perspectives*". Such connections might happen inside or outside the urban space. Moreover, this definition highlights that the physical configuration of an energy system responds to the way societal groups organize and interact around the energy use in a city.

The complexity of urban systems recognizes the interplay of aspects at the inter and intra urban space, that originates dynamic processes across the city (Grubler et al., 2012). The occurrence of such processes is derived from the necessity of cities to fulfil a variety of social functionalities, sometimes interconnected (habitat, production, services, political control etc.)(Lane et al., 2009). Energy supply is one the services on which cities rely upon to fulfil a wide range of functionalities. So, services such as water supply, treatment and disposal, transport and communication systems, food and materials, influence the way energy is distributed across the city. At the same time, energy supply affects the way the city develops (i.e. spatial organization or socio-economic arrangements within the city) (Grubler et al., 2012). This means that large part of the complexity of urban systems resides in the functioning or dynamics of the energy system that operates within the urban space.

5.2. Framing dynamics of urban energy systems

In order to analyse the functioning of energy systems, it is relevant to describe the temporal and spatial dimensions along which processes occur in cities. In that way, it is possible to recognise the structure of the energy system, identifying subsystems and components that conform them. By doing so, it becomes easier to delineate behaviours within particular boundaries and understand how they are interconnected. Such behaviours are represented by patterns. They describe interactions among components and therefore, provide insight about the dynamics of the system. Mechanisms and drivers depict forces and processes that operate in the system and trigger the occurrence of such patterns. This section presents the analysis of the information characterizing dimensions (subsections 5.2.1. and 5.2.2.), patterns (subsection 5.2.3.) and mechanisms and drivers (subsection 5.2.4.) operating in urban energy systems. This information is condenses in the conceptual framework for urban energy systems presented in Figure 6.

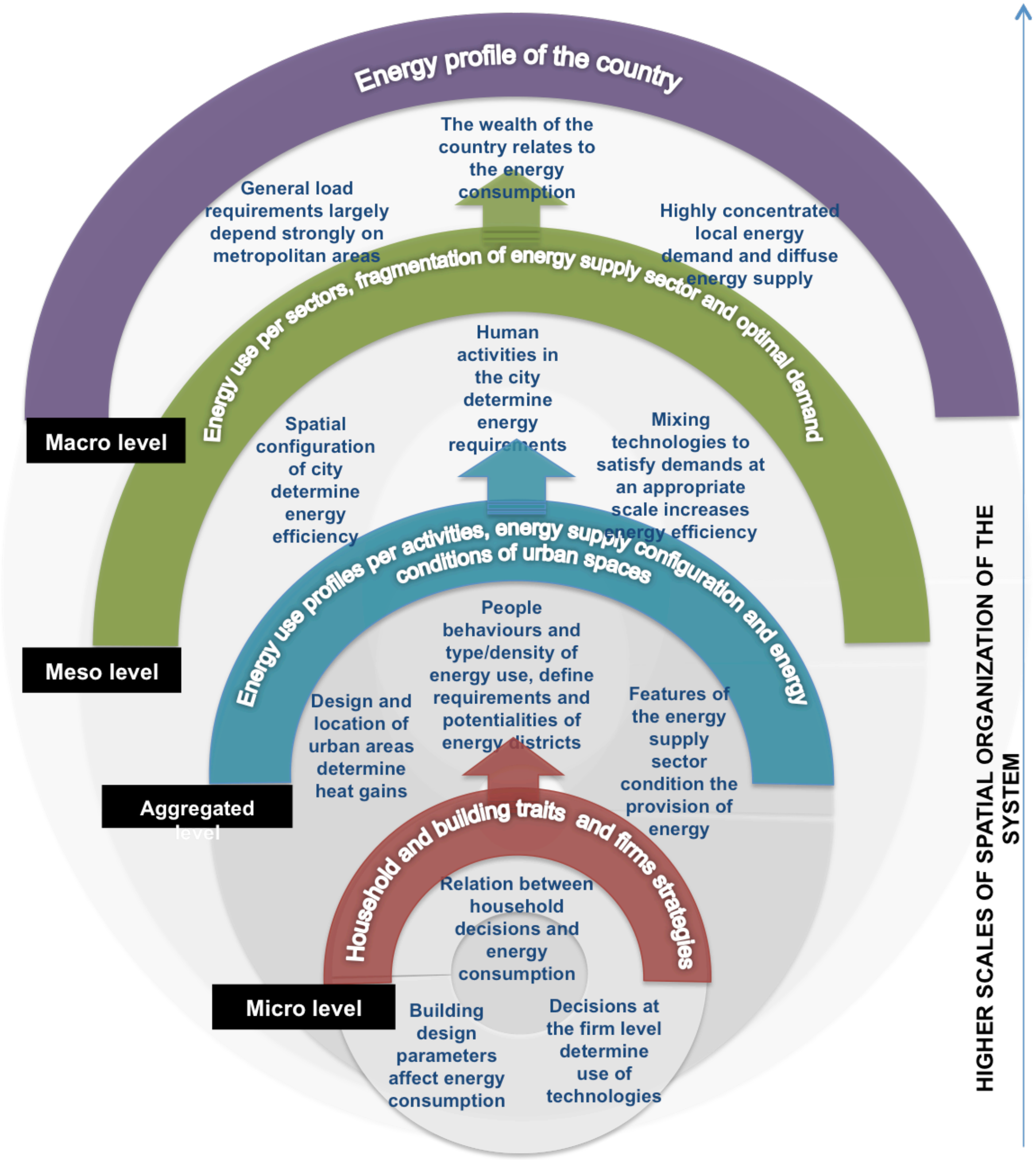


Figure 6 Conceptual framework for urban energy systems

5.2.1. Temporal dimension

The definition of the temporal dimension is usually linked to the purpose of studying a particular system, whether it intends to assess long-term decisions (e.g. annual investment decision) or, whether it devotes to a more operational level (i.e. hourly decisions). However, understanding how urban energy systems can be transformed includes looking at the long-term structural changes as well as the short-term changes. Since we are more interested in the structural configuration of urban energy systems, details on the temporal dimension are beyond the scope of this research.

5.2.2. Spatial dimension

The spatial dimension refers to the size of the components that operate in the system. In a hierarchical system, the size of the component usually depends on the level of organization where it belongs. According to that, there have been found a wide variety of scales in energy systems that play significant roles. They range from single buildings, individual dwellers or firms to groups of buildings, districts or sectorial activities as well as the whole city, system of cities or the entire country (Table No. 1). These scales represent different levels of organization that parallel the hierarchical structure proposed for ecological systems in Chapter 2. In that sense, scales in energy systems are classified as follows: individuals, firms or buildings at the micro level, sectors, districts or groups of buildings at the aggregated level, city at the meso level and country or region as the macro level. This hierarchical organization assumes that events happening at one level have implications at other levels, producing an overall influence in the whole system.

Along this variety of scales, there were identified two main approaches: The first one considers territorial and administrative boundaries, metropolitan spaces, and architectural infrastructures that involve pure physical and spatial features of the energy system. This approach focuses on energy calculations over territories, squares or buildings, with the purpose of identifying opportunities for improvement that leads to reduction of energy rates. This is consistent with measures intended to increase the energy efficiency of single or groups of buildings as well as districts by implementing technological improvements and innovations in the physical space inhabited by humans.

The second approach encompasses a bunch of scales that attempt to display the link between energy and people needs. They are based on the idea that the energy system responds to human activities and therefore, contemplate scales defined by different actors involved in the use of energy. These scales give more relevance to aspects such as life styles, economy, supply chains (supply and demand sides) or energy uses. Here we find individuals, households, firms or sectors. This approach places the human activities at the basis of the energy system and therefore, it acknowledges that the socio-economic activities of the city largely determine urban dynamics.

Table 1 Scales at each level of organization in urban energy system

Level	Scales	Description	Authors	Implications
Microlevel	Individuals	Unit of analysis that attempt to focus on human-activities.	(Brunner, Daxbeck, & Baccini, 1994) (Keirstead & Sivakumar, 2012) (Bennett & Newborough, 2001) (Stenzel & Frenzel, 2008) (Hong, Gilbertson, Oreszczyn, Green, & Ridley, 2009) (Ye et al., 2011)	-It is supported by the premise that main (material) urban flows are unleashed by human activities (Brunner, 2007) -It contrasts human needs and resources availability. –It advocates that human interactions are at the basis of urban infrastructures. -It directly challenges on human behaviour at the individual or corporate level
	Households			
	Firms			
	Single buildings	Structural units for living in cities	(Grubler et al., 2012) (Aksoy & Inalli, 2006) (Assimakopoulos, Mihalakakou, & Flocas, 2007) (Larsen, Filippín, Beascochea, & Lesino, 2008) (Wang et al., 2005)	-It focuses on energy efficiency based on technology to minimize energy use.
Aggregated level	Sectors	Breakdown of economic segments that operate in a urban area relevant for the energy system*	(Bennett & Newborough, 2001) (L. Zhang et al., 2014) (Keirstead & Sivakumar, 2012) (Pillai & Banerjee, 2007) (Grubler et al., 2012)	–It implies an aggregated effect of groups characterize by a particular function. -It advocates a causal link between economic and urban energy use. -Market processes help to capture urban processes
	Land use categories	Urban areas characterized by certain type of use	(Kalma, Johnson, & Newcombe, 1978)	-It focuses on impacts in energy use due to land activities -It mainly focuses on heat flows
	Districts	Area of the city characterized by a particular feature	(Grubler et al., 2012) (Weber, Keirstead, Samsatli, Shah, & Fisk, 2010)	-Optimisation of energy use of individual housings
	Groups of buildings	Buildings stocks/urban squares	(Kämpf & Robinson, 2007) (Jo, Carlson, Golden, & Bryan, 2010a) (Jo, Carlson, Golden, & Bryan, 2010b) (Hu et al., 2010) (Meyn & Oke, 2009) (Yezioro, Capeluto, & Shaviv, 2006)	-Effect on energy flows from the design of grouped buildings -It promotes energy efficiency at the building level

Table 1 (cont.) Scales at each level of organization in urban energy system

Level	Scales	Description	Authors	Implications
Meso level	City	Inhabited area delimitated by administrative boundaries	(Decker, Elliot, Smith, Blake, & Rowland, 2000) (Keirstead, Samsatli, Shah, & Weber, 2012) (C. Kennedy et al., 2011) (Larivière & Lafrance, 1999) (Y. Zhang et al., 2009b) (Sahely, Dudding, & Kennedy, 2003)	-It conceives cities as entities that use and transform resources -Input-Output approach focused on demand and neglecting supply (because it normally comes from outside) -Wide spread use of "metabolism" -Spatial approach of energy use -Artificial models of cities -It lacks socio-economic interactions
Macro level	Urban system/Megacity	A metropolitan area composed by different cities related by commuting distances between the core and surroundings	(Chris Kennedy, Stewart, Ibrahim, Facchini, & Mele, 2014)	-It tries to embrace supply and demand perspectives but is still limited
	Country	Particular territory delimitated by administrative boundaries	(Stenzel & Frenzel, 2008)	-It tries to embrace the entire chain of energy production -It commonly focuses on renewables

At the meso and macro level, scales such as city, megacity urban system and country show a mixed approach. On one side, they provide a geographic view based on the administrative boundaries that apply for planning and spatial matters, and on the other side, they attempt to include a perspective based on the energy supply and demand. So, this mixed approach implies that the energy system describes flows of energy along the supply chain within a particular geographical territory.

5.2.3. Patterns

Patterns are the outcomes of interactions happening throughout the system that, at the same time, influence the system as a whole. This section describes patterns on urban energy systems extracted from the literature, occurring across the four levels of organization: micro level, aggregated level, meso level and macro level. These patterns depict relations between variables at each level that responds to, and influences, behaviours at other levels.

Micro level (Individuals, households, buildings and firms)

Patterns at the micro level involve individuals, households, buildings or firms (Appendix 8.1). These patterns describe relations among variables with some incidences in the energy use across the system. For example, some patterns show a relation between household behaviour, household income or household size and per capita energy consumption and energy efficiencies. In the context of firms, patterns evidence a relation between firms´ strategies and adoption of new technologies and the level of integration of the energy supply chain. For the case of buildings, there was a quite evident relationship between design parameters of buildings and energy consumption with respect to variations on parameters such as heat gain and cooling load per building. According to these patterns, features at the micro level have an incidence in the energy consumption along the system.

Aggregated level (sectors, groups of buildings, districts, squares)

Patterns at the aggregated level involve different scales such as sectors of economy (i.e. energy supply, building industry) and urban areas (i.e. districts, squares) (Appendix 8.2). In this case, the grouped effect of actors at the micro level, generate characteristics at the aggregated level. For example, energy requirements of districts is better explained by people's behaviours based on patterns of occupancy; layouts of heating districts were found more sensible to heating densities derived from similar energy uses than dwellers densities. Referring to the commercial sector, the potential of renewable energy is determined by the type of use of a particular sector and the strategies implemented by companies in the energy supply sector. In the spatial context, parameters of design of buildings, squares or areas are related to the energy use because of variations of parameters such as insolation, cooling loads, heat gains, heat storage or heat island energy cost.

Meso level (city as geographical settlement)

Patterns at the meso level involve the city as a geographical settlement (Appendix 8.3.). In this case, the growth of cities relates to an increase of energy flows whereas the increase of electricity use is not necessarily related to the size of the city. That means that the impact of the city size depends on whether it entails the expansion of socio-economic activities or affects the type of use of the energy. For example, higher dense cities with lower automobile dependency appear to relate to lower transport energy use. Such patterns reflect the influence of decisions of people around energy use. Referring to the commercial aspect, mixing technologies fuelling a particular demand may increase the energy efficiency in the urban area. Likewise, optimized scales of settlements relate to higher energy efficiencies as well as better autonomy to manage their own power; thus larger cities are not necessarily more efficient than smaller ones (e.g. in terms of emissions).

Macro level (region and country)

Patterns at the macro level are mostly concerned to the country and the regional background (Appendix 8.4). In this case, the level of industrialization of a country and the country level of income relate to per capita final energy use of dwellers and CO_2 emissions, respectively. Other patterns show that the diffused energy supply at the national level, originally based on raw materials, tend to serve a highly concentrated local demand that continuously throws into a more value added energy sources. This tends to narrow the spectrum of energy suppliers with consequences for the configuration of the energy supply chain. In the spatial context, patterns describe that load requirements of power at the regional level depend on the implementation of measures (such as cooling roofs) over the entire metropolitan areas located in that region.

All these patterns evidence energy dynamics produced as result of interactions occurring between slow-moving and fast-moving processes, and between processes that have large spatial reach and relatively localized, as it was suggested in section 2.1.2. It means that patterns occurring at one particular level have implications at the higher levels through an accumulative effect. Conversely, patterns at higher levels can also influence to the lower ones. In general, we recognise a hierarchical structure in the organization of the urban energy system that evidence links between scales at different levels of organization, with several implications on energy consumption, energy requirements, energy flows or even emissions in cities (Figure 6)

According to the structure of the conceptual framework, while behaviours at the household level explain per capita energy consumption, the aggregated effect of individuals influences on energy requirements of districts. Likewise, the influence of household income in per capita energy consumption is also evidenced at higher levels, where industrialized countries tend to exhibit higher final energy use. This shows how individual behaviours at the micro level have implications not only at the same level, but also at higher levels through their aggregated effect. On the other hand, individual strategies of companies to adopt or not certain technologies define the potential for renewables in the energy supply sector. This illustrates how the decisions of firms at the micro level, determines the market structure at the aggregated level that also affect decisions of energy users. Such implications are determinant for the use of energy in cities.

With respect to the spatial configuration of cities, parameters of design of single buildings determine energy consumption of households at the micro level; furthermore, aggregated effect of buildings affect several conditions at the city level by influencing variables such as urban heat island effect, cooling loads and heat storage of urban areas. The same is observed when size and density of cities produce impacts on the levels of electricity, power, energy transport or emissions while at the same time, play an important role in the load of energy requirements at the regional or even at the country level.

5.2.4. Mechanisms and Drivers

According to the patterns, there are two main characteristics of the dynamics of energy systems in the urban context. In the first place, the functioning of the energy system occurs along the supply chain, where different actors interact with each other in order to move the energy from the supply to the demand side. Such interactions occur at the basis of commercial relations among different types of societal organizations. All these patterns evidence relations between levels of organization of the system with several implications for energy requirements. So, what type of energy use?, from which type of source? how much energy to use?, for what purpose?, how much to expend on energy?, who uses it? are questions underlining most of the patterns around energy use. This situation lead us to the second characteristic, according to which, individual decisions are at the core of the urban energy dynamics. In this respect, human choices define not only the uses for energy, but also set the rules for interactions between actors like the market structure and the technological deployment. In consequence, mechanisms and drivers in urban energy systems are those that underlie most of the human decisions (Figure 7).

The first driver we found relevant to contribute to the dynamics of energy systems is *self-realization*. According to this, individual consumption is derived from the motivations that operate in humans. This has to do with the fulfilment of all the wants that we as individuals are entitled to pursue. Two main mechanisms operate on that direction: the continuous increase of GDP per capita, and the large supply of services and goods in urban centres. The existence of these two mechanisms is evidenced by patterns that connect energy consumption to the household income and behaviours that lead to the increase of the fraction of disposable income with the purpose of acquiring more services and goods available.

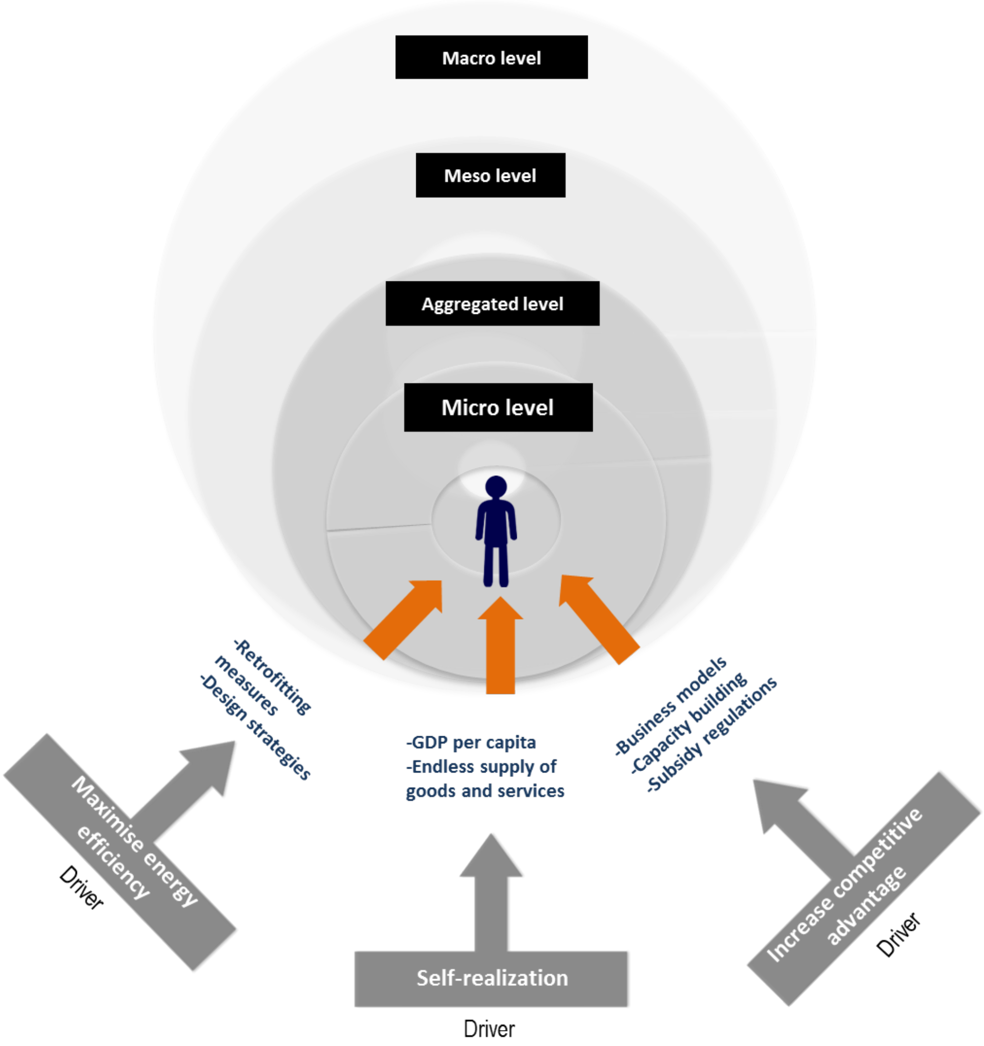


Figure 7 Mechanisms and drivers of urban energy dynamics

The second driver is the *increase of competitive advantage* by offering consumers greater value, either by means of lower prices or by providing greater benefits and services that justifies higher prices. This driver has strong incidence in the configuration of the energy supply sector in terms of technological offer, economic values and energy carriers, which in the end help to configure the market structure. Therefore, it determines to large extent the decisions that individuals are able to make around the energy use. Many different mechanisms take place upon this driver, such as capital-intensive business models, subsidy regulations and capacity building of energy firms. Some of the patterns related to those mechanisms are business monopolies, technological lock-ins and suboptimal scales of energy supply and demand.

The third driver is the *maximisation of energy efficiency*. It derives most of the technological advances that operates in the urban energy system and therefore, exerts a significant role in people's decisions. Technology as a mankind creation, intends to modify the environmental conditions where people live in order to find a balance between the quality of life and the use of resources. In urban energy systems, one general application of technology has to do with the improvement of efficiency of home appliances such as heating and cooling systems. This causes direct implications on the spatial configuration of houses, buildings and urban spaces in general. According to the literature, we found several mechanisms operating in this direction such as retrofitting measures and design strategies, which derives some impacts in the energy consumption not only at the household but also at higher levels. All these drivers and mechanisms work together to produce most of the patterns described in Section 5.2.3. They do not operate isolated from each other but in conjunction because they all provide the playground where human decisions are taken with regards to the energy use.

Describing energy systems by using the framework developed for ecological systems, allows us to identify key considerations for the regulation of energy dynamics in the urban space:

- Patterns of behaviour in ecological systems exhibit relations across levels (Figure 5). Similar relations are evidenced in urban energy systems and therefore, aspects at the micro level also influence energy requirements at the higher levels of organization (Figure 6). However, most of the patterns in ecological describe allometric relations which underlie most of the non-linear behaviours in ecosystems. Then, variables at the population level can change in a different proportion in which changes occur at the organism level. In contrast, there is no such evidence of a comparable behaviour in urban energy systems across levels. In most of the cases, patterns depict relations among variables that respond proportionally to the strength of the stimuli. For example, higher incomes at the household level are related to higher per capita energy consumption; in parallel, higher income countries also exhibit higher energy consumption. This shows how level of income produces an equivalent effect in energy consumption throughout the levels of organization of the system.

- In ecological systems, individual organisms continuously adjust their metabolism according to their internal requirements and the availability of resources represented the micro level. In that sense, they are able to modify rates (e.g. respiratory, circulatory etc..) or prioritize organic functions in order to regulate the use of energy. In urban energy systems, micro level represented by individuals, households, buildings or firms placed at the basis of the system, do not show evidences of such internal adjustments that lead to changes in energy use.

- Populations, as aggregations of individuals, show a balance between energy use and productivity. They perform within an energy budget that maintain thanks to the trade-off that exist with organisms. In that sense, metabolic regulations help to control the energy use at higher levels of the organization. In the urban context, aggregated and micro level do not exhibit a similar association by which they can balance their energy use.

- At the meso level in ecological systems, trophic chains organise by shaping an energy pyramid in which populations at the top have less energy available that the lower ones, in order to cope with inefficiencies on energy transfers. This dynamics is also controlled by metabolism. At the meso level in the urban context, city is characterized by highly concentrated local demands supplied by diffuse energy sources that, very often spread out the boundaries of the city. This configuration has no implications for the efficiency of energy transfers across the energy supply chain

- Macro level in urban systems is characterized as region or country. In ecological systems no similar classification was defined because landscape (Section 2.1.) is considered a too broad to be paralleled with the regional or national context in urban energy systems.

- The first driver that takes place in the metabolism of ecological systems is the minimisation energy losses. This performs against the second law of thermodynamics, according to which energy is less useful after it is transferred or used. Therefore, organisms evolve volume/area preserving networks to make all energy uses and transformations as the most efficient possible. This produces a self-constraining effect that regulates sizes, prioritise functions and determine configurations of most organizations in nature. In contrast, drivers in urban energy systems are more directed to motivate energy consumption by inducing people to consume more and renovated goods and services, whereas structuring a competitive market full of possibilities for consumers.

- The second driver in ecological systems attempts to maximise the use of resources. The mechanism behind this driver induces the acceleration of chemical reactions when external energy is available (i.e. temperature); in that way, organisms are able to increase the use of energy use only when there are sufficient resources to support it. In urban energy systems, maximisation of energy efficiency mainly works by means of technological innovations addressed to obtain more benefits from the energy translated into less costs or additional added values for consumers.

6. INTEGRATION OF URBAN METABOLISM INTO URBAN ENERGY DYNAMICS

The comparison between ecological and urban fields indicates that ecological systems exhibit a continuous regulatory process operating at the individual level and influencing the system across levels, known as metabolism. Drivers and mechanisms guiding metabolism are able to recognise the limitation of resources and, therefore, intend to make an efficient use of what is available at a certain moment. On the contrary, in urban energy systems there is no regulation of energy use across levels and therefore, energy consumption shows linear patterns throughout the whole organization. Although, urban energy systems also deal with limited resources, this evidences the lack of a process such as urban metabolism in the urban space.

This brings out a different perspective for urban metabolism compared to the input-output accounting of flows of cities (Sahely et al., 2003; Y. Zhang et al., 2010, 2009a; Li, Zhang, Yang, Liu, & Zhang, 2012; Y. Zhang et al., 2009b; L. Zhang et al., 2014; C. Kennedy et al., 2011). The use of this concept as an accounting method looks at the city as a "super organism" organised as one single level system (Patten & Odum, 1981). Such view disregards the aim of the concept to theorise and describe networks and flows of cities because it does not recognise different levels of the organization and their influence on the dynamics of the whole system. Such influence is recognised in studies indicating impacts of the metropolitan structure in the commute behaviour of people (Schwanen, Dieleman, & Dijst, 2004). In contrast, this research proposes a comparison of ecological and urban systems as hierarchical structures composed by different subsystems that acknowledge the existence of a multi-level organization in both (Lane et al., 2009; Warren, 2005). Although, the multilevel approach for cities has been discussed in the field of human geography focused on the levels of social organization, its relation to the regulation of the system dynamics contributes to a new approach within the urban metabolism theory.

The knowledge integration proposed on this research is based on the analysis of ecological and urban as complex systems. According to this, several characteristics and properties of complex systems were identified in both, ecological and urban systems. This link between both fields has been largely discussed by several authors as they conceive cities more close to biological than to mechanical systems (Odum, 1971; Patten & Odum, 1981). This originates the popularization of the concept of urban metabolism in urban studies (Batty, 2012; Chris Kennedy et al., 2014; Christopher Kennedy, Cuddihy, & Engel-Yan, 2007; C. Kennedy et al., 2011; Wolman, 1965; L. Zhang et al., 2014; Y. Zhang et al., 2010, 2009b). Base on that, this research sets the theoretical foundations for the integration of knowledge between fields. This was done by developing a conceptual framework that parallel the multilevel organization in both systems, with the purpose of capturing the fundamentals of the system dynamics and its regulation in ecological systems, and discussing them for their application in urban systems.

6.1. Ecological dynamics according to the conceptual framework

The conceptual framework was organised upon different categories such as levels of organization, patterns of behaviour, variables, mechanisms and drivers defined from the basis of ecological systems in Chapter 4. The resultant structure places the micro level at the basis of the organization as the core of the system dynamics (Figure 5). Thus, patterns at the micro level unleash behaviours at the higher levels and, therefore, become very crucial for the dynamics of the whole system. Connections between levels are produced from variables that respond to and influence the behaviour at each level. This configuration aligns to the fundamentals of the metabolic theory of ecology that links the performance of individual to the ecology of populations due to the effect of metabolism (Brown et al., 2004; V. M. Savage et al., 2004).

The categories defined on the framework succeed on making visible the general structure of the system and how metabolism, at the micro level, derives important consequences at the higher levels of the organization. In addition, it clarifies that drivers and mechanisms attributed to metabolism, operate as balancing forces at the micro level of the organization. The interpretation provided by this conceptual framework hints a new perspective for representing complex systems that differs from the causal loop and the network diagrams. Within this new perspective, the different scales are emphasized and it is possible to examine the emergence of patterns due to aggregated behaviours.

6.2. Urban energy dynamics according to the conceptual framework

From fitting the information collected from the urban field in the conceptual framework (Section 5.2), several aspects were identified and discussed with regards to the structure, functioning and regulation of urban energy systems:

1) Section 5.2.2. shows that there are two different interpretations of the components that comprise urban energy systems. On one side, there is an interpretation that concentrates on the physical configuration of spaces where humans develop, which entails a material dimension of energy use. This interpretation focuses on levels of organization such as buildings, urban areas, districts and cities. This particular view creates a physical dynamics in which patterns of energy use mostly depend on infrastructure and spatial arrangements. The capability of the system to perceive and to respond to changes resides in technological implementations destined to regulate the distribution of energy. This has no major incidence in the regulation of

process that lead to the energy use itself. On the other side, a different interpretation focuses on the links between human activities and energy use. In that sense, energy is connected to human activities and the behaviour of the system is based on the fulfilment of needs. Upon this view, urban dynamics is mostly concerned to the increase of energy requirements aligned to the economic growth of urban centres. However, none of these interpretations recognises the limitation of energy supply and do not include any strategy for constraining energy expenditures and so, decrease the energy inputs at the higher levels of the organization.

2) Placing the micro level at the basis of the urban system results consistent with the view of cities as a creation of individual and group decisions or as a product of self-organization (Batty, 2012; Lane et al., 2009). This coincidence among ecological and urban systems highlights the individual role in the dynamics of systems and gives relevance to the emergence property, according to which, larger entities and patterns arise through interactions among smaller entities ("Concepts: Emergence | NECSI," 2015). In urban energy systems, the behaviour of individuals, households, buildings and firms cannot explain independently the whole dynamics at the city level. This means that the interactions happening at the micro level (between different actors) need to be further explored for the analysis of the dynamics of the system.

3) The structure of the energy system at the city level is characterized by highly concentrated local demands supplied by diffuse energy sources (Rutter & Keirstead, 2012). This configuration denotes the importing character of the city and contrasts it with the self-sufficiency of ecological systems. Upon this perspective, any attempt of regulation of energy within the urban space is pointless, since the provision of the resource is coming from some other source not included in the overall picture of the system. Some authors have recalled to the same aspect proposing the expansion of the concept of city into a larger dimension (Decker et al., 2000). Others instead, have promoted the implementation of appropriate scales for energy supply within the urban space assuring that it might improve the energy efficiency (Fragkias et al., 2013; Grubler et al., 2012; Keirstead, Samsatli, et al., 2012). We considered that succeeding in the endeavour of regulating the energy use, requires the urban dynamics to be analysed upon all the levels of organization that cover the entire system. This can be either, the regional or the transnational scale that, in one way or another, is attached to the energy system that supports the urban space.

4) In ecological systems there is a trade-off between the populations and the individual organisms that conform them. This relation permits the regulation in the use of resources so, individual organisms constraint themselves in order to give rise to the population. This guarantees the survival of the population as a group that is able to reduce its requirements in comparison to the added requirements of

individual organisms. In urban energy system, aggregations and individuals do not show such type of relation. The aggregated behaviour exhibits the cumulative effect of individuals without any balance or reduction in the energy use. In terms of the energy system, this means that the aggregated levels do not exhibit the emergence of a particular behaviour that compensates for constraints at the micro level. This situation diverts from the principles of the emergent property attributed to complex systems, according to which, components are joint together in constraining relations to construct a higher-level aggregated object ("Emergent property | Define Emergent property at Dictionary.com," n.d.). Many authors have claimed for a disaggregated view of the city in order to unveil the internal dynamics (Grubler et al., 2012; Pillai & Banerjee, 2007; van der Vleuten & Raven, 2006; L. Zhang et al., 2014; Y. Zhang et al., 2009b). However, the relevance of this, resides more in the possibility to create a trade-off between the micro and the aggregated levels, so they can lead to the emergence of different patterns of behaviour that counteract the limitations on the energy supply of urban systems.

5) Mechanisms and drivers that operate in the dynamics of energy systems stimulate energy consumption across levels. Self-realisation at the household level, and the increase of competitive advantage at the firm level, both contribute to enhancing energy requirements by enlarging and diversifying the supply of goods and services throughout the whole system. This behaviour opposes the constraining effect of metabolism in ecological systems, according to which, limitation of resources are coped by balancing the use of energy at the organism level. The technological deployment implemented as a tool for increasing the energy efficiency in urban systems, has failed on that purpose as it is shown by the rebound effect (Hong et al., 2009). According to this, expected benefits from increasing efficiencies due to technological implementations are not truly achieved, because of the effect on individuals behaviour that decide to consume more, either for raising their comfort expectations, or because there is more accessibility of energy services due to lower prices (A. Greening, Greene, & Difiglio, 2000). This raises important implications for addressing the internal motivations that trigger human behaviour for the regulation of the dynamics of urban energy systems.

In short, several aspects need to be tackled in urban energy systems in order to emulate the process of regulation that metabolism produces in ecological systems. First, urban energy systems need to be portrayed by flexible components able to perceive and to respond to changes across the different levels of organization. Second, the structure of the system needs to be built upon the interactions at the lower level of the system. Third, the system needs to rely on a condition of limited resource supply and therefore, include strategies for constraining the energy use. Fourth, there must be a trade-off between the micro and the aggregated levels that contribute to the emergence of behaviours and compensate for individual constraints. Fifth, drivers operating in the urban energy system need to address mechanisms that tackle internal motivations, lifestyles or habits at the micro level, so they can draw regulatory effects at the higher levels of the organization.

This situation highlights two important implications for understanding urban energy systems. On one side, energy systems as constituted by physical structures that facilitate the use of energy to humans. Upon this view, a regulatory process mostly relies on technological innovations or home appliances as the energy efficiency intends to do. On the other side, urban energy systems as a social construct that requires more attention to the human behaviour for the purpose of regulation. Studies on this matter demonstrate that the reduction on greenhouse emissions is more related to home size than to the number of population, which brings out more relevance to analyse the considerations people make to choose one or another size of a home (Swim, Clayton, & Howard, 2011). This contrasts the role of urban metabolism as a mechanism that challenges consumption and waste production of cities only by making explicit the pressure for resources (Golubiewski, 2012; Rapoport, 2011), with an alternative view as a strategy that questions how people's conducts at the individual level, determine the structure and functioning of the larger system.

Focusing on human behaviour can lead urban dynamics to behave more similar to the way ecological systems operate in nature. This means that mechanisms for implementing regulation need to address the drivers that motivate individual consumption. Swim and other authors, determined that consumption drivers are divided into contextual and psychological (2011). According to them, contextual refers to the cultural and social contexts that encourage or discourage people to make relevant decisions (we would also add spatial and economic contexts) while psychological are mostly concerned to the individual motivations and abilities (actual and perceived). In this respect, mechanisms for regulating the use of energy in the urban context need to tackle both aspects. In the first place they to inspire changes in the perception of consumption as the acquisition of material goods, towards a different view more focused on satisfaction of needs. And secondly, they need to endorse sentiments of collaboration by incentivizing engagement, communication, sense of common purpose and identity among individuals, institutions and organizations that play a role in the urban energy systems (Benkler, 2011).

The previous appraisal presents some theoretical foundations for the conceptualization of urban metabolism as a regulatory process. The conceptual framework gives a new interpretation for urban energy systems as complex systems, providing different insight in terms of the role that metabolism plays in the regulation of dynamics upon conditions of limited resource supply. However, details on how this condition affects the behaviour at each level of the urban organization are not depicted in the framework. Moreover, the two-dimensional representation of the framework falls short to display feedback loops as well as conflicting forces within each level. These interactions are relevant to explain the dynamics of the whole system and the study of them should be part of further research on this field.

6.3. A missing concept for urban metabolism

In ecological systems, the self-regulatory process of metabolism is linked to body size. This means that this feature is crucial for the analysis of the regulatory function of metabolism and as such, requires special attention for the conceptualization of urban metabolism. Organisms regulate themselves through its ontological history and amongst different populations and species, which means that the ability of regulation is maintained irrespective of a particular body size. Body size exerts a dominance in the way organisms live: it determines for how long, on which rate of living and extraction of resources and consequently, how many of its class can live simultaneously on a unit of habit (Calder, 2001). It is tightly linked to organisms' needs and so, to the uses that organisms require to fulfil. Then, metabolism carries out a stewardship of such uses by modifying aspects of the body size and in consequence, body size exhibits relations to rates of ingestion, respiration, growth and reproduction as well as aspects of the prey-predator relationships. In that way, metabolism set the limitations for demand of resources by controlling functions such as feeding, growing and reproducing in accordance with the external availability of resources (Peters, 1986).

In the urban context, the size of a city is particularly irrelevant for the regulation of the city dynamics. This feature responds to factors that influence urbanization and to some extent, to certain patterns of energy consumption (Grubler et al., 2012). However, there is no evidence of regulation on energy use due to changes in the city size, not to mention the size of a household. This estimation aligns to observations in CO_2 emissions of U.S. cities, where larger cities did not result necessarily more emissions efficient that smaller ones (Fragkias et al., 2013). In the economic aspect, Grubler and co-authors also state that large cities and small towns do not show special advantages in economy and therefore, they assert that there is no economies or diseconomies of scale with respect to the size of the urban settlements (2012). Then, we state that city size has an incidence in energy patterns but not in the regulation of energy use.

Energy requirements of cities are often represented as the energy demand that estimates the amount of energy consumed by a city population and it is usually expressed as energy demand density (Grubler & Fisk, 2012). This concept characterizes the city in terms of the energy flows that people use but does not offer information about the type of use or service that this energy is providing. In contrast, the concept of energy services describes the city in terms of the uses that people make of energy in order to fulfil their needs (Haas et al., 2008). In that way, 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 may facilitate the collaboration across levels allowing constrictions at the micro level to be compensated by the management of the energy service at the higher levels. In that way, the enlargement of the system does not necessarily mean an increase in the resource input. This perspective opens space for the intelligent management of energy across the levels of organization in urban systems, and creates the link to ecological systems to support urban metabolism.

7. CONCLUSIONS

The lack of theoretical support to the analogy of urban metabolism as a bridge between ecological and urban fields, has led to the implementation of this concept as an input-output accounting method, that disregards the impact of internal flows in the dynamics of the urban system. In response to that, this research developed a conceptual framework for analysing the role of metabolism in ecological dynamics and paralleling it, with the dynamics in urban systems as a way to integrate the existing knowledge from both fields and create a new perspective for the urban metabolism. This study focuses on the energy dynamics as a fundamental resource that nourish cities. Therefore, this research sought to answer the following question: *How can be the concept of urban metabolism be conceptualised from an ecological perspective so, it provides insight about the regulation of urban energy dynamics.*

The integration of knowledge applied on this research was based on the analysis of ecological and urban systems from the perspective of complex systems theory. From that, ecological and urban systems paralleled as hierarchical structures, were described as multi-level organizations resulting in two conceptual frameworks (Figure 5 and Figure 6). Portrayal of the system dynamics was done by characterization of the categories proposed in the conceptual framework for both, ecological and urban systems (*levels of organization, patterns, variables, drivers and mechanisms)*. It was found a tight association between the structure and the dynamics of ecological dynamics, where metabolism acts as a regulatory process at the organism level. Hence, metabolism gives rise to the higher levels of the organization by ensuring the distribution of resources throughout the whole system upon conditions of limited supply.

Findings from the energy systems revealed that there is no such regulatory process in the urban context. Patterns in the urban systems evidenced proportional relations across the levels of the organization, that create linear behaviours unlike the non-linear behaviours exhibited in ecological systems. As an example, energy requirements are proportionally related to income across the different levels of the organization. In contrast, in ecological systems, the use of resources at the population level are lower than the added amount of resources required by the individual organisms conforming that population. In that sense, we found that the urban energy systems do not entirely perform as ecological systems. In terms of energy use, there are no indications of the emergence of a particular behaviour at the aggregated level that differ from the added effect of the individuals that compose it.

In order to implement urban metabolism in a similar way in which metabolism operates in ecological systems, some aspects of the understanding of urban energy systems need to be revised. In the first place, it is required a different interpretation of the urban energy system that includes: (1) a full disclosure of the changing nature of cities as socio-economical systems created by humans, (2) the examination of the ability of urban systems to produce emergent patterns across levels (3) the definition of the boundary conditions of the system that acknowledges the limitations in energy supply, and consents the implementation of constraining strategies to face them. Secondly, the flexibility of the system to deal with constraints in energy use requires a different approach on the character of the resource itself. In that sense, we encourage a shift in the conception of energy, from the traditional materialistic view implemented by urban metabolism studies (Chris Kennedy et al., 2014; C. Kennedy et al., 2011; Pincetl, Bunje, & Holmes, 2012; L. Zhang et al., 2014) to a different perception more related to the services that energy provides (Franceschini, 2015). The material dimension of energy makes difficult to contemplate strategies in which constraints at the micro level might contribute to the reduction of energy use for the whole system, without weakening the quality of life of people.

Given those conditions, urban metabolism can be envisioned as a process that regulates the use of energy at the individual level by endorsing the management of the energy service to the higher levels of the organization. In that way, individual constraints at the micro level can be balanced from the redistribution of the energy service at the aggregated level. As an example, energy constraints at the household level would be compensated at the building level by the shared management of the service that energy provides. Hence, the overall input of energy for that particular use could be reduced. In that way, urban metabolism would realise a regulatory function in the system dynamics comparable to that of metabolism in ecological systems.

Understanding urban metabolism only as accounting method provides insight in terms of energy requirements of cities. However, upon this view cities are perceived as one single level system, limiting the study of the emergence of patterns across the different levels of the organization where urban metabolism performs its regulatory function. In that sense, the conceptualization of urban metabolism proposed by this research, offers a new perspective to complement the knowledge for understanding the behaviour of cities. The insight obtained from this study poses significant attention to the relations across the levels throughout the entire organization. These relations constitute the alternative for compensating constraints on energy use at the individual level. Thinking on individuals, households, buildings, districts and the entire city as the different levels, what this concept proposes is the reduction of the energy use as the system enlarges. Such view challenges the traditional estimation of environmental impacts as the relation between population, technology and affluence and, proposes an alternative for the reducing the impacts of cities (Chertow, 2000).

Even though, the practical implementation of this concept is still limited due to divergences in the conceptualization of urban energy systems, we encourage future researches to contribute with clarifications in this respect. For now, we backed our findings up on the human perspective of urban systems as social constructs. We advocate for a shift in the study of energy systems from the materialistic view of energy flows, towards a more service-oriented perspective that genuinely responds to the human needs. We place individual decisions at the core of the system dynamics and therefore, mechanisms directed to enhance urban metabolism need to address drivers that motivate people behaviours. Moreover, the implementation of urban metabolism should be accompanied by the promotion of collaboration among individuals and the conditions to do so (socio-economic context). In that way, individuals can join together in aggregations that perform more ecologically to reduce energy inputs by sharing or redistributing the services provided by energy. In short, the concept of urban metabolism proposes to change the current trends of cities of "*using more for more*" or "*doing more with less*" towards a different philosophy of "*using less for more*".

8. APPENDIX

8.1. *Patterns and variables at the micro level*

Table 2 Patterns of urban energy systems at the micro level

	Micro level	
No.	**Pattern**	**Variables**
1	**Household** income is positively related to per capita energy consumption (Liu, Wang, & Yang, 2005)	-Per capita energy consumption -Urban household energy end-use -Number of home appliances -Disposable income of the household
2	Efficiency of energy saving measures at the **household** level is reduced due to the take back effect [1] (Hong et al., 2009)	-Household neutral temperature [2]
3	Negative relation between **household** size and **per capita** energy consumption (Liu et al., 2005)	-Household size -Per capita energy consumption
4	The strategic reactions of **firms** to these regulations set forth a process of technology adoption or non-adoption (Stenzel & Frenzel, 2008)	-(A) Firm strategies: (e.g. defensive, reactive, anticipatory or proactive).
5	Vertical integration of **companies** led to the emergence of utilities owning assets along the supply chain (Stenzel & Frenzel, 2008)	-(A) Internal supply integration
6	**Building** design parameters affects the energy consumption of buildings (Aksoy & Inalli, 2006) (Jo et al., 2010b)	-Energy consumption per square meter -Heat gain of buildings

(A) Variables suggested

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[1] The extent to which the estimated energy savings enabled by the enhancement in energy efficiency are reduced by the behavioural response (i.e., higher consumption) to the increase in efficiency (Gavankar & Geyer, 2010)

[2] Ambient temperature at which the occupants are most likely to experience thermal comfort (Hong, Gilbertson, Oreszczyn, Green, & Ridley, 2009)

8.2. Patterns and variables at the aggregated level

Table 3 Patterns of urban energy systems at the aggregated level

	Aggregated level	
No.	**Pattern**	**Variables**
1	Energy requirements of an urban **district** is better explained by the occupancy and behaviour patterns of people living there (Kämpf & Robinson, 2007)	-Energy use profile/sector or activity (Page, Robinson, Morel, & Scartezzini, 2008)
2	The type of energy use of a **sector** and the payback period of a technology, determines the potential for renewable energy (e.g. Hot water usage of for solar heating systems (Pillai & Banerjee, 2007)	-Energy carrier/sector or activity (Hot water usage patterns/sector) (Abrams & Shedd, 1996)
3	The layout of a **district** heating system does not change because of the dwelling density as long as the heating density is large enough (Weber et al., 2010)	-(A) Heating density/sector or activity
4	The surface quality of urban **land uses** determine the waste heat[3] disposal (Kalma et al., 1978)	-(A) Waste heat/land use activity
5	The access of renewable energy depends on regulatory strategies that overcome lock ins to enter in the conventional energy supply **sector** (Stenzel & Frenzel, 2008)	-(A) Grid access
6	Renewable energy projects tend to fail at the **local** scale because of business monopolies (Stenzel & Frenzel, 2008)	-(A) Local ownership of renewable energy business
7	Insolation of an urban **squares** depends on the relation between height and width of buildings that conform it (Yezioro et al., 2006)	-(A) Shading areas
8	Cooling load of **buildings** contribute to the urban heat island effect (Jo et al., 2010a, 2010b)	-Cooling load/buildings (energy/cost) [4]
9	Limiting the heat gain of **buildings** can reduce the urban heat island effect (cooling roof) (Jo et al., 2010a, 2010b)	-Heat gain[5]/buildings
10	Cooling load of **buildings** in **suburban** areas is low due to local flows (breeze) and high vegetation (Assimakopoulos et al., 2007)	-Heat storage/area
11	Urban heat storage largely depends on the heat fluxes of **building´s** walls, ground and roads (Meyn & Oke, 2009),	- Heat storage/buildings
12	The heat island energy cost is large for **central areas** with heavy traffic and high buildings (Assimakopoulos et al., 2007)	-Heat island effect (energy/cost)[6]

(A) Variables suggested

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[3] Waste heat is produced by any activity that does work or uses energy and released into the environment.

[4] Amount of heat or cost of removing it from a building

[5] The increase of heat within a given space as a result of direct heating by solar radiation and of heat radiated by other sources such as lights, equipment, or people.

[6] Difference between the monthly cooling load of a particular location and a value of reference established within the urban space (Assimakopoulos, Mihalakakou, & Flocas, 2007).

8.3. Patterns and variables at the meso level

Table 4 Patterns of urban energy systems at the aggregated level

	Meso level	
No.	**Pattern**	**Variables**
1	The growing of **cities** increases energy flows due to the human socioeconomic activities of transforming and transferring goods and services (Decker et al., 2000)	-(A) Urban wealth[7]
2	Electricity use appears to grow somewhat over proportionally with **city** size (Grubler et al., 2012)	-(A) Shares of electricity uses
3	Large **cities** exhibit lower transport energy use if there is a high population density on lower automobile dependency (Grubler et al., 2012)	-(A) Automobile dependency
4	Efficiency of urban energy systems increases when implement a mix of technologies to satisfy demands at an **appropriate scale** (Keirstead, Samsatli, et al., 2012)	-Primary energy-efficiency [8] -(A) Technological efficiency/scale
5	Apart from the population size, energy consumption of a **city** is influenced by its structure and spatial configuration (Fragkias et al., 2013)	-(A) Urban economic activities -(A) Urban microclimates -(A) Urban seasonality
6	There is an economic and physical limit to the size of **settlement** that can manage its own power at a few thousand people (Grubler et al., 2012)	-(A) Fragmentation of the electricity supply sector (economic and physical terms)
7	Larger **cities** are not necessarily more emissions efficient than smaller one (Fragkias et al., 2013)	-Energy efficiency/area

(A) Variables suggested

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[7] Per capita personal income

[8] Cost and amount of primary energy required to service the final demand for heat and electricity (Keirstead, Samsatli, Shah, & Weber, 2012)

8.4. Patterns and variables at the macro level

Table 5 Patterns of urban energy systems at the aggregated level

Macro level		
No.	**Pattern**	**Variables**
1	**National** average of energy use in industrialized countries is higher than per capita final energy use of city dwellers (Grubler et al., 2012).	-Per capita final energy use/National average energy use
2	**National** and **regional** greenhouse gas emissions vary as a function of income (Auffhammer & Carson, 2007)	-(A) CO2 emissions/income
3	**Regional** energy inputs increase marginally less than the rate of population growth (Sahely et al., 2003)	-(A) Regional inputs/use
4	**National** energy systems characterize by highly-concentrated local energy demands and often diffuse energy supplies (Rutter & Keirstead, 2012)	-(A) Energy supply density Vs. energy demand density
5	**Countries** tend to replace the supply of energy from raw materials to more value-added energy sources (Fouquet & Pearson, 1998)	-(A) Electricity cost/energy carrier
6	Load requirements of **regional** power plants can be lower if cool roof systems are incorporated over the entire metropolitan areas (Jo et al., 2010b)	-(A) Urban energy requirements/regional systems

(A) Variables suggested

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