# Reshaping Urban Infrastructure

## Material Flow Analysis and Transitions Analysis in an Urban Context

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**Summary**

Urban policy makers and researchers consistently recognize the challenge of more effectively reshaping the linkages between cities, urban infrastructure, ecosystem services, and natural resources. The aim of this article is to consider the potential value of developing connections between two currently disconnected approaches to resource use and cities—material flow analysis (MFA) and transitions analysis (TA). This article attempts to address this deficit and looks critically at resource flows through cities and the infrastructures that have been—or could be—reconfigured to more effectively manage these flows from the perspectives of MFA and TA. This is an issue that has not been addressed, with the result that inadequate attention has been paid to the reconfiguring of urban infrastructures whose construction and maintenance are, in turn, often the largest expenditures at the city government level. Insufficient attention has been given to the fact that the design, construction, and operation of infrastructures (specifically energy, waste, water, sanitation, and transport infrastructures) create a sociotechnical environment that plays an important role in shaping, and potentially reshaping, how resources are procured, used, and disposed of by the city. The challenge, of course, is how such a transition takes place, who leads it and what social and governance processes are best suited to facilitate such city transitions. This article assesses the role of MFA and TA in understanding these resource flows and urban infrastructures, making it possible to begin to tackle this challenge in practical transformative ways.

## Introduction

The majority of the world's population now live in cities. Cities are where the large bulk of resource consumption takes place so the pressures, and potentials, to find ways to reconcile economic growth, wellbeing and the sustainable use of resources will be significant in these urban contexts. Indeed, there is mounting evidence that many significant innovations are already being incubated and applied experimentally with aspirations for systemic change in cities in both developed and developing countries. This should not be surprising because cities are unique spaces that connect a wide range of actors, networks, infrastructures, resource flows, cultures, social processes, and histories within specific biophysical, ecological, and political contexts. There are three key aspects of cities that are thus of critical concern to this article.

First, a second major wave of urbanization is under way: since 2007 the majority of the world's population of more than 7 billion people can be classified as living in urban settlements, with a projected growth of 4 billion urban dwellers in developing world cities taking place between 1950 and 2030. In the 200 years leading up to 1950, slightly more than 400 million people migrated to the world's cities in what is often referred to as the

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"first wave" of urbanization. Current projections suggest that by 2050 more than 6 billion people—almost 70% of the total world population—will live in urban areas (UN 2010). The 3 billion people expected to be added to the global population between 2005 and 2050 will mainly be in Asian and African cities.

Second, global economic production and consumption is now concentrated in cities: 80% of global gross domestic product (GDP) is now produced in cities, with 60% produced in 600 of the most productive cities where one-fifth of the world's population now lives. However, a significant shift in economic power from cities of the developed world to those in emerging economies is expected in the next 15 years (McKinsey Global Institute 2011, 12). A third of the developed world cities currently on the list of the top 600 in terms of GDP will no longer make the list in 2025, and 136 new cities from developing countries like China, the Democratic Republic of Congo, Nigeria, Indonesia, Pakistan, and India will make it onto the list for the first time. By 2025, middleweight cities—those with populations between 150,000 and 10 million—in emerging markets are expected to contribute to 40% of global growth, outperforming all the megacities—those with populations exceeding 10 million—of the developed and developing world combined.

Third, global consumption of resources is concentrated in cities: by 2005 the global economy consumed 60 billion tonnes (t) of resources[1] and 500 exajoules (EJ) of energy,[2] with approximately 75% of these global energy and material flows consumed in cities. As cities grow, average household occupant numbers are expected to drop from 3.2 people to 2.7 people by 2025, resulting in a growth in the number of households that is 2.3 times the population growth rate in the world's top cities (McKinsey Global Institute 2011). This will have a dual impact on demand for resources by increasing the number of housing units requiring land and building materials, and reducing the efficiency of resource use per capita compared to that achieved by sharing resources in larger households (Liu et al. 2003). About 85% of demand for housing will be in the cities of emerging economies, and 50% will be from China's cities (McKinsey Global Institute 2011). Considering that the global construction industry currently consumes approximately 50% of resources, 40% of water, 70% of timber products, and 45% of energy, this construction boom is likely to have a major impact on resources (Van Wyk 2007). As cities continue to attract investment and skilled workers, rising income levels are expected to be a more significant driver of economic growth than population. Between 2010 and 2015, an additional 460 million people will enter the middle class from cities in China, India, Russia, Indonesia, Brazil, Turkey, Mexico, and South Africa (Boston Consulting Group 2010, 13). By 2025, the number of households earning more than $20,000 per year[3] in emerging economy cities will be 1.1 times greater than the number in developed region cities (McKinsey Global Institute 2011). It is estimated that India could potentially increase its aggregate urban consumption sixfold between 2005 and 2025, and consumption could increase more than sevenfold in China (McKinsey Global Institute 2011).

Given that many of the energy and resource flows that cities depend on are finite, it follows that the continuation of global economic growth will depend on the decoupling of this economic growth from escalating resource use.[4] However, resource flows through cities are conducted by complex networked infrastructures which, in turn, have been designed, built, and operated in accordance with a particular set of technical modalities and governance routines that for the most part assume a continuous supply of resources. It follows that in order to decouple economic growth rates from escalating global resource use, it will be necessary to reconfigure the world's urban infrastructures to reshape resource flows through cities in more innovative ways.

The aim of this article is to consider the potential value of developing connections between two currently disconnected approaches to resource use and cities: material flow analysis (MFA)[5] and transitions analysis (TA) (see table 1). These two different approaches have a number of similarities. First, each approach has taken an increasing interest in the application of the analytical framework to the urban context, considering such issues as the material flow accounts of particular cities and the potential of cities to structure systemic changes in resource use. Second, each approach takes a significant interest in infrastructure and resource flows—in the case of MFA, focusing on assessing and accounting for resource flows, and in the case of TA, by focusing on transitions within infrastructure systems (energy water and waste, etc.). Third, both approaches have been interested in normative questions about systemic and purposive change in urban contexts: in the case of MFA, to decouple resource use from economic growth, and in the case of TA, to develop an understanding of the pressures and

**Table 1** Material flow analysis and transitions analysis compared

| *Approach* | *Analytical frame* | *Urban component* | *Infrastructure dimensions* | *Urban infrastructure issues* |
|---|---|---|---|---|
| Material flow analysis (MFA) | Ecological analysis of resource flows, dynamics, and intensity | Bounded character of resource flows through cities | Focus on resource flows of energy, carbon, water, etc. | For example, decoupling growth and resource use |
| Transitions analysis (TA) | Analysis of pressures and transitions in systems | Relational capacity of cities to shape transitions | Focus on the sociotechnical organization of infrastructure | For example, new styles of infrastructure provision |

practices of systemic change in infrastructure through low-carbon transitions.

But despite these similar concerns, there has been very little attempt to think about the potential resonances and affinities between MFA and TA in the academic or policy literature. This is not surprising, given the significant differences between the two approaches. First, in disciplinary terms MFA has its origins in industrial ecology and has not been primarily focused on questions of scale, mainly looking at global resource flows, while TA, with its origins in the sociology of innovation, has also been ambiguous on questions of scale and place. Second, methodologically each approach uses very different techniques: quantitative modeling for MFA, while TA uses much more qualitative approaches to understanding processes of lock-in and transformation in sociotechnical systems. Third, despite increasing focus on the city, there have been few funding opportunities or drivers to develop systemic analysis of the interconnections between these two approaches.

This article attempts to address this deficit and looks critically at resource flows through cities and the infrastructures that have been—or could be—reconfigured to more effectively manage these flows from the perspectives of MFA and TA. This is an issue that has not been addressed, with the result that inadequate attention has been paid to the reconfiguring of urban infrastructures whose construction and maintenance are, in turn, often the largest expenditures at the city government level. Insufficient attention has been given to the fact that the design, construction, and operation of infrastructures (specifically energy, waste, water, sanitation, and transport infrastructures) create a sociotechnical environment that plays an important role in shaping, and potentially reshaping, how resources are procured, used, and disposed of by the city. The challenge, of course, is how such a transition takes place, who leads it, and what social and governance processes are best suited to facilitate such city transitions. This article assesses the role of MFA and TA in understanding these resource flows and urban infrastructures, making it possible to begin to tackle this challenge in practical transformative ways.

The article has three sections. The first section examines MFA as a means of quantifying urban resource flows in the pursuit of more sustainable infrastructural configurations for decoupling. The second section considers purposive transitions toward more sustainable infrastructure, and how they might unfold at the urban scale. Finally, the conclusion uses these insights to reconceptualize how we understand urban flows in the future.

## Urban Material Flow Analysis

The application of MFA to the global economy and national economies is now quite well established (Eurostat 2002; Giljum et al. 2008; Krausmann et al. 2008; Krausmann et al. 2009; National Research Council of the National Academies 2003; OECD 2008; Rogich et al. 2008; Russi et al. 2008; Steinberger et al. 2010; UNEP 2011; Weisz et al. 2006). In this section we review the application of this approach to the city-region that has started to emerge in the academic literature in recent years and we focus on what conception of the city is developed through MFA and identify the implications for urban strategies.

### *Applying Material Flow Analysis to Cities*

The systematic application of MFA from an industrial ecology perspective to the city-region has started to generate some sophisticated frameworks for grasping the complex empirical dynamics of resources flows through (mainly developed world) cities (for recent examples see Barles 2009, 2010; Costa et al. 2004; Fernandez 2007; Kennedy et al. 2007; Saldivar-Sali 2010; Weisz and Steinberger 2010). A number of cases have been published that demonstrate the robustness of the urban metabolism methodology (see Barles 2009; Brunner et al. 1994; Burstrom et al. 1998; Daxbeck et al. 1997; Faist Emmenegger and Frischknecht 2003; Hammer et al. 2006; Kennedy et al. 2011; Niza et al. 2009). When applying MFA to city-regions, it is necessary to modify the framework that is normally adopted at the national and global level (see figure 1, developed by Sabine Barles based on her work on the Paris city-region).

Using standard Eurostat data, Barles has slightly modified MFA in order to develop an approach that is suitable to cities. The difference between a country and a city is that the latter are open systems that will always require sources (of resources) and sinks (for wastes) that are located outside their borders. For example, a substantial proportion of the wastes generated by the city are eventually exported out of the city either into the wider region or beyond. Also, domestic material consumption (DMC) of resources in a city is equal to domestic material input (DMI) minus what is exported out of the system. (DMI comprises both locally extracted and imported materials.)

The advantage of these methods is that they make it possible to identify and distinguish between the differentiated direct and indirect flows that get sourced from within and beyond the city, then get conducted through the city with some ending up as net addition to stocks (NAS), and then moving into or beyond the city as wastes, goods, and services. It is, of course, urban infrastructures that primarily conduct these flows. For example, the DMI per capita for a city where mobility is dominated by the private car will be very different from the DMI per capita in cities that have an excellent public transport system.

Although the application of MFA to cities is very new, and therefore there are limited publications to draw on, Weisz and Steinberger (2010) found enough literature to substantiate much of what was commonly believed but not fully supported by empirical evidence. First, they were able to show that the unique configuration of cities can give rise to very different levels of domestic material consumption per capita (DMC/cap) even though there are similarities at the national level. For example, DMC/cap was 20.8 tonnes per capita per year (t/cap/yr) for Lisbon, Portugal, 18 t/cap/yr for Singapore, 7.6 t/cap/yr for Geneva, Switzerland, 5 t/cap/yr for Paris, France, 3.6 t/cap/yr for London, England, and 3.3 t/cap/yr for Cape Town, South Africa. Second, this kind of detailed quantification of urban

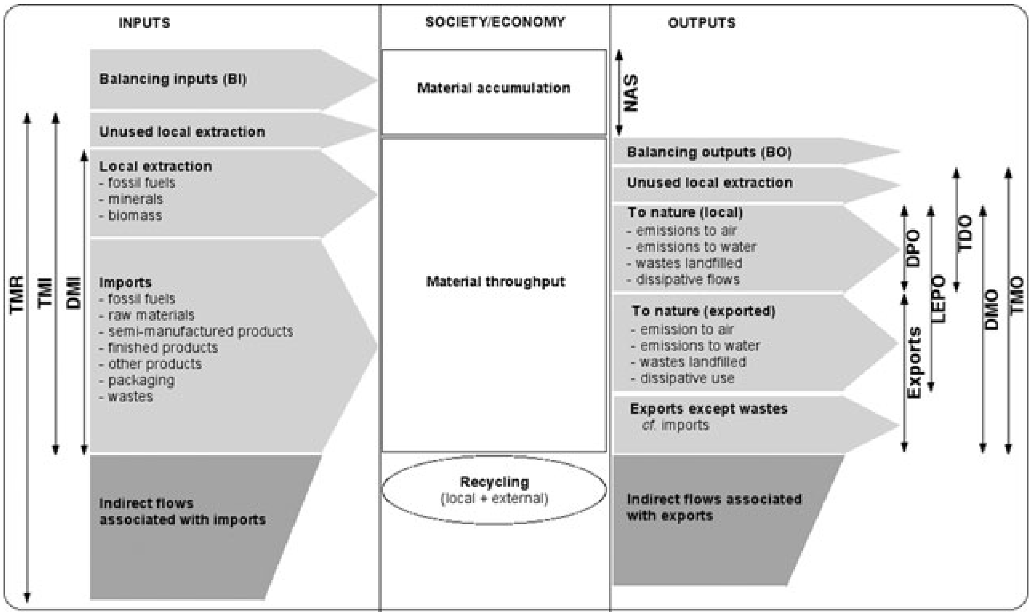


**Figure 1** Urban material flows. Main flows and indicators. Note the following: (1) The system (Society/Economy) is limited by its political or administrative borders; it comprises the society as a whole (population and artifacts) and excludes nature, from which it extracts primary material. (2) Water balance is not included. TMR = total material requirement; TMI = total material input; DMI = direct material input; NAS = net addition to stock; DPO = domestic processed output; LEPO = local and exported processed output; TDO = total domestic output; DMO = direct material output; TMO = total material output. Reproduced from Barles (2009, 900) with permission from Wiley-Blackwell.

material flows makes it possible to define what decoupling could mean for a particular city in quite specific terms. To retrofit or design new urban infrastructures to achieve the goals of decoupling for resource efficiency or resource productivity, the focus will need to be on "converter," "demand," and "reconverter" technologies. However, during the early stages of urban development, relative decoupling with a focus on materials will be the strategic focus, but later on, as NAS becomes less important, the focus will shift to rising energy demands as income levels rise. Third, what really drives up total material and energy use is not urbanization per se, but rather rising household income and therefore levels of resource consumption per capita. If urbanization tends to correlate with rising GDP per capita, then it follows that cities do become the spatial nodes where upwardly mobile households tend to concentrate. At the same time, cities are where the capacity for innovations exist that could make possible the decoupling of rising income (up to a point) from rates of resource use.

The most significant outcome of the application of MFA to the city-region is that it facilitates the re-embedding of urban systems within the wider nexus of ecological services (e.g., water supplies, soils, air quality, landfill space) and natural resource extraction (such as, e.g., fossil fuels or building materials that can be drawn from multiple sources). This is what one could call the "recoupling" of urban systems with the natural systems that support them. This effectively recognizes that decoupling urban growth from increased use of constrained and nonrenewable resources will depend on a conceptual "recoupling" of "urban systems" to more abundant and renewable resource sources.

## *Decoupling Through Urban Infrastructure*

While there is some evidence to indicate that relative decoupling is taking place (mainly in developed country cities), absolute reductions in the use of nonrenewable resources are unlikely to happen without deliberate intervention to stimulate broad, systemic (including behavioral) changes. The decoupling argument may be perceived to focus on reducing environmental degradation and the consumption of limited resources (e.g., fossil fuels, fresh water, rare metals), but it must be acknowledged that globally human needs for food, shelter, and mobility are still not fully met for a significant percentage of the world's population. Efficiency and resource productivity improvements can at best prolong the life span of limited resources, but without a complementary commitment to sufficiency, existing inequalities could persist. A combination of resource productivity improvements, increased use of local renewable resources, and reuse of waste products can allow cities to better manage the flows passing through them in pursuit of decoupling.

### *Improve Resource Efficiency*

Improvements in resource efficiency are often considered to be a "first step" toward sustainable resource management (Codoban and Kennedy 2008; Hawken et al. 1999; Van Timmeren et al. 2004; von Weizsäcker et al. 2009; WBCSD 2000). Resource efficiency refers to achieving more material output with fewer material inputs, and investments in improving productivity are easy to justify due to their economic rationale. Typically this involves engineering and/or institutional solutions to fine tune the components of existing systems to reduce the amount of water, electricity, or fuel wasted in meeting human needs. However, to achieve resource productivity, a "whole system" design perspective that can facilitate more radical system changes is needed. Indeed, sometimes substantial savings can be generated by just operating existing technologies in far more efficient ways. Approaches to improving resource efficiency differ across infrastructural services and cover a range of technical complexities and scales. While improving resource efficiency can be interpreted as a demand-side management (DSM) measure, it can also influence the manner in which certain services are supplied. Electricity interventions typically focus more on reducing demand from end users by encouraging efficient lighting and appliances, and reducing the need to use electricity for heating by insulating buildings and making use of waste heat. In the case of potable water, there are demand- and supply-side measures, in particular the maintenance of water transfer systems to repair leaks and reduce unaccounted for water losses. Similarly, when dealing with transport infrastructure, reducing fossil fuel use per capita often requires the provision of cycling paths and shared modes of transport as alternatives to private vehicles, and can extend to the planning of cities to reduce commuting distances. Improvements in resource efficiency can be described as a relative decoupling strategy, as fewer resources are used to achieve the same goals, or the same amount is used to achieve greater results. However, in the case of limited resources, it does not fundamentally eliminate dependence on these resources, and runs the risk of being pursued without any understanding of the impact on total resource consumption. In the case of nonrenewable resources, efficiency measures alone can suffer from the "rebound effect" (Alcott 2008; UNEP 2011), effectively cancelling out net environmental benefits with consumption increases that have been encouraged by efficiency gains (von Weizsäcker et al. 2009).

***Use Renewable Resources and Ecosystem Services***

As a stand-alone strategy to manage nonrenewable resources, improvements to resource productivity in the context of a growing population can only help to prolong the status quo until limits are reached. A certain amount of material is required to support a good quality of human life, so reducing per capita consumption of resources can only be pursued up to a certain point. A switch from consumption of finite resources to sustainably managed renewable resources[6] like sunlight, wind, and biomass opens up the possibility of being able to meet the needs of more people—some distinguish this decoupling strategy as "transmaterialization," or switching to materials that deliver a service with a lower impact per unit (Azar et al. 2002). This shifts the focus from reducing damage to generating new alternatives, and broadens the scope of innovation for sustainability beyond the status quo. Examples of these responses include "positive energy" houses that contribute to grid electricity in Vauban's (Freiberg, Germany) solar settlement, installation of photovoltaic panels on the roof of the town hall in Totnes (Devon, UK), and retrofitting government housing with solar water heaters in Cape Town, South Africa.

***Reuse Wastes***

Wherever there are human settlements, wastes of one form or another are generated. The metabolism of a typical modern city can be described as "linear" in that it extracts resources from beyond its boundaries, makes use of them within its boundaries to support urban activities, then deposits the resulting wastes in high concentrations back to the external environment (Costa et al. 2004; Girardet 2004; Ravetz 2000). In this way, the modern city's metabolism is fundamentally different from that of a natural ecosystem, which produces no waste and survives off its immediate environment (Girardet 2004). The city's major shortcoming is that it falsely assumes an endless supply of resource inputs for consumption and nature's unlimited capacity to absorb the concentrated wastes it produces. Returning to more circular, location-specific urban metabolisms is now considered to be a necessity if cities are to survive a future of resource and climate uncertainty (Costa et al. 2004; Girardet 2004; Hodson and Marvin 2009; Van Timmeren et al. 2004). Where growing cities have traditionally expanded the boundaries of the hinterlands on which they depend for survival as a means of accommodating growth, there are signs of a trend toward relocalization and attempts to create more autonomous circular or "closed-loop" metabolisms in some of the world's leading cities (Hodson and Marvin 2009).

The notion of "recycling" runs the risk of being limited to the separation and collection of household packaging wastes, but can include the consideration of all "waste" streams generated by urban production and consumption activities in terms of how they might be used as valuable inputs. Even the built fabric of the city has the potential to be reused as buildings are retrofitted instead of being replaced, salvaged bricks and other materials from demolitions are reused as inputs into construction, and rubble is processed for use in road surfacing and other projects. Similarly, organic wastes in the form of food, sewage, and animal wastes contain valuable nutrients, gases, and water that can be reused to meet the needs of the city. Instead of viewing waste organic matter as something offensive to be dumped and buried as quickly as possible, municipal sewage treatment systems can be built to capture the methane so that it can be harnessed to generate heat and electricity—in Stockholm, Sweden's case, to power the bus fleet—while reducing greenhouse gases released into the atmosphere. The remaining biomass can be composted and used to increase the fertility, water retention, and even carbon dioxide ($CO_2$) absorption of soils. Wastewater is not only a potential source of water for nonpotable uses, but the nutrients it contains can be reclaimed and used as an affordable alternative to artificial fertilizers.

More efficient use of limited resources, improved management of renewable resources, and the reuse of wastes are becoming the focus of new initiatives that could well bring about the decoupling of rates of resource use from well-being and economic growth. For whole-system efficiencies to be realized at the city scale, strategic coalitions with a shared vision for decoupling will need to emerge. The following section focuses on what a transition toward sustainability at the city scale might look like in order to formulate an agenda for facilitating purposive transitions toward decoupling in different contexts.

## Urban Transitions Analysis

Urban MFA provides an analytical framework for mapping and measuring resource flows through cities that are primarily, but not wholly, constituted as flows through urban infrastructure networks. In order to decouple economic growth from resource use, part of the response needs to actively consider changes in how urban infrastructure systems are organized and managed to develop systemic and purposive responses that accelerate and upscale decoupling. In this section we look outside of MFA to alternative frameworks that can provide ways of understanding what relationships exist between cities, infrastructure systems, and the organization of resource flows and how these might need to change to realize more sustainable outcomes.

### *Approaches to Infrastructure Transitions*

The multilevel perspective (MLP) provides an ambitious attempt to develop an understanding of "system innovation" in sociotechnical systems such as infrastructure networks (Geels 2002a, 2002b). An analytic understanding of these processes of system innovation and sociotechnical transitions is based on an interrelated three-level framework of landscape (macro), regime (meso), and niche (micro).

First, regimes are seen as *socio*technical in that technologies and technological functions coevolve with social functions and social interests. In this view, technological development is seen to be shaped by a broad constituency of technologists and engineers as well as policy makers, business interests, nongovernmental organizations (NGOs), consumers, and so on. The interrelationships of these interests through regulations, policy priorities, consumption patterns, and investment decisions, among other things, hold together to stabilize sociotechnical regimes and their existing trajectories (Geels and Schot 2007). The emphasis on regimes—the meso level—therefore highlights the opportunities and constraints on new technologies breaking through, where the existing regime is strongly aligned to the existing rather than new technology (Geels 2002a). Second, the concept of "landscape" is important in the MLP in seeking to understand the broader "pressures" for transitions. The landscape operates at the macro level, focusing on issues such as political cultures, economic growth, macroeconomic trends, land use, utility infrastructures, and so on (Geels 2002b), and applies pressures on existing sociotechnical regimes, creating windows of opportunity for responses (Geels and Schot 2007). Landscapes are characterized as being "external" pressures that have the potential to impinge upon—but do not determine—the constitution of regimes (meso) and niches (micro) (Geels and Schot 2007). Finally, the idea of sociotechnical niches, which operate at a micro level, is one of "protected" spaces, usually encompassing small networks of actors learning about new and novel technologies and their uses. These networks agitate to get new technologies onto "the agenda" and promote innovation by trying to keep alive novel technological developments (Hoogma et al. 2002). The constitution of networks and the expectations of a technology they present are important in the creation of niches.

Regime change is predicated on the ways in which shifting pressures impinge on a regime and the extent to which responses to these pressures are coordinated (Berkhout et al. 2003; Smith et al. 2005). Landscape pressures can be articulated in a number of different ways, either in very general terms (e.g., demographic change) or in relation to specific regimes (e.g., the impact of climate change on the fossil fuels industry). It is not only the articulation of these pressures, but also the adaptive capacity, or the relationships, resources, and their levels of coordination, that constitute a response to these pressures. The process of enacting adaptive capacity can be seen as the governance of regime transformation. However, this can be the outcome of historical processes (e.g., a gradual shift in consumer choices or the evolution of new technologies) or purposively informed by a strategic coalition with a shared vision and capacity to implement. By highlighting the context of regime transitions, the importance of governance processes, and the need to coordinate adaptive capacity, it becomes possible to understand a variety of transition pathways along which infrastructure may be developed.

Although these rather abstract descriptions of regime-change modes make sense at a general level, they cannot be unproblematically applied to a city. In other words, a "city" cannot be equated to a "regime." Instead, a city is a *space* where a multiplicity of energy, water, waste, mobility, and food "regimes" coexist in ways that can be both functional and dysfunctional at the same time. Due to the fact that urban governments are notional "managers" of the spaces within which these "regimes" operate, they are implicated in the way these regimes change over time either directly due to their control of the service delivery agencies or indirectly as a key policy actor with some degree of policy influence and/or regulatory authority. Needless to say, however, there are (mainly in developing countries) cities where networked infrastructures service only a minority of citizens and urban governments have very limited capacity to either extend or operate these infrastructures. In these contexts, bottom-up initiatives by households, streets, neighborhoods, and associations (e.g., taxi drivers who invest in road maintenance) fill the gaps in ways that, over time, could build new kinds of governance capacities for infrastructure transitions.

### *Cities in Multilevel Transitions Approaches*

Despite an impressive breadth of focus on substantive areas as varied as transport, energy, water, waste, and food systems, frequently within a context of wider transitions to sustainability (Elzen et al. 2004; Geels 2005; Green and Foster 2005; Hoogma et al. 2002; Van der Brugge and Rotmans 2007; Verbong and Geels 2007) and with an institutional and governance focus (Voß et al. 2006), the MLP has thus far neglected the spatial dynamics of cities. This raises the issue of where cities "fit" within the multilevel perspective and, in particular, where cities sit within the landscape–regime–niche hierarchy. There is a need to explore how innovative activities within cities interrelate with wider national and societal transitions. Central to this potential is the relative positioning of cities in terms of their own location in urban hierarchies and governance arrangements. This, in turn, implies that cities may have differentiated capacities to either shape or be shaped by national transitions.

Understanding the role of cities in a multilevel transitions perspective also needs to take seriously multilevel governance (Bache and Flinders 2004) and different scales of action. Agency at the level of the city cannot be reduced to understanding the variety and coalitions of actors (e.g., local authorities, mayors, universities, local economic actors, etc.) attributed to work at this scale. It also involves, and requires an understanding of, the influence of actors at the national and supranational scales of action who influence—both intentionally and through unintended consequences—action at a city scale through the production of new state spaces (Brenner 2004). By taking into account the way decisions at national/regional scales cascade downward, it becomes possible to conceive of cities not merely as sites for receiving transition initiatives, but also potentially as contexts for more purposive urban transitions.

### Understanding Purposive Urban Infrastructure Transitions: A Framework

The relative neglect of cities in discussions of transition to sustainable development needs to be addressed. This gap is addressed here by developing a framework for understanding the distinctiveness of purposive urban infrastructure transitions. This, of course, raises questions as to who is driving the transition and who is claiming to speak on behalf of cities. What is particularly interesting here is that territorial priorities at the scale of the city (e.g., economic growth targets, carbon emissions reduction aspirations, resource security) are becoming strategically intertwined with the reconfiguration of sociotechnical infrastructure systems that may or may not be organized at the scale of the city. In other words, urban territorial social interests (municipal and local policy makers and officials in particular) may sit outside of sociotechnical infrastructure regimes, but may need to gain degrees of influence and control over these regimes in order to achieve territorial objectives.

The issue here is the degree to which there is separation or alignment between territorial policy agendas and the power to manage urban infrastructure regimes. To use the language of the MLP, it is the extent to which the territorial priorities of an urban governance network—and the social interests that produce them—are able to actively manage sociotechnical regime change.

In short, urban responses to these pressures will be variable. Cities and other geographies will not only experience these challenges differently, but also differ in their historically organized infrastructure provision and capacity to respond to the emerging pressures at an urban scale. Three issues are important here: the degree of regime change required, the capability to enact such changes, and the ways in which there would be common understanding of the outcomes.

#### *Shared Visions of Urban Infrastructure Transitions*

In thinking through what an urban transition would look like, it is necessary to understand whether there is a shared understanding between a wide range of urban policy makers and those who manage the energy, water, waste, and transport infrastructure regimes. "Visions," which are a central part of prospective transitions management approaches (Kemp and Loorbach 2005; Rotmans et al. 2001), offer the potential to present a shared understanding of citywide and regime interests (without implying in advance that everyone *must reach* consensus). Visions of an urban transition may bring together both an understanding of the changes envisaged in a regime over time and changes in citywide priorities. In terms of urban infrastructure, a vision-building process may involve representatives of utilities, municipal government, regulators, developers, business, citizens, "users," and so on. Visions and the goals they outline provide a reference point through which networks can be built, gaining commitments to "participate," orienting the actions of potential participants and constituencies, and persuading potential participants of the desirability of transition (Russell and Williams 2002). Although visions are not fixed and will change over time with the variety of social interests that become involved, the key question is whether, on the one hand, visions are articulated around narrow coalitions of self-interest (be that from within existing sociotechnical regimes or narrowly constituted urban governance coalitions) or, on the other hand, in terms of a more broad sense of what a purposive urban transition could look like. Referring back to the work cited earlier by Smith and colleagues (2005), the ideal outcome often stems from a vision-building process that procures new external knowledge into sociotechnical regimes that have the internal capacity to manage a transition. Low capacity and dependence on internal institutional knowledge is often the worst combination from a transition perspective.

#### *Translating Visions: Intermediary Organization*

The production of a vision provides a framework and a direction of travel for a purposive urban sociotechnical transition, but it says little about *how* this will be done. A vision in that sense is a necessary but not sufficient condition for a purposive urban transition. What is required is a sense of how an "effective" capacity can be coordinated to act on the vision and the process of manifesting that capacity in action. An ad hoc and reactive alignment of social interests will not achieve the priorities encompassed in a vision. Coordinating capacity and mobilizing capability requires the creation of "new" intermediary organizational contexts. The creation of intermediaries is necessary to constitute a space outside of the obduracy of both existing urban governance regimes and existing sociotechnical regimes (Hodson 2008; Van Lente et al. 2003). This creates a context for the discussion of competing priorities, helps to access fresh external knowledge into a particular regime, and either provides capacity that is lacking to manage a transition or helps mobilize untapped internal capacity. Although intermediaries bear a generic title, they encompass a wide variety of different organizational priorities and motivations, funding streams, and organizational capabilities that are predicated on the pursuit of different political priorities aligned with interventions. Many different kinds of institutions can be found in cities acting as intermediaries: consulting companies, university-based research units, NGOs, citizen-based coalitions (often with strong political links), international lobbying groups (e.g., the Clinton C40 league), formalized urban development agencies (constituted either by the municipal government or the private sector, or both as a partnership), or even relatively autonomous internal strategy units. Intermediaries can be characterized in terms of three aspects of their mediating function:

- They often mediate between production and consumption rather than focusing solely on production or consumption issues.
- They can mediate the different priorities and levels of different funders, "stakeholders," policy interests, social interests, and regulators.
- They invariably also mediate not only between different priorities in the production of a vision, but also in their "application."

Intermediaries are of such critical importance because they are usually brought into change processes by key players to provide two primary services: knowledge and/or capacity. Knowledge services involve a wide spectrum of activities, including purely descriptive or rapid short-term scoping analyses, right through to in-depth research, innovation, and long-term strategic guidance/management. Capacity refers to skills and staff time to help (co-)manage some or all aspects of a transition. Funding, staff, trust, learning, networks, and communication are all important in embedding the intermediary within a specific urban context and facilitating the development of resources, relationships, forms of knowledge, and communication, and thus visibility, to be able to affect a credible influence. But the intermediary also needs to develop a shared organizational view as to how it would know if it was influential beyond the often-narrow metrics of external funders.

## Conclusion

Urbanists outside industrial ecology interested in sustainability have in recent years integrated the general concept of resource flows into their analyses of urban infrastructures and economies (Crane and Swilling 2008; Guy et al. 2001; Heynen et al. 2006; Hodson and Marvin 2009, 2010; Swilling 2010a, 2010b). While the industrial ecologists are interested in empirical quantifications of the flows themselves, the urbanists are more interested in the sociotechnical systems (and related governance arrangements) that conduct these flows through urban systems. From a research and policy perspective, it is clear that the two approaches have much to offer. Whereas the empirical analysis of flows highlights the dependence of cities on specific sources and sinks for the resources and wastes they require, the analysis of sociotechnical systems addresses the highly complex regulatory, institutional, and knowledge systems that conduct these flows. If policy makers want to promote a more sustainable city, this research enables them to make decisions about the building of new or the retrofitting of existing urban infrastructures that take into account the long-term flows of strategic resources into and out of the city.

### *Urban Flows*

Urban flows are introduced here as an integrative concept for identifying areas of potential intervention for decoupling at a city level, and the need for investment and capacity to reshape urban resource flow function. In order to understand how cities might provide a context where various catalysts for decoupling emerge and thrive, it is important to view them in terms of the flows of resources that pass through them. Cities are actually gigantic networks of interlocked infrastructures that have been built over many years to manipulate vast and varied flows of resources that enter into, circulate within, and exit from them in support of human prosperity. Ravetz (2000) likens the city to a living organism, describing the continuous flow of inputs and outputs as its "metabolism." Studying the patterns of matter and energy moving through cities is critical in finding solutions to optimize them in the pursuit of sustainable resource management (Costa et al. 2004) and is an important starting point for identifying opportunities for decoupling.

Integral to studies of urban metabolism is an analysis of stocks and flows. Stocks include the urban fabric and resources available within the city (buildings, roads, infrastructures), whereas flows involve resource inputs from within and outside the city and outputs from the city to areas within and beyond its borders. Costa and colleagues (2004) refer to the buildup of what they call "socio-economic stocks" within the city, consisting of material stocks (e.g., buildings and infrastructural systems) and the resources that go into maintaining and using those stocks (e.g., energy and water). Studying the patterns of matter and energy moving through cities is critical in finding solutions to optimize them in the pursuit of sustainable resource management. However, a complete study of metabolism should include cultural, social, political, and ethical issues, which are made visible through TA.

The design, construction, and operation of urban infrastructures to provide key urban services such as piped water; sanitation; waste removal and processing; electricity for light, warmth, and productive activity; and mobility for people and goods will directly determine how resources in the form of water, nutrients, materials, and energy pass through the system, and in what manner. For example, in some developing country cities where formal networked sanitation systems may be nonexistent, nutrients and water from sewage will not circulate through the urban system in the same way as in cities that have a formal networked sanitation system. Similarly cities that are not hardwired with fiber-optic cables will not be populated by businesses that depend on 24/7, high-speed, low-cost connections to global information flows.

### *Further Research*

Generally the role of cities in shaping systemic changes in the organization of infrastructure and the level of resource flows is not well understood or researched in an interdisciplinary and comparative manner. In particular, there is a disconnect between studies of urban resource flows using MFA and TA of the social organization and urban political dynamics of resource flows. These two sets of issues need to be brought together in a more comparative and systematic manner. At present the many different initiatives, experiments, and demonstrations described above have not been subject to formal evaluation of their efficiency and effectiveness. Instead, what emerges is a partial picture with some understanding of how selected initiatives may shape resource flows, but in many cases success is asserted and initiatives have assumed emblematic and exemplary status without effective evaluation. There is a huge amount of experimentation and demonstration that needs to be assessed to tell us about the limits and opportunities for systemically reshaping resource flows. The main gaps for further research are as follows:

- To place cities' resource flows in an existing context there needs to be an understanding of the current status of material flows, the social and technical organization of utilities and infrastructure, the pressures and drivers in individual cities, and an assessment of the existing or latent sociotechnical capability to shape resource flows.
- The evaluation of specific initiatives needs to be placed in this wider context in terms of the impacts on resource flows, but the missing learning is what these experiments can tell us about the degree of obduracy within existing infrastructure regimes—how do existing social relations, institutions, and regulations prevent or slow the upscaling of initiatives and which changes are required to accelerate transitions?
- There is a need for learning across different experiments within the same city (as well as comparatively) in terms of what second-order social learning from experimentation can help inform the development of intermediary capability. This is what would contribute to the upscaling of initiatives and help us to understand how learning can then be used to reshape the organization and priorities of infrastructure regimes at other levels. Taken together, this type of learning can help us understand existing systems, the degree of flexibility and autonomy in developing new configurations, and the issues involved in upscaling and accelerating transitions.

A clear implication of the analysis offered by this approach is the need to promote the proliferation of MFAs for cities across all regions of the world. We have suggested that the work by Barles (2009) on Paris could be used for this purpose. This will complement—and help extend—the kind of global comparative work that has been initiated by the Massachusetts Institute of Technology (MIT) (Saldivar-Sali 2010). As we deepen our understanding of urban metabolism, it will become possible to focus analysis of the total material requirements (TMRs) of cities, including both direct and indirect flows. This will reveal how dependent cities are on material imported from other localities within and beyond national boundaries. What will emerge is an understanding of the material content of imports that have significant environmental impacts in other localities. This raises three very important issues that connect the quantitative approach provided by MFA to the TA social science approach: First, is the need for much better assessment of indirect flows and urban ecological footprints (see, e.g., Billen et al. 2012). Second, taking into account indirect flows will make it possible to better define targets for action. For instance, Paris's final energy consumption has been stable for ten years, while its primary energy consumption continues to increase. This means that reducing urban consumption is as important as improving downstream energy supply (Kim and Barles 2012). Another example is that of food, where indirect flows are much more important than direct ones (see, e.g., Chatzimpiros and Barles 2012). Finally, emphasizing indirect flows does not mean that action at the city level is irrelevant. It helps to assess what is possible to achieve within an intraurban approach and suggests that it is necessary to reconsider producer–consumer links and relationships—for instance, rural–urban ones—and to place the city within the broader system of flows and stakeholders that make it possible for the city to function.

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## Notes

1. One tonne (t) = $10^3$ kilograms (kg, SI) ≈ 1.1 short tons.
2. One exajoule (EJ) = $10^{18}$ joules (J, SI) ≈ $9.48 \times 10^{14}$ British Thermal Units (BTU).
3. Households with incomes of $20,000 or more are commonly identified by companies as those with purchasing power beyond necessities.
4. The term "decoupling" has come to be associated with efforts to break the causal link between economic prosperity and the depletion of finite resources or degradation of environments, and can

be used as a lens through which to envision the reconciliation of human and environmental interests in rapidly growing cities. There are two modes of decoupling. Resource decoupling or "dematerialization" involves reducing the rate at which primary resources are used per unit of economic output. Impact decoupling, on the other hand, seeks to increase economic activity while decreasing negative environmental impacts like pollution, $CO_2$ emissions or the destruction of biodiversity.
5. Editor's Note: In the industrial ecology literature, MFA is used to abbreviate both material flow analysis and material flow accounting. In this article, MFA is used as an abbreviation of material flow analysis.
6. The term "renewable resources" refers to those that cannot be depleted by human use (e.g., sunlight or wind) and those that can be regenerated or returned to full utility as fast as they are being consumed (e.g., wood, water, topsoil).

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