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Strategies of socio-ecological transition for a sustainable urban metabolism

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Urbanization plays a key role in the human activities causing and feeding climate change. At present, climate change and other environmental issues are directly or indirectly related to the metabolism of cities. However, cities may also play a central role in the fight against climate change. This is the reason why Urban Metabolism (UM) has become a powerful concept to account for and understand the way in which complex systems such as cities use and dispose of material resources, also suggesting measures to change their operational regimes. The rightsizing and optimization of UM is basically a matter of social innovation. It implies changes in the way a city collectively produces and reproduces its physical stocks and provides services to its inhabitants. This article aims at identifying strategies, scenarios, and pathways to slow down urban metabolic processes while improving their efficiency, thus managing a successful transition to an urban (more) circular economy, as well as decreasing the material intensity of the urban economy. The main objectives of the article are the following:

1. The development of a renewed approach for studying Urban Metabolism based on transdisciplinary approaches and methods aimed to model metabolic agents' patterns of practices.
2. The definition of urban patterns of resource use of different agents shaping urban metabolism (households, corporate agents, communities, and public authorities).
3. The exploration of the main policies and administrative tools that cities use to manage environmental problems leading to different urban regulation regimes.
4. A tool for generating future scenarios and roadmaps to reach a low-carbon future. This tool is crucial for engaging experts, stakeholders and the public looking for new solutions.

KEYWORDS

systems thinking, urban metabolism, social innovation, socio-economic rightsizing, material intensity, urban economy, sustainable urban planning and governance

Urban metabolism as a concept to evaluate the urban sustainability

To perform their functions, cities demand matter and energy from the environment and dispose of the residues of consuming processes (waste). As we know, global urban growth implies increasing consumption of resources, goods, and services. Indeed, the specular aspect of the city as a growing machine is that of a "spatial unit of collective consumption" (Castells, 1972). Urban system functions are arranged in huge areas of activities aimed at reproducing the system itself. To perform these cultural or political functions, cities must exchange matter and energy with the environment. Due to the increase in the global demand for both raw materials and energy, urban growth is one of the greatest challenges the transition toward sustainability must face (Cristiano and Gonella, 2019; Cristiano et al., 2020). According to the UN-HABITAT, the world's cities are responsible for 75% of the global energy consumption, and up to 70% of greenhouse gases emissions that are driving climate change, while occupying just 2% of the global land and being home to more than half of the global population (UN-HABITAT, 2020). The fact that cities are one of the climate change's drivers has recently led to a growing interest in how urban systems use energy and material resources. Cities have thus acknowledged playing a central role in the fight against climate change, but also other social issues: see the Sustainable Development Goal (SDG) #11 "Make cities and human settlements inclusive, safe, resilient and sustainable" (United Nations General Assembly, 2015). However, policy options for implementing sustainable urban models are constrained by a limited understanding of how material and social variables interact. In fact, cities are complex entities where the "urban symbolic", or the set of socially produced meanings, is inherently intertwined with the "urban metabolic"' or the set of energy and material flows that the cities import, transform, use, and eject to reproduce themselves. Theoretically speaking, such features merge into the "urban fenomenon" (Lefebvre, 2003). This article suggests an approach to operationally move away from a city-nature dualism to instead see the city as a dynamic intersection between social and biophysical dimensions, or even a socio-natural hybrid.

We focus on the concept of "Urban Metabolism" (UM) conceiving it as a set of socially organized physical throughputs characterizing the functioning of a city. UM may be regarded as the organizational structure of resource inputs and outputs, formed by the complex network of stocks and flows necessary to the city's operations (Yan et al., 2020). UM is also a multidisciplinary platform providing tools to explore cities in terms of complex systems shaped by various social, economic and environmental forces (Barles, 2010). When considered as metabolic entities, cities appear as systems open to the exchange of energy and matter with their outer environment. Cities are veritable transformers of matter and energy: to sustain the expansion of their exoskeleton, they extract from their surroundings sand, gravel, stone, and brick, as well as the fuel needed to convert these into buildings (Simmons, 1996). Support areas or hinterlands may not be necessarily close to the city: in a globalized world, they can reach the planetary scale (Brenner and Schmid, 2015; Brenner, 2016). Like any system capable of self-organization, cities are open (or dissipative) systems, with matter-energy flowing in and out continuously. Cities' organizations and inhabitants use raw materials, food, water, and energy to transform them into physical structures, body components, material bases for urban services and social reproduction activities. The outflows of energy and matter, including solid waste, food losses, greenhouse gas emissions, and energy losses are therefore an indicator of paramount importance to assess the degree of ecological efficiency, or the "circularity" of an urban economy. The literature on metabolic studies has been growing recently, covering cities like Shangai (Lu et al., 2016), Bangalore (Paul et al., 2018), Mexico City and Santiago de Chile (Guibrunet et al., 2017). Metabolic profiles of European cities include Brussels (Athanassiadis et al., 2017), Barcelona (Pérez-Sánchez et al., 2019), Paris (Barles, 2010), Birmingham (Lee et al., 2016), Athens, Helsinki, Florence, and London (González et al., 2013). Most metabolic assessments address the biophysical dimensions of cities' processes, but rarely do they engage with an investigation of the agents activating and regulating metabolic practices (Padovan and Arrobbio, 2016; Padovan and Sciullo, 2016).

Urban metabolism entails different interconnected activities carried on by different organized agents (Dickens, 2004). It corresponds to the whole process of reproduction of the system itself and of its parts. This process might be deconstructed into different fields of practice, entailing different agents and sociotechnical systems along all the goods provision chain: appropriation, production and transformation, distribution, consumption, and finally disposal. All these interrelated activities are subject to different organizational regimes, rules, knowledge, and capabilities. This is the reason why we consider cities not only as physical entities that can be investigated with tools for the quantification of the resources flowing in and out urban settlements, but also as social entities that deserve a description about "who" uses those resources and "how" (further elaborations on cities following crucial pronouns "who," "whose," and "for whom" are addressed e.g., in Cristiano and Gonella, 2020; Cristiano and Zilio, 2021). Consequently, we need flexible analytical tools to reassemble urban system in a new understanding. Practice approaches might help in this effort. Practices can be of all kinds. There are practices implied in the reproduction of largest social systems, as well as practices aimed to reproduce everyday life; practices aimed at the production of means of production, and practices designed to produce stuffs and goods for households, as well as practices for disposing waste. We might say that practices are the basic units of social affairs. Combining input-output analysis e practices approaches try to develop a "sociology of flows" (Mol and Spaargaren, 2005) focusing on the social practices and institutions that "govern" the inputs, the outputs, and the throughputs crossing urban systems, trying to push them toward sustainability.

The objectives of this article are the following:

1. Renew the current conceptual and methodological tools to investigate UM and the use of resources in urban systems,

merging in a more consistent way both biophysical and socio-cultural aspects of the urban complex.
2. Introduce a new set of biophysical indicators, inspired by the Emergy accounting approach, as explained below, to assess and compare the Urban Metabolism of cities, their material consumption, and the material intensity of their economy while taking into account interrelated flows potentially reaching the planetary scale.
3. Suggest an approach for identifying urban pattern of resource use of different agents shaping urban metabolism (households, corporate agents, communities, and public authorities). This work focuses on social practices that influence the demand of material flows in different forms—energy, water, food, biomass, final goods, mobility—their use and transformation in stocks, and their final disposal.
4. Explore the strategies and the tools that municipalities use to assess and govern the urban metabolism. This pinpoints the emergence of urban regulation regimes and identifies possible leverage points to enhance the transition toward a more sustainable and more circular urban economy.

Material and emergy flows accounting

Typically, UM is studied using material flow analysis (MFA) which, using statistical data, accounts for the physical flows of particular substances—usually energy, raw materials, water, and biomass—as they enter, are consumed, converted, and expelled from a bounded urban system (Brunner and Rechberger, 2016; Graedel, 2019). MFA distinguishes stocks (manufactured artifacts and population) and flows (i.e., entering and exiting the system). In a simple form, the stocks or the Net Addiction to Stock are the result of the inputs minus the outputs of the urban system over a specific period (most often a year). The stock accumulation may change over time due to changing development patterns. The throughput of consumed resources results in waste flows that are either reused, recycled, or discharged into the environment. The concept of the circular economy (The Ellen MacArthur Foundation, 2013; Ghisellini et al., 2016) appears to be applicable in urban environments. A quantitative approach (Cristiano et al., 2020) is often applied to account for the metabolic processes, gathering data from available statistical databases including the inflows, outflows, stocks of biomass (B), minerals (M), water (W), and energy (E) directly used or embedded in goods and services consumed by the urban system. An important improvement that we suggest is to move toward an Emergy analysis of flows, which will release outcomes in terms of emjoule (from "emergy Joule"), as explained below. This approach, that entails Input-Output Analysis (Christ, 1955) plus Life-Cycle Assessment (see e.g., Hauschild et al., 2018), will evaluate the per capita and per urban GDP unit emergy intensity of the economy of cities.

Figure 1 shows the different sectors that contribute to the overall urban metabolism, made of three different fields: market urban economy, services provisioned by more or less public organizations, and households (incuding their overall final consumption). This figure shows sources, flows, stocks, waste, and processes that constitute urban metabolism. Agents performing practices in the urban fields will be presented in the next paragraph.

For investigating the quantitative dimension of UM (Gasparatos, 2017), we propose an EMERGY perspective. EMERGY (from EMbodied enERGY) is defined as "the available energy of one kind previously used up, directly and indirectly, to make a service or product" (Odum, 1996). Emergy is therefore a quantitative measure of the overall investment necessary to obtain a service or a product in terms of all the resources that have been invested to produce it. By including the indirect environmental support embodied in human labor and services, this approach shifts the attention from a user to the donor perspective, i.e., ultimately, to the non-negligible geobiophysical foundations of human societies. The lesser the emergy required to deliver a given product or service, the higher its optimization. The general methodology of Emergy Assessment (EMA) is developed following the preparation of a stock-flow diagram of the studied system (e.g., the one in Figure 1), evidencing all the significant inflows and outflows, the stocks and the feedback loops network. After some inventory and computing steps, a set of indicators provides all the information necessary to evaluate the various aspects of the system sustainability (Brown and Ulgiati, 1997). Among these, the Environmental Loading Ratio, the Emergy Yield Ratio, the % Renewables, the Renewable Support Area, and more. Emergy per unit money is obtained by dividing the annual total amount of emergy used by a nation by its gross domestic product (GDP). Emergy databases at the national level are the National Environmental Accounting Database (NEAD) (after Sweeney et al., 2007), also available online (www.emergy-nead.com/home). The outlined methodology is also called Emergy Accounting, since it provides a static evaluation of the socio-economic and environmental performances of a system. In Figure 1, a typical stock-flow diagram for a generic city is outlined. After the proper conversion of units, each flow may be in associated to an emergy flow, so computing the overall flows of resources that concur in the city metabolism operations. Through this approach, the evolution of a complex system can be analyzed, and the leverage points of the system (Meadows, 1999) identified, i.e., those stocks, flows, or processes where even a small change of some parameter may give rise to a general systemic re-configuration. Emergy and its systems thinking bases represent frontier approaches to geobiophysically and transdisciplinarily investigate urban metabolism and its sustainability, yet it is already supported by some key literature (Agostinho et al., 2018; Viglia et al., 2018; Cristiano and Gonella, 2020).

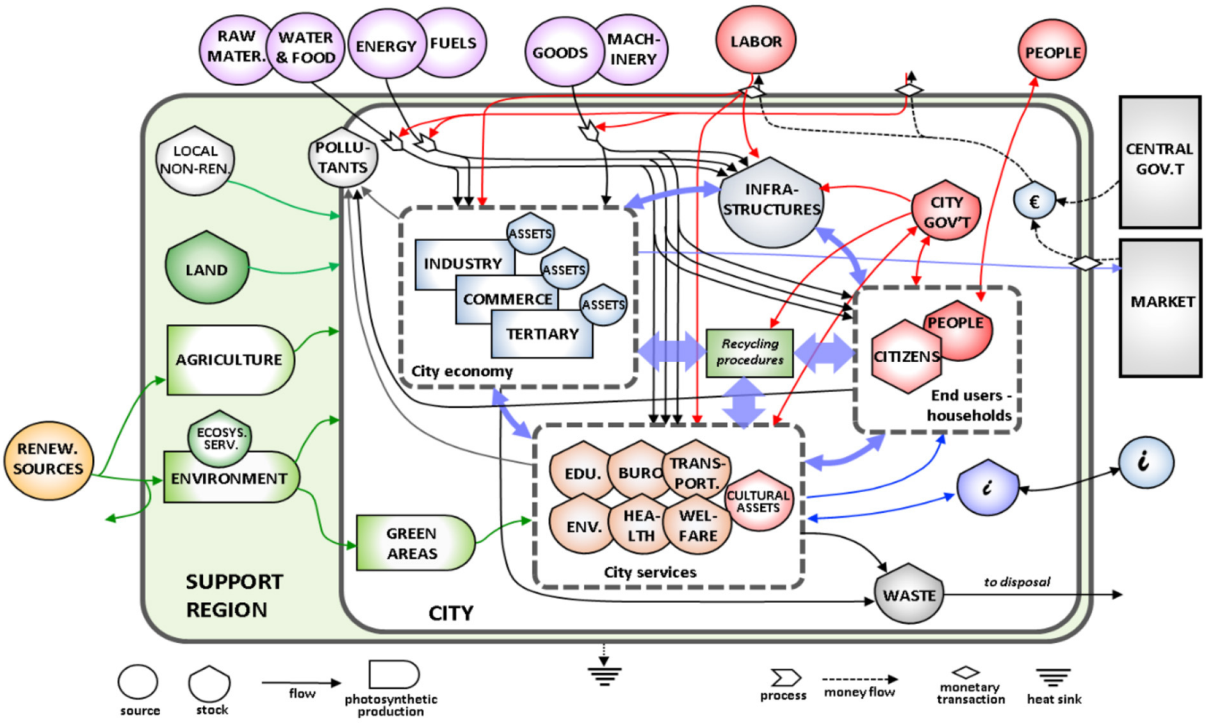

FIGURE 1
Stock-flow diagram of a city and its support region (adapted from Gonella, 2019; Cristiano et al., 2020).

Patterns of resource use

New conceptions of urban metabolism are emerging from approaches which see it as consisting of more than just material cycles. We need to conceptualize urban metabolism as consisting of several interconnected dynamics, and mutually transformative physical and social processes. Our perspective suggests investigating not only the biophysical dynamics of a city but also the ways urban agents use resources to perform their social practices differentiated in four main fields:

- Urban economy performed by corporate actors that include industry, commerce, and retailing services, and tertiary activities.
- Urban collective services provided by different public and public/private agencies such as education, transport, health, security.
- Households' reproduction performed by householders including different categories of daily consumption such as mobility, food and goods consumption, heating and cooling, housing, and other daily practices.
- Urban communities that develop new forms of collective action able to shape urban metabolism dynamics such as energy communities, food communities, mobility communities, housing communities, and so on.

All these activities will be defined and investigated as practices that will be seen as the basic units of the urban economy and at the end the drivers of urban metabolic flows. A widely accepted definition understands "practice" as routinized behavior stemming from the interconnection of different situated activities composed of practical understanding, engagement, motivations, and material "things and their use" (Shove et al., 2009; Hui et al., 2016). Special relevance is devoted to households' ordinary daily-life practices and to routinized organizational behaviors,[1] but they can also be extended to the business activities and to the service provisioning by public agencies. Practices can be eco-efficient. Yet they all stem from a combination of knowledge, routines, and situational constraints. We see the agents and their practices as having the capacity to affect urban metabolism. In this perspective, agents are "carriers" and "performers" of practices, whereas practices are the activators of a societal metabolism as well as the interlocked biochemical processes (enzymes) are the

1 Here behavior has not a behavioral meaning but refers to "[A] routinized type of behavior which consists of several elements, interconnected to one other: forms of bodily activities, forms of mental activities, 'things' and their use, a background knowledge in the form of understanding, know-how, states of emotion and motivational knowledge" (Reckwitz, 2002).

activators of the individual organism metabolism. Shopping, cooking, moving, cleaning, heating, cooling, and waste disposal are arrays of activities that trigger the exchange of matter and energy between social and natural systems. These practices are socially determined and influenced by habitus or in other words "the practical enactment of a set of objective conditions of existence". Of course, agents make sense of their own situation, and they adapt their practices in various ways, determining modifications in the shared practice patterns.

In addressing the question "why do people consume as they do and what are the environmental consequences of escalating demand?", we must deal with the environmentally crucial forms of "inconspicuous" consumption in areas connected to the demand for energy, water, food, and other natural resources or with rough objects. In some way, we have to deal with a renewed vision of consumption, considering that it is not only a means of communication or an apparatus of identity-building, but also that it is made of many environmentally sensitive practices or conditions. Urban metabolism introduces a new order of problems regarding the nature of consumption itself, for example its prosaic materiality or its repetitiveness, or again the fact that it indirectly incorporates the consumption of many others. Most of what is consumed is explained in terms of practical responses to living conditions, rather than by cultural factors. The portrayal of consumption as an outcome of free choice ignores the fact that most domestic consumption is an adaptive response to the present-day living conditions and is best seen as obligatory (Lodziak, 2000). In short, consumption is not the realm of freedom; rather it is a realm of necessity, even though it is masked by free choice (Binkley, 2006).

Each agent shows different practices, which directly affect urban flows and show different opportunities and potentialities to make Urban Metabolism more sustainable. Urban agents whose practices we intend to investigate in a deeper way are the following:

- Households, which may present a variable mixture of reflective choice and unreflective behaviors based both on actual or perceived constraints and on habit or particular ways a space of choice is presented.
- Corporate actors, who may show three different behavioral styles: steady (business-as-usual), reactive (behavioral changes according to perceived constraints coming from new regulations, "greening" of customer orientations, etc.) and proactive (anticipating changes in rules and attitudes and promoting new behaviors).
- Local governmental authorities and offices which are crucial in affecting metabolic trends through rules, norms, and public regulation.
- Urban communities that encourage different initiatives involving agents in such a way that their practices can change.

Obviously, these agents interact among themselves. Decisions in one side influence practices and behavior in another side. Public rules concerning, for example, the temperatures inside homes and offices have consequences on the (perceived) comfort of families and workers,[2] but they can significantly reduce energy consumption. Measures aimed at regulating collective consumer behavior are not always peacefully accepted. In the case, for example, of the reduction of indoor temperatures in offices during winter time or the increase of the same during the summer, they can find significant resistance from users, just as it becomes difficult in places used collectively such as shopping centers or schools. It can be difficult to find a common comfort that meets all specific individual needs. Faced with the climate emergency and the current high cost of fossil energy, municipalities should regulate the use of energy for heating and cooling more strictly than they normally do, abandoning the usual regulatory mechanism of final energy demand. consisting of the availability of expenditure. Urban metabolism implies a regulatory and planning approach that often is lacking in urban governance policies and styles. However, it is not a question of thinking in terms of planning and regulating urban collective consumption in a top-down model, but in a more complex process of bottom-up planning involving—precisely to avoid disputes—the different urban agents and their practices that we have outlined above. Here we enter the perspective of the self-regulation by people and other stakeholders, and of their metabolic practices.

To summarize, we contend that social practices are the building blocks of Urban Metabolism and that they shape the existing modes of production, consumption, and organization of the material aspects of urban life. Social practices are also the foundational site of regulation in terms of behavior, wider social narratives, and formal rules. Each city has its own model of resource uses—in terms of behaviors and practices usually executed—depending on the interactions of the practices of different agents to conduct their daily life business, on their structural and cultural features, and on the subjective way to approach urban sustainability issues. This aims at understanding social processes linked to the use of energy, water, bio-mass, and raw materials flows channeled by providers—public or private—and thus illustrating models of resource consumption and their impact onto Urban Metabolism.

Urban Metabolism not only depends on abstract work managed by great global organizations. It is also supported by bundles of everyday life activities aimed at the reproduction of social material life, made of different activities such as cooking, cleaning, heating, caring, educating, and aimed at the stable and recursive reproduction of human beings. This kind of practices is mainly out of the market, but an increasing part of them

2 At least in the presence of biased expectations and habits and, instead, in the absence of easy canniness or, indeed, social innovation.

is becoming more and more in charge of market itself, being one of the main sources of environmental crisis. These aspects of ordinary and daily life activities are rarely highlighted. We might see social practices are the basic unit of metabolism, the triggering activities that start metabolism while at the same time they are outcomes of metabolism itself. Our novel approach allows to investigate these metabolic regimes and their direct links with models of resource use.

This understanding opens the potential for change. Whereas, we understand that the collective action of urban settlers can change modes of consumption, subtracting themselves from the technical organization of consumption practices, new models of self-production and consumption can be built, for example in the field of food or energy.

Mapping urban metabolism regulation agents and their potential for change

Urban metabolism is a matter of regulation. To address such an issue, we should develop a decisional perspective: What, where and whose are the decisions that affect metabolism? Can statistics tell us a little bit about the "average" citizens and their decisions, in their household roles, their consumer roles, their work and leisure activities and (too often forgotten) their roles as agents of change, within and outside formal politics. The broad flows of metabolism are piled up by a veritable amount of daily decisions and acts. Probably most of these decisions or acts are ruled by habits and structural constraints, they are reflected upon only in some situations. At this stage, we will investigate actions, policies and innovations able to positively influence changes at the household final consumption level.

As said, a city is not only a metabolic unit but also a social system. Making sense of the triggers of the metabolism of a city and the way one can work on such triggers, so that metabolism may shift toward more eco-efficiency, requires an understanding of the political, institutional, and cultural factors that affect the way its use of matter and energy (i.e., its economy) works. From a regulation viewpoint, urban metabolism corresponds to an accumulation regime. To analyze its mode of regulation we adopt the following rationale:

(a) Urban metabolism, once characterized, becomes a dependent variable to be explained. Part of this explanation depends on environmental factors independent of human intervention (at least at the considered urban scale). The remaining part depends on an emergent systemic configuration of practices affected by many factors.
(b) Direct causal factor of urban metabolism are practices of household members. Household practices as units of analysis can be regarded as including a variable mixture of reflective choice, unreflective behavior based on habit or the particular way a space of choice is presented and (actual or perceived) constrained. For example, going to the workplace by car or by bus depends in most cases upon all three types of factors. Urban planning (e.g., closure of areas to private traffic, provision and distribution of car parks at the borders of such areas, etc.) typically acts as nudge. The price of fuel and of bus tickets acts as a more or less strong constraint, according to household affluence. The endorsement of ecological values and information may affect choice as well.
(c) Choices, incentives and constraints depend, as the example suggests, on four elements: rules, understood as formal or informal behavioral indications, with related rewards for compliance and sanctions for non-compliance; ideas, either cognitive (e.g., data on and inferences about urban pollution) or normative (values, principles, e.g., sense of duty with regard to one's own contribution to reducing GHG emissions), which affect the definition of the situation, the issue at stake, social relationships, options availability, etc.; socio-technical affordances, i.e., individual technological devices and expert systems with their embedded normativity (e.g., the layout and timetable of the urban public transport system); and finally money, as a symbolic mediator of relationships capable of affecting the affordability ranking of performances in most (if not all) problem-situations.
(d) These elements, in turn, mediate the relationship between households and three other types of actors, according to their own rationales. For local government actors, we can distinguish—following Bulkeley and Kern (2006)—three basic styles of action: authority (using political power to impose specific behaviors to the other actors); provision (providing directly goods and services to the other actors); and enabling (enacting strategies that should orient the other actors' behavior as desired). The fourth strategy indicated by Bulkeley and Kern, i.e., self-governing (adopting eco-efficient solutions for own functioning, such as green procurement), is of course relevant, but can be logically drawn to the problem-situation of household units, being affected by the same factors. For civil society actors we can distinguish between initiatives that keep a private character (individuals and households organize themselves in order, for example, to get food, use energy, or travel in a more eco-efficient way); public initiatives, on the contrary, aim at involving the whole community beyond the formal adherents to a group or association (for example, educational campaigns, or the organization of a public service for taking children to school); mediating initiatives are those which keep a private character, not being open to the whole community, yet for their resonance they become exemplar for a broader audience. For corporate

actors we can distinguish three behavioral styles: steady (business-as-usual), reactive (behavior changes according to perceived constraints coming from new regulations, "greening" of customer orientations, etc.), proactive (changes in rules and attitudes are anticipated and even promoted). For each of these types of actors there can be a number of reasons for their adoption of one or the other style. Essentially, however, these reasons can be traced to the same four basic elements to which households are sensitive: rules, ideas, money, and sociotechnical affordances. Strong regulatory pressures from the central government or the European Commission, for example, may act as triggers for the activation of the local government. But this may stem also from political competition at the local level, for example if a particularly effective green party is present. The financial situation and the availability of funds obviously plays a major role in orienting all actors, and sociotechnical affordances may play a major role as well, especially in the form of path dependency. Moreover, it is not in principle clear if and to what extent a particular style of action leads to more eco-efficient results. One cannot say *a priori* if a corporate reactive strategy to traditional forms of regulations works better or worse than government incentives aimed at promoting a proactive response. Nor can one say that the initiative is always on the side of governmental actors: business and civil society initiatives can act as triggers of the activation of the public administration. So this is pretty much a matter of empirical inquiry.

Modes of municipal governance of urban metabolism

Regulation analysis implies the identification of major agents involved in practices of production and consumption (reproduction). This is clearly a functionalist approach, but it is useful as preliminary exercise to identify main urban sectors of city reproduction and their rulers or drivers. The way in which different agents perform certain activities and the telos they pursue give rise to different metabolic regimes, depending on the time and space scales that are taken into account. Metabolic regimes have 2-fold functions: on the one side, they answer social needs by transforming resources into usable and consumable objects; on the other side, they lay the ground for the process of wealth accumulation. It means that urban metabolism is not a clearly delimited, socially disembedded sphere of physical relations which tends toward a general stability or instability. Rather, metabolism is a complex process that tends to accumulate capitals—natural, human, technical, and monetary capitals—while providing objects, artifacts, and services of social usefulness. Both these functions are not in contrast but complementary, and they can be addressed in terms of complex activities of production and consumption that periodically allow for accumulation and social stability, conditions that are suddenly challenged by new emerging crises. Periods of relatively stable accumulation leave the place to unforeseen and unexpected crises inducing then restructuring, rescaling, and reregulating urban metabolism. The alternation of stability and crisis depends on both the mode of regulation of metabolic regimes and the interactions of many factors and agents: institutions, collective engagements, shared visions, norms, conventions, networks of reproduction, procedures, modes of calculation, natural agents, and technology (Jessop and Sum, 2006). All these agents interact in unpredictable ways they contribute to structuring or destructuring, facilitating or complicating metabolic and accumulation processes. Also links between processes of production and consumption fluctuate over time, depending on social forces acting upon resources, and giving rise to different constellations of activities that vary and move at the spatial and temporal levels.

Municipalities play an important role in governing Urban Metabolism and more generally urban (formal) economy. Their practices deserve a careful investigation in order to identify the strategies, plans, and tools they use to govern UM. Urban governance deals with its own environmental—but not only—issues in two ways: top-down and bottom-up.

Top-down approaches are the conventional mode by which municipalities govern urban systems by using established tools that take the form of rules, administrative measures, and incentives to accomplish change in urban dwellers' behavior. This perspective sees the urban system as modeled by institutional practices that enact two interacting elements: (a) a city's structural and technical properties (e.g., population, types of corporate activities, infrastructures); (b) regulation frameworks made of rules, goals, habits, technical arrangements. An urban government may influence agents' practices with different policies tools: social mechanisms (imitation, conventions), market dynamics (competitiveness, incentives, marketing, labeling and certification, product standardization), legal constraints (including urban planning tools and standards), education, and communication campaigns. However, it may happen that municipalities strive to deliberate and implement environmental and low-carbon policies. This implementation gap, which can be caused by a lack of data, economic resources, or of technical, political, and social support, can be overcome by nuancing this model toward a bottom-up style (Barber, 2017; van der Heijden et al., 2019).

The second mode of governance is bottom-up in the sense that governance and regulation result from a combination of social practices performed by different actors and institutional assets. Here social practices are foundational of existing modes of regulation of urban activities. Shifting the lens to practices allows to identify them as a foundational site of regulation in terms of establishing norms, behavior, social discourses, and formal rules (Shove, 2010). This approach allows to improve our understanding of how UM stocks and flows are managed, how individuals accept, deny, or more often negotiate institutional attempts to encourage certain behaviors. In other words, modes of regulation stem from the social practices performed daily by people engaged in collective endeavors.

We suggest investigating modes of governance of the UM scrutinizing the following aspects:

- The basic styles of municipal action, distinguishing them in four ideal modes (Bulkeley and Kern, 2006): authority (using political power to impose specific behaviors to other actors); provision (providing directly goods and services to other actors); enabling (enacting strategies that should orient other actors' behavior as desired); self-governing (adopting eco-efficient solutions, such as green procurement). Our proposed approach allows to compare the styles by which each city tries to regulate and manage UM inflows, stocks, and outflows.
- The temporal aspect of municipal action, trying to understand if future choices at the local governance level are linked to a temporality beyond the political mandate, carried out by technically and socially competent personnel able to lead to innovative forms of municipal governance, including tools to boost dialogue and engage urban actors.
- The possibility of a co-evolutionary perspective of change that does not deny the possibility of meaningful policy action, and that recognizes that policies' effect is never in isolation and that interventions go on within, not outside, the processes they seek to shape (Schatzki, 2002; Shove, 2010). More than population density, settlement patterns or technologies in use, institutional, organizational, and social practices directly affect resources use.
- The significant presence of groups of people—mainly aged, migrants, and women living alone, and anyway people who are undergoing difficulties in accessing basic human livelihoods such as energy, food, and housing—all deserve particular attention when deliberating urban policies as acknowledged by UN-HABITAT (2020). An investigation of possible solutions to cope with phenomena such as food deserts, obesity, scarce mobility, energy accessibility, and varied aspects of "positional consumption" of resources is also welcome.

Practical applications and expected outcomes deriving from applying such a renewed transdisciplinary urban metabolic approach to urban governance (including both spatial planning and local policy making) may include, for instance:

- The accounting of the material consumption or of the Urban Metabolism of a given city, thus connecting it to its close and extended hinterlands (Brenner and Schmid, 2015; Brenner, 2016) and, in the light of this, operatively acting upon its prospective resilience in an era of scarcity (Kraehmer and Cristiano, 2022).
- The definition of urban patterns of resource use of different agents shaping urban metabolism (households, corporate agents, communities, and public authorities), in order to decrease the complexity of the planning and policy-making actions, and to correctly allocate given tasks to existing offices and practitioners;
- A renewed and more aware exploration of the main policies, plans, and other administrative tools that city councils use to manage environmental problems leading to different urban regulation regimes;
- A renewed approach to practices implied in the reproduction of largest social systems, to practices aimed at reproducing everyday life, to practices aimed at the production of means of production, to practices designed to produce stuffs and goods for households, and to practices for waste disposal;
- A novel tool for generating future scenarios and roadmaps to reach a low-carbon future—this tool, e.g. inspired on Xue et al. (2021) and Yuan et al. (2023), is crucial for engaging experts, stakeholders, and the public looking for new solutions;
- Inasmuch as nudging tools, urban plans and urban policies may be subject to momentous advancements, inspired on our discourses on and novel approach to urban metabolism.

Conclusion

With this article we have started to reflect about the following aspects:

- A renewed approach to the study of Urban Metabolism, including both theoretical perspectives (considering the micro generation of urban patterns) and analytical considerations (e.g., modeling metabolic patterns of practical conduct held by different agents). We have meant at providing a holistic model to analyse the city's urban metabolism emerging as a (non-linear) result of the interactions between agents at different levels of the urban system, including inflows from often planetary hinterlands or support areas. Furthermore, we invite scholars to explore hybrid tools blending top-down and bottom-up approaches.
- Top-down approaches are already well-developed in both literature and practice, and these methods are used to assess the biophysical dimensions of the urban metabolism of cities. Our perspective relies on the integration of a top-down biophysical accounting based on the eMergy approach—which represents an important innovation—with bottom-up analyses investigating social practices and policies regulation strategies related to resources' use. An expected outcome of such a hybrid approach is the development of a renewed systemic approach

to understand the functioning of urban systems, their metabolism in terms of inflowing, outflowing, and stocks, and the main points where action is expected to produce more effective changes toward more sustainable practices.

- New visions to improve the sustainability of UM of different cities, obtained by the identification of agents (households, corporate actors, communities, and public authorities) in relation to types of agencies, modes of activity, patterns of resource use, and their potential for change. Gender agency is here relevant because it is at the core of the domestic economy and other practices of reproduction.
- The field of urban metabolism is approached to map existing social models of resource use and the main agents triggering the urban metabolism, thus coupling urban resources use and social practices of different urban agents. In other words, the characteristics of urban metabolism are not only deduced from big data, but they are also reconstructed starting from the consumption practices of households and organizations. Its benchmark focuses on the regulation of the metabolism rather than on its control. The application of methodologies such as social practices analysis innovates the field of social regulation of urban metabolism.
- A new set of sociological tools to investigate and reconstruct different policy strategies in the domain of UM, based on different configurations of the three main UM policies: flows' prevention, use and final management. The identification of past and present strategies will enable the understanding of paths of interdependency, strengths and weaknesses of current regulation schemes and to underline the potential for change of current practices. Urban Metabolism management is a dynamic field in constant evolution. Each city is already at work to find new strategies, patterns, ways, and tools to manage (not always to reduce) material flows and stocks. The problem with these projects is that they are rarely monitored, accounted, and integrated. Often it is not possible to know if these strategies really bring benefits for the environmental, economic, and social sustainability of cities.
- One of the objectives we set ourselves is to carry out an exhaustive mapping of the sources of quantitative data useful for satisfying the analysis model of urban metabolism. This mapping is not only a prerequisite for the implementation, feeding and analytical functioning of an urban area; the proposed mapping is also a valid research objective in itself.
- Inasmuch as nudging tools, urban plans and urban policies would take advantage of momentous advancements, inspired on our discourses on and novel approach to urban metabolism.

Data availability statement

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

Agostinho, F., Sevegnani, F., Almeida, C. M., and Giannetti, B. F. (2018). Exploring the potentialities of emergy accounting in studying the limits to growth of urban systems. *Ecol. Indic.* 94, 4–12. doi: 10.1016/j.ecolind.2016.05.007

Athanassiadis, A., Bouillard, P., Crawford, R. H., and Khan, A. Z. (2017). Towards a dynamic approach to urban metabolism: tracing the temporal evolution of Brussels' urban metabolism from 1970 to 2010. *J. Ind. Ecol.* 21, 307–319. doi: 10.1111/jiec.12451

Barber, B. R. (2017). *Cool Cities. Urban Sovereignty and the Fix for Global Warming.* New Haven, CT: Yale University Press.

Barles, S. (2010). Society, energy and materials: the contribution of urban metabolism studies to sustainable urban development issues. *J. Environ. Plann. Manag.* 53, 439–455. doi: 10.1080/09640561003703772

Binkley, S. (2006). The perilous freedoms of consumption: toward a theory of the conduct of consumer conduct. *J. Cult. Res.* 10, 343–362. doi: 10.1080/14797580601014565

Brenner, N. (2016). The hinterland urbanised? *Architect. Des.* 86, 118–127. doi: 10.1002/ad.2077

Brenner, N., and Schmid, C. (2015). Towards a new epistemology of the urban? *City* 19, 151–182. doi: 10.1080/13604813.2015.1014712

Brown, M. T., and Ulgiati, S. (1997). Emergy-based indices and ratios to evaluate sustainability: monitoring economies and technology toward environmentally sound innovation. *Ecol. Engg.* 9, 51–69.

Brunner, P. H., and Rechberger, H. (2016). *Handbook of Material Flow Analysis: For Environmental, Resource, and Waste Engineers.* Boca Raton, FL: CRC Press.

Bulkeley, H., and Kern, K. (2006). Local government and the governing of climate change in Germany and the UK. *Urban Stud.* 43, 2237–2259. doi: 10.1080/00420980600936491

Castells, M. (1972). *La question Urbaine.* Paris: Maspero.

Christ, C. F. (1955). *A Review of Input-Output Analysis. Input-Output Analysis: An Appraisal*. Princeton, NJ: Princeton University Press. p. 137–82.

Cristiano, S., and Gonella, F. (2019). To build or not to build? Megaprojects, resources, and environment: an emergy synthesis for a systemic evaluation of a major highway expansion. *J. Clean. Prod*. 223, 772–789. doi: 10.1016/j.jclepro.2019.03.129

Cristiano, S., and Gonella, F. (2020). 'Kill Venice': a systems thinking conceptualisation of urban life, economy, and resilience in tourist cities. *Human. Soc. Sci. Commun.* 7, 143. doi: 10.1057/s41599-020-00640-6

Cristiano, S., and Zilio, S. (2021). Whose health in whose city? A systems thinking approach to support and evaluate plans, policies, and strategies for lasting urban health. *Sustainability* 3, 12225. doi: 10.3390/su132112225

Cristiano, S., Zucaro, A., Liu, G., Ulgiati, S., and Gonella, F. (2020). On the systemic features of urban systems. A look at material flows and cultural dimensions to address post-growth resilience and sustainability. *Front. Sustain. Cities* 2, 12. doi: 10.3389/frsc.2020.00012

Dickens, P. (2004). Society and Nature. Cambridge: Polity Press.

Ellen MacArthur Foundation. (2013). *Towards the Circular Economy*. Chicago: Ellen MacArthur Foundation.

Gasparatos, A. (2017). "Urban metabolism," in *Defining the Urban: Interdisciplinary and Professional Perspectives*, eds D. SIossifova, C. N. H. Doll, and A. Gasparatos (New York, NY; London: Routledge).

Ghisellini, P., Cialani, C., and Ulgiati, S. (2016). A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. *J. Clean. Prod.* 114, 11–32. doi: 10.1016/j.jclepro.2015.09.007

Gonella, F. (2019). The smart narrative of a smart city. *Front. Sustain. Cities.* 1, 9. doi: 10.3389/frsc.2019.00009

González, A., Donnelly, A., Jones, M., Chrysoulakis, N., and Lopes, M. (2013). A decision-support system for sustainable urban metabolism in Europe. *Environ. Impact Assess. Rev.* 38, 109–119. doi: 10.1016/j.eiar.2012.06.007

Graedel, T. E. (2019). Material flow analysis from origin to evolution. *Environ. Sci. Technol.* 53, 12188–12196. doi: 10.1021/acs.est.9b03413

Guibrunet, L., Calvet, M. S., and Broto, V. C. (2017). Flows, system boundaries and the politics of urban metabolism: waste management in Mexico City and Santiago de Chile. *Geoforum* 85, 353–367. doi: 10.1016/j.geoforum.2016.10.011

Hauschild, M. Z., Rosenbaum, R. K., and Olsen, S. I. (2018). *Life Cycle Assessment*. Cham: Springer International Publishing.

Hui, A., Schatzki, T., and Shove, E. (2016). *Nexus of Practice. Connections, Constellations and Practitioners*. Milton Park: Taylor and Francis.

Jessop, B., and Sum, N. -L. (2006). *Beyond the Regulation Approach. Putting Capitalist Economies in their Place*. Cheltenham; Northampton, MA: Edward Elgar.

Kraehmer, K., and Cristiano, S. (2022). "Città oltre la crescita," in *Un dibattito internazionale per trasformazioni urbane ecologiche e sociali*, ed Castelvecchi (Rome).

Lee, S. E., Quinn, A. D., and Rogers, C. D. (2016). Advancing city sustainability via its systems of flows: the urban metabolism of Birmingham and its hinterland. *Sustainability* 8, 220. doi: 10.3390/su8030220

Lefebvre, H. (2003). *The Urban Revolution*. Minneapolis, MN; London: University of Minnesota Press [French original edition La révolution urbaine 1970].

Lodziak, C. (2000). On explaining consumption. *Capital Class* 24, 111–123. doi: 10.1177/030981680007200106

Lu, Y., Geng, Y., Qian, Y., Han, W., McDowall, W., and Bleischwitz, R. (2016). Changes of human time and land use pattern in one mega city's urban metabolism: a multi-scale integrated analysis of Shanghai. *J. Clean. Prod.* 133, 391–401. doi: 10.1016/j.jclepro.2016.05.174

Meadows, D. (1999). *Leverage Points. Places to Intervene in a System*. The Sustainability Institute.

Mol, A. P. J., and Spaargaren, G. (2005). From additions and withdrawals to environmental flows: reframing debates in the environmental social sciences. *Org. Environ.* 18, 91–107. doi: 10.1177/1086026604270459

Odum, H. T. (1996). Environmental Accounting: Emergy and Environmental Decision Making. New York, NY: John Wiley and Sons.

Padovan, D., and Arrobbio, O. (2016). "Growing or steady cities? Accounting the urban metabolism of italian cities, in towards post-carbon cities," in *Proceedings of 16th Sustainable Built Environment Conference, Torino 18-19 Feb*., 75–85.

Padovan, D., and Sciullo, A. (2016). "Towards a micro-foundation of urban metabolism", in *Towards Post-Carbon Cities, Proceedings of 16th Sustainable Built Environment Conference, Torino 18-19 Feb.*, 64–74.

Paul, R., Kenway, S., McIntosh, B., and Mukheibir, P. (2018). Urban metabolism of Bangalore city: a water mass balance analysis. *J. Ind. Ecol.* 22, 1413–1424. doi: 10.1111/jiec.12705

Pérez-Sánchez, L., Giampietro, M., Velasco-Fernández, R., and Ripa, M. (2019). Characterizing the metabolic pattern of urban systems using MuSIASEM: the case of Barcelona. *Energy Policy* 124, 13–22. doi: 10.1016/j.enpol.2018.09.028

Reckwitz, A. (2002). Towards a theory of social practices. *Eur. J. Soc. Theory* 5, 243–263. doi: 10.1177/13684310222225432

Schatzki, T. (2002). Social science in society. *Inquiry.* 45, 119–138.

Shove, E. (2010). Beyond the ABC: climate change policy and theories of social change, *Environ. Plann. A Econ. Space* 42, 1273–1285. doi: 10.1068/a42282

Shove, E., Trentmann, F., and Wilk, R. (eds.). (2009). *Time Consumption and Everyday Life: Practice, Materiality, and Culture.* Oxford: Berg.

Simmons, I. (1996). *Changing the Face of the Earth: Culture, Environment, History.* Hoboken, NJ: Wiley-Blackwell.

Sweeney, S., Cohen, M. J., King, D., and Brown, M. T. (2007). Creation of a global emergy database for standardized national emergy synthesis. *Emergy Synth.* 4, 483–497.

UN-HABITAT (2020). *World Cities Report 2020, The Value of Sustainable Urbanization*. Nairobi: UN-HABITAT.

United Nations General Assembly (2015). *Transforming our world: the 2030 Agenda for Sustainable Development*. New York, NY: United Nations.

van der Heijden, J., Bulkeley, H., and Certomà C. (2019). *Urban Climate Politics, Agency and Empowerment.* Cambridge: Cambridge University Press.

Viglia, S., Civitillo, D. F., Cacciapuoti, G., and Ulgiati, S. (2018). Indicators of environmental loading and sustainability of urban systems. An emergy-based environmental footprint. *Ecol. Indic.* 94, 82–99. doi: 10.1016/j.ecolind.2017.03.060

Xue, J., Liu, G., Cristiano, S., Casazza, M., Nawab, A., Ghisellini, P., et al. (2021). Development of an urban household food-energy-water policy nexus dynamic simulator. *J. Clean. Prod.* 328, 129521. doi: 10.1016/j.jclepro.2021.129521

Yan, N., Liu, G., Ripa, M., Wang, N., Zheng, H., and Gonella, F. (2020). From local to national metabolism: a review and a scale-up framework. *Ecosyst. Health Sustain.* 6, 1839358. doi: 10.1080/20964129.2020.1839358

Yuan, Q., Bellezoni, R. A., Cristiano, S., Shah, A. M., Liu, G., Puppim de Oliveira, J. A., et al. (2023). Quantification of the food-energy-water nexus in urban green–blue infrastructure: a synthesis of the literature. *Resour. Conserv. Recycl.* 188, 106658. doi: 10.1016/j.resconrec.2022.106658