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LETTER

A comparison of carbon emissions perspectives for a single city and insights for data developers and policymakers

Grant Allan[1], Lena Kilian[4], Sandeep Kodoli[5], Craig Michie[5], Anne Owen[3], Christos Tachtatzis[5] and Jack Williamson[2,*]

1 Department of Economics, University of Strathclyde, Glasgow, United Kingdom
2 Fraser of Allander Institute, Department of Economics, University of Strathclyde, Glasgow, United Kingdom
3 School of Earth and Environment, University of Leeds, Leeds, United Kingdom
4 Institute of Environmental Sciences, Leiden University, Leiden, The Netherlands
5 Department of Electronics and Electrical Engineering, University of Strathclyde, Glasgow, United Kingdom
* Author to whom any correspondence should be addressed.

E-mail: jack.williamson@strath.ac.uk

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Abstract

Cities are setting targets for emissions reductions, however a lack of consensus on methodologies has produced a range of metrics. This makes it important for policymakers to understand how policies might impact metrics, and to communicate the impacts of policy choices. We take the municipality of Glasgow (Scotland) as a case study to calculate and compare four emissions accounting metrics. Our results reveal variation across metrics, arising from differences in the coverage and elements included, and large differences in major areas—emissions from housing and transport. Taking specific local policy ambitions to reduce emissions—the development of heat networks and reducing passenger kilometres driven—we describe conceptual and measurement issues in how these will impact on each metric. Our findings suggest a critical pathway forward for development of city-scale emissions data, and lessons for policymakers on the use of metrics and demonstrating the impact of policies.

1. Introduction

Cities worldwide are increasingly adopting net zero carbon targets [1]. Robust systems for measuring and monitoring emissions are essential to assessing progress. Many cities rely on self-reported emission inventories, yet no internationally agreed upon, peer-reviewed metric exists [2], and carbon accounting approaches remain contested [3]. A review of urban carbon accounting reveals a wide range of approaches, including *in-situ* atmospheric measurements using sensors and remote sensing, life cycle assessments, and Input-Output analysis for production and consumption-based perspectives [4]. Key debates include: whether the term 'carbon' covers all greenhouse gasses (GHGs); applying Global Warming Potentials (GWPs) to non-CO_2 GHGs [5]; and uncertainties associated with measuring emissions from Land Use, Land Use Change and Forestry [6].

There is currently no standardised framework for cities to measure emissions or define boundaries. The term 'boundary' may refer to geographic limits of a city—often difficult to delineate [7, 8], or the extent of a city's responsibilities for emissions. The Scope 1, 2, and 3 emissions frameworks, adapted from corporate carbon accounting for urban contexts [9], presents challenges, as cities are more complex and less clearly defined than firms. Scope 2 covers indirect emissions associated with electricity, steam, heating and cooling but should electricity purchased by businesses registered in a city, but physically located outside, be included? Scope 3 is even more challenging: emissions from purchased goods and services risk double-counting, as one organisation's Scope 3 may be another's Scope 1 within the same city. On the other hand, some authors note that the same 'emissions' being accounted for by several agencies only increases the potential reduction capability [10].

Different accounting principles, inventories and metrics yield disagreeing emissions estimates and produce inconsistent longitudinal trends. Yet focussing on a single emissions metric risks overlooking the mitigation potential of key sectors or activities [9]. Using multiple metrics may provide a more comprehensive understanding of urban emissions [11–13]. However, the choice of measurement framework can influence how cities set their targets—for instance, aiming to be 'climate neutral', 'carbon neutral' or 'fossil fuel free' [8]—which may sound similar but differ in scope and implementation. To unify approaches, 'cities should be primarily concerned with the exploitation of all possibilities for action both on the production- and demand-side rather than the benchmarking of their performances [8].'

This paper illustrates the conceptual and practical challenges facing cities reporting emissions estimates by taking the municipality of Glasgow, a mid-sized, Scottish city of 630 000 residents, as a case study. Glasgow is a good case study for this comparison, as, like many cities, it has set an ambitious 2030 net zero carbon target requiring deep policy actions [14]. It is administered by a single local authority and currently tracks progress towards its target using the Territorial emissions metric. Sufficient data are available to construct other emissions metrics for Glasgow. In addition, ongoing investment in real-time air quality and atmospheric monitoring will support further development of spatio-temporally modelled estimates. These features allow multiple emissions metrics to be examined side-by-side for a single city. We show how four commonly used emissions metrics vary in their measurement of carbon dioxide emissions for Glasgow. We consider Territorial emissions (the metric used by the city to track emissions), Production-based, Consumption-based and a spatio-temporally modelled metric (ST Modelled CO_2) which relies on local atmospheric measurement. Scope 1, 2 and 3 emissions reports are not available for Glasgow so have been excluded. We choose the year 2019 since it is not affected by the COVID-19 pandemic and we select carbon dioxide—rather than the full suite of GHGs due to the uncertainties around GWP application. Rather than undertaking ex ante modelling, this paper aims to conceptually compare commonly used emissions metrics, highlighting how they are constructed, the activities they include or exclude, and how these structural differences might influence the impact that policy actions might have. This offers important insights for the urban emissions data community, both users and developers, and policy makers tracking the impact of policies on emissions metrics.

In section 2 we set out the approach and data used in calculating the four city-level carbon emissions metric, while in section 3, we show the conceptual overlaps between the metrics and take two examples from Glasgow's decarbonisation policy ambitions—supplying domestic heat through heat networks and reducing car kilometres driven in the city—and show how achieving each ambition would manifest conceptually in each emissions metric. Finally, in section 4, we make recommendations for action regarding the collection, development and use of city-level carbon emission data.

2. Method and data

In this section, we set out our approach for producing the four widely-used metrics for city-level emissions. A more detailed description of these methods and the data uncertainties can be found in the SI.

2.1. Territorial

Territorial emissions capture emissions from industry, agriculture, domestic use and transport which are produced within a specific territory [15]. These are typically measured through emissions inventories [16] and relate to the emissions which are directed impacted by the policy actions taken in that geography[6]; this includes emissions embedded in exports [17]. Territorial emissions statistics for local authorities in the UK are produced annually by the Department for Energy Security and Net Zero [18]. These provide spatially disaggregated [19] estimates from the UK GHG Inventory on an 'end-user' basis, meaning that emissions from energy production are allocated to the household or firm which consumes the energy.

2.2. Production-based

Production-based emissions allocate emissions from the production of goods and services by ownership. In that sense, they are consistent with measures of gross domestic product [20]. The Office for National

[6] Additionally, territorial accounts are unable to assign CO_2 emissions emitted in international territory to specific countries [23, 25]. These so-called bunker fuels are only reported as a memo, limiting the scope of governments to measure their progress towards reducing these. By contrasts, Production-based emissions typically allocate emissions from international shipping and aviation in accordance with where the operators are based.

Statistics does not currently produce production-based emissions at a subnational level. For this analysis, we aggregate UK-level production-based emissions by industry [21] to industry section, before calculating gross value added by industry section for Glasgow and the UK [22]. We use Glasgow's share of activity in each industry as a proportion of the UK to allocate UK production emissions by industry to Glasgow. In 2019, the values for industry sectors ranged from 0.4% in Sector T (Activities of households) to 1.9% in Sector K (Financial and insurance activities).

Alongside the industry sections, UK production-based emissions include emissions by consumers: 'Consumer expenditure—not travel' and 'Consumer expenditure travel'. The latter consists of road transport emissions. To estimate Glasgow's share of these emissions, we used Glasgow's share of GB road traffic estimates [23] for miles driven by all vehicles. The former category refers to the consumption of fuels and other products and allocate Glasgow a proportion based on its share of UK population [18].

2.3. ST modelled

The ST Modelled CO_2 emission dataset is a high-resolution nation-wide baseline inventory for atmospheric carbon dioxide emissions at 1 km spatial and hourly temporal resolution. The data presented in this study is a subset of cumulative national emissions, spatially extracted using Glasgow shapefile. The anthropogenic component of data closely resembles the territorial emission dataset, with key difference in temporal disaggregation. The data was produced using UKGHG spatio-temporal modelling developed by the UK Centre for Ecology and Hydrology (UKCEH) using the National Atmospheric Emission Inventory (NAEI) data, and modelled biospheric fluxes [24, 25]. The data disaggregates national inventories with spatial proxies, temporal activity data and uses national statistics spanning 1993–2018. Biogenic flux components in ST Modelled data include plant carbon uptake and soil respiration simulated through the CARbon Data MOdel fraMework [26]. The downscaling process introduces some uncertainty through the allocation methodologies, and the limited availability of observations [27]. This high-resolution data is valuable for refining local emission inventories using ground-based and remote sensing observations through top-down emission estimations. In this study, we present the annual sectoral sums for each category of the modelled emissions.

2.4. Consumption-based

Consumption-based emissions are allocated at the point of final consumption, rather than production. The CBA for the UK is calculated using the UKMRIO (see [28]), an environmentally-extended multiregional input-output database. $F = eLy$, determines the total CO_2 emissions associated with UK final demand (F) as the product of e (a vector of CO2 emissions per unit of output by industry), L (the Leontief inverse matrix which is used to reallocate from industry to product) and y (a vector of UK final demand by product). Finally, direct household emissions (from fuel burning associated with heating and private cars use) are combined.

UK emissions are disaggregated to the subnational (Glasgow) level using a hierarchical approach based on the proportion of UK spend on each consumption item from each lower-level geography [29, 30]. Thus, we use microdata (table 1) to calculate Glasgow (Scotland) resident's share of Scotland's (UK) consumption by product.

3. Results

3.1. Areas of overlap and difference between metrics

Carbon emissions can be measured in various ways, each contributing to understanding an area's local, regional, national and global impacts. Each metric will include or exclude certain emissions which may or not be included in the others. Figure 1 illustrates the overlaps and differences among the four metrics central to this paper.

In figure 1, the pink and blue shaded areas represent emissions within and outside of Glasgow respectively. The entirety of global emissions is the sum of these areas. Territorial (dark blue box) covers all emissions occurring within Glasgow's boundaries, plus Glasgow's consumption share of emissions from grid-connected electricity generation occurring across the UK. ST Modelled CO_2 (dark pink box) overlaps all elements included in Territorial, with the addition of emissions related to biogenic flux, land use and atmospheric measurement.

Production-based (green box) relates to emissions at the point of production, differing from Territorial as they allocate emissions by ownership. While much of this production would take place in the city—and overlap with Territorial and ST Modelled CO_2—Glasgow-owned businesses operating

Table 1. Microdata used to calculate subnational Consumption-based emissions.

	Data source	Notes
Domestic gas and electricity	Regional and local authority consumption statistics [31].	Calculate proportion of UK energy used by Glasgow residents. Home energy use represents ∼25% of a household's consumption-based emissions. Using real energy use data leads to a more accurate estimate of household consumption-based emissions.
All other consumption	Living Costs and Food Survey (LCFS) [32] and the output area classification (OAC) [33]	The LCFS can be used to sum the Scottish portion of UK household spend by product and to give the Scottish CBA The OAC is a geodemographic classification of UK neighbourhoods and we know the total number of households of each type living in Glasgow. The LCFS is used to find spend profiles by OAC type which can generate a spend profile for the whole of Glasgow, which in turn can show the Glasgow portion of Scotland's spend and the CBA for Glasgow

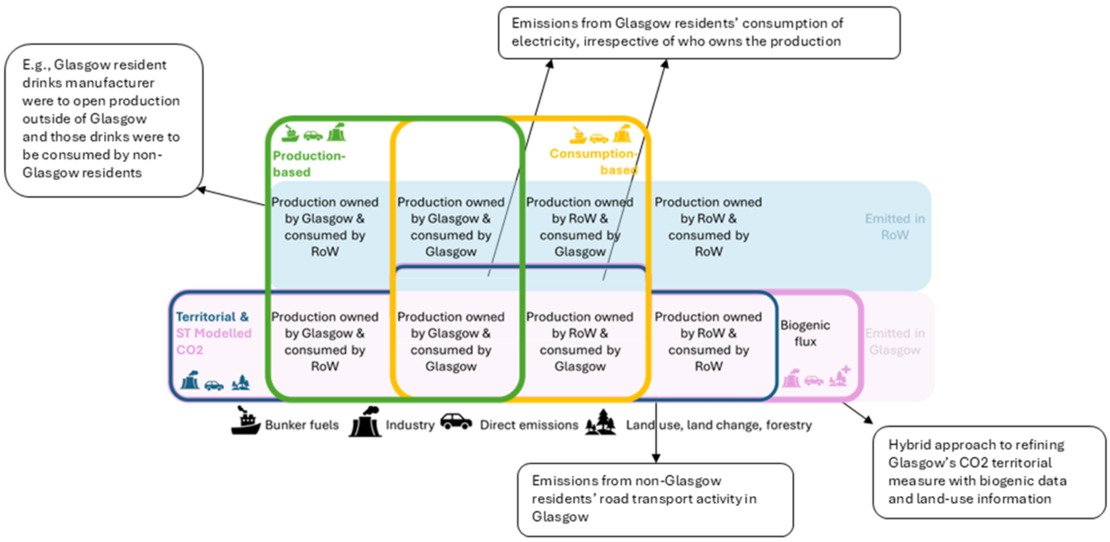

Figure 1. Conceptual comparison of four emissions metrics for Glasgow.Notes: Schematic showing the allocation of emissions under the Territorial (dark blue), ST Modelled CO_2 (dark pink), Production-based (green) and Consumption-based (yellow) methods. Blue and pink shaded areas represent the location of emissions (Glasgow or RoW). Examples and annotations illustrate how specific sources (e.g. electricity use, biogenic flux, non-Glasgow road transport activity) are treated within each metric. Note: 'RoW' refers to rest of the world (including rest of UK).

beyond the city would also be captured here. Emissions by activities not owned in Glasgow are omitted from this metric.

Consumption-based (yellow box) identifies emissions attributed to Glasgow residents' and government's consumption, irrespective of location and ownership of production. Unlike other metrics this includes emissions in the global (including Glasgow) supply chain at the point of final demand. Emissions in Glasgow from Glasgow-owned production where those products are consumed outside the city (e.g. exports) would not be included in Glasgow's Consumption-based emissions. Finally, emissions occurring in, owned in, and driven by consumption in the Rest of the World, are not included in any of the four metrics we consider.

Table 2. Scale of four carbon emission metrics for Glasgow, 2019.

Metric	Total $ktCO_2$	Relative to ST Modelled CO_2
ST Modelled CO_2	1963	1.00
Territorial	2540	1.29
Production-based	3849	1.96
Consumption-based	4935	2.51

Note: Authors' calculation.

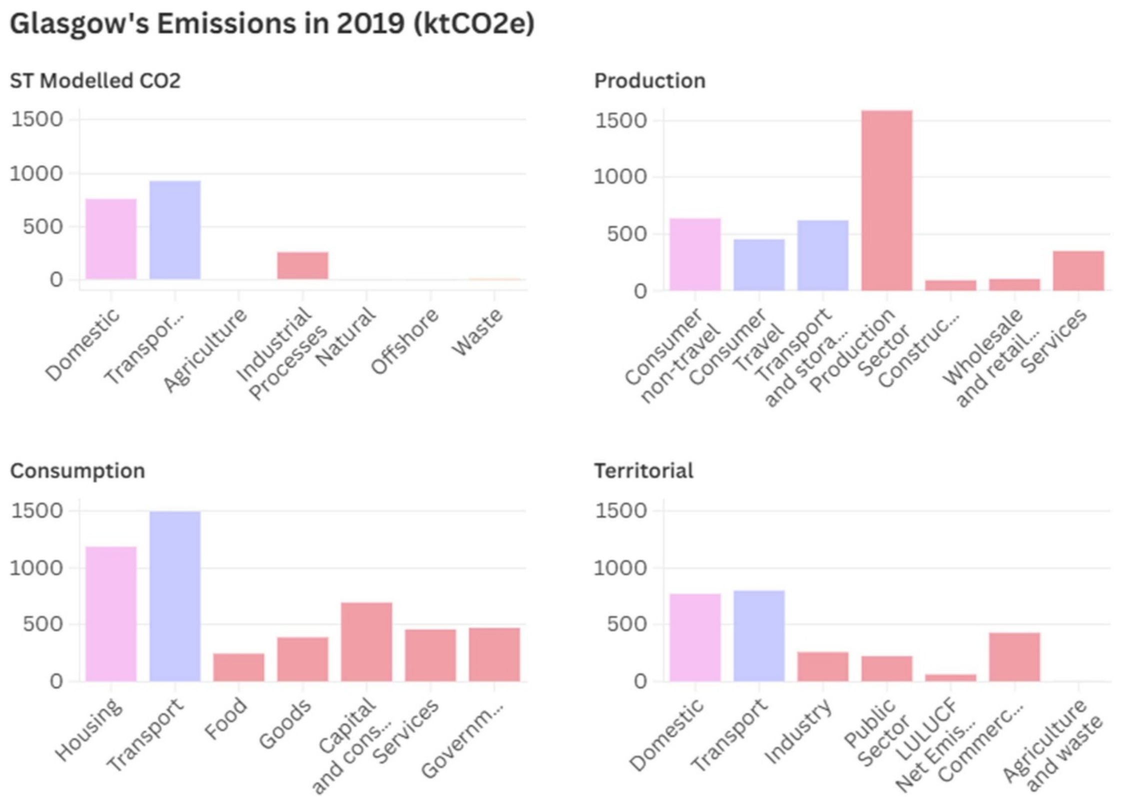

Figure 2. Comparison of four carbon dioxide emission metrics for Glasgow, 2019. *Notes*: emissions metrics shown include ST Modelled CO_2, Production-based, consumption-based emissions, and territorial emissions. Bars show each sector's contribution within a given metric, with sector definitions varying by metric. Pink bars indicate domestic/household emissions, blue bars indicate transport, and red bars indicate all other sectors.

3.2. How do these metrics compare when applied to one city?

Table 2 shows Glasgow's 2019 carbon emissions by metric. ST Modelled CO_2 (1963 $ktCO_2$) and Territorial (2540 $ktCO_2$) are most similar, reflecting their broad overlap in scope. Production-based emissions total 3849 $ktCO_2$, while the Consumption-based metric is highest at 4935 $ktCO_2$—over 2.5 times the ST Modelled CO_2 estimate.

Figure 2 compares categories of emissions (in $ktCO_2$) across the four metrics. We aggregate to a common set of categories to enable comparisons. High emissions come from transport activities and domestic/housing, so we focus on these two categories across all four metrics.

3.2.1. Domestic/housing emissions in each metric

Figure 2 shows that household energy emissions vary by metric. Territorial (771 $ktCO_2$) and ST Modelled CO_2 (760 $ktCO_2$) are closest since both are based on household energy purchases—primarily electricity and gas—and their associated emissions factors. Production-based (638 $ktCCO_2$) takes a population share of the UK's non-travel emissions, while Consumption-based (1187 $ktCO_2$) draws on Glasgow resident household's spending on energy, building maintenance and repair, also incorporating emissions in the supply chains.

Table 3. Impact of implementing heat networks in Glasgow by metric.

Metric	Critical factors impacting outcome
ST Modelled CO_2	Domestic electricity and gas consumption Non-domestic electricity and gas consumption
Territorial	Domestic electricity and gas consumption Non-domestic electricity and gas consumption
Production-based	Consumer expenditure on domestic electricity and gas SIC97 Activities of households as employers of domestic personnel purchases of electricity and gas Purchases of electricity and gas by firms of all sectors connected to the heat network
Consumption-based	Domestic electricity and gas consumption Non-domestic electricity and gas consumption is reflected in consumer purchases made from Glasgow businesses

3.2.2. Transport emissions in each metric

Transport emissions in ST Modelled CO_2 (928 ktCO_2) and Territorial (800 ktCO_2) both include road and diesel-powered rail emissions. Both apply an 'activity × emissions factor' approach, where activity is defined by traffic counts, vehicle class, and fuel type. Data distinguish between major vehicle classes: passenger cars, light goods vehicles, rigid and articulated heavy goods vehicles, buses/coaches, and mopeds/motorcycles—each further subdivided by fuel type (petrol or diesel). Differences may stem from scope, vehicle fleet composition, driving behaviours or road use in Glasgow and the (available) data of Scottish/UK averages which are used in Territorial.

Production-based transport emissions separately identify industrial and consumer behaviours, namely Glasgow's transport sector—covering buses, taxis and private rental cars, trains, freight—and Glasgow households respectively. In total (1075 ktCO_2), these are similar to transport emissions under the ST modelled CO_2 metric, however this similarity is coincidental: Transport emissions under Production-based relate to fuels used, irrespective of the location of use, while transport emissions in ST modelled CO_2 relate to emissions in Glasgow (figure 1) and include those from residents of other areas both of Scotland and beyond, commuters and tourists.

Consumption-based transport emissions (1495 ktCO2) include those by Glasgow residents and government in and outside Glasgow, however these also capture emissions in the (global) supply chains for transport goods and services consumed in the city. This includes, for instance, flights taken by Glasgow residents, as well as the production of motor vehicles and motoring oils which are purchased by Glasgow residents. The inclusion of flight emissions in transport presents a main difference to the other metrics.

3.3. Understanding the impacts of policy actions through these metrics

We now consider the conceptual impacts and practical challenges of specific local policies on the four emissions metrics. The specific effects of these policies are beyond the scope of this paper; rather, we trace how such actions would register within each emissions metric. It is helpful to consider whether the effect of the policy can be described as direct or indirect or somewhere in between. A direct policy impact would clearly and unambiguously impact the metric itself. Household decarbonisation offers an example of a policy in this space.

3.3.1. Household decarbonisation

Glasgow's Local Heat and Energy Efficiency Strategy (LHEES) [34] sets out the vision for reducing emissions across the built environment. At the national level, there is a 6TWh target of heat to be supplied by heat networks. While there are no specific TWh targets in Glasgow's LHEES, we can consider the ways in which city-wide heat network adoption may impact our metrics differently (table 3).

Domestic and non-domestic (industry, public sector, and commercial) emissions under the Territorial metric are calculated by combining gas and electricity consumption statistics with emissions factors. For households and businesses connected to district heating systems, a decrease in local gas consumption would result in lower emissions being attributed to Glasgow. The impact on Domestic emissions in the ST Modelled CO_2 metric would be similar as both metrics apply emissions factors to local gas consumption estimates.

Theoretically, increased uptake of district heating in Glasgow should influence several emissions categories within the Production-based metric, following the same gas consumption pathway observed in the Territorial and ST Modelled CO_2 approaches. First, emissions associated with consumer (non-travel)

Table 4. Impact of a 30% reduction in car kilometres in Glasgow by metric.

Metric	Critical factors impacting on outcome
ST Modelled CO_2	• Amount of fuel burnt • Road type • Car fuel source (petrol or diesel)
Territorial	• Road type • Car fuel source (petrol or diesel)
Production-based	• Road type • Car fuel source (petrol or diesel) • Residence of driver (UK/non-UK resident)
Consumption-based	• Amount of fuel purchased • Residence of driver (Glasgow/non-Glasgow resident)

expenditure are likely to decline as household gas use decreases. Second, firms in sectors such as production, construction, wholesale and retail, and services that are connected to district heating systems would also be expected to see reduced gas consumption. As with the Territorial and ST Modelled CO_2 metrics, these estimates are based on NAEI data, which draws on local authority-level gas consumption figures. In practice, however, Glasgow's Production-based consumer expenditure (non-travel) emissions are estimated by allocating Glasgow's population share from the UK total. As a result, this metric would not reflect the policy action: any UK-wide emissions reduction from such a localised change would be apportioned to all areas according to population share.

Consumption-based housing emissions are likewise expected to decrease as households reduce gas usage once connected to district heating networks. Moreover, theoretically, where households buy from businesses within Glasgow, which now have decreased heating emissions, this will be reflected in other household consumption. However, due to data limitations, some policy impacts may be harder to observe. In many cases subnational Consumption-based emissions are disaggregated from the national footprint. In the UK's case, municipal data on domestic gas and electricity demand is used for this disaggregation, allowing for a detailed analysis of household gas and electricity footprints. Purchases from Glasgow businesses are harder to isolate, as the model and data used to calculate the consumption-based footprint includes supply-chain information at country, rather than city-level. Thus, the data used for the UK footprint cannot distinguish between businesses based in Glasgow or elsewhere in the UK. As a result, while the impact of this policy on household heating is trackable, lack of municipal supply chain data means that the impact of lower heat consumption of Glasgow businesses on the consumption-footprint is averaged across the UK.

3.3.2. Transport

Transport offers an example of a policy area at the city-level which has a more indirect connection to the emissions metrics. *Glasgow's Transport Strategy* [35] sets out the goal of achieving a 30% reduction in car kilometres within the city by 2030. How these might be seen in our four metrics in shown in table 4.

The impact on ST Modelled CO_2 and Territorial metrics should be similar. Both are derived from the UK GHG Inventory and NAEI and use the same core methodology for road transport emissions. A decrease of car kilometres on Glasgow roads should be reflected in both metrics. However, both are sensitive to road (urban, rural, motorway) and vehicle type, meaning the petrol/diesel split in car kilometres and road type will also influence the change in each metric.

The Production-based metric includes two transport categories: one for Glasgow's transport sector and one for household vehicle use. The Production-based metric allocates a share of UK production-based emissions to Glasgow. Like ST Modelled CO_2, it relies on NAEI data and the 'activity $\times$ emissions factor' method. However, it includes adjustments based on residence and assigns emissions to the transport and storage section or consumers. If taxi and private rental car use or UK resident car use decreased in Glasgow, we would likely see an impact on the Production-based metric.

The Consumption-based metric is likely to show the greatest difference. While the policy focusses on where the reduction occurs, the consumption-based metric is primarily influenced by whose demand

Table 5. Pros and cons of each metric for their use in policy.

Metric	Benefits	Limitations
ST Modelled CO_2	Allows for an assessment of local baseline CO_2 emission statistics; very spatially granular (measured 1-by-1 km grid); available by sectors; high temporal granularity (available hourly)	Measures emissions that occurred in neighbourhood, rather than by residents; No links to global impact.
Territorial	Allows for an assessment of energy efficiency and production side interventions	Changes in emissions could come from outsourcing; emissions inventory does not include bunker fuels; Spatial granularity can vary by country; Time lag 18 months. Limited use of local information on transport fleet (Scotland-level for Glasgow). Scope 1 mainly, with Scope 2 for electricity consumption.
Production-based	Allows for an assessment of energy efficiency and production side interventions	Changes in emissions could come from outsourcing; Time lags can be significant (circa 3 years in the UK); Spatial granularity can vary by country
Consumption-based	Allows for an assessment of demand side interventions and carbon inequality	Indicator alone does not show if changes in emissions come from supply chain changes (which can be linked to other countries' policies) or consumption changes; Time lags can be significant (circa 3 years in the UK); Spatial granularity can vary by country

in car fuel is reduced. From a consumption-perspective, this 30% reduction in passenger kilometres may be allocated to other municipalities, or countries (e.g. tourism), if drivers not residing in Glasgow reduce their mileage in line with this policy. For instance, a 30% reduction in commuting into the city might strongly affect the consumption-based footprints of surrounding municipalities. In practice, Glasgow's consumption-based transport emissions are calculated by disaggregating the UK emissions using microdata. A combination of geodemographic information and household expenditure data is used to estimate Glasgow's footprint [29, 30]. This introduces two data limitations. First, while typical for this type of research, using expenditure as a proxy for the amount of fuel purchased adds uncertainty to the findings, where fuel prices vary. Second, for UK municipal footprints, this means that the emissions of each municipality are a summary of the neighbourhood in this municipality and region [29]. While this provides a distinct emissions profile for each city, geographic locations are only estimated, rather than certain. While research has shown that this method provides a good approximation of spatial emissions estimates [30], this data limitation may lead to missing or misallocating some of the impacts of *Glasgow's Transport Strategy* [35].

From our analysis of the four metrics, we set out benefits and limitations for each in table 5, where appropriate, we highlight specific data limitations for cities in the UK.

4. Discussion

Building on our analysis, we frame our discussion around seven points of pathways forward and recommendations for action. The first three relate specifically to data, while the remainder focus on the use of data to aid policymakers and the broader public.

First, data producers must develop and improve emissions metrics for local areas, including cities. As noted in table 4, metrics have differing time lags between publication and the policy action time-period. The Territorial metric has a lag of just under 18 months, while the Consumption-based can lag by three years. Shortening this would give policy makers faster feedback, enabling them to adjust or halt actions with unintended or negative outcomes.

These metrics come with uncertainty relating to how they are calculated. Territorial emissions are subject to uncertainty in emissions factors, activity data and the spatial disaggregation of national inventories, particularly for transport. ST Modelled CO_2 introduces additional uncertainty through spatial downscaling and the treatment of biogenic fluxes. Production and Consumption metrics utilise additional datasets and microdata which are themselves subject to uncertainty. As a result, point estimates should be interpreted with caution when comparing metrics.

Second, while it is appealing to have metrics with a high degree of accuracy and scientific detail, focussing solely on these indicators runs the risk of losing sight of other local, accurate, consistent and available data to measure progress across multiple dimensions. A city without the ability to measure outcomes, should not use that as an excuse to delay or avoid actions. Other metrics, which indicate the trajectory of change, rather than the levels, may be more readily available and so hence useful for policymakers. Such metrics would align with the call to prevent the limiting of actions to those which impact on the specific metric chosen to target [8].

Third, the 'consumption corridor' literature recognises that individuals have specific 'satisfiers', which might include energy, and access to transport, for instance, through which (higher level) 'needs' are met. Focusing purely on household consumption does not tell us whether households are able to satisfy their needs. The range of potential metrics could usefully broaden beyond those included in the measures described above. For example, reduced energy consumption—often seen as a policy success—should not disproportionately affect the worst-off or leave households unable to live in comfort, taking this perspective.

Fourth, as cities work within multi-level governance hierarchies, any metrics used at the national level should be downscalable to lower levels. This would help cities (or cities with their neighbouring areas) to demonstrate how they are contributing to national objectives.

Fifth, emissions metrics have an important value in the evaluation of policy interventions. However, differences in the elements included in metrics currently makes it hard to link policy actions across metrics. As we have seen, a policy focusing on reducing the distances driven in Glasgow would not necessarily show up as emission reductions in Glasgow, depending on the metric. Thus, a greater understanding of these different metrics will allow policy makers to measure the full impact that policies can have within and beyond city boundaries.

Sixth, local areas should develop, systematically monitor and report changes on all available emissions metrics. Importantly, we do not advocate the selection of a single 'preferred' emissions metric for policy evaluation. Each metric varies in the extent to which it captures aspects of policy actions. Recommending a single measure risks narrowing policy attention to activities that are visible within that metric, rather than those with the greatest mitigation potential.

Finally, a wider public understanding of how citizens' actions lead to changes in metrics is fundamental to building confidence in the effects of net zero policies. This is irrespective of which level policies are being developed, and on which target they are reporting, especially where this is costly for households. Without credible evidence on the consequences arising from policies, which will increasingly require changes in the way in which household are engaging with energy issues, there runs a serious risk of disillusionment in broader net zero aspirations.

5. Conclusion

We have illustrated four carbon emissions metrics available for cities and shown that that while each vary in the specifics of what is included, there are also conceptual overlaps between metrics. Noting this, we show that city strategies to reduce emissions—namely household decarbonisation and transport reductions—can have differing impacts upon each metric, complicating the communication of the consequences of such policies. Further research from this work could extend in several directions. First, it would be useful to understand the public's understanding and perception of different emissions metrics. Second, we could examine the specific changes in emissions metrics for cities under a range of implemented policies, to practically show the measurement issues highlighted in our paper. These steps would help to ensure that the measures used to measure emissions in cities are consistent with the ambitions for policy and for those influenced by the policies introduced to be able to understand the consequences of such policies.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Supplementary Methods available at https://doi.org/10.1088/2515-7620/ae5d98/data1.

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ORCID iDs

Grant Allan 0000-0002-1404-2768
Lena Kilian 0000-0002-0885-1198
Sandeep Kodoli 0009-0008-3998-3434
Craig Michie 0000-0001-5132-4572
Anne Owen 0000-0002-3872-9900
Christos Tachtatzis 0000-0001-9150-6805
Jack Williamson 0009-0008-2043-7847

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