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How cities can govern their carbon footprints despite measurement challenges—an analysis of climate planning in eight international anchor cities

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Abstract

Cities are increasingly positioned as key climate actors through transnational networks and greenhouse gas emissions reduction pledges. Upstream emissions from the consumption of goods and services account for a major portion of total urban carbon footprints. However, most city climate action plans (CAPs) only account for territorial and energy consumption-related upstream emissions, rather than addressing full consumption-based emissions. This gap is often linked to the legal limitation of municipal authority to territorial boundaries. Here, we show that cities have substantial untapped policy potential to address consumption-based emissions. The greatest missed opportunities are found in cities with extensive legal powers rather than limited authority. By analyzing eight international cities, we found that household carbon footprints ranged from 2 to 12.1 tCO_2eq per capita and year. Current CAPs addressed sectors representing 60% of indirect emissions with at least one mitigation measure, while sectors representing 40% of indirect emissions remained entirely unaddressed. All cities can address their entire carbon footprint through soft measures, and six out of eight could address over 75% of indirect emissions through hard regulatory measures. The scope of climate action on consumption-based emissions is determined by political will, policy prioritization and administrative capacities rather than legal constraints. We discuss pathways for cities to address these emissions despite the ongoing challenges of accurate measurement and monitoring. Strengthening local democratic decision-making processes can enhance the legitimacy and accountability of consumption-focused climate action, and city networks as well as national legislation could play a key role in scaling up implementation.

1. Introduction

Over the past few decades, cities have increasingly been identified as important players in climate policy. This positioning has been supported by international governance frameworks (Angelo and Wachsmuth 2020) and the scientific discourse on sustainability (Castán Broto *et al* 2025) which emphasize the potential of cities to bridge the gap between national climate commitments and actual greenhouse gas (GHG) emissions reductions (Castán Broto 2017, Gordon and Johnson 2018). Today, many cities belong to one or more of multiple transnational climate networks (Acuto and Leffel 2021) which help to coordinate

the setting and monitoring of specific emission reduction targets and climate policies (Acuto and Leffel 2021, Song *et al* 2024).

Most city climate action plans (CAPs) focus on territorial emissions and those from direct energy use, while excluding other consumption-based emissions generated outside city boundaries. Because cities import large amounts of goods and services whose production drives substantial external emissions, research has long emphasized the importance of extending territorial emission accounts with consumption-based accounts to capture the full environmental impact of cities (Larsen and Hertwich 2009, Kennedy *et al* 2010, Jones and Kammen 2011). Data and method availability have improved substantially since these early efforts (Minx *et al* 2013, Pichler *et al* 2017, Jones *et al* 2018, Wiedmann *et al* 2021), confirming the scale of consumption-based emissions and their policy relevance. For C40 cities, for example, external emissions associated with city consumption account for around two-thirds of the total footprint (Wiedmann and Allen 2021).

Taking into account the full urban carbon footprint when developing urban climate mitigation strategies enables the identification of effective intervention points for changes in final demand that facilitate emissions reductions across all sectors (Creutzig *et al* 2022), helps to avoid the displacement of emissions outside the city boundaries and enables the monitoring of potential rebound effects (Wiedmann *et al* 2021).

There are many reasons why cities may choose not to integrate consumption-based emissions into their GHG inventories and climate pledges. Data and method requirements may exceed the resources available to most municipalities (Wiedmann and Allen 2021). International climate frameworks provide limited technical support for consumption-based approaches (Zhang *et al* 2024). Policymakers are often reluctant to target consumption directly, as this may conflict with local economic growth objectives (Wiedmann and Allen 2021). Additionally, the focus on legal authority being limited by administrative boundaries often leaves the broader policy leverage cities have over transboundary impacts underexplored, despite evidence that substantial tools exist (Seto *et al* 2021, Zengerling *et al* 2022).

To examine the scope and scale of consumption-based emissions that cities are addressing in their current CAPs and those that they potentially could address, we analyze eight international cities with differing levels of regulatory authority and ownership of provisioning systems in a team of authors that covers expertise in the fields of industrial ecology, urban planning and law. We first estimate their urban household carbon footprints to establish the relative scale of carbon footprints in individual consumption sectors. We then identify current climate measures from each city's climate action plan affecting consumption-based emissions across these sectors. Finally, we examine the legal scope of action in all the cities to investigate what consumption sectors they could potentially further address with climate policy given their respective governance contexts. We conclude with an extensive discussion on how cities can address indirect emissions even if accurate measuring and monitoring remains challenging.

2. Methods

2.1. Case study selection

The eight case study cities, Cairo, Delhi NCT, Hamburg, Lagos, New York, São Paulo, Shenzhen, and Toronto, have been chosen because they are anchor cities in countries that account for more than half of the global urban population and operate in highly diverse governance settings.

2.2. Data

City carbon footprints: In order to calculate the carbon footprint of our eight case study cities, we used a combination of: 1) city-specific household expenditure surveys and the environmentally-extended multi-regional input–output (EE-MRIO) model EXIOBASE (version 3.8.2., product-by-product) for the indirect emissions calculation, and 2) city-specific carbon inventories, where available, and population data, for the direct emissions from housing and transportation calculation. Because the consumer expenditure surveys at city level tend to occur infrequently, when calculating the carbon footprints, we used the most recent consumer expenditure survey we were able to access and then used the carbon inventory for the direct emissions calculation from the same year as the expenditure survey if possible, or else the closest possible year. We express the carbon footprints in tons of CO_2eq per capita and year.

CAPs: For the policy analysis we used the latest CAPs available for the cities as of February 2023:

City	Year	Climate Action Plan
Cairo	2018	Giza Governorate Strategy
Delhi NCT	2019	State Action Plan for Climate Change
Hamburg	2019	Hamburg Climate Plan
Lagos	2021	Lagos Climate Action Plan
New York	2019	One NYC
São Paulo	2020	Climate Plan SP
Shenzhen	2021	Shenzhen's 14th 5 Year Plan for Ecological Environment Protection
Toronto	2021	Transform TO+ Net Zero Strategy

2.3. Emissions accounting

To establish the relative scale of consumption sectors for policy analysis, we calculated carbon household footprints for our eight case study cities following the method applied by Pichler *et al* (2017). We integrated the city-specific household expenditure data into the EE-MRIO EXIOBASE to estimate upstream emissions embedded in the production of goods and services consumed locally. To achieve this, local consumption categories were concorded with the national economic sectors used by EXIOBASE, with local currencies converted to euros. Conversion of non-CO_2 gases to CO_2-equivalents is based on GWP100, IPCC AR4. Deviating from Pichler *et al* (2017), we used direct emissions data for local fuel use for housing and transportation from the carbon inventories provided by the cities directly, since EXIOBASE's direct emissions categories lack the spatial and sectoral resolution needed for city-level allocation. For two cities, Shenzhen and Cairo, we were unable to locate and access a carbon inventory close enough to the expenditure survey year, so here we used total direct emissions from households per country (China for Shenzhen) or region (Middle-East for Cairo) in EXIOBASE, divided by total population from the World Bank database to calculate those emissions per capita, and then split the emissions into a 'housing' component and a 'transportation' component using data from other sources. While more comprehensive methods exist (Wiedmann *et al* 2021), we selected this approach due to its applicability across all case study cities and adequacy for our analytical purposes. The data sources used for our city carbon footprint calculations are detailed further in the supplementary information section S1.

2.4. Policy analysis

The policy analysis identified which consumption sectors are already addressed directly or indirectly by existing climate action plan measures and determined which sectors are addressable via hard or soft modes of urban climate governance within the cities' respective scope of action.

We aggregated the 200 EXIOBASE sectors into 39 policy sectors, considering their respective shares of emissions (see appendix table S1 for full sector definitions). The policy analysis was conducted at this 39-sector resolution to maintain analytical precision. For visualization purposes, we further aggregated these 39 sectors into 14 policy sectors under four aggregate sectors: Food (Dairy, Meat, Plant, Other, Waste), Housing (Electricity, Fuels, Other), Transport (Air, Land & Water, Other), and Other (Goods, Services, Waste).

We conducted a systematic content analysis of each city's climate action plan to identify measures that reduce household consumption emissions. Each identified measure was coded by one or multiple sectors (using our 39-sector framework) and assigned to one of six governance modes. Building on prior research by Kern, Bulkeley, Alber and Castán Broto (Bulkeley and Kern 2006, Kern and Alber 2008, Bulkeley and Castán Broto 2013; Castán Broto and Bulkeley 2013) we differentiated between six modes of urban climate governance: regulation (local law-making and planning, exerting local authority), provision (provision of infrastructure and services), self-governance (governing own activities), enabling (support, coordinate and incentivize activities with or of private businesses, NGOs, local communities and citizens), partnership (cooperation with other stakeholders), and experimentation (testing innovative actions). We defined regulation and provision as hard modes of urban climate governance because in these modes the city has the ability to reduce GHG emissions unilaterally, legally or de facto binding and potentially long term. Self-governance, enabling, partnership and experimentation were qualified as soft modes of urban climate governance as they address either only GHG emissions of the city itself (self-governance), rely on cooperation (enabling and partnership), or are cooperation-based and short term (experimentation).

Finally, we assessed each city's potential to address urban GHG footprints again building on the six modes of urban climate governance. Since the use of soft modes of urban climate governance primarily depends on political will, financial, and administrative capacity, our analysis of addressability of household consumption emissions focused on the two categories of hard urban climate governance: regulation and provision. The regulatory scope of action of a city is fundamentally defined by constitutional provisions and more specifically spelled out in national and sub-national laws. For each jurisdiction we therefore conducted a legal analysis along the multi-level government system of the respective jurisdiction covering constitutional provisions on municipal scope of action, laws at national and sub-national level that regulate municipal scope of action at a rather overarching level, such as municipal regulations, planning laws, and procurement laws, as well as key sector specific legislation on building, energy, food and waste. We scrutinized the respective legislation and asked if it grants the cities regulatory scope of action for local law-making that addresses household consumption emissions under the 39-sector framework. With a view to provision we investigated if the cities own (majority shares of) housing, energy, mobility, food or waste infrastructures and thus may influence consumption emissions through their position as (co-)owners. We identified key infrastructure providers in the respective sectors for each city and shares of ownership drawing on information publicly available through the providers' websites.

2.5. Limitations

The aim of this paper is to explore the extent to which cities currently address, and could potentially address, emissions associated with household consumption. Despite the application of state-of-the-art methods, limitations resulting from data availability mean that our numerical results are largely illustrative. For example, the sectoral emission intensities in EXIOBASE are national averages that do not necessarily reflect the supply chains specific to individual cities. Additionally, we focus on household expenditures for the footprint calculations and omit government spending and capital investments due to a lack of city-specific data even though urban mitigation policies may cover both. See Wiedmann *et al* (2021) for an attempt to estimate these flows. Finally, urban CAPs vary considerably in their level of detail and specificity with regard to sectoral mitigation policies and the scope of emissions that would be covered by their implementation. This introduces uncertainty into comparisons of measures across cities, as well as into the amount of emissions covered by a given mitigation measure once mapped onto one of our 39 emission sectors. For example, a policy that eliminates meat from the menus of public canteens across a city is mapped onto emissions from meat consumption, but does not address all meat consumption. In the results section, we attempt to mitigate any potential confusion arising from this by reporting that measures address 'sectors representing a given share of emissions', rather than reporting that measures cover that share of emissions entirely. For the same reason, we refrain from reporting measure counts on sectors to indicate policy activity. An overview of measures identified across cities and sectors can be found in supplementary figures S1 and S2.

3. Results

3.1. Urban carbon footprints

Our analysis reveals substantial variation in household carbon footprints across the eight case study cities, with emissions ranging from 2 tonnes CO_2-equivalent per capita and year (tCO_2eq/cap) in Cairo and New Delhi to 12.1 tCO_2eq/cap in New York City (figure 1(a)). This order of magnitude difference aligns with documented patterns in prior research (Pichler *et al* 2017, Moran *et al* 2018, Wiedmann *et al* 2021). New York City has the highest consumption-based emissions, followed by Toronto (9 tCO_2eq/cap) and Hamburg (6.8 tCO_2eq/cap). Shenzhen's emissions are 4.9 tCO_2eq/cap, São Paulo's 3.8 tCO_2eq/cap, and Lagos' 2.4 tCO_2eq/cap. These patterns mainly reflect household spending power, the GHG intensity of local consumption behaviors and infrastructures, as well as climate conditions. Compared to direct household emissions from city GHG inventories, indirect, consumption-based emissions typically constitute the majority share of the household GHG footprints ranging from 50% in Cairo to 91% in Shenzhen.

The sectoral composition of indirect emissions (figure 1(b)) also shows results comparable to previous studies (Pichler *et al* 2017, Wiedmann *et al* 2021), with food and housing having the largest shares of indirect emissions across cities. Housing emissions, which include electricity and thermal conditioning, often represent large shares but depend on household incomes, climate, living space per capita, and existing urban infrastructure. They range from 46% New York City to only 17% in New Delhi. The 'Other' category, encompassing goods and services, typically increases as incomes rise above basic needs levels, explaining the large shares in cities with high spending power like Toronto (37%) and Hamburg

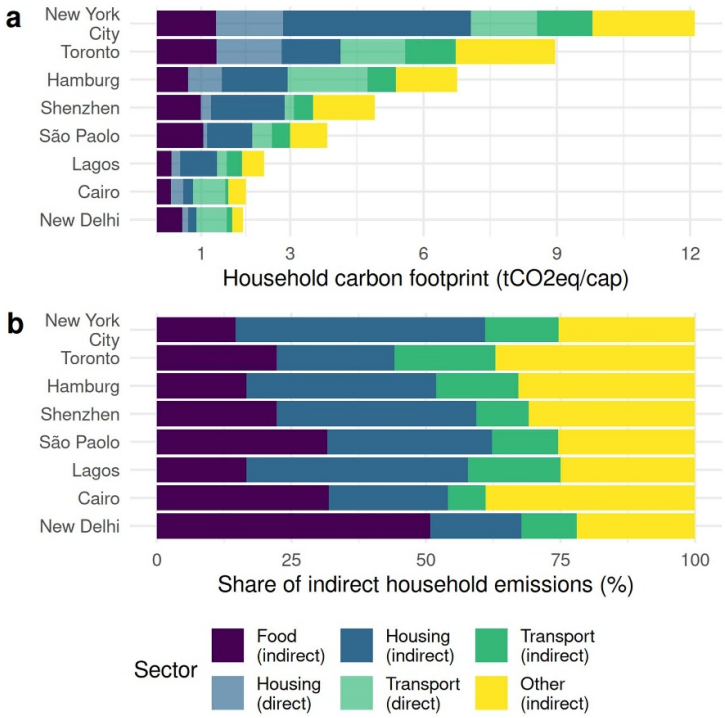

Figure 1. Greenhouse gas footprints of household consumption disaggregated by sector and direct and indirect components in tons CO_2eq per capita (a). Shares of indirect emissions from household consumption across food, housing, transport and other sectors (b).

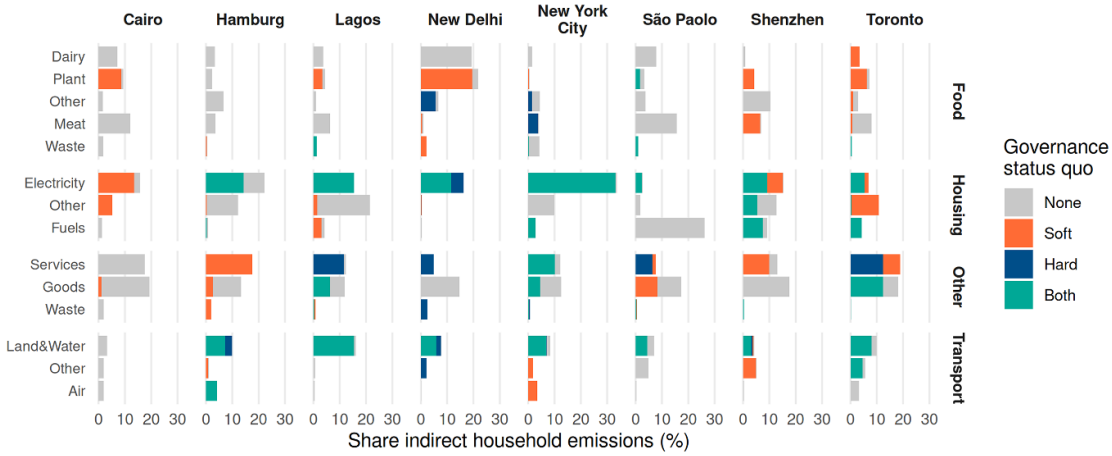

Figure 2. Policy sectors addressed by at least one mitigation measure (none/soft/hard/both) in current climate action plans of cities. Bar size corresponds to the share of indirect household emissions represented by the sector.

(33%). Food emissions show the inverse pattern: they represent larger shares in cities with lower spending power where food expenditure constitutes a major portion of overall expenditure, such as New Delhi (51%) compared to Hamburg (17%). Transport indirect emissions (upstream fuel production plus collective transport systems) vary from 7% (Cairo) to 19% (Toronto), reflecting differences in transport infrastructure and usage patterns. These footprint patterns provide the baseline against which we assess cities' current CAPs and their future potential.

3.2. Analysis of current CAPs

Current CAPs include at least one mitigation measure in policy sectors representing 60% of indirect emissions across all eight cities (figure 2). Of these, 18% of emissions are covered by soft measures only (enabling, partnership, experimentation, self-governance), 7% by hard measures only (regulation and provision), and 35% by a combination of both. This leaves policy sectors representing 40% of indirect emissions that are currently not addressed by any mitigation measures.

Transport (79%) and Housing (67%) show better coverage than the goods and services ('other', 61%) and food (35%) sectors, also because measures targeting direct emissions in transport and housing can simultaneously affect their indirect emissions. In particular, the food sector stands out, with only 11% of emissions covered by hard measures.

Mitigation measures in the food sector show uneven coverage across subsectors. Plant-based food has the broadest coverage (representing 79% of total emissions in this subsector across all eight cities), with seven cities implementing predominantly soft measures that enable local or urban agriculture through farmer training, infrastructure support (composting facilities, solar equipment), and consumer awareness campaigns aimed at shortening supply chains. Four cities implement hard measures for food waste (Lagos, New York, São Paulo, Toronto), though with lower overall emissions coverage (30%). Toronto's food waste measures combine waste management regulations with community grants and infrastructure provision, including an additional organics processing facility with renewable energy generation. No city deploys dairy-specific measures, though Toronto's general food procurement target (25% emissions reduction) applies across all food categories.

In the housing sector, electricity is at least partially covered by either soft or hard (often both) measures across all eight cities (93% of total emissions in this subsector), followed by fuel (48%) and other (31%). Toronto (100%) and New Delhi (98%) deploy measures in sectors covering (nearly) all of their housing emissions while São Paulo only addresses electricity (8%). Toronto's enabling measures include Home Energy Loan Programs for retrofits, Net Zero Existing Buildings Strategy implementation, and natural gas phase-out framework development. Hamburg, by contrast, uses predominantly regulatory approaches, including mandatory sectoral emission reduction targets, renewable electricity supply infrastructure requirements, and electric heating bans in new/refurbished buildings from 2025.

Of all transport subsectors, land and water transport has the broadest coverage (85% of total across cities and more than 90% in Hamburg, Lagos, New Delhi and Shenzhen), followed by Other (73%) and Air (66%). Cairo is the only city with no transport measures. Hard transport measures favor provision over regulation, as illustrated by Lagos, where measures include expanding the public transit network with four new bus terminal gateways, 300 low-emission buses and 17 passenger ferry routes, alongside targets for 52% electric buses and 20% electric motorcycles by 2050. Only two cities address air travel: Hamburg implements provision measures for synthetic fuels and infrastructure plus self-governance approaches, while New York implements partnership measures for sustainable aviation fuels and airport equipment electrification.

In the goods, services and waste (Other) sector, mitigation measures cover subsectors representing 92% of total emissions in waste across cities, 88% in services, but only 36% in goods. The six cities that do address goods deploy contrasting approaches: New York uses predominantly hard measures aimed at supply chain decarbonization within and outside the city boundary including Green Loading Zones for zero-emission commercial vehicles, fleet emissions reduction measures, and single-use plastic bag bans. Toronto, on the other hand uses predominantly soft measures addressing consumption patterns through Sewing Repair Hubs to reduce textile waste via repair and reuse workshops, sharing and reuse spaces implementation, and development of a Circular Economy Roadmap governance structure.

Comparing cities, Toronto has the broadest coverage across sectors representing 78% of household emissions, followed by New York City (69%). New Delhi (62%), Lagos (59%), Shenzhen (58%), and Hamburg (52%) all implement measures on sectors representing more than half their indirect emissions. Cairo (28%) and São Paulo (26%) currently have more limited coverage.

3.3. Analysis of potential policy measures

All cities can theoretically address their complete urban GHG footprints through governance measures, though the mix of available tools varies dramatically. Soft measures (self-governance, enabling, partnership, and experimentation) are (by definition) universally accessible across all emission sectors. Their deployment depends solely on political will, decision-making majorities, and local capacities. Hard measures through regulation (local law-making and planning, exerting local authority, including pricing) and provision (infrastructure and services), however, depend critically on cities' legal scope of action and ownership shares of public infrastructure.

The potential for expanding hard governance coverage ranges from highly constrained to extensive. Cities like Cairo face structural limitations, with potential hard coverage reaching only 16% of emissions. In contrast, cities like Delhi (94%), Hamburg (86%), and Shenzhen (86%) could theoretically deploy hard measures across sectors representing most of their footprints. Current use of hard governance varies enormously. New York City already covers 64% of emissions with hard measures but could reach 83%. Cities like São Paulo (16% current, 83% potential) and Delhi (39% current, 94% potential) show massive untapped hard governance capacity (figure 3). This analysis examines where cities could

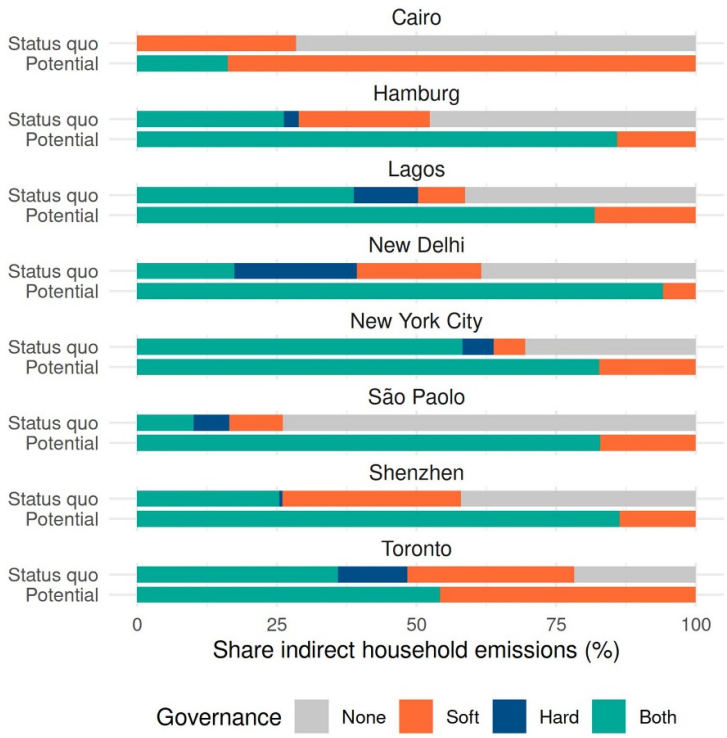

Figure 3. Indirect household emissions shares currently addressed through hard and soft modes of urban climate governance in climate action plans (status quo) vs indirect household emissions shares that could be addressed based on policy analysis (potential).

expand their climate governance of indirect emissions through available hard governance tools and identifies the legal and institutional factors that enable or constrain such expansion.

Toronto has the broadest sector coverage among cities and its climate action plan covers sectors representing 48% of emissions through hard governance. This coverage is high relative to its limited potential for hard governance (54%), which ranks second-lowest after Cairo's 16% and well below cities like Hamburg (86%) or Delhi (94%). Toronto shows the smallest gap between current and potential hard governance coverage.

Lagos operates with state-level climate planning authority, large regulatory scope, and high influence on provision infrastructures, enabling extensive climate action with 100 measures across all sectors, yet has significant sector-specific gaps. Housing Other Services (20% of emissions with no measures) is their largest uncovered sector, followed by Other Goods Chemicals/Pharma (4% with no measures). For pharmaceuticals, for example, the Lagos State Ministry of Health has direct regulatory scope over pharmaceutical consumption, enabling them to improve medicinal education to discourage unnecessary pharmaceutical use, enforce prescription requirements to reduce antibiotic overuse, integrate traditional medicine into healthcare systems, and reduce drug application in public hospitals.

São Paulo operates as a third-level government under Brazil's Constitution with large regulatory scope and significant influence on provision infrastructures, yet represents the biggest untapped potential among the cities studied. Three massive gaps dominate: Housing Fuel Non-Renewable (26% of emissions with no measures), Food Red Meat (14%), and Food Dairy (8%). These three subsectors account for 48% of São Paulo's emissions.

For housing fuel, despite federal constraints on energy supply, São Paulo has unused tools including building codes (they required solar water heating in 2007), land-use planning incentives for cooking stove electrification, and energy efficiency standards for heating systems. For food, São Paulo has clear regulatory scope through municipal procurement and zoning powers. They could require reduced meat and dairy in municipal facilities (schools, hospitals, offices), use zoning authority to favor plant-based food sales at transit stations, and add climate criteria to existing food safety controls.

Hamburg operates as a city state with large regulatory scope and high shares of ownership of provision infrastructure, yet reveals significant gaps concentrated in the food sector. Food Other nec (5% of emissions), Food Dairy (3%), and Food Red Meat (2%) all lack any governance measures. Housing Electricity Services (8%) and Housing Other Services (12%) also receive no policy attention.

Hamburg has extensive unused food system authority. They directly own canteens and catering infrastructure, providing immediate control over institutional food policies, and have legal scope to support lower emission food supply infrastructure through land use planning and urban development contracts. For food waste, Hamburg has direct influence through waste collection regulation and 100% ownership of waste processing companies.

Despite China's unitary state structure, cities are highly financially decentralized. Shenzhen as a special economic zone enjoys even higher financial decentralization from central government, enabling large scope of influence on local economies including provision infrastructures. Nevertheless, significant gaps remain in specific sectors: Housing Other Services (7% of emissions with no measures), Other Goods CE and ICT (6%), and Other Goods Apparel & Textiles (6%).

These gaps represent unused authority rather than legal constraints. Shenzhen has broad powers to directly regulate businesses and industries for sustainability, with authority that exceeds typical municipal scope. They can issue binding regulations on manufacturing processes, service delivery standards, and resource recovery across major economic sectors but deploy no measures in these high-emission areas.

New York City shows strong housing performance, implementing measures in housing sectors representing 36% of emissions. But significant gaps remain in specific subsectors: Housing Other Services (10% with no measures), Food Waste Treated (4%), and Food Dairy (1%).

The remaining housing services gap represents underutilized authority rather than legal constraints. NYC governs most infrastructure except those managed at state and federal levels and could regulate water system efficiency, facilitate rooftop solar through zoning changes, and require energy audits for building services.

As a capital city, Delhi NCT operates with specific powers, but also shares parts of infrastructure governance with the national government. This may explain some of the difficulty to implement hard measures. Despite having the ability to affect significant provision infrastructure, major gaps remain in food system sectors: The Food Dairy sector (accounting for 19% of emissions with no mitigation measures) and the Food Plant-based sector (accounting for 20% of emissions with only soft mitigation measures) together represent 39% of emissions.

Delhi controls key levers of the food system through the regulation of the Public Distribution Service, the regulation of municipal food markets, and licensing of private sellers allowing measures at points of distribution. The government owns and operates schools with mid-day meal schemes, owns key agencies that support knowledge for farmers, and manages many local parks and gardens which can also be leveraged to take up indirect measures.

Cairo faces the most constrained legal environment. With authority split across three governorates (only Ghiza has a climate action plan), regulatory power concentrated at the national level, and provision infrastructure owned by national government or privatized, our analysis has only found sectors representing 16% of Cairos emissions across Food, Transport and Other where Cairo could implement hard measures where currently there are none. For example, they could implement hard measures in food waste management through the Cairo Cleaning and Beautification Agency's waste collection authority. Given Cairo's constrained regulatory scope and lack of infrastructure control, they must otherwise rely heavily on soft measures to address their currently unaddressed emissions.

4. Discussion

We have analyzed the CAPs of eight cities to establish the extent to which they already cover indirect emissions from household consumption. We found that all cities have policies in place that can reduce these emissions either directly or indirectly. While breadth and depth of coverage vary across cities, direct emission sectors (housing and transport) currently receive more policy attention than indirect emission only sectors (Food and Goods, Services and Waste (Other)). This is hardly surprising as all city inventories focus on territorial emissions or emissions from direct energy consumption within the city.

Our policy analysis shows that cities could dramatically expand their governance of consumption-based emissions. All cities could cover all sectors with soft measures and, except for Cairo and Toronto, all cities could cover sectors representing more than 75% of their indirect emissions with hard measures. This suggests that political will, policy prioritization and administrative capacities, rather than legal constraints, determine the scope of possible climate action on indirect emissions. Currently, the greatest missed opportunities are not found in cities with limited authority, but in those with broad legal powers that do not use their scope of action to reduce consumption-based emissions. The pertinent question then is: why is this the case? Why are cities so hesitant to include consumption-based emissions into

their CAPs, even if they have the political and legal authority to do so? In the following we discuss what we consider key reasons for this reluctance and how they could be overcome.

4.1. Perceived and actual lack of authority

City governments are very aware that their spatial authority ends at their administrative boundary. While scope 2 emissions are still spatially linked, scope 3 emissions may originate far from cities and seem not addressable. As we have shown in our study this lack of influence is only perceived. It is important to raise awareness in city governments that the design of local infrastructures within their administrative boundaries has a high influence on local lifestyles and thus consumption-based emissions anywhere. Climate action planning and respective emissions' accounting should therefore regularly encompass all emission sectors of a city, including those that only cause indirect emissions.

Our study has shown that six of the eight analyzed cities could address sectors representing more than 75% of their indirect emissions with hard measures. If cities want to broaden their hard scope of action over consumption-based emissions, it is important to bear in mind a fundamental difference in origins of competence with regard to provision and regulation. The degree to which a city may influence provision-based emissions depends on its degree of ownership of provision infrastructure and not on higher levels of government. If a city owns public infrastructure or holds majority shares in a privatized model (e.g. in the energy, housing, mobility, water or waste sectors) it can govern GHG emissions through hard policy measures.

This is different with regulation. The regulatory scope of action of a city is not in the hands of the city but determined by higher levels of government. It can only be broadened if the respective higher level of government, e.g. state or national government, endows cities with more regulatory power. While many cities have broad regulatory scope of action in land use planning and medium scope of action in the housing and transport sectors (Fuo *et al* 2022, Zengerling *et al* 2022), climate action planning as such usually remains a voluntary task. In Germany, we can currently observe a stark rise in cities strategic planning for the so-called heating transition. This is due to a new national law that was passed at the end of 2023 and obliges cities to enact heating transition plans. According to the principle of connexity this new obligatory task also comes with obligatory funding; thus, cities receive national and state funds to implement the new task. The local decarbonization of heating supply infrastructure significantly reduces consumption-based emissions of fossil heating fuels. A similar empowerment of cities could be enshrined in national law for climate action planning in general, ideally with the explicit task to address direct and indirect GHG emissions of cities. The advantage of such an obligation is at least threefold: climate action planning addressing direct and indirect emissions would be massively scaled beyond the current coalition of the willing (Kern *et al* 2023), cities would receive funding to implement the new tasks, and would gain climate interests more weight in local decision-making (see also Britz 2025).

Finally, reducing consumption-based emissions is not the sole responsibility of cities. For one, all upstream emissions from the perspective of the city are the direct emissions of other entities, from the companies to the nation states involved along the entire supply chain. However, reducing and shifting demand from carbon intensive sectors substantially facilitates mitigation efforts elsewhere (Creutzig *et al* 2022). Successful polycentric climate governance (Jordan *et al* 2015) is based on an 'all hands on deck'-approach (Hale 2016). Therefore, national and supra-national regulation should oblige companies to account for and reduce direct and indirect GHG emissions in line with the warming limit of the Paris Agreement. For example, supply chain regulation at national and EU level requiring companies to enact and implement climate transition plans and clauses in Free Trade Agreements that align trade and climate targets are important regulatory mechanisms to enable sufficiently transformative dynamics towards decarbonization (Zengerling 2020, Böhning-Gaese *et al* 2025). Furthermore, with Lliuya v. RWE (Germany) and Milieudefensie vs. Shell (Netherlands) we have already seen landmark cases in climate litigation establishing that companies can be held liable under civil law for their direct and indirect GHG emissions. In their latest climate litigation snapshot Setzer and Higham (2025, 34, 37) identify at least 20 other of these corporate framework cases seeking to reduce scope 3 emissions of companies globally.

4.2. Lack of data and methods

Measurement limitations for consumption-based emissions are fundamental and will persist, but cities can act on well-established magnitude differences between high and low-carbon choices. The most comprehensive method, EE-MRIO analysis which we applied here, is useful to identify sectoral emission hotspots (Pichler *et al* 2017, Wiedmann *et al* 2021) but faces inherent constraints: sectoral aggregation cannot distinguish carbon-intensive products from decarbonized substitutes (e.g. internal combustion versus electric vehicles), and tables update only every 5–10 years. Urban applications face additional challenges,

as city-level analysis typically combines national input-output tables with local expenditure data, assuming urban supply chains match national averages. While progress continues, most city administrations lack the data and capacity for regular EE-MRIO analysis.

Life cycle assessment (LCA) offers no practical alternative. Though LCA databases compile product-level supply chain emissions, they suffer from serious aggregation and truncation biases (Guillaume *et al* 2011). Because LCA is micro-based, establishing or purchasing databases (the largest are commercial, e.g. ecoinvent) for individual products exceeds city government capacities even more than MRIO implementation.

However, these limitations should not prevent cities from addressing consumption-based emissions. Reducing urban carbon footprints is fundamentally a problem of scale and political will, not measurement precision. The magnitude differences between high and low-carbon options, such as meat-based versus plant-based diets, fossil fuel-based versus active or renewable-driven mobility, or fossil versus renewable heating, are well documented and confirmed by both MRIO and LCA methods. Knowing these order-of-magnitude differences for the key products, technologies, and infrastructures that define the urban metabolism is straightforward, even for small municipalities. Practical suggestions on how to deal with these challenges can be found, for example, in the C40 Cities guidelines on how to select actionable data indicators as proxies to monitor mitigation policies for consumption-based emissions (C40 Cities 2023).

4.3. Three major ways for cities to address consumption-based emissions

Given these order-of-magnitude estimates, cities can address their indirect emissions through three strategies.

First, cities can increase the energy efficiency of final energy demand. For example, insulating homes or shifting transport modes from individual motorized transport to active travel reduces both direct emissions from fuel combustion within the city, but also reduces emissions from extraction, manufacturing and transport of the fuels as well as the vehicles. Consumption-based accounting avoids simply shifting territorial emissions outside city boundaries and allows monitoring potential rebound effects (Wiedmann *et al* 2021). Second, cities can decarbonize their direct energy use via electrification (e.g. heat pumps or switching from ICE vehicles to EVs) as well as their supply chains via self-governance measures within their own operations, such as green procurement in public canteens, hospitals and offices, or, in some legal contexts, with regulation of supply chain requirements.

Third, cities can have a large impact on indirect emissions using governance measures that reduce overall consumption or shift it towards more sustainable options. These so-called demand-side solutions, including sufficiency measures that aim at reducing 'excess' consumption, are increasingly recognized as a key element for a successful sustainability transition (Sandberg 2021, Creutzig *et al* 2022, Wiese *et al* 2024). For such demand-side measures to be effective, they must target reduction of energy-intensive consumption in households (often via non-energy policy (Royston *et al* 2018)) that currently consume excessive amounts while ensuring adequate access for the entire citizenship (Jaccard *et al* 2021). The latest assessment report of the IPCC identifies reducing long-haul aviation and providing short-distance low-carbon urban infrastructures and switching to plant-based diets as the two most effective interventions (Creutzig *et al* 2022). We discuss some concrete challenges and opportunities for urban demand-side or sufficiency policies in the following sections.

Experiences and good practices in these three major ways of reducing consumption-based urban emissions could be shared more extensively within city networks and promoted under initiatives of the Global Climate Action Portal.

4.4. Conflicts with local growth objectives and limited resources

Even if the myths of lack of authority and accounting are successfully countered, conflicts with local power dynamics as well as lack of administrative capacities and resources are likely to significantly hinder cities' climate action on consumption-based emissions. Urban climate governance is a political process shaped by power relations, conflicting interests, and the embeddedness of climate action within existing urban systems, rather than an isolated, solely technical or managerial challenge (Broto 2017). This structurally disadvantages demand-side (or sufficiency) measures in most places. Supply-side actors are typically focused on expanding demand, are well organized and have disproportionately more impact on policy than the significantly less organized group of demand-side actors (i.e. citizens) (Kuzemko *et al* 2017). This is the case across all sectors, including in the housing market whose structures and policies are often barriers to, rather than enablers of sufficiency policies (Sylvia and Spangenberg 2019).

This structural disadvantage needs to be balanced to enable local demand-side and sufficiency measures. In addition to clear proof of and transparency on the relevance of and authority for such

measures, administrative capacities and resources are key to empower local governments in their role of representing common good-interests in designing and implementing measures in all six hard and soft modes of urban climate governance. If state or national legislation requires holistic and thus supply- and demand-side urban climate action planning the weight of common good-interests is strengthened in decision-making. Furthermore, at least in the jurisdictions that adhere to the connexity principle, these new tasks also go along with state and national funding and thus strengthened capacities. In addition, climate funding at national and supra-national levels may support cities' demand-side climate planning and implementation.

4.5. Local democratic decision-making

In climate planning cities face the challenge of being accountable towards both the global and the local demos or electorate. Working towards the Paris mitigation targets regularly goes along with at least perceived higher burdens than benefits at the local scale. However, as shown in our analysis, cities can steer structural changes that reduce consumption-based emissions by provisioning without targeting individual behavior, because they have authority over much of the provision infrastructure that determines consumption (see also Sandberg 2021). For example, zoning decisions from single houses in the periphery to apartments in central locations reduce private car use and dwelling size including indirect emissions e.g. from fossil fuels, concrete and steel, appliances and furniture (Säynäjoki *et al* 2015). There are other systemic interventions like privileging shared mobility services over individual motorized transport or supporting product longevity through repair cafes (Dablander *et al* 2025). Furthermore, many of the most promising sufficiency approaches have in common that they do not target individual consumption behavior directly but instead target time use by expanding the availability of consumption-free, locally accessible public amenities, shifting us toward inherently lower-carbon activities while maintaining or increasing quality of life (Druckman *et al* 2012, Wiedenhofer *et al* 2018).

One key strength of urban climate governance lies in cities' capability to directly involve citizens and local interests into their climate planning and implementation to ensure a high degree of local legitimacy and accountability. For example, innovative formats of public participation and institutionalization of citizen councils can be observed as part of the policy cycle of climate planning in many cities. There is robust evidence that citizen assemblies on climate change mitigation strongly advocate for sufficiency and regulatory policies (Lage *et al* 2023), and thus support ambitious climate action planning also with regard to consumption-based emissions. This holds true for democratic systems, and—depending on the practice of local decision-making—even bears the potential of increased legitimacy and accountability in non- or less-democratic regimes.

It is thus important to strengthen local democratic decision-making and improve public participation where cities' climate planning is still a rather technocratic process. Cities have a unique potential to design and implement decarbonization measures that are responsive to local voices, identities and needs. This is not only key to address supply- and demand-side measures and ensure local well-being but also to avoid that cities fall prey to global capital flows (ab)using climate funds for investments in mega projects that expand debts politics, dependencies and green colonialism at the expense of local well-being.

5. Conclusions

Cities often hesitate to integrate consumption-based emissions into climate planning due to perceived limits on their authority over emissions produced outside their boundaries. Our analysis of eight diverse anchor cities shows which consumption-based emission sectors are currently addressed in CAPs, or could potentially be addressed given their diverse legal frameworks. Leveraging expertise in industrial ecology, urban planning, and law, we based our analysis on 39 policy sectors derived from 200 economic input–output sectors.

Our findings contribute to the understanding of urban carbon footprints in three key ways. First, in line with previous research, household carbon footprints significantly vary, with Cairo at 2 tCO_2eq/cap and New York City at 12.1 tCO_2eq/cap. Second, while sectors associated with 60% of indirect emissions are already addressed in current plans with at least one measure, 40% remain entirely unaddressed. Notably, direct emission sectors like housing and transport receive more attention compared to indirect sectors such as food, goods, services, and waste. Third, theoretically, cities could address their entire GHG footprints using soft measures, contingent upon political will and local capacity. However, substantial potential exists for hard measures; six cities could tackle sectors representing over 75% of their indirect emissions, ranging from 16.2% in Cairo to 94.1% in Delhi NCT, indicating large untapped

opportunities for policy action. In sum, we find that the greatest missed opportunities are not in cities with limited authority, but in those with broad legal powers that do not use their scope of action to reduce consumption-based emissions.

To overcome the reluctance of cities to address GHG footprints, it is crucial to raise awareness of the viability of addressing indirect emissions. Challenges in measuring consumption-based emissions should not hinder action, especially as proven intervention strategies exist. Additionally, blending provision-focused interventions with urban climate planning, supported by higher government mandates, can align climate objectives with local development goals. Enhancing local democratic processes ensures that climate actions reflect community needs and identities. City networks and initiatives within the Global Climate Action Portal play a vital role in scaling these insights and supporting implementation.

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Data availability statement

All software code used for analysis and to produce figures, tables and manuscript are available at Zenodo (DOI: https://doi.org/10.5281/zenodo.20538571) and at: https://gitlab.pik-potsdam.de/pichler/cityfootprints.

Supplementary material includes the urban carbon footprint results, climate plan coding, as well as all data behind the figures and tables. Archived climate plans are on file with the authors.

The data that supports the findings of this study are openly available in the supplementary files of this article.

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