Sustainability transitions require an understanding of smaller cities

DOI: 10.1111/jiec.13434

FORUM

JOURNAL OF INDUSTRIAL ECOLOGY WILEY

Sustainability transitions require an understanding of smaller cities

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Editor Managing Review: Gang Liu

Funding information
University of Reading Undergraduate Research Opportunities Programme (UROP)

Abstract

As we approach an era where more than 60% of the global population lives in cities, urban areas must be our focal point in the transition to the flourishing societies of future decades. While much attention has been paid to understanding urban consumption patterns over the past decade, the overwhelming majority of recent urban metabolism research has focused on larger cities with populations over 1 million inhabitants. Meanwhile, estimates show that more people live in urban areas with populations between 300,000 and 1 million people than in mega cities. Indeed, given their relatively small size, there are many more of these cities to study than larger cities; many more urban governments need to be informed of the solutions that are relevant to the context of their less dense populations. Our goals to decarbonize and dematerialize societies require discussions of measures that are applicable to different types of urban areas across various population scales. We take the example of the town of Reading, United Kingdom to illustrate how per capita urban metabolic flows differ within small- and medium-sized cities, as well as for megacities. For example, relative to Reading, we find that there is substantial variability in energy demand for small cities (i.e., Le Mans is 150% higher) and for larger cities (50% higher for other European and North American megacities). This underscores the need to explore this under-researched area of urban metabolism, as well as the development of a typology to enable comparisons and differentiate strategies for sustainability transitions.

KEYWORDS
industrial ecology, material flow analysis, resource flows, small- and medium-sized cities, sustainable cities, urban metabolism

1 | OUR (SMALL- AND MEDIUM-SIZED) URBAN PLANET

Material flow analysis (MFA) has a rich history of application to the study of urban metabolism. Indeed, the now-retired global urban metabolism dataset compiled by the Metabolism of Cities lists over 120 cities globally where MFA has been applied in some fashion to quantify resource inputs, stocks, and/or waste output (Metabolism of Cities, 2018). Of those with population data provided in this dataset ($n = 41$), none had a population of less than 1 million inhabitants; indeed, only six had a total population below 5 million. However, as can be seen from Figure 1, the global urban population is distributed across many different-sized urban areas; there are nearly twice as many people living in urban areas with populations

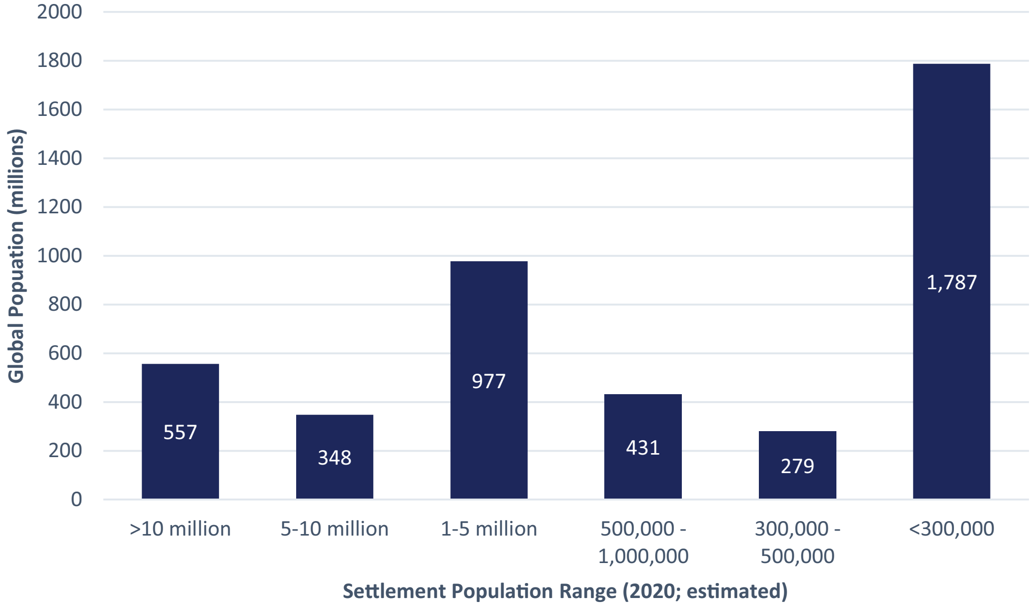


FIGURE 1 2020 global population distribution (in millions) amongst different settlement sizes (United Nations, 2018).

ranging between 1 and 6 million as there are living in megacities (United Nations, 2018). Indeed, there are over 25% more people living in even smaller cities with populations between 300,000 and 1 million than in all the world's megacities. It follows that the absolute number of smaller cities will be much greater, as will the number of context-specific solution sets applicable to achieving the low-impact, equitable urban areas that we desire.

When planning for the dematerialized, carbon-negative/neutral future of urban areas, the resource demands of urban populations and associated urban forms must be considered when developing solutions. Following the Deming cycle used in environmental management,[1] measurements of resource flows are necessary before we can properly plan how to improve their efficiency. MFA and its cousin urban metabolism (UM) can be used as helpful frameworks for gauging progress on dematerialization and decarbonization measures geared at mitigating impacts on our sustaining hinterlands. Further, an understanding is needed of the differences in resource efficiency measures that can be deployed, along with variations that can be expected due to differing urban form/sizes.

Evidence continues to accumulate that small- and medium-sized cities[2] (SMCs) face different challenges in mitigating climate change compared to larger cities. When coupled with relatively a low population density, SMCs may be unable to support public transportation options such as light or heavy rail to mitigate GHG emissions (Kennedy et al., 2014), let alone active transport options. Sugar and Kennedy (2020) demonstrated that these higher-order transportation modes arise only when transportation costs and social interactions are sufficiently high. Furthermore, a number of studies have found that cities with low population density also tend to have higher total car trips/distances travelled per week (Breheny 1995; Newman & Kenworthy, 1989). Butt et al. (2022) found that lower density urban areas in the United Kingdom struggled to a greater degree with the mitigation of transportation emissions. Bettencourt et al. (2007) demonstrated that smaller cities tend to have higher gasoline sales per capita (United States) and lower demand for roadway infrastructure (Germany); beyond transportation, they also tended to have lower domestic electricity demand per capita (China).

When it comes to mitigation planning, SMCs experience advantages and disadvantages. Oliveira et al. (2014) and Fragkias et al. (2013) suggest that small cities are not more carbon intensive and may even hold a carbon advantage compared to their larger counterparts. Fragkias et al. (2013) even point to the limits of the UM metaphor, given the observed departure from the trend of increasing efficiency with size found in nature. As well, when rolling out new low-carbon infrastructure, SMCs may benefit slightly from lower land and labor costs, with Richardson (1993) estimating a 4%–7% reduction. On the other hand, from the perspective of governance, SMCs may be at a disadvantage in addressing climate change or other environmental challenges (as well as boosting resilience; Bristow & Mohareb, 2019) because of their relatively limited administrative capacity and resource base (Haughton & Hunter, 1994; p.75). Collectively, this suggests a complicated picture and further underscores the need to explore the resource consumption characteristics of SMCs. Beyond opportunities for GHG mitigation, there are other social implications of city size.

Questions have historically arisen about whether SMCs provide more hospitable and/or manageable urban space. Many urban thinkers have suggested optimal city sizes on the scale of SMCs, such as Samuel Barnett (250,000–500,000), Ebenezer Howard (30,000), Dantzig and Saaty (starting at 250,000), Plato (5040 inhabitants), and Alexander and colleagues (500,000) (Alexander et al., 1977; Batty, 2015). When considering their maximum urban benefit metric ("a city's social output minus dissipative costs of infrastructure"), Sugar and Kennedy (2021) found that the top three performing cities were SMCs (though it should be stated that the bottom three were as well). It is likely that population is a less important metric

TABLE 1 Key statistics for Reading, 2015, with sources.

Indicator	Unit	2015	Source
Population	Number	160,825	(ONS, 2019)
Land area	km^2	40.40	(Ordnance Survey, 2017)
Population density	per km^2	4043	From above
Gross value added (GVA)[a]	£ million	6679	(Office for National Statistics, 2017)
Average daily temperature	°C	11.19	(University of Reading, 2017)
Annual precipitation	Mm	574.8	(University of Reading, 2017)

[a]GVA is gross domestic product (GDP) excluding taxes and subsidies on products.

than focusing on a characterization of how well a city functions (i.e., through some form of subjective measure of how well it meets the needs of its inhabitants) (Batty, 2015).

Quantitative analyses of SMCs are understudied in the sustainability literature. However, some exceptions include benchmarking studies across large and small cities, such as the eco-efficiency study of 88 European cities (from 300,000 to over 1 million inhabitants; Gudipudi et al., 2018), the effect of city size on municipal solid waste generation in 930 cities in Poland (from less than 2000 to over 100,000 inhabitants; Wowrzeczka, 2021), and the carbon intensity variation between Beijing, China (20 million inhabitants) and Issaquah, USA (30,000 inhabitants) by Chen and Chen (2017). To date, the limited coverage of SMCs requires remedying if we are to understand their unique contexts toward dematerialization and decarbonization.

As mentioned earlier, UM & MFA studies in industrial ecology that focus specifically on SMCs are rare with some exceptions including those that examine trends in small and relatively sparsely populated countries where even main cities are generally of limited size (e.g., Denmark; Lanau et al., 2021; Lanau & Liu, 2020). Moreover, owing to the lack of complete sets of data at the municipal level, small-city studies are normally performed at the level of the encompassing metropolitan region rather than at the scale of the municipality itself (such as in Bahers et al., 2019). This is challenging because the standardization of the system-boundary setting is critical for ensuring cross-case comparability.

This forum piece uses a UM case study for an SMC (Reading, United Kingdom) with data for key short-residence flows (food, energy, and water) to understand their relevance for decarbonization and dematerialization. Further, resource efficiency (per capita basis) of selected resource flows of this case study are contrasted with small cities in different countries in Europe (Le Mans, France, and Odense and Aalborg, Denmark) and larger global cities (Kennedy et al., 2015) to understand how they vary in their consumption. The aim of these objectives is to provide an example of the data that are needed for SMCs, provide a comparison with similar-sized urban areas, and underscore how SMCs are an important part of realizing the low-carbon transition, given their sizeable contribution to the global population and their unique characteristics.

2 | READING, UNITED KINGDOM AS AN SMC CASE STUDY

2.1 | Background of case study

Reading is a local authority in the South East of England, with an estimated population of 161,800 in 2019 (Office of National Statitsics, 2020). While not technically a city under UK naming conventions (the title is only granted by the monarch and is not provided solely on the basis of population; Sandford, 2020), Reading is the largest town in the United Kingdom. For the analysis below, the local authority of Reading is the boundary applied. Key statistics are provided in Table 1.

As shown in Figure 2, the largest land-use type in Reading is suburban, covering 56% of total land area (see Table s1 for more details), followed by urban areas (20%), giving a combined total of 76% of land used for urban development. Land uses that can be considered more natural (neutral grassland, improved grassland, broadleaf woodland, and arable and horticulture) cover the remaining area. Thus, Reading is a predominantly urban environment, with most spaces characterized as developed land use that drive resource throughput, with limited productive capacity.

2.2 | Populations and densities of small cities

To understand the populations and densities of SMCs compared with other larger city classes, we use examples from the United Kingdom and the United States. Below are summary statistics for SMCs in the United Kingdom and the United States (Figure 3). It should be noted that population densities differ between the United States and the United Kingdom (data for England and Wales) due to differences in the definition of "urban"; the US definition incorporates any directly-adjacent territory (i.e., those with lower population densities) in addition to the denser urban

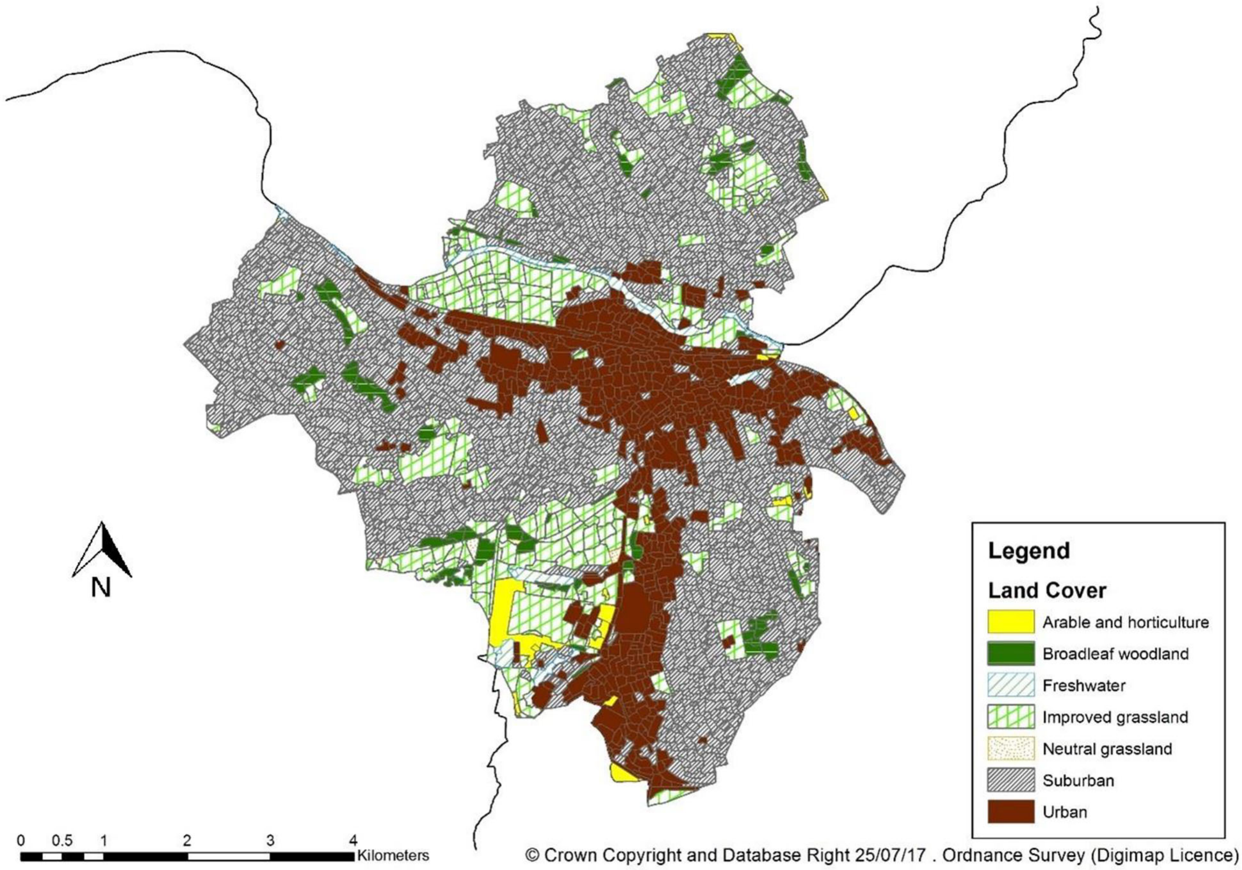


FIGURE 2 Land-use map of Reading (Ordnance Survey, 2017).

centers, while the United Kingdom considers "built-up areas" as those that are "irreversibly urban in character" including villages, towns, and cities (Nomis, 2013; US Census Bureau, 2016). Interestingly, the mean population size across these categories tended to be consistent between countries. It is also observed from these data that densities tend to increase with absolute population; meanwhile, relative standard deviations (i.e., standard deviations relative to the mean) of population density tend to decrease as city sizes increase, suggesting greater heterogeneity in smaller cities (Figure 3c).

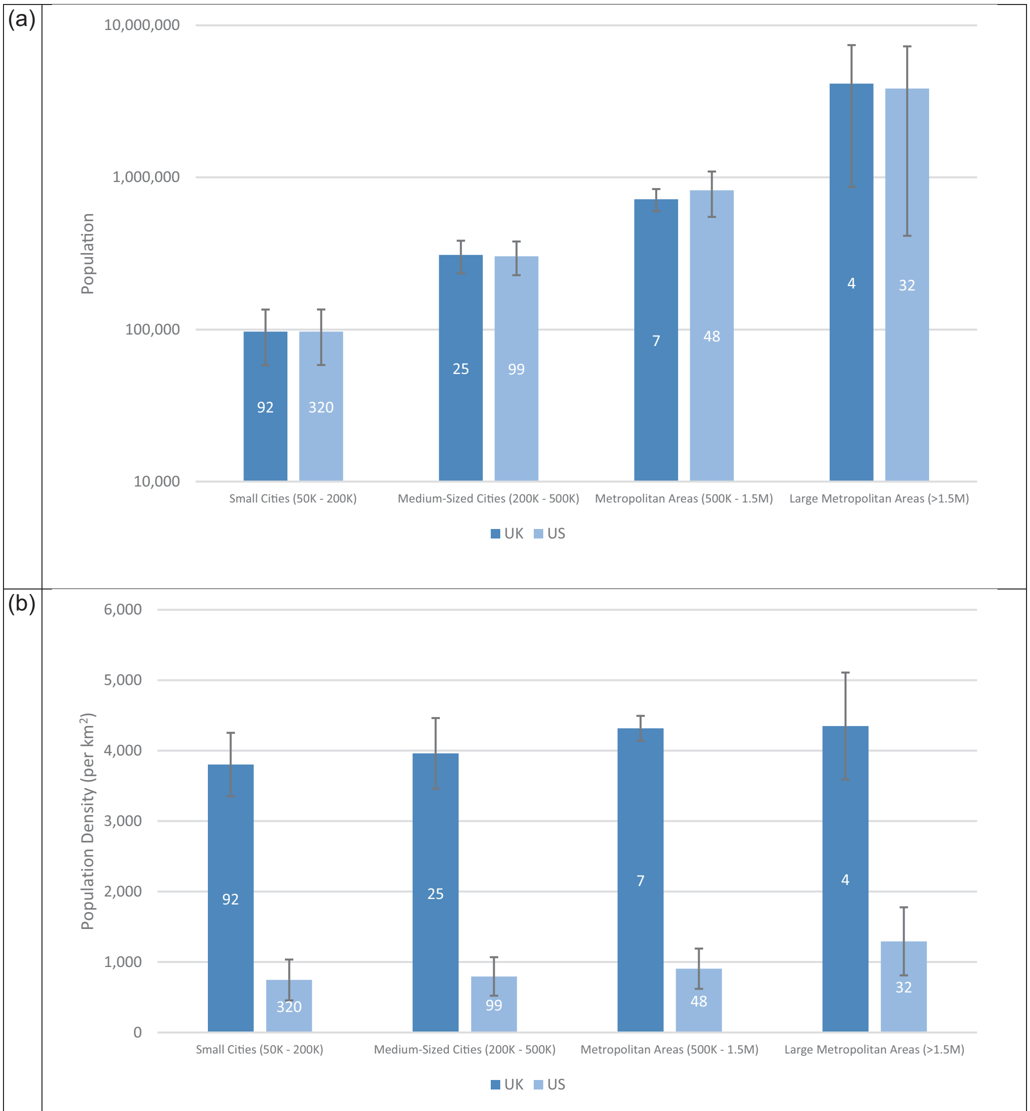
3 | READING'S MATERIAL FLOW ANALYSIS

3.1 | Overview

Reading's MFA is provided in Table S.3 of the supplementary information, covering 2010–2015. A brief explanation of each metabolic flow assessed is provided below, including food (nutrients), water, energy, and waste (as a proxy for materials), to provide context for these data.

3.2 | Water

Reading's water supply is managed by Thames Water, which abstracted, treated, and distributed roughly 16.7 Mm^3 (16,730 kt) of water in 2015. Approximately 70% of all water abstraction each year is taken from groundwater, with the remaining 30% coming from surface water (Thames Water, 2015). Taking data for the Kennet Valley Water Resource Zone, the vast majority (>90%) is used domestically. Leakage and losses were estimated to be over 40%, including distribution, building level, and treatment losses due to the aging infrastructure and housing stock.



(c)

	Relative Standard Deviation for Population Density			
	Small Cities (50K - 200K)	*Medium-Sized Cities (200K - 500K)*	*Metropolitan Areas (500K - 1.5M)*	*Large Metropolitan Areas (>1.5M)*
UK	0.466239	0.162355	0.024489	0.018338
US	0.298859	0.090142	0.034758	0.012569

FIGURE 3 (a) Log plot of mean population. (b) Linear plot of density data of UK[1] and US[2] cities of various types , labeled with standard deviation whiskers and *n* values. (c) Relative standard deviations of population density for UK and US cities; taken[1] from data on 2011 Census Built-Up Areas for England and Wales (Nomis, 2013); taken[2] from 2010 US Census (2016).

3.3 | Energy

Domestic and transportation energy demand data are available, with estimates for the energy carriers within each. Domestic energy consumption is presently dominated by natural gas, supplying over three quarters of the final domestic energy demand and is largely attributable to space heating; this is provided by gas mains, with 73% of all properties in the energy performance certificate database, or 92% if flats are excluded (DLUHC, 2022). With the United Kingdom's decarbonization of housing strategy expected to address these demands over the coming decades, it is expected that heat services will increasingly shift from gas to electricity; current national government targets seek the installation of over 600,000 domestic heat pumps annually by 2028.

Incentives were also in place (2010–2019) to encourage renewable energy deployment, with a feed-in tariff scheme subsidizing generation from small-scale installations including solar photovoltaic, wind, and anaerobic digestion (Ofgem, 2022). All grid-connected installations during the study period were captured within the scheme, and a small but growing contribution of renewable energy inputs are demonstrated. For context, the contribution of in-boundary renewable electricity generation was less than 1% of the total energy input as of 2015.

3.4 | Food

With a relatively small productive arable land area within Reading, agricultural yields are small (~0.09 kt per year). Meanwhile, imports of food are nearly three orders of magnitude greater, at 83,000 kt. The United Kingdom is estimated to have imported 46% of the food it consumed by 2020 (DEFRA, 2021).

Looking at food waste flows, food was estimated to be 25% of total UK household waste in 2018 (Office for National Statitsics, 2021; DEFRA, 2022a). In 2021, a source-separated food waste program was initiated in Reading, with food waste increasingly being anaerobically digested for electricity and fertilizer production going forward (Reading Borough Council, 2022).

3.5 | Waste

Nearly 74 kt of municipal solid waste were collected in 2015, an increase of nearly 5% from 2010. A smaller share (24%) of this was sent to landfills in 2015, although an increasing share (43%) was being sent to waste-to-energy (20% increase relative to 2010); total waste-to-energy capacity in the United Kingdom doubled to 8.48 Mt per year by 2015, with a further doubling to 16.36 Mt by 2020 (Tolvik Consulting, 2016, 2021). Further, it should be noted that the carbon impact of the combustion of residual household waste was 21 $kgCO_2e/t$ in 2015, owing to the fossil carbon component of the residual waste stream (DEFRA, 2022b).

4 | COMPARING METABOLIC FLOWS OF DIFFERING URBAN SCALES

4.1 | Comparing Reading with small/medium-sized French and Danish cities

A study of the metabolism of the metropolitan area surrounding the city Le Mans, France, was conducted for the year 2021 (Bahers et al., 2019). This study of "intermediate cities" also supported the case for the further study of SMCs, as they observed the unique characteristics of these intermediaries between urban demand centers and rural producers. Le Mans Métropole (population 184,000 at the time the study was conducted in 2012) consists of the City of Le Mans (population 144,000; 2017) and 18 other surrounding municipalities. The City of Le Mans extends over 1/3 of the Le Mans Metropole land area but has 70% of the Le Mans Metropole population. The city's economic focus is predominantly agricultural, which provides an additional difference with Reading's service-based economy for comparison.

Reading local authority (161,000 in 2015) has a population comparable to that of Le Mans Métropole which makes the comparison of their UM relevant even across their two different administrative scales. Le Mans Métropole's total land area (157 km^2) is nearly four times the size of that of Reading (40 km^2), even though they have a similar urban–rural land-use distribution, with approximately ¼ of the total land devoted to agriculture and greenspace. Because of the contrasting urban form (low-density urban sprawl is much more prevalent in "intermediate city" Le Mans than in Reading), Reading's population density (4043/km^2) is nearly four times higher than that of Le Mans Métropole (1197/km^2). When comparing using similar administrative boundaries, Le Mans City (143,000 in 2017) has a comparable land area (53 km^2) to Reading, and this difference in density is less pronounced, with Reading's density "only" 70% higher than Le Mans (2707/km^2). A comparison of the total building floor area in each city (or average building floor number) would help ascertain whether this is due to the number of stories in buildings or due to overcrowding in dwellings. In any case, a comparison of the two UMs (Table 2; along with Denmark's Odense and Alborg) allows a valuable exploration of the resource efficiency of two SMCs that are similar in population but differ substantially in the way they organize their land occupation and use.

The metabolism of Odense and Alborg (Denmark), studied by Lanau et al. (2021), can also be compared because of their similar populations to Reading, but different population densities. Despite being considered as a medium-sized city according to the OECD (2012) classification above, Odense (population 197,480 in 2015; density 650/km^2) is the fourth most populous city in Denmark. The economic focus of the city has recently shifted from manufacturing to services. Denmark's third most populous city, Aalborg (population 207,805 in 2015; density 182/km^2), might be considered a similar case. The city is now one of the main green/knowledge economy hubs in Denmark despite its heavy industry heritage and the inclusion of large agricultural areas within its administrative boundaries. Moreover, Aalborg has large agricultural areas that are responsible for the city's higher water demand (industrial water consumption was responsible for 34% of the total in 2015), though its water losses represent a much lower leakage rate than Reading (8%–9% vs 44%). Odense and Alborg have much lower urban densities than Reading (6 and 22 times, respectively) but similar current economies which make them two complementary cases for comparison in addition to Le Mans.

TABLE 2 Annual urban metabolic (UM) flows observed across selected small- and medium-sized cities.

UM flow (t per capita per year)	Reading (2015)	Le Mans (2012)	Odense (2015)	Alborg (2015)
Fossil fuel imports	1.1	2.6	2.0	1.5
Food production	4.5×10^{-4}	3.2[a]	np	np
Food import	0.51	5.2[b]	1.2	1.2
Waste out	0.46	0.66	1.4	1.2
Water in (m^3/cap)	108.4	np	40.9	48.3

Abbreviation: np, not provided.
[a]Includes biomass and minerals.
[b]Biomass, but it is stated that most of this is food.

TABLE 3 Comparison of key urban metabolic inputs and outputs between Reading, European/North American megacities, and global megacities, 2011.

Jurisdiction	Energy demand - Total (MJ/cap)	Energy demand - Ground mobility (MJ/cap)	Water demand (m^3/cap)	Waste production (kg/cap)
Reading	55,300	10,500	108	461
All megacities	56,800	14,800	147	380
Europe and North America	85,900	28,900	146	700

A wide variation in the values of UM flows can be observed across the four cities in Table 2. There is plentiful room for speculation of the reasons for the differences across SMCs below, but correlation (e.g., between urban forms, density, economic structure, and specific resource flows) cannot be investigated without consistent, thorough, and widespread compilation of MFA data. Establishing an SMC-specific MFA approach is an essential first step to this end.

4.2 | Comparisons with megacities

A further comparison can be made with megacities using the global assessment conducted by Kennedy et al. (2015). Examining Table 3, the 2011 per capita resource consumption metrics tend to be lower for Reading, except for waste production. A portion of these differences may be explained by differing quantification approaches or boundaries for data collection; for example, the data gathered for Reading focus on the town itself, while the megacities encompass the city region and all their suburbs—differences in energy demand for ground-based mobility provides a potential indicator of the implications of these differing boundaries. Water consumption is also lower in Reading; is this attributable to the prevalence of service sectors relative to other global megacities, as well as smaller suburban population in relation other European and North American megacities? Are these patterns observed in other SMCs beyond those described in Table 2? We can only speculate. However, the scale of these differences further emphasizes the need for more investigations of SMC MFA.

It is also worth noting that there are dramatic spatial differences within cities, such as the comparison between an urban center and its surrounding suburban development. For example, some case studies have demonstrated that suburban settlements have substantially greater emissions than their denser urban centers (Glaeser & Kahn, 2010; Vandeweghe & Kennedy, 2007) whilst others have demonstrated otherwise (Heinonen & Junnila, 2011; Wilson et al., 2013). Context-specific factors (e.g., urban form, consumption patterns, climate) are crucial for understanding the spatial variation in resource demands and associated environmental impacts across the urban continuum.

5 | CONCLUSIONS AND RECOMMENDATIONS

5.1 | Need for further study, typology development

The main conclusion of this analysis is that these diverse SMCs require further study toward understanding what differentiates them from each other and from larger cities. Additionally, as discussed by others, the application of a uniform method is essential for this type of comparison (Rosado et al., 2016; Voskamp et al., 2017). While comparisons were attempted above, the differences observed may be attributable to several study design factors (e.g., spatial boundaries, inclusions/exclusions of sub-elements within resource flows). This leads to a further conclusion of the value of developing a typology of (SMC) cities to enable reasonable comparisons and understanding how solution sets should differ.

Further, the density of demand plays a role in self-sufficiency, with energy (and, by proxy, distance) influencing the circularity of resource flows; for example, in low-density, single-family housing developments, on-site utilization of (waste) resources (i.e., solar energy, food waste, greywater, and rainwater) may be able to satisfy a greater share of total resource demand (i.e., for compost, flushing, and irrigation, respectively). Studies have also shown the proximity of end-users for resource recovery and circularity (Metson & Bennett, 2015; Metson et al., 2012); might smaller cities have an advantage given their lower density and relatively greater ratio of peri-urban agricultural land to urban land?

Another key factor in the sustainability transition of SMCs is their (degree of) readiness to adopt decentralized infrastructure for resource supply at different levels, from the housing to district level. For example, district heating systems (DHS) that co-generate electricity through incineration have a long tradition in Denmark, and fossil fuels have been increasingly replaced with biomass in their mix (Johansen & Werner, 2022). The share of DHS in total heating demand in SMCs has been increasing overall, including in Odense (from 2010 to 2015), where a decrease in the use of fossil fuels in the DHS mix has also been observed (Lanau et al., 2021). In France, a similar move toward decentralized DHS and district cooling systems (DCS) was discussed in the annual review of DHS and DCS (based on 2019 data; FEDENE and SNCU, 2020) and maps by the French Environmental Agency (CEREMA), with three DHS and three DCS located in the region alongside several surface geothermal installations (IGN, 2023). Thus, if using the case of Denmark and France, the general growing adoption of DHS and DCS could potentially lead to other decentralized options for utility networks in SMCs, both at the district and (even though less developed nowadays) housing levels.

By contrast, in Reading (and as a general tendency in the United Kingdom as a whole; HM_Government, 2021) technological adoption of decentralized low-carbon measures has received more attention at the housing level although solutions might be potentially upscaled to the district level. At present, only 2% of UK households are connected to a district energy system (Energy Technologies Institute, 2018). Given this, it may be prudent to include some measure of technological context when developing a typology, perhaps a measure of infrastructure decentralization to determine its influence on resource demands and their mitigation. Future areas of research for cities of all sizes could include the development of indices of (de)centralization for specific infrastructure systems (transportation, housing, heating, electricity, water, and waste treatment) to enable a deeper analysis of their resultant resource demands.

One potential SMC category is that of an "intermediate city." Previous research on SMCs in France and Denmark compared their socioeconomic metabolism to that of megacities and rural areas. According to Bahers et al. (2019), the metabolism of several SMCs in France can serve as intermediaries for the consumption of rural resources to support larger metropolitan areas; they are geographically situated between rural areas (with higher proportions of consumption to support exports) and large urban centers (with lower relative direct consumption per inhabitant due to reliance on imports). Intermediate cities serve as logistics centers for major metropolitan areas, with most of the flows identified as transiting through them only as hubs receiving resources from more rural areas toward larger cities. Hence imports in these intermediate cities (e.g., Le Mans, Aalborg) may be more likely to be exported than in larger cities. These specific conditions of SMCs as agricultural/industrial logistic hubs might not apply to SMCs in service-oriented economies such as Reading, whose metabolism might be described more accurately as "demand centers" (i.e., less dependent on strong metabolic relations with its hinterland and nearby larger cities), similar to the trade-balanced cities identified by Chavez and Ramaswami (2013). Hence, the wider possible variations in the economic role of SMCs compared to larger cities would make the establishment of a typology of SMCs for UM analysis an essential step forward. Baseline criteria for establishing such a typology should include economic structure as well as other criteria, such as urban form, population density, and technological/infrastructural criteria.

Another key feature in assessing the metabolism of SMCs is the relevance of a territorial focus, through which a clearer understanding of the sources and destinations of resource flows can be embedded into the analysis including their variability depending on the economic structure of the SMC. In other words, the distance between the SMCs and the place where the input and output flows are processed (produced, consumed, and/or disposed of or recycled) can be a key indicator of the nature of the SMCs economy (or vice versa). In this sense, a multiscale approach quantifying the metabolic relations of SMCs with other important co-dependent urban, agricultural, or industrial systems across geographic scales can help address key challenges related to the socio-spatial and political aspects of future resource management in SMCs (Bahers & Kim, 2018; Guibrunet et al., 2017). This is in line with the ongoing discussion on the value of spatial disaggregation within cities and the data challenges (e.g., proxies for required data) associated with the gathering of high-resolution spatially disaggregated datasets for SMCs (Bahers et al., 2022; Peña et al., 2022).

5.2 | Conclusions

Evidence of the policy relevance of SMCs is presented above, making the case for the development of more UM/MFA studies at this urban scale an essential condition to tackle urban transition challenges. This involves a clearer understanding of key criteria and factors that differentiate small cities from large cities or capital cities, which are commonly studied using the UM approach. A typology of SMCs that considers changes in economic structure, urban form, density profiles, and trade dynamics, can be realized if more SMC MFA studies are conducted, allowing for the identification of different paths for decarbonization and dematerialization.

AUTHOR CONTRIBUTIONS

For this research, Eugene Mohareb and Daniela Perrotti both developed/conceptualized the research idea, analyzed data, wrote, and edited the manuscript.

ACKNOWLEDGMENTS

This research received support from the University of Reading Undergraduate Research Opportunities Programme (UROP). Four UROP students (Jayke Morris, David Smith, Ho Yan Ho, and Rory Mattinson) assisted with the data compilation within this study.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

All data used in this study are publicly available and freely accessible from the sources cited.

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NOTES

[1] The Deming cycle is the foundational process of continual improvement (plan–do–check–act) used in environmental management to gain a greater understanding of how to improve a product, process, or service (Deming Institute, 2023)

[2] Small cities are those with 50,000–200,000 inhabitants, while medium-sized cities are those with populations between 200,000–500,000 (OECD, 2012).

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Mohareb, E., & Perrotti, D. (2023). Sustainability transitions require an understanding of smaller cities. *Journal of Industrial Ecology*, 1–11. https://doi.org/10.1111/jiec.13434