Drivers of urban metabolism: Toward a framework for urban transformations

Anastasia Papangelou, Jean-baptiste Bahers, Lynda Aissani

Drivers of urban metabolism: towards a framework for urban transformations[1]

Anastasia Papangelou,[1,3*] Jean-Baptiste Bahers,[2] Lynda Aissani[3]

[1] Sustainable Energy, Air, and Water Technology, Department of Bioscience Engineering, University of Antwerp
[2] CNRS, UMR ESO, Université de Nantes, Nantes, France
[3] Research Unit OPAALE, INRAE, Rennes, France

*Corresponding author : anastasia.papangelou@uantwerpen.be

Abstract: The environmental and social crises in, and of, cities call for radical future visions that can incite transformative change. Yet, urban metabolism research typically adopts an explanatory, retrospective approach to the drivers of urban flows and stocks, resulting in conservative, business-as-usual future outlooks. In this study, we present the results of a narrative literature review on drivers and futures of urban metabolism, and consequently use these results to propose and apply a framework that can be used by researchers (i) to systematically identify the drivers of urban metabolism, and (ii) to critically engage with these drivers for the development of transformative future visions. The framework comprises seven thematic categories of drivers (demographic, economic, cultural, political, technological, environmental and infrastructural) and an eighth category (power) to be used as the lens through which the interactions between drivers, activities, and flows in the city are critically examined. Applying the framework to the case study of biowaste management in Rennes, France, we found it useful for the systematic identification of often overseen drivers. The proposed framework, allowing for a combined analysis of flows and drivers, can become a useful tool towards a solution-oriented urban metabolism research.

---

[1] This is the peer reviewed version of the following article:
Papangelou, A., Bahers, J.-B., & Aissani, L. (2023). Drivers of urban metabolism: Toward a framework for urban transformations. Journal of Industrial Ecology, 00, 1–17, DOI: 10.1111/jiec.13435
which has been published in final form at https://doi.org/10.1111/jiec.13435.

1 Introduction

The year 2022 has been eventful for waste in Rennes, a medium-sized city located in north-west France. Firstly, a new resources and waste strategy (RWS) was approved by the local council, setting the metropolitan area's targets and ambitions for 2030 (Rennes Métropole, 2022a). The document, which is the result of an almost yearlong consultation process with a committee of citizens, defines targets around six main thematic areas: responsible consumption, changing inhabitants' practices, longer product lifespans, decentralized management of biowaste, improvement of collection services, and increased valorization of waste, including energy production from incinerated waste. A few days after the plan was voted, the 54-year old incinerator in the city of Rennes was temporarily closed to enable major maintenance and the replacement of the treatment line equipment, works that will increase the conversion efficiency of electricity by 100% and of heat by 35% (Rennes Métropole, 2022c). These works will cost 103 million euros, i.e. 11% of the total Rennes budget for 2022 (Rennes Métropole, 2022b). Waste reduction and reuse are the stated priorities of the RWS; the budget allocation, on the other hand, tells another story, as more than 100€Mi of public money are spent on strengthening waste-to-energy valorization. Will the future waste metabolism in Rennes be dominated by a general willingness to reuse and reduce, or by the availability of a modern incinerator within the city limits?

The story of the incinerator in Rennes, echoing similar stories around Europe, including Paris, France (Berlingen, 2019), Gothenburg, Sweden (Corvellec et al., 2013), and Zwentendorf, Austria (Behrsin & De Rosa, 2020), exemplifies people's often partial appreciation of the driving forces behind flows and stocks in cities, not only related to waste management systems but to the urban metabolism (UM) in general. Cultural shifts and changing attitudes are easily identifiable driving forces (drivers); re-investment in existing infrastructure, on the other hand, and the resistance to change it entails, sometimes goes unnoticed. Without a comprehensive understanding of all possible drivers, efforts in research and practice towards better resource use in cities may prove ineffectual or counterproductive.

Researchers have recently started to explicitly focus on drivers: Dijst et al. (2018) and Voskamp et al. (2020) identified different categories of drivers (demographic, economic, cultural, etc.), and argued for addressing them as an integral part of analyzing the UM. However, we still lack paradigms to systematically identify drivers and study their influence on metabolic flows and stocks. While long-term research on urban metabolism has provided retrospective insights into how historical, political, and social conditions and events have affected urban metabolic flows, e.g. of food (Billen et al., 2009; Schmid Neset et al., 2008), or energy (Baynes & Wiedmann, 2012; Krausmann, 2013), there has been less engagement in the UM literature with future- and solution-oriented approaches (John et al., 2019) that can go “beyond understanding, to identifying and implementing real-world solutions for urban sustainability” (Childers et al., 2014). Developing and implementing transformative future visions that address structural barriers to change, e.g., the power of existing infrastructure or the goal of economic growth (Angheloiu & Tennant, 2020), is necessary to address the complex social and environmental crises in (and of) cities, such as developing resilience to the climate crisis, or ensuring social justice and cohesion (Cook & Swyngedouw, 2012; Gandy, 2018; McPhearson et al., 2021).

There is, therefore, a two-fold gap in UM research: on the one hand, a scarcity of studies explicitly focused on drivers, i.e. the factors that define and influence flows and stocks in UM; on the other, a lack of research with a prospective outlook on drivers of UM, which could lead to radically different future urban systems. In this study, we seek to fill this gap, by (i) synthesizing existing knowledge on drivers of urban metabolic flows; (ii) proposing a framework for the drivers’ analysis and inclusion in prospective UM studies, and (iii) testing this framework on a case study.

To address these objectives, first, we conducted a narrative review of the UM literature, to identify drivers of urban flows and stocks, and to establish a conceptual framework of the influence that these drivers can have on future states of urban systems (see methodological details in section 2). We present and discuss the findings of this analysis in section 3. Second, we used the insights gained from this review to develop a conceptual framework for drivers of a city's current and future metabolisms (section 4). Third, we tested the framework on a case study (in section 5): the management of biowaste in the metropolitan area of Rennes in France (hereafter Rennes *Métropole*). We conclude this paper with a summary and future outlook in section 6.

2 Methodology

2.1 Literature review: search and analysis

The basis of this study is a narrative literature review in which we combined a systematic search for documents with a narrative synthesis of their content. We opted for a narrative review because the main goal of the study was to deepen our understanding of the drivers of current and future states of urban metabolisms, and to develop a conceptual framework, rather than to compile an exhaustive summary of the research accomplished thus far (Greenhalgh et al., 2018; Torraco, 2005). Recent studies on related topics have successfully implemented this approach (Newell & Goldstein, 2019; Urbinatti et al., 2020).

We searched the database Scopus for published works in English or French that included the string "urban metabolism" AND (driver OR determinant OR factor). The search returned 131 results (last check on March 11, 2023). We then did two rounds of screening (abstracts and full texts), and eliminated studies (i) that did not focus on the drivers, (ii) whose abstracts included the terms of the search string in different contexts, and (iii) studies whose scope was too narrow, i.e. where the focus was on a specific sector (e.g. gravel) or on the description of a specific model, and there was no systematic discussion of what drives the flows and stocks of UM. After this step, 17 papers remained, 13 of which from the field of Industrial Ecology. To diversify this sample and enrich the insights into drivers of UM, we added nine articles, based on our knowledge of the literature. These are mostly interdisciplinary studies that offer critical analyses of urban systems and more radical visions of urban sustainability. The full list of papers included in the final set is given in Table S1 in the Supplementary Information (SI).

Based on our research objectives, we analyzed this set of 26 papers around three main themes:

- Their research field and methodology;
- The drivers of UM they identified and discussed;
- Their approach to future visions and trajectories for UM.

A potential limitation of our methodology is the exclusive use of "urban metabolism" in our search string, which might have excluded disciplines that do not typically use the term (e.g. literature on sustainability transformations). We believe to have partially counter-balanced this limitation by including the additional nine studies in the sample.

2.2 Theoretical framework: urban transformations and drivers of urban metabolism

2.2.1 Drivers of urban metabolism

We based our analysis on the conceptualization of UM developed by Dijst et al. (2018). In this framework, extended by Voskamp et al. (2020) (Figure 1a), material and energy flows and stocks are mobilized by different activities like eating, sleeping, work, mobility etc., to fulfill human needs, e.g., for nourishment, shelter, and transport. The fulfillment of these needs can either be facilitated or constrained by factors such as the existing infrastructure, the standard of living etc. Both the needs and facilitators/constraints are influenced by drivers, i.e., "large scale developments in the societal context […] that cause a particular activity to occur" (Voskamp et al., 2020). These three elements, needs, facilitators/ constraints, and drivers, are together considered the causal determinants of UM.

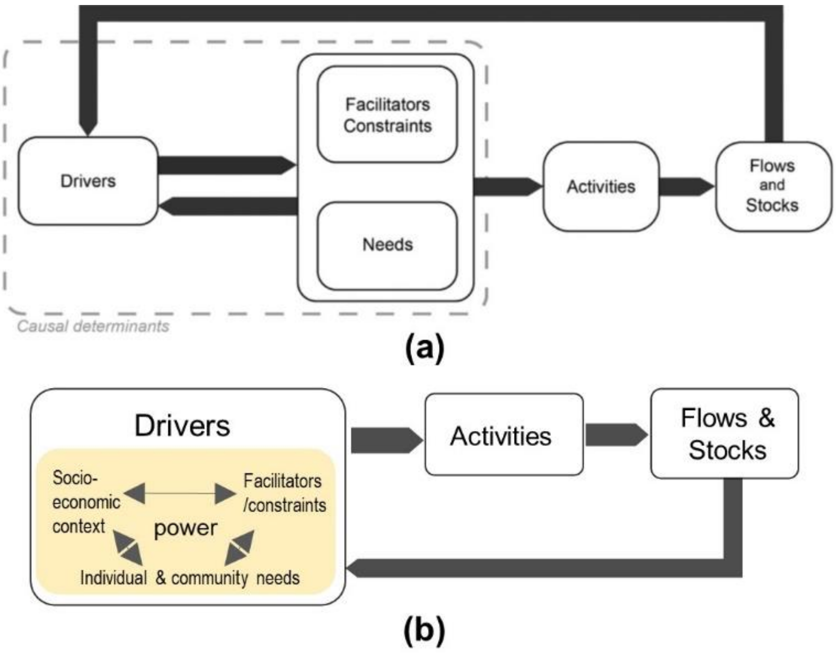

Figure 1 The five interrelated elements of urban metabolism (a) (Dijst et al. 2018) in (Voskamp et al. 2020), and the adjusted version used in this study (b).

In our analysis, we do not distinguish among the causal determinants, but consider them all to be drivers. By doing so, we want to highlight that the activities that occur in an urban system are not necessarily the direct expression of human needs, and that these needs cannot always be clearly distinguished by the socio-economic context within which they are expressed. Research in the field of urban political ecology (UPE) shows that urban resources within a capitalist system are not equally distributed among social actors (Pichler et al., 2017), but are predominantly controlled by elites, and used to serve specific interests (Broto et al., 2012; Heynen et al., 2006). Urban metabolic flows then, like all the socio-environmental processes that produce the city, are an expression of who holds power and a result of the power struggles between different actors (Cook & Swyngedouw, 2012; Heynen et al., 2006). Consequently, resources within a city are not mobilized to simply satisfy human needs and promote human well-being; they are also used to perpetuate the status quo, even if that means accentuating social and geographical inequalities. For these reasons, in our analysis we refer to all causal determinants as drivers, and we bring into focus questions of power and inequalities that affect all causal determinants and their interactions (Figure 1b). We define drivers of urban metabolism all those factors and conditions that influence (i) which activities (can) take place in an urban system and (ii) how these activities mobilize resources, i.e. their type, quantities, origins, flow rates, etc.

2.2.2 Urban transformations

According to the above definition, knowledge on the drivers from an UPE perspective will provide insights on the reasons why resources flow in a certain way within an urban system. However, to harness this knowledge for the production of actionable solutions towards more sustainable urban systems, knowledge on the drivers should connect to future visions, and go beyond describing the past and present (problem-oriented), towards providing tools to think, plan, and implement future actions (solution-oriented) (Feola, 2015). This is a central premise of sustainability transformations research. [Urban] sustainability transformations are fundamental changes within an [urban] system, which have the potential to address wicked problems in their root (Brand, 2016; Frantzeskaki et al., 2021). In addition, transformations research is a transdisciplinary endeavor: it calls for the co-creation of these solutions together with local actors and prioritizes systemic (social & political) changes (Frantzeskaki et al., 2021; Iwaniec et al., 2019) with a focus on justice and equity (Ziervogel et al., 2017). In this regard, [urban] transformation research is both an analytical lens to describe complex process dynamics in the city and a normative orientation that emphasizes the need for systemic and radical change (Hölscher & Frantzeskaki, 2021).

Leverage points is a framework well suited for sustainability transformations research (Angheloiu & Tennant, 2020). Leverage points are small-scale interventions in a system that potentially have a major impact on the system as a whole (Meadows, 1999). Meadows (1999) drafted a list of 12 such leverage points in ascending order of potential for transformational change, i.e. from “shallow” to “deep”. Abson and colleagues (2017) grouped these points in four realms or “system characteristics”, similarly ordered from the shallowest and easiest to achieve, to the deepest and most difficult (Abson et al., 2017; Angheloiu & Tennant, 2020). The four realms are:

- parameters, including those mechanistic characteristics of a system that are easily modifiable and thus often targeted by policy makers, e.g. taxes and incentives, material flows and stocks;
- feedbacks and delays, referring to the ways in which the different elements of a system interconnect;
- design or system structure, i.e. information flows and rules of the system;
- intent or mental models, including the goal of the system (e.g. economic growth), mindsets and paradigms, as well as the capacity to transcend paradigms.

Using leverage points as a framework to explore sustainability transformations has gained popularity with academics and practitioners (Fischer & Riechers, 2019). The discussion on leverage points brings to the surface the importance of values, mindsets and worldviews (deep leverage points) for sustainability transformations, while drawing connections between deep and shallower, more easily influenced leverage points. Additionally, the leverage points framework combines causality and forecasting (where known cause-and-effect relationships are extrapolated to the future) with teleology and backcasting (where phenomena are explained according to the purpose they serve) (Fischer & Riechers, 2019). Combining leverage points with the UM framework can therefore offer a useful tool for connecting past and future in urban metabolism research, as well as critical analysis of the drivers of UM with transformation research towards radically different future urban systems.

3 Literature analysis: approaches, drivers, future

3.1 Approaches to identify and analyze drivers

From the analysis of the 26 selected studies, we distinguished three different approaches that authors use to identify drivers and to investigate relationships between drivers and metabolic flows: *correlation*, *categorization*, and *critical engagement*. Studies within each of these approaches largely share research objectives, methods of analysis, as well as fundamental assumptions and worldviews.

Almost half of the studies fall within the correlation group (Figure2a). These studies seek to establish quantitative relationships between drivers and metabolic indicators (e.g. domestic material consumption (DMC), direct material input (DMI) or energy use), using regression analysis (Athanassiadis et al., 2017; Bettignies et al., 2019; Kalmykova et al., 2016; Kennedy et al., 2015) or decomposition analysis (Chen & Chen, 2017; Deng et al., 2022; Li et al., 2019, 2021; Sun et al., 2023; Zucaro et al., 2014). Studies using statistical methods rely on large datasets on both the metabolic indicators and the drivers, datasets that span multiple years and cover different scales, from a single city or a small group of (related) cities (Chen & Chen, 2017; Deng et al., 2022; Kalmykova et al., 2016; Li et al., 2019; Zucaro et al., 2014), to several cities around the globe (Iablonovski & Bognon, 2020; Kennedy et al., 2015), to intra-urban microscales (Athanassiadis et al., 2017; Bettignies et al., 2019; Porse et al., 2016). Most of these studies explore the relationship between the metabolic indicators and small sets of pre-selected drivers. These drivers are either parameters that are relevant for urban planning (population density, building type) or derive from the IPAT equation, according to which (environmental) Impact is a function of Population, Affluence (or economic activity usually measured with GDP growth), and Technology (Chertow, 2000).

On the other hand, studies that *categorize* drivers adopt a broader view and seek to give systematic accounts of what may constitute a driver, (Peponi et al., 2022; Voskamp et al., 2020), in a descriptive, often theoretical approach (Liu et al., 2005; Wolfram et al., 2016). To tackle the complexity of the task, they often discuss categories of drivers, such as demographic, economic, political, cultural and technical categories.

Finally, studies that *critically engage* with the drivers focus on relations between political and economic powers and on the way that unequal relationships and conflicts shape the material reality of a city. These studies are characterized by their interdisciplinary approaches; most combine industrial ecology (IE) with (urban) political ecology thinking (Broto et al., 2012; Pichler et al., 2017; Pincetl et al., 2012). Such studies may also organize their analysis in categories of drivers, in a combined categorization/engagement approach (Figure 2a, 2b) (Bahers et al., 2020; Dijst et al., 2018; Marin & De Meulder, 2018; Newell & Goldstein, 2019).

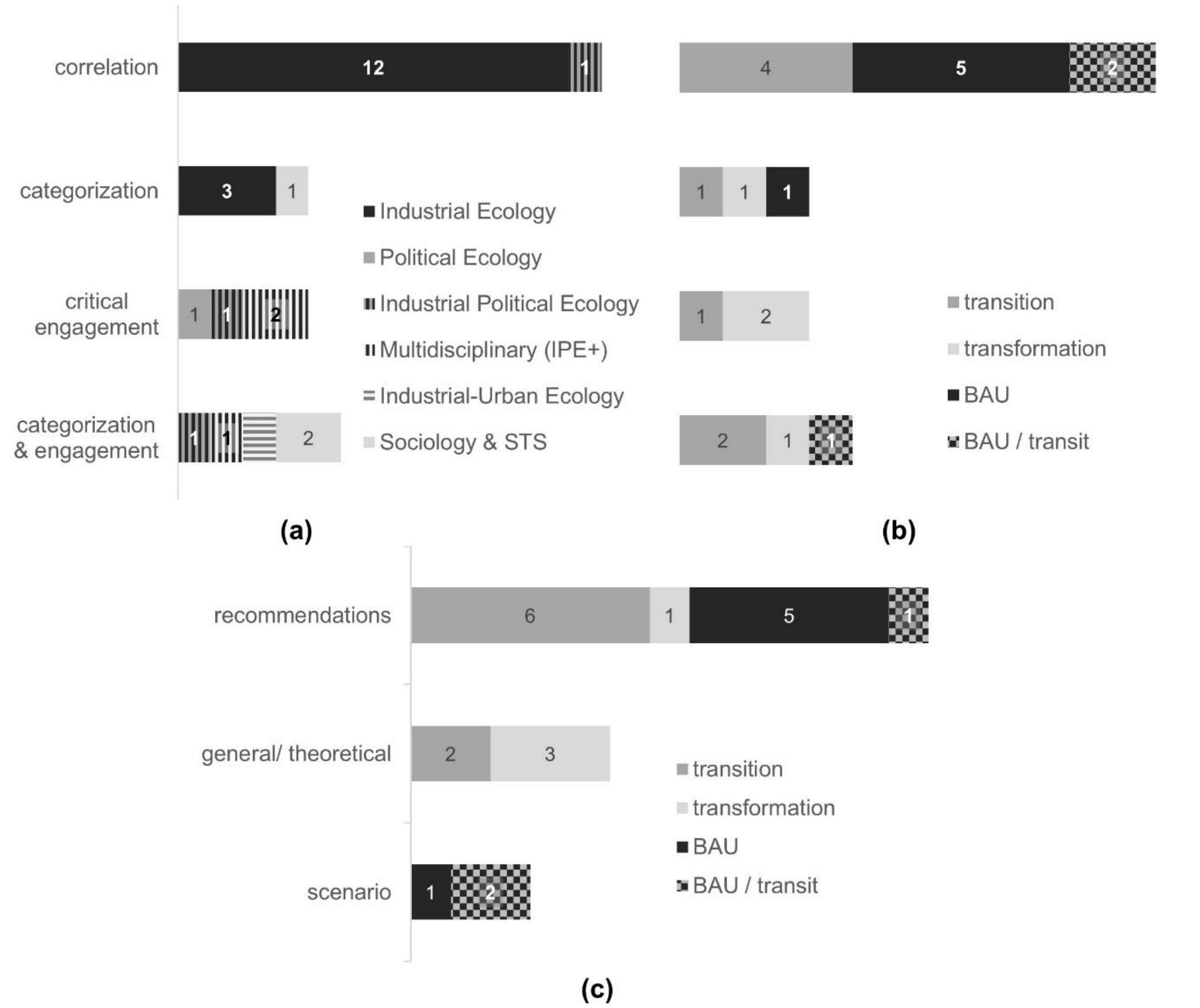

Figure 2 Characterization of the studies analyzed according to their scientific discipline and approach to drivers (a); approach to drivers and future vision (b); and approach to future and future vision (c). BAU: business as usual; STS: Socio-technical systems studies

3.2 Drivers of UM: what influences flows and stocks and how

Each of the three approaches is used to study different sets of drivers. We identified a total of 33 drivers, which we present in Table 1, along with the type of influence they are reported to have on specific flows or metabolic indicators, and future perspectives related to them. We categorized the drivers into nine thematic groups, following those studies that also use some type of categorization. The groups are the following (further details are given in Table 1):

- *Demographic drivers*, such as population size and household characteristics;
- *Economic drivers*, such as economic activity (usually measured through GDP) and household income;
- *Technological drivers*, for example, related to energy efficiency, emission intensity etc.;
- *Political drivers*, including urban policy and planning, rules & regulations etc.;
- *Cultural drivers*, such as the lifestyles and standards of living of urbanites, the levels of environmental awareness, etc.;
- *Environmental drivers,* related to the natural environment and geography of the urban system, e.g. climate and the availability of specific local resources;
- *Infrastructural drivers,* related to infrastructure and urban form, including the types and characteristics of the buildings, urban sprawl and the existence of specific infrastructure;
- *Power*, a distinctive group of drivers encompassing questions of money and power and the ways in which conflicts and inequalities manifest themselves in urban systems and shape metabolic flows and stocks (e.g. uneven urban-rural relationships).

Demographic and economic drivers were the most commonly studied. Population size is addressed in fourteen and population density in seven studies; economic activity, represented by GDP, is included in twelve studies, while the other four economic drivers are each included in between three and six studies. In contrast, the majority of the other drivers (cultural, natural environment, infrastructure etc.) are each included in one to three studies, with the exception of urban form that is included in five. One reason why population size and economic activity are so popular could be the availability of data on them in easily accessible datasets that cover extended time series and different spatial scales. Data availability is an important consideration especially for studies of the data-intensive *correlation* type (section 3.1). In addition, population size and economic activity are two of the three independent variables of the IPAT equation. By focusing on these two parameters, the studies validate the IPAT framework at the expense of exploring new insights into what influences metabolic flows and stocks. What is more, it is sometimes difficult to discern the concrete influence that a driver has on a flow or the UM; authors may mention a driver and include it in their analysis, but not explain which flows it affects and how(note how in Table 1 there are typically more sources listed in column 4 than explanations on the influence of each driver in column 3).

Finally, some of the most frequently studied drivers for which relationships between drivers and metabolic indicators have been established, are addressed in studies in the correlation group (Athanassiadis et al., 2017; Iablonovski & Bognon, 2020; Voskamp et al., 2020). Studies that go beyond correlation to investigate causal relationships are typically those in the *power* group. For example, capital accumulation and wealth flows are considered key to understanding the material base of society (Broto et al., 2012; Pincetl et al., 2012), especially of cities, as capital accumulation in cities is sustained by unequal material and energy exchanges with poorer, distant places (Bahers et al., 2020; Broto et al., 2012). Unequal exchanges between cities and hinterlands, together with intra-urban inequalities and conflicts between actors, e.g., around infrastructure and local resources, are the "drivers [that] determine access to, control over, and use of resources" (Pichler et al., 2017). Engagement with these types of issues could therefore provide important insights into the factors and conditions under which urban metabolism develops and functions.

3.3 Future visions

Most of the 26 studies do not explicitly engage with questions concerning the future. Five of them do not address the future at all, and another thirteen only do so indirectly by providing policy and research *recommendations* (Figure 2c), e.g., policy incentives to reduce consumption (Bahers et al., 2020; Kalmykova et al., 2016), to increase the energy and resource efficiency of buildings (Athanassiadis et al., 2017; Kennedy et al., 2015; Li et al., 2021; Zucaro et al., 2014), or to pay closer attention to local contexts and resources (Bettignies et al., 2019; Zucaro et al., 2014). Three studies created specific future *scenarios* that were then evaluated and compared with the current situation (Chen & Chen, 2017; Peponi et al., 2022) and with each other (Marin & De Meulder, 2018). The last group of studies engage with questions about the future in an explicit yet *theoretical* way. These studies discuss (urban) sustainability transitions and transformations (Pichler et al., 2017; Pincetl et al., 2012; Wolfram et al., 2016), and propose tools and concepts to further advance the study of urban futures (Broto et al., 2012; Dijst et al., 2018).

Table 1 Inventory of the factors that influence metabolic flows and metrics, as identified in the literature surveyed, their influence on current states and envisioned future implications. The column "Sources" lists the studies that include the driver in their analysis.

Category	Driver [No of studies]	How the driver influences metabolism	Sources	Future perspective: Recommendations (Rec), Scenarios (Sc), General/theoretical (Gen)
Demographics	**Population size [14]**	Increasing population leads to higher total energy and water consumption (1,24), increase in absolute metabolic indicators, such as DMC & DMI (2), growth of material consumption (3), and material stock accumulation (24) Cities with higher populations have lower per capita energy consumption (5) and lower per capita gas & electricity consumption (7)	1, 2, 3, 4, 5, 6, 7, 9, 10, 11, 12, 18, 24, 25, 26	**Rec – BAU**: Policies and measures to control the size of the population (no details provided) in order to promote sustainable development (4); **Sc – BAU**: population growth as a variable in scenario building (6)
	Population density [7]	Higher density correlated with higher DMC (2), reduces per capita energy use at intra-urban scales (5, 7), and reduces energy used for transportation (11)	1, 2, 5, 7, 9, 11, 18	**Rec – BAU**: Voluntary relocation policies to reduce population density (12)
	Home ownership [1]	Energy use (both total and per surface area) is slightly higher in owned houses and majority owner buildings; differences are attributed to differences in income (9)	9	
	Socio-demographic profile of households [2]	Factors such as gender, age, income, education level etc. affect lifestyle choices such as transport, residential choices, and consumption patterns (21); negative relationship between household size and per capita energy consumption (24)	21, 24	
	Human Development Index (HDI) [1]	A higher HDI indicates a "more developed" country, i.e., one where most of the metabolism is externalized and the flows consequently hidden (18)	18	**Rec – BAU**
Economy	**Economic activity/ level of economic development [12]**	Increasing GDP connected to increasing water and final energy consumption (1), increased material consumption across cities (3, 4), increased DMC (10), growth in electricity use and fossil fuel consumption (11), and material stock accumulation (25) DMC remains constant with growing GDP/capita (10) Fossil fuel consumption dropped with increasing GDP for Stockholm (10)	1, 2, 3, 4, 10, 11, 12, 16, 18, 24, 25, 26	**Rec – BAU**: Policies and measures to control the economic growth (no details provided) in order to promote sustainable development (4); **Sc – BAU**: value added as a variable in scenario building (6) **Rec – Transition** : "further dematerialization and stronger decoupling rely on mass adoption of renewable energy and the circular economy and innovation in green markets and products."(26)
	Household income [6]	Increased income, connected to increased educational level, reduces DMC (10) No correlation between income and energy use (5)	5, 7, 9, 10, 11, 24	

	Structure of the economy [6]	De-industrialized cities, with a large tertiary sector, have overall lower resource consumption because the household & service sector rely mostly on hidden flows in hinterlands (1,2) No clear indication of correlation (3,4,6) Construction sector dominates stock accumulation (25)	1, 2, 3, 4, 6, 25	**Rec – Transition**: "a service-oriented economy may probably stimulate a more material-intensive mode of life"(26)
	Total consumption [4]	A higher per capita volume of consumption increases the city's carbon footprint (6) Increased material consumption is offset by higher material intensity (consumption per GDP or per capita (4))	3, 4, 6, 10	**Rec – BAU**: prioritize policies to optimize the intensity of material consumption (4) **Rec – Transition /BAU:** target consumption of non-fossil materials, e.g. electronic goods and textiles by promoting smaller dwellings, renovating products and a sharing economy; change consumption-related norms & values (10) **Rec – BAU**: Reduce unnecessary waste and luxury (12)
	Consumption structure [3]		3, 4, 6	
Culture	**Lifestyles & living standards [3]**	Increases in income lead to changes in lifestyle / a higher standard of living, and hence higher consumption of resources, such as fossil fuels, and higher DMC (10); a modern urban way of life means more water and energy consumption (24)	1, 10, 24	**Rec – Transition:** Policy action to change social norms and values related to consumption (10)
	Environmental awareness [1]	Increased environmental awareness reduces water and electricity consumption (1)	1	
	Car ownership [1]	A growing car fleet increases total fuel consumption, despite cars being more fuel-efficient (10)	10	
Politics	**Educational campaigns [1]**	Educational campaigns as a response to drought conditions reduce water consumption (1)	1	
	Rules & regulations [2]	Restricting irrigation to specific dates and times reduces water consumption (1)	1, 23	**Rec – Transformation**: Changes in legislation can prevent infrastructural lock-ins (23)
	Policy & planning [3]	Examples of policies that have reduced resource consumption: the initiative to replace petroleum use in Paris and coal in Hong-Kong, the introduction of a congestion fee in Stockholm and the adoption of energy efficiency codes in Los Angeles (1); policies that regulate building energy, the electricity mix and energy use for transportation, and waste management (10)	1, 8, 10	
	Agency & capacity [1]	Urban transformations are enabled or constrained by embedded actors: their motives, discourses, and	8	

		coalitions, as well as the institutions, resources, skills, and interactions needed to empower actors.		
Environment (& geography)	**Climate (average temperature, HDD) [4]**	Climate influences heating and cooling demand (HDD and CDD) and hence energy and fuel use (1, 11), although the actual influence may be weak compared to other factors that drive building energy use (1)	1, 11, 18, 24	
	Natural resources availability [3]	Examples: presence of a river for hydropower, locally available materials for use in industry	1, 17, 24	**Sc – Transformation**: Local materials are envisioned as "commons" in a scenario/vision that is "inclusive, ecological and post-growth, an activist spatial practice", not compromising on the values of solidarity and resilience (17) **Rec – BAU**: Optimize local resource use, such as photovoltaics, and recycled materials & water (12)
	Place (spatiality, locality, relationality) [2]	Systemic change and systemic reconfiguration are embedded in places; Agency transcends spatial, sectoral and system boundaries	8, 17	**Gen – Transformation**: the process and the outcome of changing the systemic configuration of urban areas, mostly studied with a view to its sustainability performance or achievements (8) **Rec – Transition**: Local drivers and local context "should be taken into greater consideration in policy making in order to more effectively assist cities into their sustainable transitions" (5)
Technology	**Gains in conversion/ resource efficiency [4]**	Small-scale innovations, such as gains in energy conversion efficiency have probably reduced energy consumption (1) Energy efficiency improvements responsible for per capita energy use remain stable (9) Growing resource efficiency the most important driver of resource use and emissions (26)	1, 9, 17, 26	**Rec – BAU**: Policy interventions at regional and national level to improve resource utilization efficiency can reduce resource consumption and environmental pressures (3) **Rec – BAU**: energy efficiency policies to reduce energy consumption (9, 11) **Rec – Transition:** Identifying the most energy efficient drivers and type of territorial organization can help cities and countries to decarbonize (7) **Sc – BAU**: Focusing on resource efficiency is a central point of the techno-infrastructural perspective of the 'circular city' (17)
	New technological inventions [2]	Increased motorization in the twentieth century increased petroleum consumption (1)	1, 17	**Sc – BAU**: "Clean technology" is also part of a techno-infrastructural perspective (or technocratic agenda to optimize flows) in the circular city (17)
	Emission/ energy/ material intensity [3]	The higher the emission intensity, the lower a city's carbon footprint (6) CO_2 emissions of the city increased despite the decreasing energy intensity of the economy (12) Increased material intensity inhibits stock accumulation (25)	6, 12, 25	**Sc – BAU**: The intensity of CO_2 emissions as a variable in scenario building (6) **Rec – BAU**: Policies to shift from coal and oil to natural gas (less CO_2 intensive) and less energy intensive industrial processes (12)

Infrastructure (& urban form)	**Urbanized area [5]**	The extent of green space is (weakly) correlated with higher resource consumption (2) Compactness is weakly correlated with metabolic indicators (2) Per capita urbanized area (indicating more floor area per person) is significantly correlated with per capita energy use (11) Floor area per capita is weakly correlated with an increase in DMC, because residential projects need less material than infrastructure (10) Urban-rural structure (inverse of urbanization rate) has a weak effect on urban stock accumulation (25)	2, 10, 11, 21, 25	
	Building types & characteristics [2]	Older and less efficient buildings in lower income neighborhoods of the city require more energy per surface area (9)	9, 15	
	Transport forms [2]	Public transport is (weakly) correlated with higher resource consumption (2)	2, 21	**Rec – Transition**: Promoting public and active modes of transport will probably not alter resource consumption much, because such modes of transport are implemented in cities that outsource most of their flows like city centers, and cities with a strong tertiary sector (2)
	Interdependence of infrastructure [1]	For example: if district heating is linked with an incineration plant, it will be difficult to change the plant (23)	23	**Rec – Transformation**: Constructing legitimacy around new emerging practices, laws, and physical infrastructures (23)
Power	**Capital accumulation, flows of wealth [4]**	We need to understand the institutions, rules, money and power flows, and the governance and practices that drive flows of wealth and make the economy function	13, 14, 19, 20	**Gen – Transformation:** visions of the ideal city or of a good city are ultimately driven by those who govern urban flows (13); steady state economics & degrowth (13) **Gen – Transition**: From the sanitary, modernist city to the sustainable city (14)
	Rural-urban relationships [2]	Urban flows shaped and continue to shape inequalities between the city and the countryside (13); sometimes synergetic relations like proximity, autonomy (22)	13, 22	**Rec – Transition**: Energy autonomy at an inter-territorial scale between city and region (22)
	Intra-urban inequalities / social differentiation [3]		9, 13, 20	
	Power relations & conflicts [3]	Conflicts around infrastructure, local resources, hidden flows	19, 20, 22	**Gen – Transformation**: to transform society-nature relations in a more democratic and sustainable way (20) **Rec – Transition**: Focus public policy on hidden flows (22) **Rec – Transformation**: Construct legitimacy around new emerging practices, laws, and physical infrastructure (23)

Concerning the type of future vision represented in each of these studies, we distinguished three different attitudes or visions of what an imaginable or desirable future could be:

- a *business-as-usual (BAU)* vision, in which scenarios and recommendations refer to a future state of the system that is merely an extrapolation of the present, e.g., (Li et al., 2019, 2021);
- a *transition* to a more sustainable future state. Here we refer to studies whose authors use terms like ecological or energy transition, e.g., (Bahers et al., 2020; Bettignies et al., 2019; Dijst et al., 2018; Iablonovski & Bognon, 2020), and to studies that refer to more sustainable future states, e.g. (Athanassiadis et al., 2017; Bettignies et al., 2019; Voskamp et al., 2020);
- a *transformational vision* of a radically different future. Such studies explicitly name the type of radical vision they consider, e.g., a post-growth economic system (Broto et al., 2012; Corvellec et al., 2013), or they discuss the need for transformational change to address the challenges of the Anthropocene (Pichler et al., 2017; Wolfram et al., 2016).

Business-as-usual (BAU) visions are the most frequent approaches and are mostly found in studies that analyze demographic, economic, and technological drivers (Table 1). For example, Chen and Chen (2017) develop future BAU scenarios by extrapolating four parameters: carbon intensity (technological driver) population growth (demographic driver), final consumption, and value added (economic drivers). Other studies propose policies to control population size and economic growth (Li et al. 2019), to limit the consumption of non-fossil materials (Kalmykova et al. 2016), and to improve resource and energy efficiency (Kennedy et al. 2015; Li et al. 2021; Marin & De Meulder 2018; Porse et al. 2016). *Transitions* are linked to cultural drivers, e.g. changes in lifestyle (Kalmykova et al. 2016), the need to consider local contexts and resources in UM studies (Bettignies et al. 2019), and questions of infrastructure such as public transport (Iablonovski & Bognon 2020). More generally, transitional and *transformational visions* are usually expressed in relation to drivers that have to do with infrastructure, geography, and power. Transformational visions include the sustainable city, as opposed to the sanitary modern city (Pincetl 2012); energy autonomy at the territorial scale (Bahers et al. 2020); and steady-state economics and degrowth (Broto et al. 2012).

The overall trend in our set of studies is one of incidental engagement with the future, and of mostly conservative, business-as-usual future visions. What is more, there are often inconsistencies between the drivers that are analyzed and the kinds of recommendations made (notice how some of the future perspectives in the last column of Table 1 refer to studies that are missing from the respective drivers column). Among the twelve studies that documented the correlation between growing GDP and resource consumption, only one provided a relevant recommendation to "measure and control economic growth" (Li et al. 2019) and another one pointed to the need for decoupling GDP growth from material consumption (Sun et al., 2023). In contrast, six studies recommended improvements in resource utilization efficiency, although they did not actually address efficiency in their analysis (Athanassiadis et al. 2017; Kennedy et al. 2015; Li et al. 2021). In other words, studies show that economic growth correlates with a growing urban metabolism, but to contain this growing UM, they recommend increasing efficiency. This is telling of the need for a more targeted engagement of UM studies with future visions that can serve as roadmaps for transforming urban systems.

4 A framework to identify drivers and use them to envision the future

To sum up, the two main trends we identified in the literature on drivers and futures of UM are that (i) concrete visions of the future, especially radical ones, are usually not included in studies that address drivers of metabolic flows, and (ii) a focus on demographic, economic, and technological drivers links to business-as-usual visions of the future, while a discussion of power & inequalities to transformative ones. This last observation is in line with literature on leverage points (Meadows, 1999), according to which, questioning power, rules and paradigms in a complex system has the potential to reveal deep leverage points and bring about radical change.

Using leverage points terminology, the literature on drivers of UM we analyzed is predominantly concerned with *parameters* (technological and economic drivers) and emphasizes causality and forecasting, i.e., providing recommendations and BAU visions of the future. We visually summarize this approach in the top panel of Figure 3 (Future: BAU). In contrast, we argue that, to bring about the radical change that is urgently required in the city of the Anthropocene, we need to focus more sharply on deep leverage points. This means accounting for feedbacks and delays, i.e., the ways in which drivers, activities and flows interact and interconnect, and engaging with a greater variety of drivers of UM, e.g., political and cultural ones that co-shape the rules of the system. In order to establish causal relationships between the drivers, activities, and flows in the city, a critical engagement with questions of power, money and inequalities is needed, borrowing tools and concepts from UPE. This is necessary to move beyond a technocratic view of the city, towards a deeper understanding of where the leverage for greater change lies: in shifting the goals of the system, e.g. economic growth (Broto et al., 2012), mindsets, e.g., the ideal of a "sanitary, modern city"

(Pincetl, 2012), and paradigms, e.g., taking invisible hinterlands for granted (Bahers et al., 2020) or normalizing the domination of certain world regions over others (Pichler et al., 2017). Our re-worked version of the conceptual framework of UM to account for future visions is summarized in the bottom panel of Figure 3. In this framework, shallow and deep leverage points come together to facilitate the systematic identification and analysis of the drivers of UM (causality); the analysis of the relationships between the identified drivers and the resulting activities and resource flows and stocks can lead to the formulation of clear, transformative future visions, as well as the trajectories needed to reach them (teleology).

The following section documents how we applied this framework in the case study of biowaste management in Rennes.

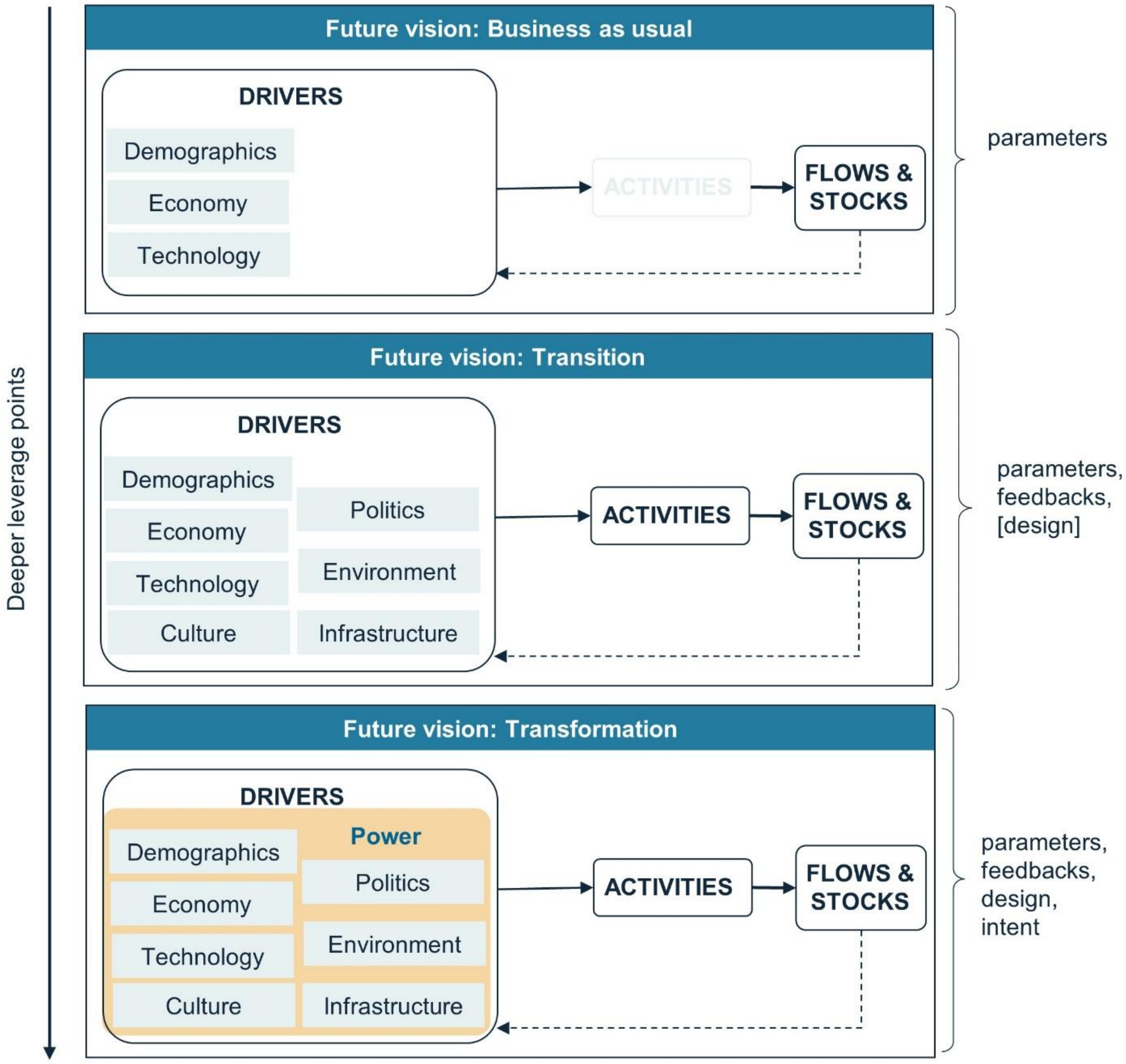

Figure 3 Proposed framework to understand and operationalize the link between the drivers of metabolic flows and three common future visions: business as usual scenarios (BAU, top panel), transitions (middle panel) and radical visions of the future (transformation, bottom panel).

5 Implementation of the drivers/flows framework: the case of biowaste in Rennes *Métropole*

5.1 Biowaste management in Rennes *Métropole*

As a last step, we applied the framework on a case study, i.e., the management of biowaste in the metropolitan area of Rennes (460’000 inhabitants). The case study was conducted independently for broader research purposes and the data gathered were then analyzed in an exploratory way using the framework in Figure 3. Actual future visions and trajectories will be developed at later stages of the research project.

Biowaste in Rennes (in this study, ‘biowaste’ refers to everyday food waste and green/garden waste generated by households and small businesses) is mainly collected together with residual municipal solid waste (MSW) and incinerated. Large quantities of green waste are collected separately at recycling parks and composted at centralized platforms (Figure S5). Decentralized composting, both at the individual and community scale, is well established (Bahers & Giacchè, 2018), with approximately 500 sites throughout the region (Rennes Métropole, 2019).

To implement our driver/flow framework, we first developed a simple MFA model for biowaste management in Rennes *Métropole* over the last 20 years (for details on the model see Table S2, Figure S3, and (Aissani et al., 2022)).

Next we assembled an inventory of potential drivers, based on the analysis of relevant regional planning and policy documents, including waste management and circular economy strategies at the metropolitan and regional levels, and semi-structured interviews with 12 stakeholders from the public, private and associative sectors. For details on the documents consulted and the guide used for the interviews, see (Aissani et al., 2022).

5.2 Biowaste flows: past and present

Municipal organic waste in Rennes Métropole is collected door-to-door from households, services, and small business (together termed “small producers”) and incinerated (Figure 4). The fly ash from the incinerator is landfilled, and the bottom ash exported for treatment and reuse in road construction. Green waste from private and public green spaces is collected at several recycling parks and composted at large-scale, centralized composting platforms. We assume that this compost is reused within the metropolitan area. Despite the emergence of new ways for managing biowaste, such as decentralized composting and anaerobic digestion, the situation in Rennes has changed little over the past 10 years (see also the diagram for 2010 in Figure S4 of Supplementary Information).

Table 2 Examples of drivers of biowaste flows in RennesMétropole as identified through the analysis of stakeholder interviews (1) and of public documents (2).

Category	Driver (general)	Drivers specific to Rennes (examples)
	Drivers for Future vision: Business as usual	
Demographics	Population size	None
	Population density	None
	Home ownership	None
	Socio-dem. profile of households	None
Economy	Economic activity/ level of economic development (GDP)	The French ministry of environment sees the Circular Economy as a means to protect the French economy against reliance on imports (2)
	Household income	The current waste tariffication system, based on the polluter pays principle, may perpetuate social injustices (1)
	Structure of economy economic specialization	Social & Solidary Economy are key for local innovation (2)
	Consumer products' consumption	Improving the efficiency of the current models for production and consumption is one of the priorities at the regional level (2)
Technology	Efficiency of treatment technology	Advanced nutrient removal technologies are needed, because soils in Brittany are susceptible to leaching (2)
	Emerging technologies	If anaerobic digestion is implemented, it needs to be adapted to the specific territory (1,2)
	Emission/ energy intensity	Green transport is needed to avoid high emissions from waste collection (2)
	Drivers for Future vision : Transition	
Culture	Lifestyles & living standards	Reuse & recycling make waste and overconsumption visible (1)
	Levels of environmental awareness	People who are informed of how much they waste they compost more (1)
Politics	Educational campaigns	Central role of authorities to accompany citizens, raise awareness, and set the conditions (2)
	Rules & regulations	National laws regarding Circular economy with obligation for source separation will come into force by 2023 (2)
	Policy & planning	High costs of separate collection important for Rennes; budget mostly for collection, not prevention (1)
	Agency & capacity	Enhanced capacity of users & an established framework for composting are key to the success of composting (2)
Environment (& geography)	Climate (average temperature)	Wet weather leads to lots of garden waste (2)
	Local resources	Biowaste is an important local resource. Rich soils in Brittany, susceptible to N & P leaching due to livestock (1)
	Geography	Proximity of agricultural land/ outlet. A radius of 30-50 km for the valorization of biowaste (1)
Infrastructure (& urban form)	Building characteristics	Apartments vs houses with garden (2)
	Urban density/ urbanization degree	Dense, urban city center vs rural areas in periphery (1)
	Transport forms	None
	Existing infrastructure	Need to feed existing digesters (1)

Drivers for Future vision : Transformation		
Power	Capital accumulation, flows of wealth	Private actors prefer big perimeters & infrastructure for high investment (1)
	Rural-urban relationships	Digestion mostly used to hide the problem of manure & presented as a green solution (1)
	Intra-urban inequalities / social differentiation	Need for more and different solutions, according to the citizens' need (not everyone can or wants to compost) (1)
	Power relations & conflicts	Citizens feel like their voice is not heard (1)

5.3 Identifying main drivers and influences

In parallel with the development of the metabolic model of the biowaste flows in Rennes, we compiled an inventory of the drivers of these flows based on the analysis of our stakeholder interviews and of public documents. We were able to identify drivers in all the categories listed in Table 1 and section 3.2 except for demographics (see Table 2 for representative examples of the different drivers and Table S6 for the full list). This is probably because the influence of demographic drivers on the urban metabolism is obvious (e.g. an increase in population increases total material consumption) and almost impossible to influence (i.e., the socio-demographic characteristics of households, such as size or education level). In general, however, the eight categories of drivers proved to be a useful framework for the compilation of the inventory.

Political and cultural drivers, especially environmental awareness, educational campaigns, and policy & planning, were frequently mentioned during stakeholder interviews and in the public documents. These drivers reflect the emphasis on waste prevention of the RWS, and thus on the role that citizens/consumers will have to play in implementing the strategy. In fact, raising awareness and providing training and resources to citizens is central to how Rennes *Métropole* sees its role in waste management (Rennes Métropole 2022c), in addition to providing waste collection services. This emphasis on individual action is logical when the focus is on household waste, but at the same time it obscures the ways in which decisions and actions upstream of the consumer (e.g. packaging, retail options) could reduce waste at the household level.

The discourse of local authorities in the various reports and policies we analyzed emphasizes politics and technology (see Table 2). On the other hand, stakeholders were more inclined to discuss drivers related to power. They pointed to tensions and conflicts between actors, neighborhoods and territories, such as the unwillingness of some powerful industrial actors to adopt more environmentally sound practices, or the current waste tariff system that favors wealthier classes and perpetuates inequalities. Stakeholders also discussed power relations between different actors and highlighted the need for territorial complementarity, as well as

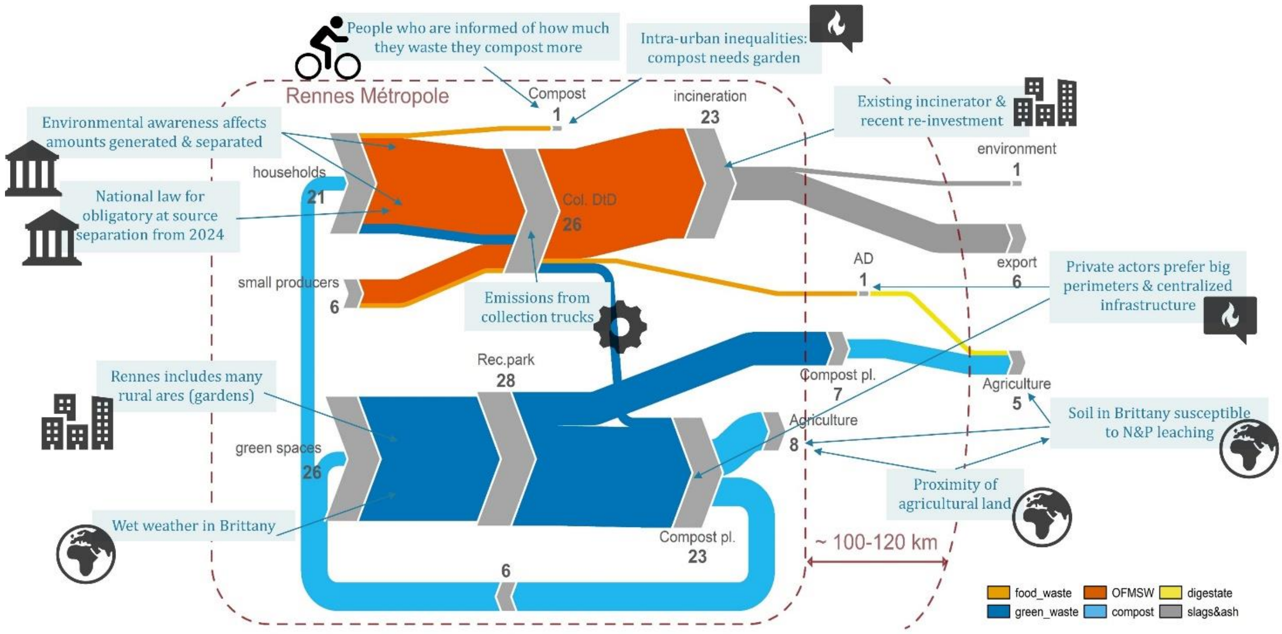

Figure 4 Flows of household organic waste in Rennes Métropole in 2019 (kt/y of fresh weight) and link to some of the drivers identified from interviews and document analysis. For an interpretation of the icons next to the drivers' boxes, which represent the category of the driver, see Table 2. AD: anaerobic digestion; DtD: door-to-door; OFMSW: organic fraction of municipal solid waste; Rec.: Recycling; Compost pl.: Compost platform

the need to reduce inequalities and to implement citizen-centered infrastructure. Although the variety of drivers related to power & inequalities was inevitably stimulated by the type of questions we asked during the interviews, it was precisely by asking these questions that we were able to get such a rich engagement with socio-political and territorial issues, beyond the typical technological drivers.

5.4 Towards a critical drivers/flows framework

Having applied the proposed framework to the case study, we can confirm that it is a useful tool to identify a wide range of drivers, and to locate blind spots in the strategies designed by public and private actors. In a final step, we have tried to combine the two main results of the case study and to outline the links between the drivers and the metabolic flows (Figure 4). Drivers can influence the urban metabolism in different ways: they can affect the quantities of flows (e.g., wet weather in Brittany favors the generation of green waste), direct flows in specific ways (e.g., educational campaigns can motivate more people to compost), or influence the nodes of the system (processes), which then will attract and distribute flows differently (e.g., the proximity of agricultural land or the preference of strong economic actors for centralized treatment processes).

Combining drivers and flows in the same visualization can help stakeholders to identify key drivers and leverage points towards desirable future states, and to draw the trajectories towards these states. It can also reveal causes of resistance to change, e.g. power struggles and inequalities that are usually not addressed in metabolic models. This way, such a combined analysis can allow for transformational future visions to emerge and trajectories towards them to be designed and implemented. Future research on the application of the proposed framework would allow to further appraise its usefulness and applicability, and result in more actionable, solution-oriented urban metabolism research.

6 Conclusion

In this study, we analyzed the literature on the drivers and future states of urban metabolism, and proposed a framework for developing this line of research. We highlighted the lack of, and need for, engagement with radical future visions of UM, beyond business as usual. To achieve this goal, we propose the systematic identification of the drivers of UM, and their critical examination under the lens of the power conflicts and inequalities played out in the city. We argued for studying the drivers from the perspective of leverage points, i.e., moving beyond drivers as explanatory variables of the current situation, to drivers of change, i.e., factors with the potential to leverage transformative change. Engaging with questions of power and inequalities, including capital flows or the unequal distribution of power in territories, can help to understand and mobilize deeper leverage points. Radical future visions of cities should account for these deep systemic root causes of the way urban metabolisms develop and function, as well as for the accelerating crises of the Anthropocene, e.g., the climate crisis, the decline in soil fertility, or persistent inequalities (see for example (Crownshaw et al., 2019; Kemp et al., 2022). No matter how dire, it is necessary to engage with these realities, to be able to develop realistic, transformative visions for the future of cities and beyond.

Acknowledgments

We thank Pierre Thiriet for designing Figure S5 and for his many contributions to the BEECOME project; Mathieu Maguet and Ariane Mathgen for their assistance with data collection; the colleagues at UR OPAALE in Rennes for discussions and feedback; and the three anonymous reviewers whose comments and feedback greatly enhanced the quality of this manuscript.

This research was funded by ADEME, as part of the research project BEECOME [Grant no 2106D0004].

References

Abson, D. J., Fischer, J., Leventon, J., Newig, J., Schomerus, T., Vilsmaier, U., von Wehrden, H., Abernethy, P., Ives, C. D., Jager, N. W., & Lang, D. J. (2017). Leverage points for sustainability transformation. *Ambio*, *46*(1), 30–39. https://doi.org/10.1007/s13280-016-0800-y

Aissani, L., Papangelou, A., Bahers, J.-B., Thiriet, P., Mathias, J.-D., Huet, S., Maguet, M., & Mathgen, A. (2022). *Trajectoires de transition vers une économie circulaire durable de la gestion des biodéchets des territoires. Projet GRAINE BEECOME 1 : rapport final.* https://hal-lara.archives-ouvertes.fr/hal-04075353/

Angheloiu, C., & Tennant, M. (2020). Urban futures: Systemic or system changing interventions? A literature review using Meadows' leverage points as analytical framework. *Cities*, *104*(July 2019). https://doi.org/10.1016/j.cities.2020.102808

Athanassiadis, A., Fernandez, G., Meirelles, J., Meinherz, F., Hoekman, P., & Cari, Y. B. (2017). Exploring the energy use drivers of 10 cities at microscale level. *Energy Procedia*, *122*, 709–714. https://doi.org/10.1016/j.egypro.2017.07.374

Bahers, J., & Giacchè, G. (2018). Towards a metabolic rift analysis: The case of urban agriculture and organic waste management in Rennes (France). *Geoforum*, *October*, 1–11. https://doi.org/10.1016/j.geoforum.2018.10.017

Bahers, J., Tanguy, A., & Pincetl, S. (2020). Metabolic relationships between cities and hinterland : a political-industrial ecology of energy metabolism of Saint-Nazaire metropolitan and port area. *Ecological Economics*, *167*(July 2019), 106447. https://doi.org/10.1016/j.ecolecon.2019.106447

Baynes, T. M., & Wiedmann, T. (2012). General approaches for assessing urban environmental sustainability. *Current Opinion in Environmental Sustainability*, *4*(4), 458–464. https://doi.org/http://dx.doi.org/10.1016/j.cosust.2012.09.003

Behrsin, I., & De Rosa, S. P. (2020). Contaminant, Commodity and Fuel: A Multi-sited Study of Waste's roles in Urban Transformations from Italy to Austria. *International Journal of Urban and Regional Research*, *44*(1), 90–107. https://doi.org/10.1111/1468-2427.12880

Berlingen, F. (2019, March 25). *Deux recours déposés contre le projet de reconstruction de l'incienrateur d'Ivry-Paris 13*. Zero Waste France. https://www.zerowastefrance.org/recours-justice-projet-reconstruction-incinerateur-ivry-paris-13/

Bettignies, Y., Meirelles, J., Fernandez, G., Meinherz, F., Hoekman, P., Bouillard, P., & Athanassiadis, A. (2019). The scale-dependent behaviour of cities: A cross-cities multiscale driver analysis of urban energy use. *Sustainability (Switzerland)*, *11*(12). https://doi.org/10.3390/su10023246

Billen, G., Barles, S., Garnier, J., Rouillard, J., & Benoit, P. (2009). The food-print of Paris: Long-term reconstruction of the nitrogen flows imported into the city from its rural hinterland. *Regional Environmental Change*, *9*(1), 13–24. https://doi.org/10.1007/s10113-008-0051-y

Brand, U. (2016). “Transformation” as a new critical orthodoxy: The strategic use of the term “transformation” does not prevent multiple crises. *GAIA - Ecological Perspectives for Science and Society* (Vol. 25, Issue 1, pp. 23–27). Oekom Verlag. https://doi.org/10.14512/gaia.25.1.7

Broto, V. C., Allen, A., & Rapoport, E. (2012). Interdisciplinary Perspectives on Urban Metabolism. *Journal of Industrial Ecology*, *16*(6), 851–861. https://doi.org/10.1111/j.1530-9290.2012.00556.x

Chen, S., & Chen, B. (2017). Changing Urban Carbon Metabolism over Time: Historical Trajectory and Future Pathway. *Environmental Science and Technology*, *51*(13), 7560–7571. https://doi.org/10.1021/acs.est.7b01694

Chertow, M. R. (2000). The IPAT equation and its variants: Changing views of technology and environmental impact. *Journal of Industrial Ecology*, *4*(4), 13–29. https://doi.org/10.1162/10881980052541927

Childers, D. L., Pickett, S. T. A., Grove, J. M., Ogden, L., & Whitmer, A. (2014). Advancing urban sustainability theory and action: Challenges and opportunities. *Landscape and Urban Planning*, *125*, 320–328. https://doi.org/10.1016/j.landurbplan.2014.01.022

Cook, I. R., & Swyngedouw, E. (2012). Cities, Social Cohesion and the Environment: Towards a Future Research Agenda. *Urban Studies*, *49*(9), 1959–1979. https://doi.org/10.1177/0042098012444887

Corvellec, H., Campos, M. J. Z., & Zapata, P. (2013). Infrastructures, lock-in, and sustainable urban development: The case of waste incineration in the Göteborg Metropolitan Area. *Journal of Cleaner Production*, *50*, 32–39. https://doi.org/10.1016/j.jclepro.2012.12.009

Crownshaw, T., Morgan, C., Adams, A., Sers, M., Britto dos Santos, N., Damiano, A., Gilbert, L., Yahya Haage, G., & Horen Greenford, D. (2019). Over the horizon: Exploring the conditions of a post-growth world. *Anthropocene Review*, *6*(1–2), 117–141. https://doi.org/10.1177/2053019618820350

Deng, T., Fu, C., & Zhang, Y. (2022). What is the connection of urban material stock and socioeconomic factors? A case study in Chinese cities. *Resources, Conservation and Recycling*, *185*. https://doi.org/10.1016/j.resconrec.2022.106494

Dijst, M., Worrell, E., Böcker, L., Brunner, P., Davoudi, S., Geertman, S., Harmsen, R., Helbich, M., Holtslag, A. A. M., Kwan, M. P., Lenz, B., Lyons, G., Mokhtarian, P. L., Newman, P., Perrels, A., Ribeiro, A. P., Rosales Carreón, J., Thomson, G., Urge-Vorsatz, D., & Zeyringer, M. (2018). Exploring urban metabolism—Towards an interdisciplinary perspective. *Resources, Conservation and Recycling*, *132*, 190–203. https://doi.org/10.1016/j.resconrec.2017.09.014

Feola, G. (2015). Societal transformation in response to global environmental change: A review of emerging concepts. *Ambio*, *44*(5), 376–390. https://doi.org/10.1007/s13280-014-0582-z

Fischer, J., & Riechers, M. (2019). A leverage points perspective on sustainability. *People and Nature*, *1*(1), 115–120. https://doi.org/10.1002/pan3.13

Frantzeskaki, N., McPhearson, T., & Kabisch, N. (2021). Urban sustainability science: prospects for innovations through a system's perspective, relational and transformations' approaches: This article belongs to Ambio's 50th Anniversary Collection. Theme: Urbanization. *Ambio*, *50*(9), 1650–1658. https://doi.org/10.1007/s13280-021-01521-1

Gandy, M. (2018). Cities in deep time: Bio-diversity, metabolic rift, and the urban question. *City*, *22*(1), 96–105. https://doi.org/10.1080/13604813.2018.1434289

Greenhalgh, T., Thorne, S., & Malterud, K. (2018). Time to challenge the spurious hierarchy of systematic over narrative reviews? *European Journal of Clinical Investigation*, *48*(6), e12931. https://doi.org/https://doi.org/10.1111/eci.12931

Heynen, N., Kaika, M., & Swyngedouw, E. (2006). Urban political ecology. Politicizing the production of urban natures. In *In the nature of cities*.

Hölscher, K., & Frantzeskaki, N. (2021). Perspectives on urban transformation research: transformations in, of, and by cities. *Urban Transformations*, *3*(1). https://doi.org/10.1186/s42854-021-00019-z

Iablonovski, G., & Bognon, S. (2020). Efficacité matérielle et performance écologique des territoires: Analyse croisée de 67 métabolismes. *Flux*, *116–117*(2), 6–25. https://doi.org/10.3917/flux1.116.0006

Iwaniec, D. M., Cook, E. M., Barbosa, O., & Grimm, N. B. (2019). The framing of urban sustainability transformations. *Sustainability (Switzerland)*, *11*(3), 1–10. https://doi.org/10.3390/su11030573

John, B., Luederitz, C., Lang, D. J., & von Wehrden, H. (2019). Toward Sustainable Urban Metabolisms. From System Understanding to System Transformation. *Ecological Economics*, *157*(April 2018), 402–414. https://doi.org/10.1016/j.ecolecon.2018.12.007

Kalmykova, Y., Rosado, L., & Patrício, J. (2016). Resource consumption drivers and pathways to reduction: Economy, policy and lifestyle impact on material flows at the national and urban scale. *Journal of Cleaner Production*, *132*, 70–80. https://doi.org/10.1016/j.jclepro.2015.02.027

Kemp, L., Xu, C., Depledge, J., Ebi, K. L., Gibbins, G., & Kohler, T. A. (2022). Climate Endgame : Exploring catastrophic climate change scenarios. *PNAS*, 1–9. https://doi.org/10.1073/pnas.2108146119/-/DCSupplemental.Published

Kennedy, C. A., Stewart, I., Facchini, A., Cersosimo, I., Mele, R., Chen, B., Uda, M., Kansal, A., Chiu, A., Kim, K. G., Dubeux, C., La Rovere, E. L., Cunha, B., Pincetl, S., Keirstead, J., Barles, S., Pusaka, S., Gunawan, J., Adegbile, M., … Sahin, A. D. (2015). Energy and material flows of megacities. *Proceedings of the National Academy of Sciences of the United States of America*, *112*(19), 5985–5990. https://doi.org/10.1073/pnas.1504315112

Krausmann, F. (2013). A City and Its Hinterland : Vienna ' s Energy Metabolism 1800 – 2006. In Singh, S., H. Haberl, M. Chertow, M. Mirtl, & M. Schmid (Eds.), *Long Term Socio-Ecological Research. Human-Environment Interactions, vol 2.* Springer, Dordrecht. https://doi.org/10.1007/978-94-007-1177-8

Li, Y., Wang, J., Xian, D., Zhang, Y., & Yu, X. (2021). Regional consumption, material flows, and their driving forces: A case study of China's Beijing–Tianjin–Hebei (Jing–Jin–Ji) urban agglomeration. *Journal of Industrial Ecology*, *25*(3), 751–764. https://doi.org/10.1111/jiec.13070

Li, Y., Zhang, Y., & Yu, X. (2019). Urban weight and its driving forces: A case study of Beijing. *Science of the Total Environment*, *658*, 590–601. https://doi.org/10.1016/j.scitotenv.2018.12.022

Liu, J., Wang, R., & Yang, J. (2005). Metabolism and driving forces of Chinese urban household consumption. *Population and Environment*, *26*(4), 325–341. https://doi.org/10.1007/s11111-005-3345-8

Marin, J., & De Meulder, B. (2018). Interpreting circularity. Circular city representations concealing transition drivers. *Sustainability (Switzerland)*, *10*(5). https://doi.org/10.3390/su10051310

McPhearson, T., M. Raymond, C., Gulsrud, N., Albert, C., Coles, N., Fagerholm, N., Nagatsu, M., Olafsson, A. S., Soininen, N., & Vierikko, K. (2021). Radical changes are needed for transformations to a good Anthropocene. *Npj Urban Sustainability*, *1*(1). https://doi.org/10.1038/s42949-021-00017-x

Meadows, D. (1999). *Leverage Points: Places to Intervene in a System*. https://donellameadows.org/archives/leverage-points-places-to-intervene-in-a-system/

Newell, J. P., & Goldstein, B. (2019). A 40 -year review of food – energy – water nexus literature and its application to the urban scale. *Environmental Research Letters*, *14*(7), 73003. https://doi.org/10.1088/1748-9326/ab0767

Peponi, A., Morgado, P., & Kumble, P. (2022). Life cycle thinking and machine learning for urban metabolism assessment and prediction. *Sustainable Cities and Society*, *80*, 103754. https://doi.org/10.1016/j.scs.2022.103754

Pichler, M., Schaffartzik, A., Haberl, H., & Görg, C. (2017). Drivers of society-nature relations in the Anthropocene and their implications for sustainability transformations. *Current Opinion in Environmental Sustainability*, *26–27*, 32–36. https://doi.org/10.1016/j.cosust.2017.01.017

Pincetl, S. (2012). Nature, urban development and sustainability - What new elements are needed for a more comprehensive understanding? *Cities*, *29*(SUPPL.2), S32–S37. https://doi.org/10.1016/j.cities.2012.06.009

Pincetl, S., Bunje, P., & Holmes, T. (2012). An expanded urban metabolism method: Toward a systems approach for assessing urban energy processes and causes. *Landscape and Urban Planning*, *107*(3), 193–202. https://doi.org/http://dx.doi.org/10.1016/j.landurbplan.2012.06.006

Porse, E., Derenski, J., Gustafson, H., Elizabeth, Z., & Pincetl, S. (2016). Structural, geographic, and social factors in urban building energy use: Analysis of aggregated account-level consumption data in a megacity. *Energy Policy*, *96*, 179–192. https://doi.org/10.1016/j.enpol.2016.06.002

Rennes Métropole. (2019). *Rapport 2019 sur le prix et la qualité du service public de prévention et de gestion des déchets*.

Rennes Métropole. (2022a). *Ressources - jeter moins, gérer mieux, préserver plus. Trajectoire déchets 2030*.

Rennes Métropole. (2022b). *Le budget métropolitaine*. https://metropole.rennes.fr/le-budget-metropolitain

Rennes Métropole. (2022c). *Moderniser l'usine - Le projet*. https://www.uve-rennesmetropole.fr/moderniser-l-usine/le-projet

Schmid Neset, T. S., Bader, H. P., Scheidegger, R., & Lohm, U. (2008). The flow of phosphorus in food production and consumption - Linköping, Sweden, 1870-2000. *Science of the Total Environment*, *396*(2–3), 111–120. https://doi.org/10.1016/j.scitotenv.2008.02.010

Sun, J., Wang, T., Lu, S., Gao, X., & Du, H. (2023). Leverage of resource efficiency over environmental emissions: Case of a megacity in China. *Science of the Total Environment*, *858*. https://doi.org/10.1016/j.scitotenv.2022.159514

Torraco, R. J. (2005). Writing Integrative Literature Reviews: Guidelines and Examples. *Human Resource Development Review*, *4*(3), 356–367. https://doi.org/10.1177/1534484305278283

Urbinatti, A. M., Dalla Fontana, M., Stirling, A., & Giatti, L. L. (2020). 'Opening up' the governance of water-energy-food nexus: Towards a science-policy-society interface based on hybridity and humility. *Science of the Total Environment*, *744*, 140945. https://doi.org/10.1016/j.scitotenv.2020.140945

Voskamp, I. M., Sutton, N. B., Stremke, S., & Rijnaarts, H. H. M. (2020). A systematic review of factors influencing spatiotemporal variability in urban water and energy consumption. In *Journal of Cleaner Production* (Vol. 256). Elsevier Ltd. https://doi.org/10.1016/j.jclepro.2020.120310

Wolfram, M., Frantzeskaki, N., & Maschmeyer, S. (2016). Cities, systems and sustainability: status and perspectives of research on urban transformations. *Current Opinion in Environmental Sustainability*, *22*, 18–25. https://doi.org/10.1016/j.cosust.2017.01.014

Ziervogel, G., Pelling, M., Cartwright, A., Chu, E., Deshpande, T., Harris, L., Hyams, K., Kaunda, J., Klaus, B., Michael, K., Pasquini, L., Pharoah, R., Rodina, L., Scott, D., & Zweig, P. (2017). Inserting rights and justice into urban resilience: a focus on everyday risk. *Environment and Urbanization*, *29*(1), 123–138. https://doi.org/10.1177/0956247816686905

Zucaro, A., Ripa, M., Mellino, S., Ascione, M., & Ulgiati, S. (2014). Urban resource use and environmental performance indicators. An application of decomposition analysis. *Ecological Indicators*, *47*, 16–25. https://doi.org/10.1016/j.ecolind.2014.04.022

Supporting information

Supporting Information

Supporting information is linked to this article on the *JIE* website: https://doi.org/10.1111/jiec.13435

Supporting Information S1: This supporting information provides details on the set of papers included in the review, methodological details of the metabolic model developed for the case study (biowaste in Rennes), and the full list of drivers identified for the case study.

Supporting Information S2: This supporting information provides the dataset of biowaste flows in Rennes for the years 2001-2020, including those used for figure 4 (2019)