Reducing energy and material flows in cities
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In the decades to come, the majority of humans will live in urban settings. Consequently, the role of cities in reducing socio-economic material and energy flows is increasingly recognized. We examine the recent literature on urban energy and material use, and their reduction potential, focusing on three aspects: the urban form, the urban building stock, and urban consumption patterns. Although there is clear evidence of the huge saving potential resulting from better urban form and better building design, implementation remains an open issue. Regarding urban consumption patterns, we point out that there is increasing evidence that household income strongly correlates with embodied energy and material use. This has implications regarding how urban specific energy and material flows should be measured, but might also lead to the insight that technical fixes will eventually be offset by the income effect. Although not the focus of this review, social inequalities in using or having access to resources in cities are stressed as a largely neglected dimension of the debate.

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Introduction

Globally, in the past hundred years, human population increased fourfold while material and energy use increased tenfold. At present humanity uses 500 Exa-Joules of primary energy and extracts 60 billion tonnes of raw materials annually [1,2]. However, huge inequalities in per capita material and energy use pertain between countries and world regions. The highest consuming 10% of the world population uses 40% and 27% of the world’s energy and materials respectively, and the richest 10% accounts for 39% of the world’s GDP [3].

This scale as well as the ongoing dynamic of the socio-economic material and energy throughput (‘social or industrial metabolism’ [4,5]) poses huge challenges for society, including exhausting the best fossil fuel and ore deposits, overuse of productive lands, extreme pressure on biodiversity, and massive emissions of climate changing gases with potentially disastrous consequences [6]. Much of the research related to reducing material and energy flows has been focusing on either the national level, targeting at a decoupling of economic growth from resource use or on the equipment (product) level, targeting at the potential for efficiency improvements.

Since the mid-1990s, however, the potential role of cities in reducing societal material and energy throughput has increasingly attracted the attention of researchers, governments, and international organizations. The past two to three years have seen a surge in activities on urban metabolism, urban energy use, sustainable cities, carbon-neutral cities and so on. In 2008 humanity crossed a historical landmark with half of the world population living in urban areas. Urban areas are expected to absorb increases in world population, adding approximately 3 billion urban dwellers by 2050 [7]. Clearly, sustainability cannot be achieved without urban-specific considerations and participation.

This review article summarizes important insights from the literature about the specific role cities have or could have in the future in reducing energy and material flows. Although this seems to be a straightforward topic, some important caveats are warranted.

(1) Lack of data: Despite the acknowledged importance of cities for the overall volume of socio-economic material and energy use, periodically available and harmonized datasets are provided by statistical offices almost exclusively for the national level. Therefore any attempt to generalize patterns and trends of urban specific resources use from the literature struggles with incomplete or incommensurable data.

(2) No common definition: ‘City’ and ‘urban area’ denote related but not equal phenomena and no common international definitions of these terms exist.

(3) Openness of cities: Cities are places of specialized production, transformation and consumption rather than resource extraction, and therefore they depend on a hinterland as provider of resources, goods and services. Increasingly this hinterland has a global dimension. It is exactly this openness of cities with

¹ For practical reasons we here use the terms city and urban area interchangeable.
regard to material and energy flows which makes it difficult to specify what the urban specific flows are [8*].

(4) Dematerialization versus securing access: The sustainability focus on decreasing resource use often ignores that a huge part of the global urban population faces the opposite challenge: that is how to get access to sufficient material and energy resources to lead a decent life [9**]? UN Habitat estimates that around 800 million urban dwellers in low and middle income countries do not have adequate access to basic energy and material services [10]. Energy poverty is also a real and present problem for the urban poor in high-income countries and in many former communist states [11,12].

(5) Relevance of the urban scale: Which components of the material and energy system are specific to urban scales, as opposed to rural or national scales? Many structural and technological factors are in principle the same at national and urban scales, but their relative importance can be very different.

In this review, we focus on cities as a specific form of human settlements that is characterized by a high concentration of biophysical structures, inhabitants and socio-economic activities along with a minimum size. The plurality of factors known to influence urban resource use and the diversity and incommensurability of the published literature suggests narrowing the scope to allow for a more differentiated discussion.

We here focus on three demand-side aspects that are particularly important in cities: the urban form, the characteristics of the building stock and urban consumption patterns. As a consequence, other important factors are not discussed here. Among these are the challenges and opportunities of urban energy and material supply systems (not only requirements for concentrated, clean energy carriers, but also opportunities for efficient networks, such as district heating, combined heat and power, or smart electric grids including vehicles as storage) and the socio-cultural implications of resource reducing measures (as e.g. social tensions and insufficient privacy in high density settlements [13]).

Aggregate material and energy flows: evidence from urban metabolism studies

Since the pioneering article of Wolman on the urban metabolism of a hypothetical US city [14], and first applications of this concept for Brussels [15] and Hong Kong [16,17], the term urban metabolism is used to denote quantitative accounts of the overall inputs and outputs of materials and energy, and of special substances such as nutrients and water to and from cities. The range of overall material and energy flows varies greatly between cities. For example, domestic material consumption per capita has been estimated at 20.8 tons/cap*yr for Lisbon [18], 18 for Singapore [19], 7.6 for Geneva [20], and 5.0 for Paris [21*]), 3.6 for London [22], and 3.3 for Cape Town [23]. The large variation in urban material consumption may be due to several factors: energy and material flows at smaller geographic scales tend to exhibit higher variability (see for instance the discussion about the national intra-EU variability in domestic material consumption [24]). The reason is that such territorial approaches are significantly determined by the economic structure within the territorial boundaries, which is indeed more diverse on smaller scales. Partly incomplete and incomparable datasets may also play a role. In this respect particularly the Lisbon results should be interpreted with caution as the authors applied a new method which is different from the one applied in all the other studies.

The 2008 World Energy Outlook chapter dedicated to cities represented a milestone in the recognition of urban energy [25]. Urban energy use garners increasing attention, partly in order to estimate and allocate urban greenhouse gas emissions, the vast majority of which are due to energy use [8***,26,27*,28*,29,30*,31,32,33*,34,35**,36,37,49**]. These studies deal with the problem posed by the openness of cities by following either a production-based or consumption-based approach. The production approach accounts for the emissions produced and the energy and materials used within the city boundaries. In contrast, the consumption approach allocates all upstream energy and material flows (i.e. all flows along the whole production chain whether they took place inside or outside the territorial city boundary) to the goods and services consumed in the city.2

Overall these studies provide clear evidence of the importance of urban energy and material flows and of the huge variability that exists between cities which points to substantial reduction potentials. From a territorial production approach, the economic and industrial activities are often the most important factor, for instance if a city is a major harbor, airport hub or industrial center. From a consumption perspective, the income level and lifestyle of the urban inhabitants will clearly be more decisive. These two complementary approaches thus highlight two policy avenues: reduction in resource use linked to economic production activities, and reduction from changes in high-income lifestyles.

The role of urban form for transportation energy requirements

Urban form, in particular density, has long been known to play a decisive role in transportation energy requirements [41]. Recent studies confirm that higher population

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1 The same allocation problem also applies to countries and in fact the term was created to denote inconsistencies of allocating CO2 emissions to nation states [39]. See also [40].
densities correlate with lower transportation energy requirements [29,42,33,35] but there is still debate on the causal factors underlying the statistical correlations (see [43] for a comprehensive review of this debate).

A number of authors emphasize the potential of choices in urban form and spatial functions in mitigating the rise in energy consumption of urbanizing Asia [44–48]. Spatially-explicit studies at the suburban level for the entirety of Australia and Toronto show that suburban dwellers are much more dependent on private automobiles [49,27], leading to concerns regarding oil price vulnerability of suburban populations [50]. An innovative spatially-explicit study conducted by Parshall and co-workers focusing on transportation and building emissions from US counties found a ‘threshold’ effect in per capita urban transportation energy compared to more rural counties [35].

In a scenario analysis Marshall estimated that for the US alone an urban development that kept current average US urban population densities constant (instead of continuing the current trend of reducing urban population densities by 34% as was observed in the decade 1990–2000) in combination with efficiency improvements of the car fleet of 1% annually could reduce urban automobile related CO2 emission by 18 Giga tones until 2054 [42]. Graz and co-authors estimated for the Netherlands that total transport-related CO2 emission are 47% lower in the highest population density class as compared to the lowest, using an econometric model based on the correlates of urban form and transportation, including travel distances and modal choices [51]. Lankao found that per capita transportation energy is elastic with income (i.e. has faster than proportional increase) [52].

Overall the evidence from the literature suggests that a robust correlation between urban population densities and transportation energy requirements exists, but this does not directly imply a causal relationship. Incentives, such as the quality of public transit, and deterrents to automobile use both play an important role, along with the attractiveness of high density centers. Reducing the car dependence of cities, is an important and feasible strategy to reduce cities’ overall material and energy flows, as has been demonstrated for a number of cities [53], but it requires integrated and sophisticated urban planning decisions [54,44].

Reducing material and energy requirements for buildings
Buildings are the largest single sector in energy end use world-wide [55,56]. Cities with their specific concentration of buildings face both unique opportunities and trade-offs in reducing the energy and material flows caused by constructing, maintaining, using and demolishing the building stock.

The operational energy demand of buildings is a function of the climate, the quality of the building stock (and its potential improvements), the urban form, and the floor area demand for residential and commercial uses, which itself is a function of income and location. Clearly climate influences the demand for heating and cooling. However, space heating energy use measures, normalized to heating degree days and square meters living space, reveal substantial ranges between 14 Wh/m²/degree-day for Australia and 70 Wh/m²/degree-day for the US in the early 1970s, and between 17 (Australia) and 44 Wh/m²/degree-day for Germany in the mid-1990s [57], indicating the importance of other non-climate factors.

Among these the influence of building technology and design is certainly important. The potential for reducing the energy used for space heating is huge: a passive house standard requires that energy use for space heating is no more than 15 kWh/m² floor area per year, for low energy houses the corresponding number is around 50 kWh/m², whereas poor thermal insulation may cause energy use for space heating of 200–400 kWh/m² in mid-European latitudes. Appropriate insulation together with other design elements, such as shading, ventilation and orientation, thus provides huge potentials for reducing energy demand for heating and cooling [43].

There are trade-offs though. Higher income is known to be correlated with higher per capita floor space [57], a trend which sets off some of the efficiency gains achieved by better building design. The temperature to which inner spaces are heated or cooled also plays a role, and is dependent on lifestyles or habits of the inhabitants. High densities, which may be desirable for reducing transportation, can limit the possibilities to implement design measures for reducing heating energy use and pose additional stresses on air quality.

The urban heat island effect is thought to reduce heating demands but may increase cooling demands [58]. A comparison of 100 US cities by Brown and co-authors shows that overall building-related energy use decreases with urban density [29], and the county-level mapping of Parshall and co-authors also indicates lower building-related emissions in urban areas — even at higher incomes [35].

Compared to the rich body of literature on operational energy use, studies on the energy and materials required to construct and maintain the buildings are rare. For the residential building stock of six Australian cities, Troy and co-authors show that the operational energy by far exceeds embodied energy, but some caution is warranted here as the operational energy included transportation in this case [59]. An in-depth analysis of the life cycle energy, material, GHG emissions and costs of a specific single-family house in the US found that the use phase
accounted for more than 90% of the total energy consumption and that the implementation of various efficiency strategies could reduce those by more than 50% [60].

Long-term simulations of the material life cycle of buildings have been conducted for the Netherlands, Norway, the city of Trondheim, urban areas in the UK and Japan, Germany as well as for urban and rural China [61,62,63,64,65,66]. Using different methods such as demand driven system dynamics models of the aggregated residential housing stock, or surveying and image interpretation, these studies point to the so far largely neglected potential of reducing the life cycle material flows and surges in demolition wastes associated with the material dynamic of the built urban environment. Fernandez examined the consumption of energy and materials attributable to the rapid increase in China’s urban building stock. He pointed out that the pure size and pace of China’s urbanization has global implications for resource use, thus making the large developing countries decisive players to achieve overall material and energy reductions [67].

**Beyond city boundaries: reducing urban household consumption**

The consumption approach accounts for the resource use caused by urban households directly on fuels and electricity, and indirectly on goods and services.

Technically such analysis is carried out using Environmentally-Extended Input–Output Models in combination with expenditure surveys which allow a consistent allocation of the industrial energy use to the final goods and services purchased by households of different income brackets at the city or country level. This method has been applied to urban households in India [68,69], Australia [49,37], and Brazil [70].

For Australian urban households Lenzen and co-workers show that indirect energy consumption is of the same order as direct energy use in high-income cities. If corrected for income, many cities may have lower energy use and emissions than the national average [49,37]. Most significantly the Australian results indicate that direct household energy use has a tendency to saturate at higher expenditure levels, whereas total energy consumption (direct plus indirect) continues to rise with expenditure (see **Figure 1**).

For Indian urban and rural households Pachauri found similar proportions between direct and indirect household energy requirements. Her study not only confirms earlier findings that household size is negatively correlated with per capita household energy use but also shows explicitly that this applies to both direct and indirect energy use, see **Figure 2** [69].

Using a multivariate regression analysis to explain variations in per capita total (direct and indirect) household energy use, Pachauri found that income by far was the most important explaining variable. The expenditure elasticity of total household energy amounted to 0.67 (implying that a 1% increase in per capita expenditure

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3 It should be noted that the method has also been applied to ecological footprint analysis, water use, emissions and wastes, although mostly on the national scale.
results in a 0.67% higher per capita energy use) [30]. However, all other things being equal, energy use was found to be 10% lower in urban than in rural areas. This is explained by the high use of inefficient non-commercial fuels in rural India in combination with fuel shifts in urban areas towards modern energy forms, such as electricity and LPG [69].

Similar results were found in a study on energy requirements of urban households in Brazil. The authors found that per capita household energy use (both direct and indirect) is strongly dependent on income and an increasingly larger share of indirect energy use is observed in higher income brackets, see Figure 3 [70].

The income dependent expenditure elasticity of energy requirements was found to be above 1 for direct energy in most income classes. The direct energy elasticity curve peaks in the mid-income class at almost 1.1 and declines with higher incomes to reach 0.9 in the highest income class. In contrast, the elasticity curve for indirect energy use rises linearly with income but stays below 1 in all income classes (Figures 3 and 4).

Overall these studies reveal compelling consistency in the main findings, despite the considerable socio-economic differences between Australian, Indian, and Brazilian cities. This supports the criticism of Satterthwaite andDodman that urbanization per se may not be to blame for high energy use and GHG emissions, but rather high-income lifestyle [9,32]. However, it is also well known that urbanization most often accompanies increases in income. Clearly more research is needed to capture the causality between urbanization and income.
Conclusions and outlook
Recent research has come a long way in establishing comparative methodologies for estimating energy and greenhouse gas emissions at the urban level, but accounting methods still require more attention, in particular for material flows.

Results from the consumption perspective suggest that urbanization per se is not the main problem, but rather high-income lifestyles which often accompany urbanization. Insights from the production perspective show that cities can significantly lower material and energy flows through efficient urban form and built environment. Overall, evidence indicates that at equal incomes, the urban type of human settlements is less resource intensive in terms of direct household energy use as compared to rural types and significant reduction potentials can be expected from better urban form, infrastructure and building design.

Cities are not equal in terms of their layout, development stage or economic basis. It would thus be most useful to develop a typology of cities, which takes into account the most important distinctions which determine the current levels and trends in urban resource use and which constrain future reduction options. Our review suggests that at least the following distinctions should be considered:

- high versus low urbanization dynamics (India, China vs. North America, Europe and parts of Africa);
- income and industrialization levels;
- history: recent automobile based (as e.g. most US cities) or dating back to medieval times (e.g. many European cities);
- economic inequality and accompanying inequalities in settlement rights;
- the role and influence of current urban planning.

Indeed, North American car-based cities, old European cities and rapidly expanding Asian cities face fundamentally different opportunities of redesigning the built urban environment towards more efficient resource use. A more generally applied consumption perspective, stratified by income, would render visible the contribution of the high-income brackets for overall resources use (in both urban and rural areas) while pointing out the necessity to provide the urban and rural poor with safe supplies of energy and material goods to live a decent life.

Bringing analysis into practice is a notorious obstacle. In the policy realm various and partly conflicting objectives have to be considered, traditionally separated policy fields need to be integrated and user-friendly information systems must be established [52,54,71–77]. To this end, comprehensive empirical results on the specific contributions of urban design and changing urban lifestyle patterns would be desirable. Such empirical evidence would also support the development of innovative policies addressing consumption patterns to lower their environmental impacts.

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References and recommended reading
Papers of particular interest, published within the period of review, have been highlighted as:

- of special interest
- of outstanding interest

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An urban metabolism study at different nesting levels of Paris, demonstrating the changes in material flow quantities when the peripheries are included.
A spatial analysis of the production based GHG emissions in Toronto, disaggregated the types of emission source.
Demonstration of a hybrid method, combining local emissions and LCA factors for some urban products for 8 US cities.
A comparative study based on household surveys differentiating urban and rural energy shifts.
Demonstration of a method for GHG emission estimations including upstream factors for energy supply for 10 global cities.
An innovative study using GIS-referenced Vulcan emissions database for transportation and building processes to analyze urban emission patterns.
A comprehensive literature review focusing on energy use and GHG emissions attributable to construction, maintenance and use of residential dwellings and the relation between urban structure and private travel behavior.
A very good introduction into the differences between a production and consumption perspective, an introduction into Environmentally Extended Input Output Analysis for measuring embodied energy and its application to a spatially-resolved study of household consumption in Sydney, and its socio-economic parameters.