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Urban energy systems within the transition to sustainable development. A research agenda for urban metabolism

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ABSTRACT

The way we make sense of urban areas stands at a critical point. To reduce energy use in cities, we need to manage the way energy flows into, through and out the city. This paper starts with an overview on energy use at different levels of aggregation which allows us to outline emerging issues on urban metabolism for further research regarding urban energy systems. The research agenda focuses on five aspects: energy services, drivers for energy services, waste, data and dynamic modelling and governance. We give indications regarding the direction we think we should aspire to follow. The variety of themes within urban energy systems demands a coordinated and multidisciplinary research effort to improve our understanding of how the research of urban metabolism can contribute to achieve sustainable development.

1. Introduction

In 1900, 15% of a global population of 1.5 billion people lived in cities (Girardet, 2008). At the end of the twentieth century urban areas in the world have grown considerably. According to the Department of Economic and Social Affairs of the United Nations (UNDESA) (2014), in 1990 there were 10 so called “megacities” with more than 10 million inhabitants, representing less than 7% of the global urban population. By 2010, the number of megacities was 27, the population they contained grew to 460 million, and these agglomerations accounted for 6.7% of the world’s population (Kennedy et al., 2015). Since 2008 cities host more than 50% of the inhabitants of the planet with the share expected to increase up to 67% by 2050 (Rosenzweig et al., 2010; UN-HABITAT, 2012). Furthermore, cities are located on less than 5% of the Earth’s land surface and yet use around 80% of the resources (Madlener and Sunak, 2011; CIESIN, 2015; UNEP 2015), and are responsible for approximately 80% CO₂ global emissions (IEA, 2008; Seto et al., 2014).

Cities exist in all shapes and sizes, this diversity could also lead to potential initiatives to decrease CO₂ emissions by reducing urban energy use and make energy use more sustainable (Girardet, 2008; Beatley, 2000). Cities can make material or waste exchanges possible between industries. The collection of recyclable or reusable wastes from homes and businesses in urban areas is generally cheaper, per person served (UNCHS, 1996; Mega, 2010). Urban planning enables the changing nature of buildings and the city to capture these benefits. As an example, changing infrastructure and urban planning can lead to a

decrease in car use in dense urban areas, and by doing so reducing health risks to city dwellers (Jackson, 2003; Heath et al., 2006; de Hartog et al., 2010; Tight et al., 2011).

There are also fundamental political reasons that give cities a key role in the battle for sustainability. Cities are places of political contention (Bakker, 2003; Heynen et al., 2005). Cities represent the possibility to develop new regulatory structures and spaces of governance (Brenner, 2002). Cities are important because they are spaces where democracy can be practiced. However, this does not mean that cities have affinity with democratic practices (Low, 2009). The concept of democracy can be interpreted in various ways and research on how this concept can be materialized on cities deserves still more attention among scholars (Purcell, 2007; Beaumont and Nicholls, 2008). Although we have not found literature that relates the introduction of democracy with an increase in sustainable development, we believe that these discussions, however interesting, do not undermine the fact that democratization (understood as a process where individuals are involved in political decision making) is of a major relevance in advancing towards sustainable development. Bailey (2007), gives some examples on how cities began implementing community-wide urban energy studies in a bottom-up manner for greenhouse gas (GHG) accounting. Furthermore, the social economy within each locality creates a dense fabric of relationships that allow local citizens to work together in identifying and acting on local problems or in taking local initiatives (Korten, 1995). Table 1 shows a number of examples and initiatives around the world where cities are trying to make changes in order to

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Table 1
Initiatives of cities aimed at leading the transition to sustainable development.

Initiative	Scope	Year of Adoption	Cities Involved	Objective
Covenant of Mayors for climate and energy	European	2008	6800	Implement EU climate and energy objectives
C40 Cities	Global	2005	83	Exchange of best practices in order to address climate change in megacities
Global Sustainable Cities Network	European–Asian	2013	60	Knowledge-sharing
Sustainable Cities International	Global	1996	7	Tackle urban issues through peer learning exchanges.
Red Ciudades	Latin-America	2012	60	Build sustainable urban spaces.
ICLEI Local Governments for Sustainability	Global	1990	1000	Make cities and regions more sustainable.
South African Cities Network (SACN)	South Africa	2005	9	Knowledge-sharing
100 Resilient Cities	Global	2013	100	Become more resilient to the challenges that are part of the 21st century
Asian Cities Climate Change Resilience Network (ACCCRN)	Asia	2008	50	Build inclusive urban climate change resilience

shift towards sustainable development.

Nevertheless, despite all the initiatives and efforts done to mitigate environmental problems associated to urban activities, one of the main questions facing those interested in creating more sustainable communities still is: “how do we set our progress towards sustainable development?” (Sachs, 2015). We argue that in order to set this progress it is relevant to understand processes that mobilize and control the flows of energy through the city. We think that focusing on the concept of urban metabolism offers the possibility to contribute to sustainable development. Several studies have followed the historical development of this concept (Fischer-Kowalski, 1998; Fischer-Kowalski and Hüttler, 1998; Rapoport, 2011; Dinarès, 2014). These studies show that the use of metabolism as a metaphor to understand processes happening in the city has been used since the late nineteenth century. They also show that the study of energy flows through the lens of urban metabolism has been an intermittent process having an increase over the past decades (Kennedy et al., 2011). Although urban metabolism has gained increased attention many issues deserve further attention. Hence, research is a key factor in advancing the field of urban metabolism to the benefit of transitioning towards sustainable development.

With interest in this topic we would like to contribute by offering a conception for this research effort. This paper wishes to help setting a multidisciplinary research agenda on urban metabolism aiming at a sustainable urban energy use. The paper is organized as follows, after a brief introduction, Section 2 reviews how energy is used at different levels of aggregation. Subsequently, Section 3 deepens the discussion of urban energy flows and urban metabolism. In Section 4 we argue that different energy flows are required to fulfill several energy services. Section 5 presents the driving factors for energy services. We proceed to explain a research agenda to understand – and help in the solution of – the energy challenges cities face. Finally, the paper ends with a concluding section.

2. Energy use

The start of industrialization – in the late 1700s – brought an increased volume and variety of manufactured goods into cities. However, industrialization also marked a shift to powered, special-purpose machinery, factories and mass production. Since then, material and energy resources flow into and out cities following the same linear pattern of functions: raw materials extraction, which are processed to manufacture a product which in turn is sold to a consumer. This product is discarded either because it no longer serves its original purpose or because there are new products available. Our understanding of cities and urban areas, in both theory and practice, stands at a turning point. Rather than separate systems by function – water, food, waste, transport, education, energy – we must consider them as a single system. Instead of focusing only on access and distribution systems, our cities need dynamic, networked, self-regulating systems that take into account complex interactions.

Energy is not only key to our economic development and wellbeing, it is also strongly related to many environmental impacts. Meta-analysis of life cycle assessments (LCA) has shown that energy correlates well with most other environmental impacts (except for toxicology) (Huijbregts et al., 2006). Johansson et al. (2012) enumerate four main challenges of energy systems: 1) Elevated greenhouse emissions, 2) Decreasing energy security, 3) Air pollution at regional and local levels and 4) Lack of universal access to energy services. Tackling these challenges would help to achieve sustainable development. Energy is a good measure of the environmental footprint of an urban area. A city can consume energy directly, or indirectly through the embodied energy in imported goods and services. In this article we focus on the direct energy use. While energy use has a direct impact on the environmental quality of an urban area (e.g. air pollution, smog, regional warming, urban heat island effect), energy use is the effect of the type of economic activities, the infrastructure and planning, human activities, as well as geographic factors. The energy use also affects itself indirectly, as the urban heat island effect may increase the need for energy use for air conditioning. Hence, it is important to understand not only the drivers behind the changing energy use, but also the inter-relationships between the different factors to accurately understand the dynamics of energy in the urban system, necessitating a systems approach (Pincetl et al., 2012).

2.1. Global energy use

According to the International Energy Agency (IEA, 2014), the world total primary energy supply increased from 256 EJ in 1973 to 561 EJ in 2012. As in 1973, fossil fuels dominate the world's energy supply. Oil has the biggest share (31%) although lower than in 1973. Coal and natural gas shares were – in 2012 – 29% and 21% respectively. The OECD countries have reduced their regional share of total final consumption from 60% to 40%. The rest of the world has increased its share. Asia (lead by China) being the region with the highest growth in consumption, growing from 14.3% in 1973 to 32% in 2012. The related CO₂ emissions due to fuel combustion were 15,633 Mt in 1973 and 31,734 Mt in 2012. The emissions by region have also changed. In 1973 the OECD countries were responsible for 66% of the emissions. By 2012, the share of OECD countries accounted 38%. As in the case of energy consumption, Asia (led by China) increased its CO₂ emissions from 9% to 37% in the same period 1973–2012. The International Energy Agency estimated in 2008 that the world will need almost 60% more energy in 2030 than in 2002 to meet growing demand for energy services. Fossil fuels are expected to account for 80% of the world's primary energy mix in 2030. Oil will remain the dominant fuel, though demand for coal will rise more than demand for any other fuel. China and India are expected to account for 51% of incremental world primary energy demand in 2006–2030. In its 2015 report, the International Energy Agency indicate possible impacts that the Intended Nationally Determined Contributions (INDCs) will have in future

energy and emission trends. In the INDC scenario energy demand will be 20% higher than 2013 levels in 2030. However, the INDC Scenario, also shows that the share of fossil fuels in the world's primary energy mix declines in 2030 (IEA, 2015).

With respect to cities and their role in the global arena, according to Creutzig et al. (2015), the global urban population consumed around 240 EJ of energy at end use. They expect that by 2050 the total energy consumption of cities could increase to 730 EJ. Hence, as the world continues to urbanize, a significant improvement in the energy efficiency of cities – particularly in megacities and those countries where urbanization processes are expected to be faster- is a crucial first step towards a sustainable future (Kennedy et al., 2015).

2.2. Energy use at a national level

Cities are the largest consumers of the supplied electricity. In India, the urban population consumes 87% of the nation's electricity (Starke, 2007). Electricity is by far the most widely used energy commodity in services. Electricity use has increased by 73% since 1990 and this has been the main factor driving the global increase in energy consumption in this sector (IEA, 2008). One relevant aspect within the power sector is the reduction of technical and non-technical losses. While the average worldwide losses in transmission and distribution are in the range of 10%, in some developing countries non-technical losses could reach up to 50% of the total electricity transmitted over the network (Antmann, 2009). Reduction of electricity losses implies reduction of electricity generation with the associated positive effects for the environment and society. Natural gas is also consumed at a large scale in some countries. As means of transportation of natural gas is limited to inflexible pipes, the EU gas infrastructure is quite complex. Western European consumers of natural gas like Belgium, France, Germany, Italy, the Netherlands and the UK, are firmly connected by an extensive gas grid, and have well-developed infrastructures, reaching around 67 million consumers, 79% of which are households (IEA, 2008). It is expected that by 2050, 86% of the total OECD countries population will be urban (Kamal-Chaoui and Alexis, 2009). Hence, it is expected that they will consume the majority of global energy being also major contributors of greenhouse gas emissions.

2.3. Energy use by economic sector

The building sector consumes nearly one-third of global final energy consumption, making it responsible for about one-third of total direct and indirect energy-related CO₂ emissions (IEA, 2013). Buildings vary tremendously in relation with several factors such as typology, age, size and location. These factors altogether have a great impact on the thermal qualities of the building stock and therefore on the energy performance of the building stock. Hence it is of major relevance to understand and analyze the characteristics and conditions of the European building stock in order to define an efficient and effective retrofit intervention path. Improving the energy efficiency of the buildings not only reduces energy consumption but also improves the aesthetics of the building, increases the value of the asset and provides healthier conditions for the occupants (BPIE, 2011).

Transport represents a similar share to the residential sector of the urban energy balance. Transport of people as well as of goods by road, rail, air and sea is a key component of today's economic activities. Trends in energy use by transport mode vary significantly amongst countries and regions. There is uncertainty when it comes to making assumptions about the rate of advancement in renewable energies, both technologically and economically. It is likely that oil will still occupy a preponderant role within the transport sector for the next decades. It is expected that transport in cities will maintain a high share of final energy consumption (IEA, 2008).

2.4. Energy use at a city level

In order to evaluate the contribution of local initiatives towards more sustainable energy future and monitor energy improvements on the urban scale, energy within the urban context should be studied. The IEA (2008), reports urban primary energy use to be around 330 EJ worldwide for the year 2006. In the European Union urban energy use accounts from 69% of primary energy use. Urban regions in China are estimated to consume 75% of the primary energy use of the country (Meng et al., 2014). The IEA also forecasts that 90% of global energy growth will be in cities. However, there are just few studies that show energy consumption per city. Kennedy et al. (2015) quantified the energy and material flows of 27 Megacities. The total energy consumption of these megacities represented around 6.7% of the global energy consumption (26,347 PJ). They also consume 9.3% of the global electricity and 9.9% of global gasoline. Dhakal (2004) estimated the final direct energy use for three cities in Asia: Tokyo, Beijing and Shanghai. The three cities had an estimated direct energy use of 1 EJ. Dhakal also estimated the embodied energy use (via imports of goods and services). The values were 2.5 EJ for Tokyo, 1 EJ for Beijing and 2 EJ for Shanghai. To date there is no comprehensive statistical compilation of energy use at the urban level. Therefore, further efforts in order to understand energy in different systems are needed to manage a transition to sustainable energy future.

An energy system may be thought of as an interrelated network of energy sources and stores of energy (supply or primary energy), connected by transmission and distribution (secondary energy) of that energy to where it is needed (Blok and Nieuwlaar, 2017). At a city level, we recognize energy sectors such as residential, commercial, industrial and transport. Each sector uses energy to provide energy in the form of heat, electricity and fuels for transporting people and goods. These uses satisfy human needs through energy services: heating provides comfort, electricity provides lighting, and transport allows mobility. The supply can be either within the city (e.g. wind and solar power) or it can be outside the geographical boundaries of a city (Fig. 1).

In order to understand the different energy challenges that cities face it is helpful to study how energy is used. There are several approaches to report energy use. They depend on the level of aggregation that researchers select. Usually, energy use is explained as a final energy mix (e.g. electricity, petroleum, gas) at a global and/or at national level. When it comes to understanding the urban energy use, this is accounted from the perspective of sectoral distribution. However, there have been just few attempts to account urban energy use (Grubler et al., 2012).

3. Urban energy flows

To minimize or eliminate the risks associated with energy use in cities, we need to manage the way energy flows into, through and out the city. A system to record, analyze and report energy flows is critical to energy management. Energy analysts have developed methods to measure and understand energy use since the 1970s. The accounting system keeps track of energy in, energy out, non-useful energy versus work done, and transformations within the system. The study of energy through an urban system is completed by considering its quality. The First and Second laws of thermodynamics have been used to explain the various transformations of energy that are possible, and to determine how much energy is needed at each point in the system and in what form that energy is (Blok and Nieuwlaar, 2017). Generally, all these use enthalpy as the basis for measuring energy, while some also use the second law of thermodynamics (entropy) in exergy accounting. When using enthalpy, efficiency is described as the relation between the energy output relative to the total energy input of an urban system. Exergy analysis considers quality differences in energy forms and efficiencies. As energy is transformed from one type to another the transformation will not be 100% efficient. Exergy analyses also allow to

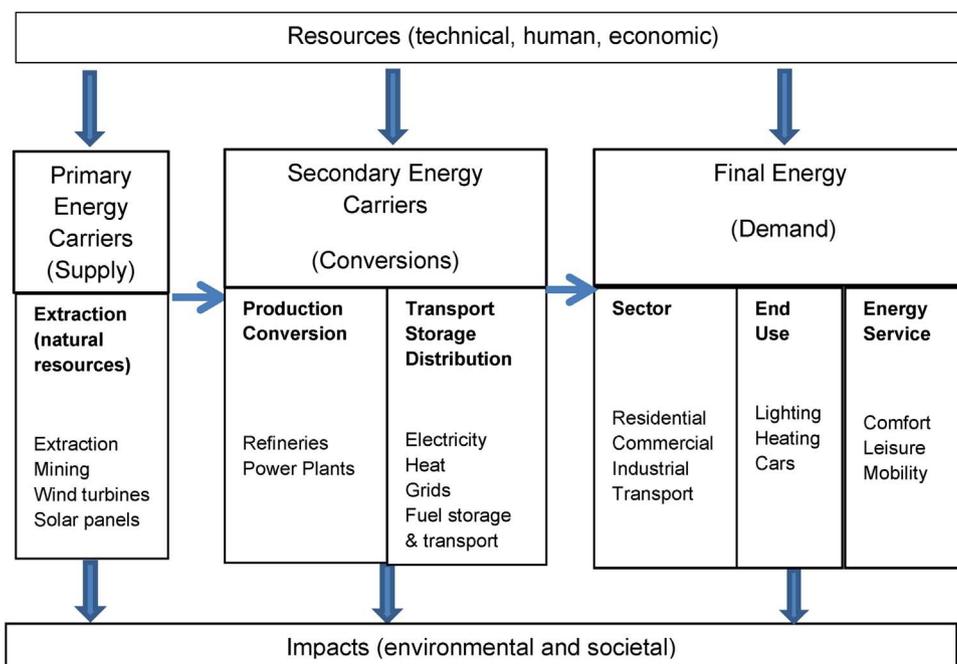


Fig. 1. The Urban Energy System.

evaluate thoroughly energy service efficiency (Bai et al., 2014). Grubler et al. (2012), summarized different energy accounting approaches that can be applied in urban systems: final energy, regional energy metabolism, regional economic activity and energy input-output. Each of these approaches can be based on two main criteria. The first one refers to the type of data used which can be either physical (energy statistics) or economic. Second is the selection of the boundary conditions of the urban system under study. This includes the definition of energy user and the inclusion of embodied energy within the accounting. Each accounting method is confronted with the same challenges: clear definition of the (system) city boundaries and data quality issues (e.g. availability, reliability and validity).

This paper focuses on direct energy flows. Most of the direct energy is used within a short time of entering the urban system (Bristow and Kennedy, 2013), and certainly within a year. One alternative to describe city’s dynamics is the concept of urban metabolism. Urban metabolism has been discussed in the realm of both social and natural sciences. Within the social sciences Karl Marx used the term metabolism as an urban metaphor to describe the transformation of nature by society in order to obtain commodities (Fischer-Kowalski, 1998; Rapoport, 2011; Dinarès, 2014). Wachsmuth (2012), explains the place that urban metabolism takes within the sociological perspectives of human ecology and urban political ecology. Urban metabolism has also been discussed in the field of political science (Heynen et al., 2005) and in relation to environmental history (Tarr, 2002). In the view of the social sciences, urban metabolism, should deal with the historical and political context where it occurs, and the social relationships that occur due to it.

Within the natural sciences, there are two main approaches to the study of urban metabolism. First, an ecological approach where the city is considered as an ecosystem, which depends on energy and materials inputs and has the ability to absorb sinks (Zhang, 2013; Grönlund et al., 2016). This way to understand urban metabolism emerged from the field of systems ecology with the purpose of studying an entire ecosystem as a unit (Odum, 1971). This was based on analogy of ecosystems envisioned as “super organisms” that interact with their environment to support life (Patten and Odum, 1981). Hence, urban metabolism considers cities as giant organisms with metabolic processes that underlie the urban system and that are responsible for its ecological and environmental problems (Zhang, 2013). This

consideration has supported the energy concept. This is, accounting where all energy is converted to solar energy equivalents, allowing to account for all flows (Zhang et al., 2009a; Zhang et al., 2009b; Grönlund et al., 2016). However, the use of energy is complex and limited to a part of the urban metabolism community (Pincetl et al., 2012). Second, an engineering approach, which considers a city as a biophysical system with associated energy –and material- inputs and outputs and accounts for the energy and material flows in terms of mass (Brunner, 2008; Kennedy et al., 2011; Holmes and Pincetl, 2012). There are extensive discussions on the different methods and case studies where engineering approach has been used to analyze different cities (Fischer-Kowalski, 1998; Kennedy et al., 2011; Rapoport, 2011; Huang et al., 2010; Kennedy and Hoornweg, 2012; Swilling and Annecke, 2012; Zhang 2013; Dinarès, 2014). The engineering approach makes explicit the pressure for resources (Golubiewski, 2012) and therefore, challenges the linearity of consumption patterns and waste production of cities (Rapoport, 2011). Regardless of the ecological or engineering approach, urban metabolism in the view of natural sciences deals with the transformation that energy and materials undertake, and the effects of this transformations on the city.

Despite the conceptual differences, urban metabolism is understood by both social and natural scientists as a process that involves the exchange of energy and materials within an specific environment. Wolman explicitly used the term Metabolism of cities for the first time (Wolman, 1965). He defined metabolic needs as “all the materials and commodities needed to sustain the city’s inhabitants at home, at work and at play”. Kennedy et al. (2007), suggest a broader definition “the sum total of the technical and socioeconomic processes that occur in cities, resulting in growth, production of energy, and elimination of waste”. Further attempts to contextualize the concept as a process of transformation, consumption and production of wastes that sustains city’s economic activities, have led to analyze other parameters as metabolic rates of cities that have been linked to consumption rates, wealth and other livability measures such as health, employment, income, education and leisure (Golubiewski, 2012). More recent studies have linked urban metabolism to economies of scale for urban infrastructure, greenhouse emissions (Zhang et al., 2014) and macroeconomic models (Fung and Kennedy, 2005).

In the analysis of urban metabolism a lot of work has focused on energy flows, both direct (in the form of energy) and indirect (in the

Table 2
Percentage of final energy consumed by end uses in residential buildings in selected regions.
Source: IEA (2013).

Service\Regions	ASEAN ^a	Brazil	China	EU (27)	India	Mexico	Russia	South Africa	USA
Lighting	2	5	2	3	9	7	2	10	7
Space Heating	0.5	4	31	66	1	2	66	8	37
Water Heating	8	37	40	14	9	45	21	25	19
Space Cooling	2	3	3	3	2	2	0	1	8
Appliances	9	18	16	9	4	15	6	10	25
Cooking	79	33	8	5	75	29	5	46	4

^a ASEAN is comprised of Brunei, Cambodia, Indonesia, Laos, Malaysia, Myanmar, Philippines, Singapore, Thailand and Vietnam.

form of materials, water, food), to better understand the scale of the metabolism. In this paper we concur on the use of enthalpy as the basis for measuring energy, as this is the most commonly used approach in energy analysis. Currently, most analysis of energy use and flows in urban systems is highly aggregated (i.e. city level). Various authors have analyzed selected urban areas (Kennedy et al., 2011; Zhang, 2013) for a review of some of these, and some over time. These studies generally follow a material and energy flows approach or input-output principles, using statistical data and assumptions. Many of these assumptions (including most I/O-tables) are based on higher aggregation levels, e.g. national statistics to estimate energy use and flows. This may hide the differences between different cities, and hence obscures local differences in geography, climate, urban planning, and demographics. Depending on the aggregation level in I/O-tables it may also not accurately reflect the intensity of economic activities like manufacturing (see below for a discussion of the different economic sectors). Meng et al. (2014) have tried to use nighttime satellite data to estimate the changing urban energy use and emissions for rapidly expanding Chinese cities. These studies provide useful insights in the size of the energy flows, energy carriers, and typical uses, but there is little connection to and understanding of the impact of location, and the dynamics of e.g. changing (economic) activities, climate, demographics, and infrastructure on the use of energy. We can conclude that, in practice, urban metabolism has only been implemented as an accounting method that says little about the state of the city and the internal dynamics that shape it and therefore, it provides no sound base to formulate and implement sustainable strategies to transform the urban context. For that reason, a conceptualization of urban metabolism by analyzing cities as systems is required, allowing for the identification of key points for interventions, and enable policy makers to build strategies that contribute to the sustainable pathway of cities. The conceptualization we suggest is based on urban energy services. Using this conceptualization, the practices of the actors within the system are placed at the center of the analysis instead of the actors themselves.

4. Urban energy services

Defining energy services is not a trivial task. A major difficulty in identifying energy services is represented by the fact that the term “service” can be discussed from different perspectives. For example, energy services could be seen as those activities that give support to key processes such as the exploration, development, extraction, production, generation, transportation, transmission, distribution, marketing and consumption of energy. However, we can also understand a service as the action of satisfying a need. Blok and Nieuwlaar (2017), define energy services as “a result of human activity obtained through the use of energy and satisfying a human need”. However, in practice it is difficult to determine energy use for energy services since the current understanding of structure of the energy sector may not be sufficient. The energy industry – albeit well discussed and with a recognized relevance – does not have an explicit place within the International standard industrial classification (ISIC) of economic activities. This industrial classification was developed by the United Nations and it has been

adopted by the IPCC in order to explain the implications of climate change on key economic sectors (Arent et al., 2014). The ISIC classifies activities in the energy sector according to the following categories: i) Mining of coal and lignite, ii) Extraction of crude petroleum and natural gas, and iii) Electricity, gas, steam and air conditioning supply. Also, there is not a clear distinction between energy goods and services within the energy industry. Some energy forms can be classified into the goods category. For example, liquid and solid fuels, which are easily stored and traded across borders. Besides, not all energy forms are that evident. The case of heat and electricity are examples of this. Heat and electricity can be produced by the combustion of other fuels or by renewable natural resources and nuclear fuels. Furthermore, heat and electricity storage still offer great challenges.

Nevertheless, when we refer to energy services within any urban setting we refer to the benefits that result from the use of energy for specific purposes, for instance, the use of illumination allow persons to read or to do sport, the use of heating allow for a comfortable indoor climate, the use of natural gas for electricity provide appropriate cooking temperatures to get necessary nutrients, the use of liquid fuels or electricity give us the mobility to get from “A to B”. Accordingly, it is essential to find a practical manner to estimate the energy use for energy services. The hindrance of considering energy services as focus for specific purposes is that the estimation of such detailed information – while desirable – is complex and time consuming. However, there are statistics regarding the energy consumption by end use in some sectors like the building sector. Table 2 shows the typical energy services found in residential buildings in different regions.

Urban energy services can be considered as a variety of activities provided to residents and businesses in urban areas. These include – but are not limited to – water, housing, energy and public transportation. Resource efficient urban energy service delivery is the key to responding to the challenges posed by an increasingly urbanized world. We agree that focusing on urban areas can address the needs of vulnerable populations and ensure sustainability. This consistently embraces the importance of interdisciplinary work with and across governments at national and regional levels.

5. Drivers for urban energy services and emerging topics for research

Drivers for energy and its impacts are largely a by-product of the demand for goods and services. We use the term drivers for energy services to describe factors that directly or indirectly cause a change in the services provided by the energy system. There are several factors that determine the extent and nature of energy services in cities, as follows:

5.1. Environmental drivers (climate conditions, resource availability)

Climate variability and change refers to temperature, precipitation, and (changing) weather patterns, their variability, extremes as well as effects such as sea level rise. The need for energy services is due to either naturally phenomena (e.g. seasonal changes in temperature,

floods) or through human-induced activities (e.g. urban expansion into vulnerable or climate sensitive areas). The Intergovernmental Panel on Climate Change (IPCC) has repeatedly provided strong evidence that climate change impacts are to be expected in the near future, as a function of continuing and increasing emissions of fossil fuel combustion products, changes in land use (deforestation, change in agricultural practices), and other factors (for example, variations in solar radiation).

5.2. Technological drivers (technology use and availability)

Technology is driver of energy services because it affects the service level and the efficiency by which energy is used to provide services. A higher rate of improvement of the quality of lighting, for instance, could lead to a lower demand for energy (to produce the same intensity of light), reducing the need to convert fossil fuels. Technological advancement, however, can also partially lead to increased pressure on energy services due to a potential rebound effect, or in the case of unmet service demand in developing countries.

5.3. Economic drivers (income, commodity production)

Economic drivers include income levels, economic structure, consumption, and income distribution. For several energy services, the higher the income, the greater the per capita consumption of commodities, up to some saturation level. For other services, high income may lead to a decrease in consumption because of a change in consumption patterns (e.g. traditional biomass consumption for heating and cooking).

5.4. Social drivers (population growth, consumer preferences, life style, governance, actors' interest)

Cultural factors are linked to political and economic inequalities and are the foundation of decision-making (Lambin et al., 2003). However, the complexity of researching changing values, beliefs and norms, and their interconnections to energy services has received little attention. Governance, namely: the quality of planning and the presence of policy enforcement; has a strong influence over the energy services that an urban area may require. Change in population and demographics will also influence the number and kind of consumers of energy services.

Understanding urban energy services and their relation with urban metabolism is a challenge for research and for practice. Broto et al. (2012), argue that urban metabolism opened a new way of thinking with regard to sustainable urban development across a variety of disciplines. They performed a comparative literature analysis to identify six interdisciplinary themes that built around urban metabolism over the past years: i) the city as an ecosystem; ii) material and energy flows in the city; iii) the material basis of the economy; iv) economic drivers of rural-urban relationships; v) the reproduction of urban inequality; and vi) re-signifying socio-ecological relationships. An alternate but complementary way to study urban metabolism is including the concept of energy services. Using this view as a springboard, we have identified five core themes for further inquiry related to energy systems within urban metabolism. We do not intend to present a detailed research plan on how to achieve the research agenda. Instead, these themes are meant to give some indications for the trajectory we think we should transit.

First, we argue for the need of a conceptual model that puts forward energy services as the unit of analysis for researchers and policy makers. We see the need to develop a taxonomy that focus not on individual units (being these persons, households or sectors) but on the final public needs. Linking the energy services to the needs will allow a better understanding and modeling of urban energy demand and especially the dynamics to forecast future energy demand. Secondly, we suggest to look into the possibilities for actors to reduce the overall

demand for energy services in distinct domains, through demand reduction or developments such as the sharing economy (Heinrichs, 2013). Finally, synergies may be found in combining energy services, and understanding the relationships between energy services (e.g. urban planning, use of private and public transport, and use of public space).

The energy flows in the urban system are determined by the types of energy services used, as well as the type of energy carrier and efficiency with which the energy service is provided. Technical energy efficiency and opportunities for improvement to provide specific energy services have been well studied, yet an understanding is lacking of the relationships and synergies between energy efficiency and other parts of the urban metabolism. This will require a systems as well as a dynamic approach to study (radical) changes in technologies, and the impact on urban energy use and metabolism.

A second concern is that, to date, limited research has focused on the relationship between drivers for energy services and the metabolic flows of energy and materials of a city. From the perspective of drivers for energy, a better understanding on how energy drivers affect the flows of energy and materials, and how this can ultimately stimulate a rethinking process of societal organization. Such a rethinking process must not necessarily be mutually exclusive with current growth-supportive restructuring processes at a systemic level (i.e. stimulation of 'green growth') but can use the innovative capacity to plan and prepare a new form of societal organization in cities.

The study of urban metabolism can help to understand how to provide the increasing amount of resources required by society to fulfill their need of energy services, which is the third emerging topic for further research. Through increased reuse, repair and recycling of goods and biological nutrients, depletion of natural resources can be counteracted (Vogtländer et al., 2001), energy saved (Corsten et al., 2013), while positively affecting the urban quality of life. This can be achieved through efficient design of products and technologies. When this is not possible, waste management is an alternative to promote the reduction and reuse (of waste) and is linked to the urban energy system, through waste incineration or other waste management technologies (note that waste collection also affects urban energy use). This means existing business models will be altered or replaced by new business models. However, knowledge is required to take balanced decisions towards changing business model for waste management. A comparison of the costs and benefits of both existing and new technologies of waste collection, separation and re-processing to produce energy can give an insight into utilization of waste given national and European targets.

Fourth, If we want to get insights in the structure, function and dynamics of urban energy systems there is the need to acquire data. Energy data has been collected at aggregated level but it is scarce as we intend to follow the energy flows inside cities (Grubler et al., 2012; IEA, 2013). Zheng et al. (2014), mention three main challenges for acquiring, integrating and analyzing of data generated by different sources in urban systems: 1) Sensing and data acquisition, 2) Dealing with the heterogeneity of data and 3) the integration of data generated in both physical and digital realms. We add a fourth challenge after the discussion followed by Grubler et al. (2012) which is the accounting method. Facing these challenges will require a collaborative effort that is an often underestimated challenge in itself. These four challenges could be seen as "technical" challenges where specific skills and knowledge are needed to solve the challenge. There is another challenge which regards the complexities in governance where the same technologies used for data acquisition and analysis, normally outsourced to private technology companies, could be used to hinder civil rights (Batty, 2012; Viitanen and Kingston, 2014).

Once data is obtained, we can use it as input for different models. We suggest to include the study of systemic interactions of energy in the context of urban energy flows and the drivers for urban energy services. We think of considering a systematic way of incorporating knowledge from several actors into a model that helps to explore possible scenarios

for the understanding of energy services within an specific urban system. The purpose of the model is not to faithfully capture all aspects and details of the system. Rather, the purpose of it would be to enrich our understanding of the key related energy services and processes that are present within a specific urban system.

Finally, the establishment of policies (and its continues monitoring) derived from urban metabolism insights is an essential issue that deserves further attention. Governance has a wide arrange of connotations. From an economic development perspective governance is a necessary condition which includes effectiveness of government bureaucracies, low degree of corruption, transparency of public decisions, prudent macroeconomic policies, elements to control and protect individuals the abuse of political power (Ndulu and ÓConnell, 1999; Jain, 2001; Johnston, 2001). When social development and environmental stewardship perspectives are included, governance goes beyond the role of the government. Governance from a wide perspective – that includes quality of life for individuals and environmental sustainability – refers to the interaction processes among the different members of a society which leads to decision making to tackle relevant challenges (Gerometta et al., 2005; Jonas and Ward, 2007; Lockwood et al., 2010). However, there is a lack of understanding about the relation among political processes, the efforts of people to deal with economic development and the connection of these two with environmental problems (Krueger and Savage, 2007; Purcell, 2007).

Additionally, urban institutional capacities are important to take into account because the stronger the institutional capacities of a city, the easier to design and implement an effective governance system (Grubler et al., 2012). It is here where urban metabolism could be used as a framework which clearly indicates where the different flows through the city are originated, who is being benefited from these flows and how these flows influence both the social and natural environment of urban areas. There is thus a variety of levels where different and complementary decisions can be taken within the urban system. Energy use can be governed at the micro level (e.g. buildings), at the aggregated level (e.g. neighborhoods), at the meso level (e.g. urban districts) and at the macro level (e.g. cities). Of course, it is also possible to link urban policies to a regional or national level. Perhaps a desirable task, although idealistic and extremely complex, would be to have a global data network on urban metabolism calculations since some of the environmental externalities at global level are associated with –direct and indirect- urban energy use.

6. Conclusion

Our aim in this paper was to suggest some direction for research on urban metabolism. In doing so, we have presented an overview of energy use at different levels of aggregation: global, national, sectorial, and urban. Stressing the potential of cities is relevant in that so many general works on sustainable development see cities as ‘the problem’ and choose not to consider how urban development can be made compatible with sustainable development goals, despite the increasing concentration of the world’s production and population in urban areas (Satherthwaite, 1999). We claim that the concept of urban metabolism is a suitable alternative to study the energy dynamics within an urban system. To this end, we introduced the concept of urban energy services to offer several but complementary themes for research. There is considerable overlapping among them allowing for a coordinated and multidisciplinary research effort to improve our understanding of urban energy use. In sum, there are several needs: i) Consider that final energy use provides different services for different socioeconomic activities, ii) Understand the link between energy drivers and urban energy flows, iii) Change waste management business models considering the way in which society use resources, iv) Be clear about how the data has been collected and organized, the assumptions that have been made, the sources that have been used, and what measures will be taken to overcome privacy issues, and v) Seek to understand the fundamental

character of interactions between nature and society which in turn will allow decision-makers at various levels to address energy use.

We have proposed a broad and challenging research agenda for urban metabolism. Notwithstanding, the final goal of studying urban metabolism is to provide a better understanding of energy – and material – flows that leads to the mitigation of the environmental stress to which our planet is subjected and its relation with society. One key aspect is the need to unify the fragmented views that exist due to the different disciplines that have approached urban metabolism through the years (Barles, 2010; Golubiewski, 2012; Broto et al., 2012; Kennedy et al., 2014). We think that the unification can succeed under the umbrella of sustainable development. Sustainable development is a difficult concept to assess and measure, due to its holistic and multi-dimensional nature with associated uncertainties and risks (Böhringer and Jochem, 2007; Bell and Morse, 2008; Caeiro et al., 2012). Despite of this difficulties, a growing awareness of the role that cities can play in achieving a sustainable development has recently led to the advancement of assessments and rankings for sustainable urban communities. Among the most known rankings are: European Green Capital Award, European Green City Index, Smarter Cities, Sustainable Cities Index, Sustainable Cities Report, SustainLane and Quality of Living Global City Rankings. Each ranking proposes its own indicators to assess energy use. Some of them include an energy related theme with a set of indicators, while others include energy indicators as part of an environmental category to be assessed. Despite the use of different indicators, it is possible to identify topics related to energy sustainability that are common. For instance, energy consumption, energy performance (of a specific area), the amount of GHG or CO₂ emissions, the energy performance of buildings, the share of renewable energy produced and consumed, and the existence of policies promoting energy efficiency.

Urban metabolism calculations could help to set concrete baselines – or boundaries – that will strengthen the indicators used by these rankings for sustainable urban communities. Urban metabolism could also serve as a framework to be used by different assessment programs which would offer a platform for benchmarking at different levels of aggregation within a city. Furthermore, urban metabolism could provide data that relate energy use with different socio-economic activities within a city. New local initiatives in the energy area in urban areas around the world (e.g. Transition towns) have shown success in mobilizing local resources and driving energy efficiency and the introduction of renewable energy sources (Aiken, 2012). Different initiatives deserve more attention in investigating the future urban metabolism, and how this may be shaped. Continuing the research on urban metabolism will provide working hypothesis about the city and suggestions on how urban energy use optimization can contribute to achieve a sustainable development.

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