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# Municipal circular economy indicators: Do they measure the cities' environmental ambitions?

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ABSTRACT

Circular economy (CE) is gaining traction in cities as an approach to reducing local and global environmental impacts. Yet, how effective are these strategies in terms of their environmental impacts? To find out, we took a deep dive into 30 CE policies from cities in high-income countries across Europe, the Americas, and Oceania. We assessed the relevance of their indicator sets with regards to their major environmental concerns. To do so, we conducted a qualitative analysis of policy documents published in eight languages, examining common environmental goals, concerns, and progress indicators of various cities. The review reveals a broad spectrum of municipal CE policies, from waste management to climate action. Key concerns include climate mitigation and securing local resource availability, but overall, very diverse environmental targets could be identified. Some of these targets aim at local impacts such as air quality and public health, while others envision global impacts such as biodiversity conservation and intergenerational justice. While greenhouse gas emissions of territorial scope are frequently monitored, the indicator sets mostly ignore that climate mitigation involves a footprint scope. Moreover, the sets mostly lack indicators to monitor other environmental pressures and impacts. To better monitor these, we provide a set of recommendations for research and policy to bridge the gap between environmental concerns and indicator needs. We suggest complementing current resource flow dominated indicator sets with measures of the local environmental state and the application of urban footprint models to help cities monitor the desired global environmental impact of their measures.

## 1. Introduction

Cities are considered global hotspots of resource consumption, causing pressures on the environment worldwide (Seto et al., 2014; Concepción et al., 2015; Kennedy et al., 2015). Local authorities have started to counter these impacts with diverse strategies. Among others, the concept of circular economy (CE) is seen as an alternative approach to managing finite resources and to mitigating various local and global environmental pressures in line with sustainable production and consumption goals (Pan et al., 2024; Herrador et al., 2023; Williams, 2021). The OECD (2020) reported 51 cities that are using CE strategies, Petit-Boix and Leipold (2018) identified over 300 CE initiatives in the urban context, and European municipalities are organised under the EU Circular Cities Declaration (ICLEI, 2023) and the EU Circular Cities and Regions Initiative (European Commission, 2023). One of the reasons for this rising uptake of the CE concept in cities may be its strong connection with the Sustainable Development Goals (SDGs) (Petit-Boix et al., 2022), particularly SDG 11 and 12. In fact, the literature proves that 'smart cities' and 'sustainable cities' are the main urban brandings associated with CE applied to cities (Crippa et al., 2023).

Yet, research questions the unconditional potential of CE strategies to alleviate environmental burdens. Critiques span from the thermodynamically ineluctable and often disregarded requirement for additional material and energy input throughout a system's life cycle when circulating materials (Cullen, 2017; Skene, 2018; Savini, 2023), to the CE rebound that describes the possible increase in overall material demand and stock accumulation when using secondary materials due to market effects (Wiedenhofer et al., 2020; Zink and Geyer, 2017). In addition,

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strong differences exist in the potential of specific strategies that are labelled 'circular' to mitigate climate change (Cantzler et al., 2020). Given the popularity of the concept, we must urgently ensure that the strategies in place effectively support environmental goals and reductions in resource use. For this reason, monitoring the environmental performance of different CE strategies and prioritising strategies accordingly is crucial (Helander et al., 2019; Korhonen et al., 2018; Wiedenhofer et al., 2020). This translates in the use of indicators tailored to policy goals (e.g. SDGs) and urban CE strategies that inform about changes in the urban metabolism (Petit-Boix et al., 2022).

Next to academia, many local authorities already evaluate and prioritise their CE strategies with diverse sets of indicators (Fusco Girard and Nocca, 2019; Gravagnuolo et al., 2019). Still, Campbell-Johnston et al. (2019) find that Dutch municipalities evaluate available performance metrics as inappropriate. Similarly, the EU Urban Agenda Partnership on Circular Economy (2019) presents the lack of suitable indicators as an implementation barrier for the CE in cities. This was shown to be concerning when reporting progress on the SDGs, as cities tend to stick to what is easily measurable (Zinkernagel et al., 2018).

Such lack in target relevance (i.e. 'salience') is especially challenging due to the diverging goals associated with the CE concept (Kirchherr et al., 2023; Blomsma and Brennan, 2017; Korhonen et al., 2018). Therefore, revealing the gaps in target relevance of current municipal indicator sets requires attaining to the specific goals of the cases under study. So far, research has conceptualized CE in cities (e.g., Lakatos et al., 2021; Winslow and Coenen, 2023), mapped cities with their respective CE strategies (e.g., Prendeville et al., 2018), and analysed the policy goals and discourses behind urban CE strategies (e.g., Calisto Friant et al., 2023; Fratini et al., 2019; Paiho et al., 2020). These studies tend to focus on large European capitals, such as London, Paris or Amsterdam, with recent examples in Japanese cities (Herrador et al., 2023). Evaluating local CE goals along with their monitoring needs remains largely unexplored, yet it is vital for an effective reporting and progress towards climate and resource use targets. For instance, the Urban Agenda Partnership on Circular Economy (2019) composes a relevant indicator set in collaboration with larger municipalities and the OECD (2020) collects indicators used in 11 larger municipalities, but explicit goals are not systematised and reported. Considering the risk of rebound and ambiguity, we need a detailed account of municipal CE goals and how they are measured in practice. In particular, research points at the paucity in the environmental assessments of CE strategies at various governance levels (Corona et al., 2019; Haupt and Hellweg, 2019; Kristensen and Mosgaard, 2020), which calls for an in-depth analysis of environmental goals and indicators in cities. To fill this gap, this study asks: *"Which indicators are (not) used in practice to monitor the environmental ambitions of municipal CE policies?"*

This article provides an overview of the environmental concerns that 30 CE policies of early-adopting municipalities target with the CE. As opposed to more general accounts of municipal CE strategies and their relationship with environmental sustainability (e.g., Petit-Boix and Leipold, 2018), we identify actual individual goals and indicators along with general trends. To do so, we conducted a comprehensive analysis of policy documents for a breath of cities beyond pioneer CE adopters, such as large European cities. With this depth and diversity, we reveal concrete gaps in the target relevance of indicator sets that have been suggested by the municipalities to monitor their CE policies. We aim to validate observations of a lack of monitoring of environmental sustainability for the municipal policy context and to discuss possible improvements with regards to the CE goals. The results not only help scholars of CE policy, urban management and environmental assessment but may also guide future indicator selection and development for prioritisation of sustainable CE strategies in cities.

Pursuing our research question, the following sections describe the methods used to sample CE policies and analyse their goals and associated indicators (Section 2), to later identify and discuss the relevance of the available indicator sets to address municipal environmental concerns (Section 3). In Section 4, we discuss the practical implications of our assessment both in policy and research.

## 2. Methods

To identify gaps in municipal CE indicator sets, target relevance was analysed from two angles: *thematic relevance* describes the relative prominence of the concern that is represented by the indicator on the political agenda, whereas *indicator relevance* describes the validity of the indicator to represent the concern "precisely, comprehensively, [and] closely" (Janoušková et al., 2019, p. 480). The subsequent sections describe the selection of municipal policy cases that refer to the CE concept and for which indicator sets and goals were compared (Section 2.1), the identification and classification of goals and indicators (Section 2.2), as well as the analysis of gaps in thematic and indicator relevance (Sections 2.3 and 2.4).

### 2.1. Sampling of municipal CE policies

A selection of cities with CE policy documents suitable for analysis was established with the following procedure (Fig. 1). Screening the first 40 results for the English language query 'circular city* AND economy' on Google Search for reports by international organisations and Web of Science for peer-reviewed publications, respectively, revealed 290 different territories that have been associated with the CE (cf. Supplementary Material A). Several search terms were tested before settling on this term, including 'circular economy municipality', 'circular city', 'circular cities', 'circular economy city' or 'urban circular economy'. The selected search term showed the best fit in terms of CE policy in cities. 'Economy' was added to the search string to exclude references to circle-shaped cities. For 104 of these territories, an action plan labelled 'circular' could be identified online for the urban, municipal or district governmental level in at least one of the 8 languages that the authors are proficient in: English, French, Dutch, Spanish, Catalan, Portuguese, Italian, and German. This screening took place in summer 2021 due to available research capacities during that time. This period also marks the formation of important networks that support the implementation and comparison of CE activities in cities, such as the Circular Cities Declaration (ICLEI, 2023), the OECD Synthesis Report on Circular Economy in Cities (OECD, 2020) and the EU Circular Cities and Regions Initiative (European Commission, 2023).

The documents of these remaining cities were screened for the presence of indicators. Indicators are system variables that "condense a large amount of information into figures that represent what is perceived as important" (Gudmundsson, 2003, p. 3). To be included in the sample, indicators had to assess the effects of the proposed policy on the urban or lower scale and had to be 1) used to *monitor* policy outputs and outcomes, or 2) used to *predict* possible future policy outputs and outcomes, or 3) used to *justify* the need for action by presenting the current situation that is to be changed by the policy (cf. Section 3.3 for examples). Indicators used for monitoring, prediction, or justification are considered relevant for the analysis, as each demonstrates information that could potentially be used to monitor and prioritise strategies. 40 % of the cases failed to show such indicators such as CE plans that focus more on describing implementation in detail (e.g., Florence or Leuven) or plans that only used EU-level indicators on the projected benefits of CE to justify the policy (e.g., Maribor or Sintra). A total of 62 cases were deemed suitable for the analysis of relevance gaps in their indicator sets, including 30 cities with ratified policies, 28 cities for which consultancy-led white papers or proposals by non-governmental organisations are available, and 4 cities about which best practice reports have been written by external actors. Our analysis focusses on the ratified policies (cf. Supplementary Information Table S1). This ensures that the environmental goals of CE in cities identified in this study are indeed the goals of the municipalities and the result of coordinative discourse among its citizens, and not just of the consultancies writing

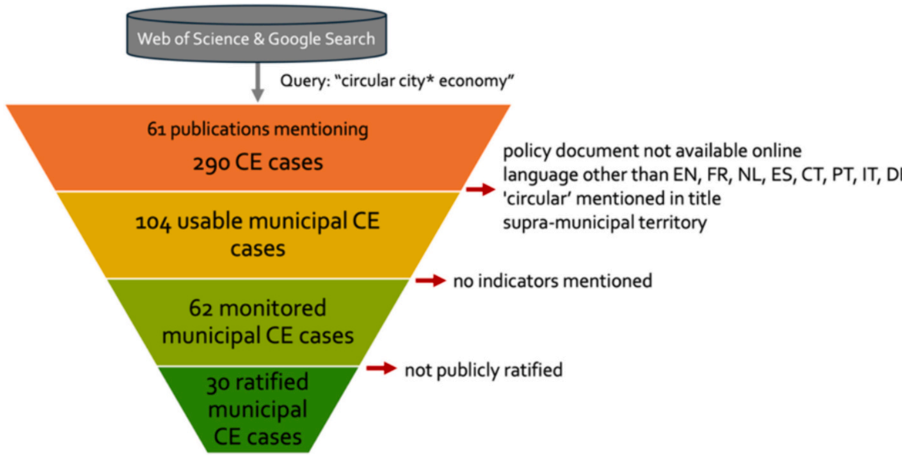


**Fig. 1.** Steps in the systematic selection of municipal CE policy cases.

white papers or reports.

The selected documents vary in style and detail in the description of goals and motivations for adopting a CE policy and the methods for calculating the specific indicators. This is partly because the documents are designed for different audiences (e.g. councillors, international public, etc.). In addition, how the CE concept is embedded in other policy frameworks strongly influences the detail with which goals and indicators are described. For instance, CE may be used as one among many measures –as with most of the climate action plans–, or it can provide a foundation for an entire CE policy package –as with many of the CE local economic development plans.

### 2.2. Identification of CE goals and indicators

Environmental goals and indicators of urban CE policy were identified and classified via Qualitative Content Analysis (QCA) following Mayring (2014). QCA provides a systematic and transparent framework for developing comprehensive coding categories for varied policy documents. The flexibility and depth of QCA was particularly valuable in understanding the differentiated environmental goals and concerns within CE policy.

For goals, sentence segments containing CE goals in a form similar to 'we want to foster the circular economy because…' or "this policy [titled 'circular'] will contribute to…" were identified examining the beginning of the CE policy document and particularly sections labelled as 'Vision', 'Context', 'Guiding Principles' and 'Aims & Objectives' (Supplementary Material B.1).

For indicators, the original formulations as well as some context information was recorded, including whether the indicator is just envisioned or whether there is evidence of use of this indicator (Supplementary Material B.2). To facilitate subsequent analysis, indicators from different cities were harmonised with a paraphrase of the format '[unit of measurement] [measured process]' e.g., t $CO_2$ eq. emissions. The indicator sets of the sampled municipal CE policies contain both indicators monitoring the policy output, i.e., the degree of implementation of the policy response designed to mitigate environmental impacts, and indicators directly monitoring the outcome of these policies, i.e., the effective change in drivers, pressures, state and impact. This study is concerned only with outcome indicators because they can give a direct indication of the degree to which the policy is successful in attaining its goals (Potting et al., 2017).

### 2.3. Identification of gaps in thematic relevance

*Thematic relevance* (cf. Janoušková et al., 2019) connects the prominence of environmental concerns with the use of indicators related to these concerns. For instance, it shows whether a city that takes up CE principles to reduce air pollution formulates an indicator related to air pollution. Prominence includes the share of cities mentioning a specific environmental concern at least once and the average centrality of this concern relative to other concerns. Gaps were identified drawing on a case-by-case (cf. Fig. 3) and aggregate analysis (cf. Fig. 2) by comparing the prominence of environmental concerns with the share of cities reporting at least one indicator related to this concern. Thematic relevance can therefore identify hidden concerns, i.e. frequently targeted but hardly monitored concerns of municipal CE policy.

To do so, the identified goals and indicators were iteratively categorised by environmental concern using QCA (Supplementary Material B.3). Although frameworks for environmental concerns exist (cf. Chandrakumar and McLaren, 2018; UN, 2015; Vanham et al., 2019), we followed inductive category formation (Mayring, 2014) to include all environmental concerns that actors associated with the implementation of CE at the municipal level. An *environmental* concern is here understood as an effect that is at least in part mediated by a pressure of human activity on the environment. In line with the driver-pressure-state-impact-response (DPSIR) framework (EEA, 1999), this includes drivers of environmental pressures (e.g. material and energy requirements), environmental pressures resulting from human-environment interactions (e.g. greenhouse gas (GHG) emissions and resource depletion), and impacts of these pressures on human and environmental welfare (e.g. health, ecosystem integrity, resource provision, and intergenerational equity). The identified environmental concerns were deductively grouped by a simplified DPSIR including *driver*, *pressure*, and *benefit*, where benefit may correspond to a state change or the avoidance of a negative impact. In this model, the CE policy is conceived as a response to some negative environmental impacts that should be avoided by targeting the environmental concern. This classification was chosen to identify on which stage of the causal chain the cities focus their efforts and concerns.

The relative centrality of an environmental concern with respect to other environmental concerns in a specific policy document was indicated on a scale from 1 (low endorsement, peripheral concern) to 3 (high endorsement, core concern). The attribution of a level of centrality depends on the frequency with which an environmental concern is mentioned in the respective policy document (i.e. 1: mentioned once, 2: mentioned once or twice; 3: mentioned multiple times), the place of mention (i.e., 1: in an enumeration within a sentence; 2: visually highlighted bullet point or whole sentence; 3: covering a whole paragraph), and the presence of degree modifiers such as 'tremendous', 'crucial', 'secondary'.


**Fig. 2.** Environmental concerns by share of cities desiring action on them vs. share of cities monitoring change. Concerns below the yellow line are more frequently mentioned as goal of the policy than monitored.

### 2.4. Identification of gaps in indicator relevance

Gaps in *indicator relevance* show whether indicators effectively measure the environmental concerns they are supposed to track (cf. Janoušková et al., 2019, p. 490). For geographical scope, we compared the scope (onsite, offsite, footprint) at which cities aim to manage the main environmental pressures with what cities actually track. Therefore, the study deductively classified the indicators into *onsite* environmental pressures within the territorial boundaries of the city, *offsite* pressures that only take place in the global consumption hinterland of the territory (e.g. mining of imported construction material), and *footprint* pressures which cover both on- and offsite pressures (adapted from Athanassiadis et al., 2018; Azapagic et al., 2007; Loiseau et al., 2018).

This geographical notion is also included in the resource flow model (Fig. 4), which was used to reveal gaps in the monitoring of environmental pressures resulting from different life cycle stages covered by the indicators. For life cycle scope, we assumed that cities aim to address impacts resulting from all stages of a product's life. Hence, we evaluated the overall tendency of cities' indicators to focus on certain life cycle stages by comparing the number of cities that had indicators for each stage of our model. The original economy-wide material flow system model by Helander et al. (2019) was expanded to model any anthropogenic resource flows including material, energy, water, and land flows. Further, it was adapted to the urban context by adding a flow for industrial symbiosis and a hinterland system. Any indicators representing resource and environmental flows such as extraction, recycling rates, and emission were classified according to the model.

## 3. Results

In this section, we first provide an overview of the municipalities and CE policies analysed (Section 3.1). We then describe the environmental concerns (Section 3.2) and indicators (Section 3.3) included in the municipal CE policies. Finally, Section 3.4 critically analyses the thematic (3.4.1) and indicator (3.4.2) relevance in the sample by drawing attention to gaps between environmental concerns and proposed indicators.

### 3.1. Context of the selected municipal CE policies

30 cases qualify as municipal policy initiatives with ratified CE policies to be analysed in this study (Supplementary Information Table S1). All these local authorities are part of high-income countries (cf. World Bank, 2017) – 43 % Western Europe, 23 % Northern Europe, 13 % Southern Europe, 6 % Oceania, 1 case each from North America, South America, and Southeastern Asia – with populations ranging from 125,099 inhabitants (Municipality of Leiden) up to more than 9 million inhabitants (Greater London Authority) and a median of around 425,000 inhabitants.[1]

While some local authorities use the CE concept as a guiding principle for their regularly updated waste management plans (e.g., London, Dunedin, Copenhagen), others use it as a climate action strategy (e.g., Ghent, Saint-Etienne, Helsinki), as a strategy or guiding principle for their environmental sustainability agenda (e.g., Haarlemmermeer, 's-Hertogenbosch, Stockholm), or a framework for their local economic development plans (e.g., Brussels, Peterborough, Rotterdam).

Further, while all policy documents selected have been published over the last seven years, the implementation period varies from 3 years in the case of the Dutch intermunicipal policy initiative Circulaire Stad, over 5 years in the case of Amsterdam, to long term strategies without a defined endpoint such as Toronto's Waste Management Plan and Montevideo's Resilience strategy. This has consequences regarding the function and feasible scope of monitoring. A policy that is not intended to be revised will not have ample resources allocated for evaluation; similarly, one with a very short time frame might not have sufficient time to perform evaluation.

### 3.2. Environmental concerns of municipal CE policies

Table 1 presents the main environmental concerns that municipalities deliberately target with CE strategies. Next to being perceived as a resource management strategy, the policy documents clearly present the CE as a climate action strategy. By far the most widely shared concern among the selected municipal CE policies is the *reduction of GHG emissions* and consequent mitigation of climate change (80 %). It is simultaneously the concern that has the strongest endorsement within individual policies (centrality 2.6). While most municipalities claim that the "circular economy contributes significantly to the reduction of global $CO_2$ emissions" (Gemeente Amsterdam, 2020, p. 5), Leiden is more cautiously stating that carbon emissions are only "a secondary driver for the circular economy" (Gemeente Leiden, 2020, p. 13). Other prominent environmental pressures include the *reduction of the environmental footprint in general* (43 %, centrality: 2.2) and, especially among the more populous half of sampled cities (with more than 425,000 inhabitants), a *reduction of global resource and land appropriation* to prevent depletion (together 33 %, centrality: 2.1). There is less of a consensus among the examined CE policies on pressures such as air, water, and chemical pollution, and various very specific examples are mentioned such as ozone depleting substances (ODS) or nitrogen emission by Amsterdam and Utrecht, respectively.

The common depiction of CE as a waste and resource management strategy (cf. Blomsma and Brennan, 2017) becomes apparent in statements associating the CE with drivers and benefits of environmental pressure reduction. Almost three quarters of the cities state a *decrease in the requirement of resources* such as energy, land, water, and material (hereafter jointly referred to as 'resource requirement') explicitly as a goal of their CE policy. Most of these cities, in particularly larger ones, also target the *generation of waste* (47 %), although not centrally within the individual vision (centrality: 1.6). In line with this, *local resource availability* is the main benefit that the municipalities aim to achieve by reducing environmental pressures (67 %, centrality: 2.1).

Further environmental benefits that the policies associate with the CE include the *safety from environmental hazards* (30 %, centrality: 2.0) and, particularly in documents written by environmental departments, *public health* (30 %, centrality: 1.9). For instance, Singapore holds that their policy would "address the existential threats of climate change, especially sea level rise" for them as a "low-lying island state" (MEWR Singapore, 2019, p. 2) and Paris claims that CE would "reduce the impact of our lifestyles on the health of our fellow citizens" (Ville de Paris, 2017, p. 2). Similarly, by reducing environmental pressures the CE is thought to reduce the potential for social discrimination by a third of the cities, thus increasing *environmental equity* within and beyond the spatio-temporal boundaries of the city. In general, benefits relating to human wellbeing are more widely shared among the municipal CE policies and receive stronger endorsement in individual policies than those relating to ecosystem integrity (*nature conservation, biodiversity conservation, nutrient cycling*), which are mainly mentioned in policies issued by environmental and sustainability departments. Hence, although *biodiversity conservation* is a goal mentioned by 17 % of the cities, it is not presented as a central concern in their policies (centrality: 1.0). Still, ecosystem integrity and the CE's contribution to it is valued for the *services ecosystems provide* to humans by 27 % of cities. For instance, Circulaire Stad (2016) highlights the importance to "maintain the carrying capacity of the earth to maintain our level of prosperity" (p. 2).

Overall, the abundance of certain environmental goals among the municipal CE policies differs with regards to the broader urban policy framework they are integrated into. Municipal CE policies embedded in *Climate Action frames* emerging since 2019 tend to largely focus on GHG emission reductions, while simultaneously addressing resource depletion. Environmental benefits are seldomly mentioned – with only local resource availability mentioned twice. For these policies a GHG-focussed monitoring framework may suffice. Earlier municipal CE policies embedded in *Local Economic Development frames*, on the other hand, share the vision of a reduced overall environmental footprint as well as human benefits such as urban resource equity and an improved local air quality, while minimising land and water consumption. Accordingly, these policies would require a more holistic monitoring that includes a variety of resources and resulting environmental pressures onsite and offsite. A more benefit-oriented monitoring would be required for *Environmental Sustainability (ES) frame* driven policies, which show a particularly strong tendency to target the benefit of nature and biodiversity conservation and connected ecosystem services and emphasise the potential of CE to reduce various kinds of environmental pollution which inhibit public health. Finally, those policies embedded in the classical *Waste Management frame* show a similar profile to the Environmental Sustainability framed policies but have a stronger focus on ensuring environmental safety and local resource availability, as well as reducing the overall environmental footprint to establish intergenerational equity. Both latter kinds of policies have been published across all examined years.

### 3.3. Indicators of municipal CE policies

Overall, the sample of municipal CE policies assembles a diverse

[1] The Dutch intermunicipal policy initiative 'Circulaire Stad' was here and in all following frequency analyses counted as a single city with an average population of 353,572 inhabitants.

**Table 1**
Targeted environmental concerns of the selected municipal CE policies, sorted according to causal stage. Centrality describes the relative intensity with which an environmental concern is endorsed compared to other environmental concerns by a specific policy initiative based on the examined documents.

| Environmental concerns targeted with municipal CE policies | | % cities | ø centrality |
|---|---|---|---|
| **Desired reduction in drivers of environmental pressures** | | | |
| Waste Generation | reduce the amount of solid waste for final disposal | 43% | 1.6 |
| Material Requirement | circulate materials within the city and reduce the material requirement | 23% | 2.3 |
| Energy Requirement | reduce the energy footprint or input to the city | 23% | 1.7 |
| Land Requirement | reduce the urban land requirement | 20% | 1.3 |
| Water Requirement | use water efficiently | 20% | 1.5 |
| Unspecified Resource Requirement | reduce amount of resources used; resource unspecified | 10% | 2.3 |
| **Desired reduction of environmental pressures** | | | |
| GHG Emission | mitigate climate change by emitting less $CO_2$ and other greenhouse gases | 80% | 2.6 |
| Environmental Footprint | reduce overall environmental footprint and stay within planetary boundaries | 43% | 2.2 |
| Resource Depletion | reduce the depletion of finite resources like phosphates, critical raw materials | 23% | 1.7 |
| Air Pollution | improve air quality by preventing emission of air pollutants | 17% | 1.4 |
| Water Pollution & Depletion | reduce water pollution to conserve freshwater | 17% | 1.5 |
| Environmental Pollution | reduce overall environmental pollution; kind of pollution unspecified | 13% | 1.5 |
| Chemical Pollution | reduce environmental and human contamination by emission of toxic elements | 13% | 1.8 |
| Land & Soil Appropriation | maintain the availability of land and fertile soil | 10% | 2.3 |
| Nitrogen Emission | reduce reactive nitrogen emission to the environment | 7% | 1 |
| Ozone Depleting Substance Emission | reduce emission of CFCs and HCFCs to maintain the ozone layer | 3% | 1 |
| **Desired benefits of environmental pressure reduction on human and ecosystem wellbeing** | | | |
| Local Resource Availability | increase/maintain the availability and secure supply of resources in the city | 67% | 2.1 |
| Public Health | maintain human public health by reducing environmental pollution | 30% | 1.9 |
| Safety from Environmental Hazards | ensure safety of citizens from environmental hazards like extreme weather | 30% | 2 |
| Ecosystem Service Retention | retain human-life-supporting and cost-reducing capacity of environment | 27% | 1.9 |
| Nature Conservation | protect natural areas and life | 27% | 1.9 |
| Global Equity | enable other humans on Earth to receive their 'fair share' of environmental benefits | 23% | 1.7 |
| Biodiversity Conservation | maintain diversity of species, ecosystem, and genetic variation | 17% | 1 |
| Intergenerational Equity | enable future generations to receive similar env. benefits as current generations | 13% | 1.8 |
| Nutrient Cycling | close and maintain nutrient cycles | 13% | 1.8 |
| Urban Equity | enable all inhabitants in the city to receive their 'fair share' of environmental benefits | 10% | 2 |
| Pleasant Living Environment | create an urban environment with little nuisance in form of odour or visual pollution | 10% | 1.8 |

picture of CE indicator sets. Different from what the literature has described as 'circularity indices' (cf. Corona et al., 2019; Saidani et al., 2019; Wang et al., 2018), 90 % of examined policy initiatives use *sets* of indicators to monitor their performance (the remaining three cases use a single simple metric such as 'waste collected' or 'emissions generated' instead of a complex index). No two indicator sets examined in this study are the same. Still, some patterns can be observed that are of relevance when compared to the environmental concerns: 1) municipal CE indicator sets are dominated by end-of-life material flows (collection rate, recycling rate, etc) and waste flows; 2) environmental pressures other than GHG emissions from the territory and from energy consumption are hardly monitored; 3) indicators included in the sets mainly monitor onsite processes.

Regardless of whether the CE policy was explicitly issued as a waste management plan, most of the sets contain municipal *waste management indicators* such as a collection rate from final use (73 % of the cases, Table 2), from industry (17 %), and from construction (13 %), an onsite recycling rate (33 %), and waste separation rate (17 %). 43 % of cities also monitor higher value R-strategies by estimating reuse and repair amounts, or by providing an overall estimate of the material diverted from final waste disposal (cf. Fig. 4).

Such mass- and volume-based waste management indicators are frequently coupled with $CO_2$ equivalent emissions, or less frequently with the environmental cost of waste management or of overall territorial processes. Some municipal CE policies resembling climate action plans (Ghent, Eindhoven, Saint-Etienne) only rely on these GHG emission indicators covering territorial and energy-related emissions, plus metrics of the local energy requirement. In terms of emissions, Amsterdam's dashboard of indicators, which has been prepared in collaboration with external consultants, stands out against the others as it takes on a consumption-based approach to evaluate the resource requirements in specific product groups. Only a third of the sets contain indicators for environmental pressures other than onsite GHG emissions -with little evidence of actual use-, and only 23 % monitor benefits other than resource availability (Table 2).

89 % of indicators in the sets focus on dispersed onsite resource and waste management indicators with only 17 % of sets monitoring overall resource requirement or waste generation (Supplementary Information Table S3). A few policies suggest using material (17 %) and water (13 %) requirement indicators, as well as the urban mass and energy balance (13 %). Most of these material requirement indicators with evidence of application are limited to specific product groups (55 %). Paris is an exception to this, having calculated its overall urban material, energy, and water metabolism with the help of a consultancy. Lisbon and Montevideo rather focus on monitoring the *increased* use of 'sustainable' materials than on a *reduction* of the overall requirement. Venice and

**Table 2**
Indicators identified in the municipal CE policy documents, includes used and suggested indicators. A question mark indicates unit unknown. Flow abbreviations: C, material collected; FWD, final waste disposal; IS, industrial symbiosis; RiP, resources in product; RU, reuse; SR, secondary resources; TMR, total material requirement.

| Flow | No. cities | Indicator |
|---|---|---|
| **Energy Requirement (43% of cases)** | | |
| RI | 2 | J energy input to individual business |
| IS | 2 | J energy input/output, individual businesses |
| RiP | 7 | J energy consumed, onsite, any/electricity |
| | 5 | J energy generated, onsite, any/biogas/electricity |
| I/E | 2 | t energy input/output from territory |
| **Land Requirement (10% of cases)** | | |
| RiP | 1 | %m$^2$ agricultural area/territory, onsite |
| SR | 1 | m$^2$ land decontaminated |
| | 1 | € price of land, onsite |
| **Water Requirement (20% of cases)** | | |
| TMR | 1 | t water extracted, onsite |
| RiP | 4 | m$^3$ water consumed, onsite |
| | 1 | # washings |
| I/E | 2 | t water input/output from territory |
| FWD | 1 | m$^3$ water lost |
| **Material Requirement (77% of cases)** | | |
| RI | 2 | t material input to individual business |
| IS | 2 | t material input/output, individual businesses |
| RiP | 5 | t material consumed, onsite, any/construction/food/electronics/textiles/compostable |
| RU | 1 | %# processes without single-use plastics / using single-use plastics |
| | 6 | t material reused |
| | 1 | # items reused |
| | 3 | t material repaired, onsite |
| | 1 | # items repaired, onsite |
| SR | 10 | t material recycled, onsite, any/organic/clothing/electronics/sludge |
| | 1 | m$^3$ material recycled |
| | 7 | %t material recycled/collected, any/household/organic/clothing/packaging |
| | 1 | t material recycled, offsite |
| | 7 | t material diverted, onsite |
| | 5 | %t material diverted/collected, any/household/organic/construction/ |
| | 1 | ? local composting |
| I | 1 | t material input to territory |
| I/E | 4 | t material input/output from territory |
| **Waste Generation (73% of cases)** | | |
| C | 2 | t waste output, individual businesses |
| | 22 | t waste collected, onsite, any/household/construction/excavation/industry/events/organic |
| | 5 | t waste collected separately/collected, onsite |
| | 1 | t waste collected, sent offsite |
| SR | 1 | %t waste-to-energy/collected |
| FWD | 1 | t waste avoided |
| | 5 | t waste disposal, onsite |
| | 1 | t waste generated, onsite |
| | 2 | t waste generated, excavation/construction |
| | 1 | t/m$^2$ waste generated per developed area, construction |
| **Resource Depletion (7% of cases)** | | |
| TMR | 1 | t material extracted, onsite |
| | 1 | t material consumed, critical |
| **Land and Soil Appropriation (3% of cases)** | | |
| TMR | 1 | %m$^2$ green area /territory |
| FWD | 1 | ? soil quality, mean deviation from EU/WHO standard |
| **Greenhouse Gas Emission (57% of cases)** | | |
| FWD | 14 | t $CO_2$eq. emissions, onsite, any/ETS-companies/waste management |
| | 1 | t $CO_2$ emissions, onsite |
| | 10 | t $CO_2$eq. emissions, footprint, energy/procured material/waste material |
| **Environmental Footprint (10 % of cases)** | | |
| FWD | 3 | X environmental pressures, footprint, consumption and production/construction material |
| **Air Pollution (3% of cases)** | | |
| FWD | 1 | ? air quality, mean deviation from EU/WHO standard |
| **Water Pollution (7% of cases)** | | |
| FWD | 1 | ? quality of water |
| | 1 | m$^3$ drainage water, purified |
| **Chemical Pollution (3% of cases)** | | |
| FWD | 1 | t 1,4-dichlorobenzene eq. |
| **Ozone Depleting Substance Emission (3% of cases)** | | |
| FWD | 1 | t CFC-11eq. Emissions |
| **Local Resource Availability (23% of cases)** | | |
| RU | 1 | # items, offered/exchanged, sharing/second-hand, furniture/material/spaces |
| RiP | 1 | %t food production/demand, onsite |
| | 1 | € produce, onsite, agroecological |
| SR | 1 | € recyclables, exported |
| | 1 | t recyclables, offered, electronic |
| | 1 | t material diverted, sold |
| | 1 | ? quality, material diverted |
| NA | 1 | # donors, food sharing |
| | 1 | # places, food sharing |
| | 1 | # e-vehicle charging stations |
| | 1 | # gardens, onsite, agroecological |
| | 1 | € energy price |
| | 1 | € expenditure saved, item replacement |
| | 1 | € investment, water supply upgrade |
| **Ecosystem Service Retention (13% of cases)** | | |
| NA | 4 | € environmental cost, consumption/production/waste management/air quality deviation/ODS emission/soil quality deviation/toxicity deviation/tree cover |
| **Public Health (7% of cases)** | | |
| NA | 1 | % # population feeling in good health |
| | 1 | yrs. average life time |
| **Safety from Environmental Hazards (3% of cases)** | | |
| NA | 1 | % # population feeling unsafe |
| | 1 | °C temperature difference urban to rural |
| **Urban Equity (13% of cases)** | | |
| NA | 1 | % # population living in deprived areas |
| | 1 | % # population strata by income and wealth (Gini coefficient) |
| | 1 | % € consumption by demographic population strata |
| | 1 | • social cohesion |
| **Pleasant Living Environment (10% of cases)** | | |
| NA | 1 | # bins, private, in public realm / contaminated |
| | 1 | • degree of nuisance |
| | 1 | dB crushing noise |

Toulouse further suggest using material, energy, and waste flow analysis to enhance industrial symbiosis of a business cluster, but not for monitoring their policy performance.

### 3.4. Gaps in municipal CE indicator sets

Based on the identified goals, two different types of gaps in the target relevance of current indicator sets emerge which are elaborated below: 1) Ignorance of certain targeted environmental concerns by the indicator sets (*thematic relevance*); 2) Monitoring of concerns at an unsuitable causal stage, geographical and life cycle scope (*indicator relevance*).

#### 3.4.1. Thematic relevance: coverage of prominent environmental concerns

While the effects of CE strategies are largely viewed as a reduction in environmental pressures and as human benefits, current material flow and GHG-dominated indicator sets do not reflect many of these diverse concerns. Whereas the municipalities abundantly suggest indicators at least thematically related to their resource requirement and waste generation concerns (Fig. 2), the indicator sets lack in indicators for targeted environmental pressures and benefits (Fig. 3). The measurement of the *environmental footprint* of urban processes is a gap for a third of the policies (cf. Fig. 3). Four policies suggest using footprint assessments to calculate an environmental cost, but only for Dunedin and Utrecht there is evidence of actual calculation of a footprint. Notably, while a few indicators are suggested to monitor more peripheral environmental pressures, such as ODS emission, chemical pollution, water pollution and land appropriation by Circulaire Stad and UNEP's indicator set for Brussels (cf. Supplementary Information Fig. S1), there is no evidence of an actual use of indicators in relation to the CE policy. Hence, to what extent cities are able to implement these indicators remains unclear.

Regarding environmental benefits, an indication of the degree to which certain strategies help achieve the final desired outcome of *health and safety* for the citizens is largely absent from the indicator sets (Fig. 2). Only Amsterdam is pioneering these concerns with indicators such as the share of their population feeling in good health or feeling unsafe, as well as the degree of nuisance that is incurred in the city. The impact of CE strategies on *ecosystem integrity* also remains completely unmonitored in practice, although it is a secondary goal for cities such as Antwerp, Dunedin, and Paris (Fig. 3). Similarly, measuring the benefits of CE strategies for *global and intergenerational equity,* which is targeted by around a quarter of the cities, seems to be an unexplored dimension of applied sustainability assessment in relation to CE in cities (Fig. 2). In contrast, urban equity in terms of resource use and exposure to pollution is monitored by municipalities who do not explicitly target it, such as Derry (Fig. 3).

For some prominent and core environmental goals such as local resource availability and GHG emission reduction, a comparably large share of cities is already applying indicators, but the monitoring rate is still not complete (Fig. 2). On the contrary, some environmental

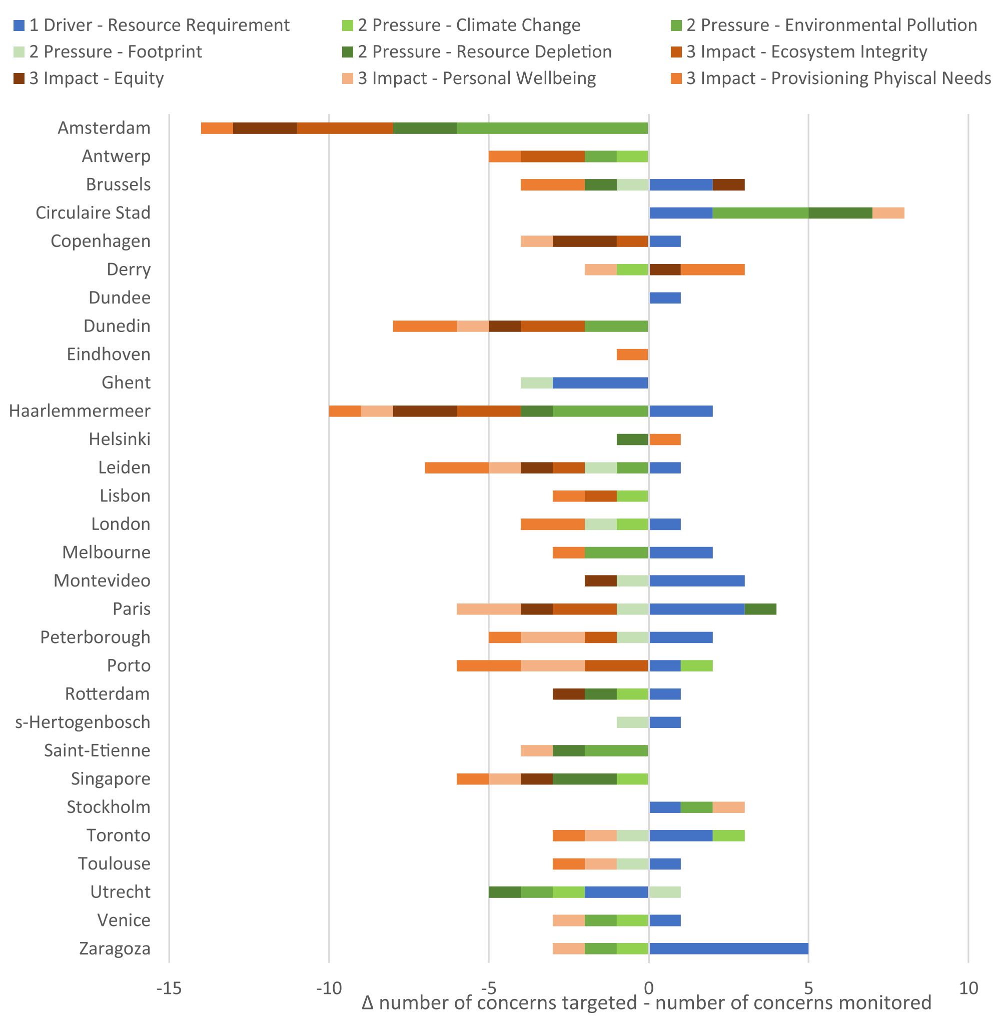


**Fig. 3.** Difference in number of environmental concerns stated as goal compared to monitored by indicator. A negative value indicates that more environmental concerns of this group are stated as goal than monitored (under-monitoring). A positive value indicates that more environmental concerns of this group are monitored than stated as goal by the municipal CE policy (over-monitoring).

concerns, especially on the side of the drivers, appear over-monitored. For instance, a greater share of cities is monitoring material and waste flows than explicitly targeting a reduction in material requirement or waste generation. The only thematic gap in resource requirement indicators concerns land use, for which fewer cities suggest indicators than the ones targeting it, although it is one of the core concerns. Only two cities monitor 'land flows': Zaragoza suggests an indicator for the share of territorial land used for organic agriculture, whereas Stockholm (which is engaged with the construction of an ecodistrict) provides an indication of land that has been 'recycled' by decontamination.

Circulaire Stad and Amsterdam stand out in a case-by-case comparison (Fig. 3). This can be somewhat explained by their policy communication styles. Circulaire Stad appears to heavily over-monitor environmental pressures next to drivers and impacts on personal well-being. This is because the founding documents of the intermunicipal collective rather offered a comprehensive overview of potential indicators than such that are feasible for the municipalities, while providing only brief context on the motivation for adopting CE principles. In contrast, Amsterdam's Circular Strategy elaborates on more than ten pages the motivation for CE, mentioning a breadth of related environmental concerns that are not even met by the applied state-of-the-art indicator set.

### 3.4.2. *Indicator relevance: (in-)complete representation of environmental concerns*

The analysis of resource and environmental flow indicators against the resource flow model (Fig. 4; Supplementary Information Table S2) elicits that, next to thematic gaps, current municipal CE indicator sets lack relevance to account for burden shifting of thematically well-covered resource requirement and environmental pressure concerns across the life cycle of urban production and consumption. Further, the majority of indicator sets lack relevance to account for outsourcing of environmental pressures offsite the city's territory.

Offsite flows of resources and environmental burdens related to urban consumption and production are hardly accounted for with current municipal CE indicator sets. The majority of GHG indicators related to the municipal CE policies, such as the ones used by Ghent, Copenhagen and Paris, do not measure offsite emissions from material consumption and its resource and environmental footprint (Scope 3). They only measure emissions from onsite production, use and waste management plus the offsite emissions from energy production (Scope 1 and 2). Only four cities measure carbon or other environmental pressure footprints resulting from urban material consumption in selected value chains (Amsterdam, Utrecht, Dundee, Helsinki). Thus, while 33 % of the policies measure offsite emissions from energy production -here conceptualized as final waste disposal from production-, only 13 % also account for the total material requirement and final waste disposal and emission from other life cycle stages due to urban material demand. When comparing with the geographical scope of the environmental concerns stated as goals (Fig. 5), it especially misses addressing adequately the goals for a global footprint impact of CE strategies on *resource depletion*, the *environmental footprint*, *environmental pollution* and *GHG emissions,* which are also among the most central and most mentioned environmental goals of the sampled municipal CE policies (Table 1).

Such a global perspective on the environmental impacts, however, is not always a priority when dealing with local measures. For concerns such as *land and soil appropriation*, *air* and *water pollution*, the scope of targeted environmental impacts is mainly restricted to the city boundaries (Fig. 5). Still, also for these territorial concerns, current indicator sets risk being blind to burden shifting and ignoring the targeted environmental pressures and benefits. While 70 % of the cities have indicators of some onsite emissions, these are mainly GHG emissions, hence omitting other local environmental pressures. Only 23 % of the cities monitor *final solid waste disposal* from the municipal waste management system onsite although the reduction of waste generation is a concern shared by almost half of the cities (Table 1). Furthermore, only three cities monitor waste generation from excavation, which is central in growing cities due to construction activities.

Hence, the analysis reveals that hardly any of the indicator sets comprise sufficient driver indicators that would allow calculating the net environmental impact of a CE strategy across life cycle stages. The driver indicators associated with municipal CE policies focus mainly on end-of-life (waste collection, recycling, disposal) and use processes within the city boundaries, but consequences of, e.g., the increase in use of secondary resources on environmental impacts or resource requirement for production and extraction, are hardly monitored. Of the indicators for which evidence of use is present, only Paris' urban metabolism model captures all resource flows (except for land) which are theoretically necessary to calculate the *overall onsite environmental pressures*. By including in- and outflows Paris also sets the ground to monitor offsite environmental pressures. However, the monitored

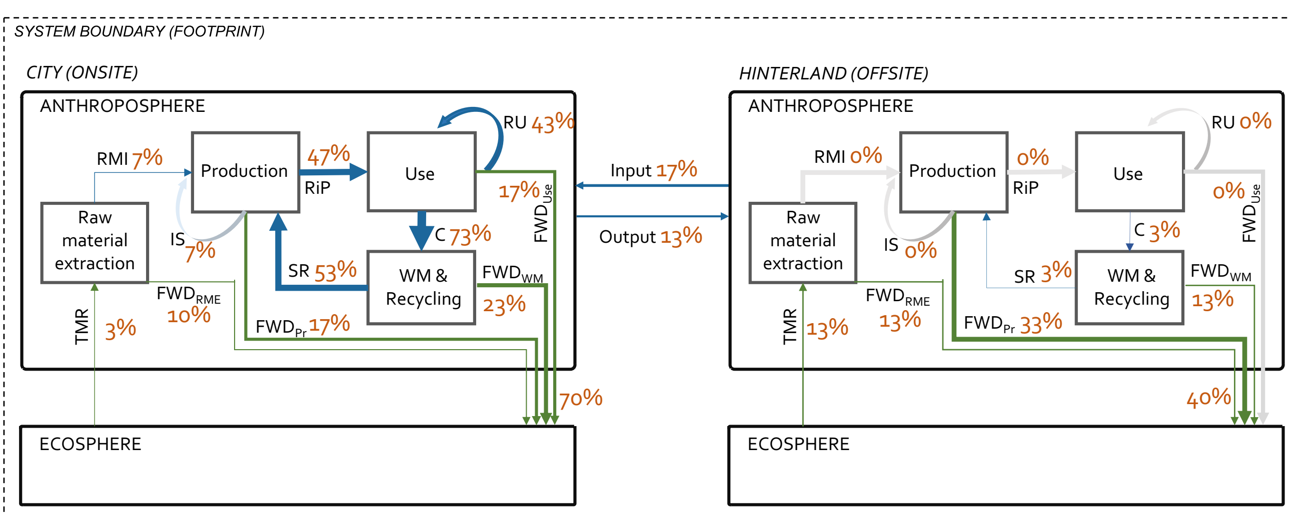


**Fig. 4.** Share of municipal CE policies referring to an indicator representing the respective resource and environmental flow. Model adapted from Helander et al., 2019. Blue arrows: drivers; green arrows: environmental pressures. C, material collected for recycling; $FWD_{Pr}$, final waste disposal from production; $FWD_{RME}$, final waste disposal from raw material extraction; $FWD_{Use}$, final waste disposal from the use phase; $FWD_{WM}$, final waste disposal from waste management and recycling; IS, industrial symbiosis (by-products reused in production); RiP, resources in product; RMI, raw material input; RU, reuse (redistribution for reuse or refurbishment); SR, secondary resources; TMR, total material requirement.

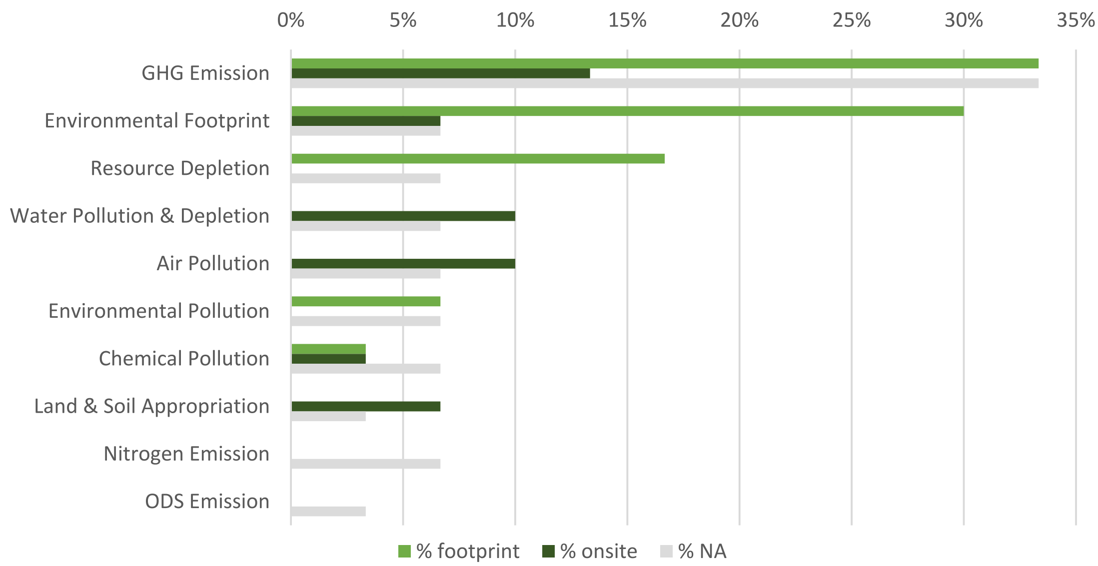


**Fig. 5.** Share of cities that desire a reduction of the environmental pressure on a footprint or onsite scope. NA: scope could not be determined from the goal statements.

product categories are still so coarse that calculation of environmental pressures will require substantial abstraction. Amsterdam has taken a similar approach, but with higher degree of detail for specific product groups, which does not yet capture all urban value chains.

## 4. Discussion

Do our findings support researchers' criticism of the lack of target relevance (i.e. 'salience') of indicators for CE goals? Yes, they do. And does this lack undermine effective reporting and progress towards these goals? Most likely. The trends identified in the indicators that cities use - or do not use - pose risks that threaten the integrity of both reporting and policy. This has important implications for research and policy. We have developed specific recommendations aimed at researchers (Section 4.1) and local authorities (Section 4.2). The recommendations for local authorities are designed to be consistent with those for researchers, so that they are mutually reinforcing. We also identify critical limitations of our study (Section 4.3).

### *4.1. Recommendations for researchers*

Our analysis shows that, apart from GHG emissions, the environmental concerns that local authorities seek to address through CE strategies are very diverse. Many of these concerns are not well captured by current indicators and they often fail to account for burden shifting. Environmental indicator sets therefore need to reflect the specific concerns that local authorities associate with the CE concept.

Based on our analysis of a large sample of municipal CE policies in Western contexts, we **propose four clusters of urban concerns that could guide further research**:

- Enhancing environmental safety and local resource availability through better waste management.
- Reducing GHG emissions through CE climate action plans.
- Reducing environmental footprints and improving social benefits through local economic development.
- Enhancing environmental integrity and public health through CE strategies.

However, accurately monitoring these hidden concerns currently requires complex modelling and extensive data collection, which can be challenging for municipalities. As shown in our analysis, the most comprehensive assessments were done in cooperation with a consultancy. To help cities to prioritise sustainable CE strategies, it is essential to simplify model inputs, provide intuitive user interfaces, disseminate information on available tools, and offer affordable consultations. Harmonising indicator sets across cities can help identify successful CE strategies that can be scaled up in similar contexts. While a universal set of indicators for all cities is impractical, identifying common concerns - as we have done in this study - is crucial for cross-city comparisons.

To help cities with a focus on waste management and onsite environmental integrity monitor local environmental issues, **researchers could expand current indicators to include basic measures of local conditions**. Air quality data, land conversion rates from GIS data, biodiversity measures and health statistics are examples of readily available data. Health and safety surveys, such as those carried out in Amsterdam, also provide valuable data on local well-being. However, these simple measures can be affected by confounding variables, limiting their usefulness for evaluating specific strategies (Loiseau et al., 2012). They may also miss the broader impacts of CE strategies, such as burden shifting or rebound effects (Leipold et al., 2023). Therefore, system models, such as urban metabolism and urban footprint models, are needed to monitor and predict the impacts of globally targeted concerns such as those contained in CE climate action plans and CE strategies for footprint-oriented local economic development.

**Research could simplify Urban Footprint models such as life cycle assessments (LCA) and environmentally extended input-output analysis (EEIOA) for cities**. Urban metabolism models can address most of the environmental concerns of urban CE policies, both locally and globally (Petit-Boix et al., 2022). These models include a territorial approach, which tracks onsite material, energy, land and water flows, and a footprint approach, which accounts for resource and environmental footprints. Such models can significantly improve the thematic and indicator relevance of CE policies. For example, territorial models can provide data on total waste generation and local resource availability (Kalmykova and Rosado, 2015). Despite their advantages, these models are underutilised in practice; only a few cities, such as Paris, have fully implemented them. To estimate the full environmental footprint of a city, methods such as LCA and EEIOA are essential (cf. Loiseau et al., 2018; Chen et al., 2020; Fry et al., 2018). These methods capture indirect resource flows and global environmental impacts, providing a comprehensive view of a city's environmental performance. However, these assessments are complex and data-intensive. They need to be simplified for practical use while maintaining rigour and completeness. Such simplification would be a major step forward in helping local authorities to use available data to meet their environmental objectives.

**Research should prioritise the development of user-friendly indicator frameworks**. While assessments for resource management policies should be available after a short period of time, urban footprint models are so complex that an update (usually performed by researchers or consultancies) occurs only once or twice a decade, if at all. At the same time, municipalities that can afford external expert advice manage to have more comprehensive information on resource flows and environmental impacts, and are therefore able to prioritise more effective CE strategies (cf. Ajuntament de Barcelona and ERF, 2018; Charlotte and Metabolic, 2019; Stadt Bern and Circle Economy, 2019). In order to also address the needs of smaller, less wealthy cities, whose concerns are markedly different, future research should focus on:

- developing models that can project contextual CE outcomes, so that sustainable CE strategies can be selected a priori,
- minimising the data input required for the models and/or taking stock of machine-learning and AI-based tools to automate data collection and application,
- adapting the models so that readily available data from communities can be fed in, and
- ensure that the models can represent the concerns of the communities through citizen science and co-creation processes.

**Research should assess the role of actors and their behaviour in environmental impact assessment.** Local governance and citizen behaviour are crucial for circular economy principles in cities that ensure sustainable production and consumption, supporting SDG 12 (Ortega Alvarado and Pettersen, 2023). SDG 12 calls for comprehensive action by businesses, policy makers and consumers to adopt sustainable practices. Nevertheless, academic evaluations of sustainable consumption policy lack in assessing the role of these actors in enabling environmental outcomes, and the feasibility of monitoring remains a barrier for local governments (Dawkins et al., 2019). Hence, it is crucial to further advance environmental impact assessment by combining it with a socio-behavioural perspective (Niero et al., 2021; Baumann and Lindkvist, 2022).

**Research funding and academic reward systems should recognise transdisciplinary research.** To meet all the above requirements, it is necessary to develop future indicator frameworks for municipal CE policies in transdisciplinary collaboration with municipalities to ensure the applicability and relevance of the models, but also to motivate the adoption of scientifically developed models in practice (Petit-Boix et al., 2022). Examples of such transdisciplinary collaborations are the REPAiR project (Amenta et al., 2019), CONEXUS (van der Jagt et al., 2023) and a Finnish collaboration on social CE indicators (Pitkänen et al., 2023). However, to enable such projects, the immense value of transdisciplinary research needs to be recognised by funders and academics.

### *4.2. Recommendations for local authorities*

Our analysis reveals that most environmental pressures and benefits associated with CE strategies are not directly monitored. This supports the findings of Corona et al. (2019), Helander et al. (2019), and Harris et al. (2021), who highlight that CE metrics often focus on material circularity rather than environmental impacts. Resource flows dominate city indicator sets and prioritise low-impact CE strategies. Steinmann et al. (2016) show that comprehensive resource footprints—including material, water, land, and energy flows—can explain variations in environmental pressures and benefits, as covered by Life Cycle Assessments (LCA). However, cities often lack the data to model these footprints accurately, and few monitor energy, water, and land use flows comprehensively.

Cities could **respond to data gaps for accurate modelling** of energy, water and land use footprints in two ways. First, they could measure environmental impacts directly on the ground. Second, they could use urban footprint models to predict the global impacts of CE strategies. However, in order to identify data gaps, cities must first identify the most relevant indicator sets for themselves. This leads us to our next recommendation.

**Cities should strive to develop a common set of indicators**, for example by activating city networks such as ICLEI. The diversity of policies and indicator sets used by cities makes it difficult to compare cities. A major problem is the focus on a few indicators, such as greenhouse gas emissions. While this focus is straightforward, it can be misleading. Other environmental pressures, such as chemical pollution and resource depletion, may be more relevant in certain communities (Corona et al., 2019; Helander et al., 2019; Harris et al., 2021). Current material flow and GHG-focused indicator sets do not adequately capture these issues.

**Cities should build cross-cutting technical expertise and knowledge to develop and monitor CE indicators.** The capacity of cities to implement different indicators remains unclear. Given the many resource and personnel constraints cities face, establishing knowledge-sharing platforms and providing training programmes can help cities overcome these barriers (Hoppe et al., 2016). In particular, this could help build cross-cutting capacity - for CE strategies and other aligned sustainability initiatives. Global city networks such as ICLEI could support and guide useful indicators for monitoring specific environmental pressures and benefits (Petit-Boix et al., 2022; Leipold et al., 2023). Improving cities' capacity to monitor their environmental impacts based on their needs and objectives could lead to better informed policy decisions and more effective CE strategies (Lehtonen, 2015).

**Cities should align their CE strategies with other urban sustainability initiatives**, such as transport or housing. Measuring the environmental footprint of urban processes is notably absent from a third of the strategies, raising questions about the seriousness or capacity of these efforts (Petit-Boix and Leipold, 2018). Land use indicators are also conspicuously absent, despite many cities struggling with urban sprawl and rising land prices, as well as conflicts over land use for conservation, recreation, construction or parking (De Roo, 2000). Only Zaragoza and Stockholm monitor 'land flows'. Recent municipal CE policies in Montreal, Buenos Aires and Richmond take first steps towards an integration by outlining the overlap in goals with other policies but remain silent on trade-offs. These findings suggest that CE strategies are not always consistent with other urban sustainability initiatives, such as transport or housing (Calisto Friant et al., 2023).

**Cities should set defined endpoints or specific targets**. The current lack of defined endpoints or specific targets, such as reducing GHG emissions by a certain percentage by 2030, obscures potential policy impacts and makes it difficult to identify best practices (Nieuwenhuijsen, 2021).

### *4.3. Limitations of the study*

The methods used in this study are subject to limitations. First, only policy documents published before summer 2021 were considered. A check in summer 2024 revealed that the number of cities retrievable via the procedure did not grow substantially over the last years: 16 % more cities are mentioned including seven cities with accessible ratified municipal CE action plans comprising Lagos, Buenos Aires and five Canadian municipalities. The dominance of dispersed onsite resource, waste management and GHG emission indicators is also visible in these policy documents, while the environmental concerns address global climate change mitigation, pollution control and local wellbeing. For instance, while Buenos Aires motivates the adoption of CE with the risk of species extinction, climate change, and ocean plastic pollution, the proposed indicators focus on the percentage of valorised recyclables. Montreal that has commissioned a consultancy to explore the circularity potential has more information available (material and GHG footprint) to justify the adoption of CE, but it remains unclear whether these indicators will also be used for regular monitoring of the policy progress. Overall, the check suggests that the key conclusions of the present study also hold for more recent cases.

Second, the sample of selected policies is subject to a language bias as the initial query on the databases is performed in English and the consequent selection of policy documents only allows to consider eight European languages. Consequently, this analysis can only reveal the concerns of internationally recognised municipal CE policies that are mainly located in the European and Western context. However, the inclusion of documents in 8 different languages is also a strength of this study. While some of the key results of this endeavour will be applicable to cities in lower-income countries – such as the diversity of goals associated with the CE –, it will be beneficial to further investigate the specific monitoring possibilities available in these regions.

Third, the sample only considers written policy documents that are publicly accessible online. It thereby ignores other policy communication styles and internal administrative information that could provide further insights into the concerns and indicator sets. Similarly, following a social constructivist approach, only concerns that have been associated on paper with the CE can be considered, but municipal actors implementing the CE might cognitively have a broader range of concerns than the ones stated, as well as more parameters apart from the CE indicators reported in their CE policies. Several documents provide very limited information on the calculation and system boundary of the indicators listed; sometimes even the unit of measurement is missing. This complicates the interpretation and classification of the indicators. In most cases, it remains unclear whether indicators are actually used or only suggested for monitoring. Still, taking the policy documents literally and processing the information provided in written form offers an unprecedented overview of the cities' environmental concerns and their monitoring capacities.

Finally, constructing environmental indicator sets only based on the concerns that are associated with a positive effect of the CE risks ignoring trade-offs between concerns positively affected by CE and those negatively affected by CE. While this study provides an analysis of the relevance of indicator sets with regards to the municipalities' own goals for the CE, final environmental indicator sets should also provide information on environmental variables not considered by the cities in relation to CE but still deemed important such as those included in the SDGs (UN, 2015).

## 5. Conclusion

Our study shows that, in practice, the environmental concerns addressed in municipal CE policies do not necessarily align with the indicators proposed to track their progress towards environmental sustainability. The trends identified in our sample of CE policies point to hidden environmental concerns that need to be monitored and to indicators that do not align in scope. For this reason, research and policy need to take stock of existing urban footprint models to help cities monitor what they conceive as central CE strategies in their urban policies to effectively determine their environmental impacts and benefits. This will avoid over-monitoring of indicators that are unrelated to current concerns simply because data for that specific indicator is accessible and for the sake of showing progress towards the SDGs (as indicated by Zinkernagel et al., 2018). By facilitating access to urban footprint models, the effects of hidden environmental concerns will come to light. However, for this to happen, these models need to be able to incorporate readily available data from communities, project contextual CE outcomes, reduce the number of inputs required, and better represent community concerns. More user-friendly models could be developed in transdisciplinary collaboration with cities. This would not only ensure their usability. It would also increase their uptake towards more sustainable cities.


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## CRediT authorship contribution statement

**Mira Kopp:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Anna Petit-Boix:** Writing – review & editing, Supervision. **Sina Leipold:** Writing – review & editing, Funding acquisition.

## Declaration of competing interest

The authors declare no conflict of interest.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.spc.2024.08.009.

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