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The city within the global: A framework for the simultaneous estimation of city emissions metrics

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ABSTRACT

In line with national targets, sub-national governments – including cities – are introducing targets to reduce the emissions associated with economic activity within or associated with a particular geography. Cities are important drivers of not only emissions but also economic activity and are embedded into complex economic systems which reach beyond their boundaries, which can raise major issues in identifying whether a city is assisting in promoting sustainability across a wider spatial level. This paper sets out a methodology to downscale global Input Output tables to city-level and use these to calculate production- (territorial) and consumption-based carbon accounts at the city level simultaneously. Illustrating this for the case of Glasgow, Scotland, we show that the city's territorial emissions are significantly lower than its consumption-based carbon footprint (considering both the Areal and Personal Carbon Footprint), but that both metrics are sensitive to assumptions about the emissions intensity of individual sectors. Our results highlight the importance of data quality and accuracy, and the benefits of local knowledge, rather than the unquestioned use of national metrics.

1. Introduction

Actions at city level to reduce emissions will be critical for the reduction in global emissions. Emissions from cities in 2015 were 25 GtCO2e (62% of global emissions) and were estimated to increase to 67% and 59 GtCO2e in 2020 (IPCC et al., 2022). Under some projections, urban areas are projected to contribute up 80% of global emissions by 2100 (Gurney et al., 2022). Cities are also connected to, and draw resources from, the wider national and international areas to meet their energy and economic needs (Athanassiadis et al., 2018). Cities have been described as "energy sinks rather than sources" (Baynes et al., 2011) drawing on resources and energy use outside of their boundaries.

At the same time, national emissions metrics are based on political territorial boundaries (Heinonen et al., 2020). There exist agreement on the nature of emissions inventories at the national level against the reporting of emissions reductions and progress against stated targets of policy. While necessary for international and national commitments, a territorial perspective raises challenges were it to be blindly applied at sub-national levels. Moving from the national to the city scale, there is a greater likelihood that inputs to economic processes are imported, leading to important questions about where to draw the boundary around emissions associated with production (Munksgaard et al., 2005) and where appropriate policy actions which could best deliver on city and national priorities. Organisations such as the C40 Cities group (a membership of 97 cities, responsible for 25% of the global economy) showcase emissions reduction practices being developed at the sub-national, including city levels (Hale et al. (2022) reviews emissions statements for 254 cities), however Ramaswami et al. (2021) note that there is no consensus on carbon accounting at city level.

Such ambitions highlight the need for appropriate emissions accounting at the sub-national level. There is a growing volume of academic study focusing on metrics of emissions at the city level. Some of these employ detailed bottom-up analysis of energy use, consumption and economic activities within a specific region. For instance, some studies analyse household consumption at local level matching these to carbon footprints at the national level (e.g. Petsch et al., 2011; Minx et al., 2013) while carbon footprints for cities have been produced by downscaling those for the national level or from the analysis of household consumption at local level matching these to carbon footprints at the national level (e.g. Petsch et al., 2011; Minx et al., 2013). A widely used framework for emissions analysis from a top-down perspective uses environmentally extended Input-Output (IO) accounts. Initially constructed to aid understanding of the economic interconnectedness

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between industries, and between production and consumption, IO accounts have also been recently extended to analysing environmental issues. These explicitly set out production links between industries, and between production and consumption, and can capture the interrelatedness between industries, nations and final consumption across the globe. Extended with environmental information on the same sectoral/national basis, these offer a useful resource with which to understand interconnectedness between economic activity and emissions due to their complete and robust methodology (Athanassiadis et al., 2018).[1]

Two main approaches use environmentally-extended Multi-Regional Input Output (MRIO) accounts to examine emissions at the sub-national level: a Production-based or a Consumption-based approach. The difference between these is simply due to the difference in perspective: Production-based emissions relate to those emissions within a specific area, for instance in the (local) use of fossil fuels in the production of output. Munksgaard et al. (2005) illustrates the differences the specific point of a steel-making facility in a city which produces output which supports activity elsewhere meaning, “it is inappropriate to apportion all the emissions from the facility to the local inhabitants”, but to take account of these by considering the *indirect* emissions, i.e., those emissions which are required to support the consumption of an area. The second perspective, that of Consumption-based accounting, include the emissions which result from the production of goods outside of the city, but which are consumed in the city, has led some to argue that territorial measures are not able to provide an accurate assessment of the sustainability of cities (Lenzen and Peters, 2010). Consumption-based accounting, including the calculation of Carbon Footprints, identifies the emissions – irrespective of where they occur globally – which are associated with consumption within a specific geography (see for instance, Munksgaard and Pedersen, 2001; Barrett et al., 2013).

In this paper, we make two contributions. First, we show a method by which the publicly-available World Input Output Database (WIOD) MRIO database can be disaggregated to construct a set of linked city-global MRIO accounts, suitable for the simultaneous and consistent (i.e., calculated within the same set of MRIO accounts) calculation of both Production- and Consumption-based carbon accounting perspectives. The use of WIOD means that the method can be applied to any city in a nation included in those accounts. These accounts are also constructed at a high degree of sectoral detail, allowing the (estimated) city accounts to reflect differences in industrial structure between the city and national economy, but not however within-country local technologies (apart from the extent to which inputs can be sourced from within the city or are imported from the rest of the nation). While others have sought to incorporate city- or subnational-specific economic accounts into global MRIO accounts (e.g., Meng and Yamano, 2017; Wang et al., 2017) ours is the first paper to use this framework to simultaneously produce Production-based as well as Consumption-based emissions metrics in this framework. Zheng et al. (2019) for instance, demonstrated how city-level MRIO tables could be incorporated into a provincial level MRIO table, calculating and demonstrating differences in cities carbon footprints, while Zheng et al. (2022) also produce consumption-based carbon emissions for city-level footprints, comparing these to carbon footprints obtained from single-region city IO tables.

Second, we highlight the importance of data uncertainty in the calculations of Production- and Consumption-based metrics for the city in our framework. Specifically, the environmental IO data we initially employ in our analysis comes from WIOD, which provides (point estimates of) emissions intensity of individual sectors at the national level, which we use initially to represent the emissions intensity of those same sectors at the city level. We set out three alternative ways to adjust national emissions-intensities to reflect local area information, while preserving the national emissions totals, and show how these different approaches impact on each metric.

As well as setting out the framework, we illustrate these points using an application of our framework using a case study of the Glasgow City Region (GCR) in Scotland (hereafter Glasgow). Although our use of Glasgow is primarily illustrative of the usefulness of the framework in deriving alternative metrics, the city makes an interesting case for analysis. Encompassing eight local authorities, this area comprises a population of 1.8 million and around 30% of Scottish economic activity and jobs. Glasgow is thus an “intermediate city” (Rodriguez-Pose and Griffiths, 2021) which have tended to be understudied relative to their representation of the size of cities across the world. As well as its economic role, there is considerable ambition and activity in seeking to reduce emissions in the area. Glasgow hosted the COP 26 in November 2021, and Glasgow City Council (the largest council in the region by population) has set itself a target to be carbon neutral by 2030.[2] Glasgow was one of the first cities to set a target for net zero carbon (in 2019) and is a member of the Carbon Neutral Cities Alliance (Carbon Neutral Cities Alliance, 2023), alongside other cities globally, which are sharing actions to reduce urban emissions.

Given the usefulness of MRIO analysis for understanding carbon emissions across space, we build on a growing literature. Our comparison is most similar to Athanassiadis et al. (2018), which finds that Brussels’ territorial emissions are roughly three times less than those estimated on a consumption-based approach, and Harris et al. (2020) which examine city-level production and consumption emissions for ten European cities. Unlike those paper however, our proposed framework produces these metrics consistently within a disaggregated city-global MRIO accounts. In the only previous comparison of territorial and consumption emissions work on Glasgow, Hermannsson and McIntyre (2014) disaggregate the Scottish IO tables into three regions representing Glasgow, the rest of Strathclyde and the rest of Scotland, and look at the flows of carbon emissions embodied in trade and consumption between these regions. They find that the city relies upon the wider regional links to supply important imports, such as electricity, which means that the city’s territorial emissions are significant reduced compared to those from a consumption perspective. Unlike their work, we place Glasgow within a set of global MRIO accounts, so as to incorporate the much wider set of emissions flows embodied in production and consumption. In addition, we also test the importance of emissions-intensity assumptions for our key results.

This paper proceeds as follows. Section 2 sets out the methodology through which MRIO accounts for a city region can be used to understand a cities production- and consumption-based carbon accounts and reviews recent applications to this question. Section 3 sets how we estimate an IO account for Glasgow City Region and embed this within the WIOD accounts to construct the necessary data for our MRIO analysis. Section 4 sets out the results from each of the metrics, including the ACF and PCF for the consumption-based perspective and the importance of alternative sectoral emissions-intensities. Section 5 discusses the data availability on three domains: its timeliness, data quality (representativeness and robustness) and its completeness, and discusses how these metrics could be impacted (differently) by policy actions while Section 6 provides brief conclusions and directions for future research.

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[1] Metrics such as the GHG Protocol (GHG Protocol, 2021) have become increasingly used to quantify the emissions associated with sub-national elements. While useful, such metrics are not adopted by all cities and even if so, they cannot be squared with economic (economy-wide or sectoral) metrics, such as Gross Domestic Product (GDP) at the same geographic level.

[2] In the UK, emissions by local authority area are allocated based on a methodology developed by Department for Business, Energy and Industrial Strategy. (2021). This attributes each local authority emissions based on energy consumption in the area (primarily electricity and gas) and from transport within the boundary of the local authority (Allan et al., 2023).

2. Input output analysis and consumption- and production-based carbon accounting

2.1. Single-region analysis

Input Output (IO) accounts have been widely used to capture the links between economic activity and environmental impact (Swales and Turner, 2017). These use the multisectoral nature of IO accounts which document the interdependencies between different sectors of the economy, and between production and consumption to relate economic activity (and environmental pressures, such as emissions) to a level of demand for an economy's output.

In a single-region case, the output for sector i (x_i)[3] is the sum of sales to intermediate uses (z_{ij}) and final consumers, F_i:

$$x_i = z_{ij} + F_i \tag{1}$$

By replacing z_{ij} with a technical coefficient expressing the share of inputs from sector i to gross inputs of sector j, i.e. $a_{ij} = z_{ij}/x_j$, putting into matrix form, and expressing in terms of final demand, we can express the level of output in terms of the Leontief matrix ($\boldsymbol{L}$) and the level of final demand:

$$x = (\boldsymbol{I} - \boldsymbol{A})^{-1}F = \boldsymbol{L}F \tag{2}$$

Extending to the environmental impacts from production is simple, with the addition of coefficients of sectoral environmental pressures, such as emissions per unit of output, $e = e_i/x_i$.

From this setup, we can identify two perspectives on emissions for the economy under investigation. First, total emissions from sectoral production are simply the sum of emissions by each i sector:

$$E = \sum_{i=1}^{n} e_i x_i \tag{3}$$

Second, emissions from economic activity can use the properties of the Leontief inverse to capture the supply chains (and emissions) from consumption. Households, for instance, will consume goods which will use other inputs in their production process, so that we can explicitly identify the emissions embodied in the consumption of goods by different consumers.

The use of IO accounts in the specific calculation of carbon footprints – the carbon emissions globally embodied in the final demand for goods and services in a specific area (i.e., nation or region) is a large field with an extensive literature (e.g. Wood, 2017). Emissions from the economy can be attributed to the levels of final demand, via:

$$E = \widehat{e}(\boldsymbol{I} - \boldsymbol{A})^{-1}f \tag{4}$$

Where $\widehat{e}$ is a diagonalised matrix of sectoral emissions-output coefficients.

Single-region IO accounts separately identify consumption which occurs in the same area as production and those that takes place outside, such as goods exported. In a single-region table, final demand can include those final demands that are *domestic* – such as households, investment and government – and those which are *non-domestic*, such as exports and non-resident (i.e., tourism) spending. Emissions in the economy in question can thus straightforwardly be attributed to domestic or non-domestic final demand via equation (5):

$$E = E_d + E_{nd} = \widehat{e}(\boldsymbol{I} - \boldsymbol{A})^{-1}f_d + \widehat{e}(\boldsymbol{I} - \boldsymbol{A})^{-1}f_{nd} \tag{5}$$

Through this we can identify those local emissions (by sector) that are attributable to domestic (E_d) or non-domestic final demands (E_{nd}) for locally produced goods. It cannot however capture the global (i.e. local plus non-local) emissions related to that demand: for this, we need to move to a multiregional input output (MRIO) treatment.

2.2. Multi-regional IO and consumption-based carbon accounts

MRIO applications to environmental applications have become increasingly common (see Wiedmann, 2009 for an early review) with more recent applications extending beyond emissions to land use (Dorninger et al., 2021) and the relationships between energy-climate-food systems (e.g., Fan et al., 2022). Heinonen et al. (2020) track recent developments in methods and applications in this rapidly growing literature, noting a recent shift towards the use of multi-region accounts, rather than single-region – mainly driven by the growing availability of MRIO databases, such as WIOD, EXIOBASE and EORA (Heinonen et al., 2020). Long et al. (2020) compare the results a single-region carbon footprint to MRIO analysis finding that the MRIO outperforms single regional analysis which underreports emissions in certain sectors.

Athanassiadis et al. (2018) notes that MRIO footprints at an urban scale can capture the links between the urban system and their "environmental hinterland" (p. 120) and understand the broader economic drivers of resource use and pollution. As well as showing the total and geographic distribution of emissions associated with consumption of a specific geography, this also draws attention to the distinction between the emissions related to household consumption (the Personal Carbon Footprint, PCF) and emissions related to total consumption (the Areal Carbon Footprint, ACF).

Table 1 sets out a schematic structure of a set of MRIO accounts for three illustrate regions, which we term "City", "Rest of Nation" and "Rest of World" for simplicity. Using the same notation as the single-region case, we can see how the framework described above can be adapted for multiregional analysis. We can thus see how output of each sector as serving two possible uses, either intermediate or final demand, either locally (i.e. where the producing and consuming sector/demand is in the same region), or non-locally (i.e. where the selling and purchasing sector/demand are in different regions).

We see that the interindustry linkages now capturing the intermediate demand in each region for the outputs of that same region (i.e., matrices Z^{ij} where $i = j$, e.g. Z^{11}, Z^{22} and Z^{33}) as well as the import of inputs for use in intermediate production (e.g. matrices Z^{ij} where $i \neq j$, comprising the other Z matrices in Table 1). We can also see how final demand in each region comprises demands for the outputs of same-region production (e.g., F^{11}, F^{22} and F^{33}) and the production of other regions (i.e., final demand imports to that region).

We can therefore rewrite equation (2) as a multiregional framework and express the relationship between final demand by region and sectoral output thus:

$$\begin{bmatrix} X^1 \\ X^2 \\ X^3 \end{bmatrix} = \begin{bmatrix} I - A^{11} & -A^{12} & -A^{13} \\ -A^{21} & I - A^{22} & -A^{23} \\ -A^{31} & -A^{32} & I - A^{33} \end{bmatrix}^{-1} \begin{bmatrix} F^{11} & F^{12} & F^{13} \\ F^{21} & F^{22} & F^{23} \\ F^{31} & F^{32} & F^{33} \end{bmatrix} \tag{6}$$

We have added an emissions vector in Table 1, which provides total emissions by each production sector in each region (e.g. ep^i). Along with vectors of regional sectoral output (x^i), we can calculate emissions-output coefficients for each sector in each region, e.g. $e_i^i = ep_i^i/x_i^i$, which shows the amount of (physical) emissions per unit of (monetary) output. With a diagonalised matrix of these emissions-output coefficients for each region (i.e., $\widehat{e}^i$) we can extend equation (4) for the MRIO case.

$$\begin{bmatrix} E^{11} & E^{12} & E^{13} \\ E^{21} & E^{22} & E^{23} \\ E^{31} & E^{32} & E^{33} \end{bmatrix} = \begin{bmatrix} \widehat{e}^1 000 \widehat{e}^2 000 \widehat{e}^3 \end{bmatrix} \begin{bmatrix} I - A^{11} & -A^{12} & -A^{13} \\ -A^{21} & I - A^{22} & -A^{23} \\ -A^{31} & -A^{32} & I - A^{33} \end{bmatrix}^{-1} \begin{bmatrix} F^{11} & F^{12} & F^{13} \\ F^{21} & F^{22} & F^{23} \\ F^{31} & F^{32} & F^{33} \end{bmatrix} \tag{7}$$

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[3] We follow standard matrix notation, with matrices denoted with capital letters, vectors in lower case and scalars as lower-case italics. Superscripts denote the region while subscripts denote the sector. Matrix F reflects the different categories of final demand for sectoral output.

Table 1

Schematic of multi-regional Input-Output accounts identifying city-nation-global linkages.

		Intermediate demand			Final demand			
		City	Rest of nation	Rest of world	City	Rest of nation	Rest of world	Gross output
Intermediate production	City	Z^{11}	Z^{12}	Z^{13}	F^{11}	F^{12}	F^{13}	x^1
	Rest of nation	Z^{21}	Z^{22}	Z^{23}	F^{21}	F^{22}	F^{23}	x^2
	Rest of world	Z^{31}	Z^{32}	Z^{33}	F^{31}	F^{32}	F^{33}	x^3
Primary inputs	City	V^1	–	–	FPI^1	–	–	pi^1
	Rest of nation	–	V^2	–	–	FPI^2	–	pi^2
	Rest of world	–	–	V^3	–	–	FPI^3	pi^3
	Gross inputs	x^1	x^2	x^3	f^1	f^2	f^3	
Emissions		ep^1	ep^2	ep^3				

The elements in matrices E can be interpreted with specific meaning for MRIO emissions analysis. For instance, the sum of matrices E^{11}, E^{12} and E^{13} are equal to E^1, i.e., the total production emissions in region 1 are unchanged, but can be attributed to either local or non-local final demand. Further, and most usefully for our analysis, Equation (7) can also be used to identify the total emissions (in any region) attributable to each regions final demand. For example, E^{11} shows those emissions in region 1 supported by region 1's final demand, while E^{21} and E^{31} are the emissions are emissions in regions 2 and 3 respectively that are supported by Region 1's final demand. The vertical sum of matrices on the left-hand side of equation (7) therefore give us the scale of the emissions footprint associated (globally) with consumption of a specific region or city. As we have set up our final demand in each region as a matrix consisting of vectors relating to distinct final consumption, households, government, investment, and so on, the emissions footprints of each element of final demand can be straightforwardly calculated in the same framework by the omission or inclusion of each respectively.

2.3. City-level carbon footprints

Applications of MRIO to carbon footprints have also grown at the subnational level, including cities. Athanassiadis et al. (2018) notes that using MRIO accounts for calculating carbon footprints at an urban scale is relatively new, it is able to capture the links between the urban system and their "environmental hinterland" (p. 120) and understand the broader economic drivers of resource use and pollution. Wiedmann et al. (2016) for instance, review cases where bespoke city-scale IO accounts have become increasingly widespread in the calculation of carbon footprints. In fully-specified accounts, these can provide detail on the pattern, structure and interconnectedness of industrial production at the city, region, national and global scales. They demonstrate the use of a set of accounts with these properties to calculate the carbon footprint of Melbourne, while Chen et al. (2017) undertake a similar analysis to understand the source of transboundary emissions for Australian cities. Some recent accounting has focused on specific economic activity such as transport (Wang et al., 2020)) or construction (Zhao et al., 2023))

For instance, Minx et al. (2013) finds that carbon footprints are higher related to territorial emissions in urban areas. Hasegawa et al. (2015) finds that consumption-based emissions for Tokyo are significantly higher than its production-based emissions, but that of the 47 Japanese prefectures considered there is an even split in the balance between production- and consumption-based metrics. Further, Harris et al. (2020), using the GHG Protocol approach (GHG Protocol, 2021) and household consumption by residents respectively calculate the Production and Consumption emissions of several European cities with the key recommendation being that any future city actions should be focused on both metrics rather than just production emissions which is currently the primary focus in many cities. Qian et al. (2022) measure the consumption-based emissions in 47 cities in the Pearl River Basin finding there was significant difference between each, with the largest footprint around 40 times larger than the smallest.

Heinonen et al. (2020) also make an important distinction between Areal Carbon Footprints (ACF) – the carbon emissions associated the consumption that takes places in a specific geography - and Personal Carbon Footprints (PCF) – which includes only the emissions associated with resident households of that area. The difference between the ACF and PCF is therefore the emissions associated with other (i.e., non-household) demand within that area, including by government, in gross fixed capital formation and by visitors to that area. At this stage we note that it may be particularly important to distinguish these two different consumption-based approaches when considering the city level, given the concentration of public sector activities, as well as infrastructure projects and tourism which takes place in urban areas. Government and investment have been found to be important elements of economic activity in city region economy, comprising between 10% and 20% of the overall carbon footprint (Ivanova et al., 2016; Ottelin et al., 2018).

A particular question also arises over data availability at the level of the city, and whether scaling down national accounts is appropriate to capture the local specifics of economic and/or environmental activity. Despite the progress of city-scale IO accounts, these are typically single-region accounts, and so do not explicitly specify production and trade in intermediate and final demands between different spatial levels, so that fully-specified environmental MRIO accounts need to be constructed by adjusting national IO tables. Chen et al. (2017)'s analysis for instance, produce a set of accounts at the city level by adjusting state and national IO tables. As noted earlier, Hermannsson and McIntyre (2014) assume that the emissions intensity of particular sectors is the same at different geographic levels, and note that this is an important assumption. We explore this question of data quality in our application which follows and show the impact of alternative assumptions.

3. Materials

3.1. WIOD table and environmental extension

Initially published in 2013, and updated in 2016, the World Input-Output Database (WIOD) records the linkages between different regions across the world. Driven by globalisation and the need to measure production patterns and trains gains, the WIOD was first developed as an alternative to the Global Trade Analysis Project (GTAP). Tables within the WIOD are based on officially published input–output tables merged with national accounts data and international trade statistics (Timmer et al., 2015). A key element of the WIOD is that a time-series of tables is available from 1995.

The characteristics of the WIOD are similar to the standard industry-by-industry input-output framework where rows record sales by industry and the columns the industrial purchases. Essentially the full WIOD is a set of individual country tables connected with each other by bilateral international trade flows.

In this paper we use the latest available WIOD database – 2014[4] –

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[4] These were the most up to date WIOD tables available at the time of writing.

published in 2016 (Timmer et al., 2015) in US dollars. This database covers 44 including 27 EU countries, 16 other major economics (such as China, Japan, UK and USA) as well as an additional rest of the world (ROW) region. There are 56 economic sectors and Final demand is separated into several components: Households, Non-Profit Institutions Serving Households (NPISH), Government, Gross Fixed Capital Formation (GFCF), Valuables, Change in inventory and Exports (both EU and Non-EU). Other sectoral inputs, in addition to intermediates, are taxes less subsidies, compensation of employees, gross operating surplus and imports.

In addition to the multi-regional IO, the WIOD also contains satellite accounts which allow for further detailed analysis of the global economy. The Social Economic Accounts (SEA) contain Industry-level data on employment, capital stocks, gross output and value added at current and constant prices for the 43 countries within the WIOD. There is also the Environmental Account (Corsetea et al., 2019) which estimates the CO_2 emissions by industry by country.

3.2. Glasgow IO table and environmental extension

Currently there is no officially published IO table for the GCR thus, for our analysis, we derive a table by regionalising the 56 sector 2014 UK Industry-by-Industry (IxI) table developed from the WIOD. A variety of methods exists with enable the regionalisation of IOTs (Davidson et al., 2022). Due to the data available we use a top-down Location Quotient (LQ) framework. Appendix A outlines the regionalisation of the UK table in detail, but in essence proxies – such as output, GVA or employment – are used to estimate several quotient values which are then used to adapt (regionalise) the national table. These quotients take account of a regions specialisation in an industry compared with national specialisation. To generate the GCR table we rely on a several data sources, which and the methods used outlined in Table 2.

We then extend the WIOD to 45 regions by substituting the (two-region) regionalised GCR-rest of the UK table in place of the (single-region) UK table. The key objective of this paper is to measure city-level emissions, and as outlined in Section 2.2, for this to be achieved we need industry level emissions coefficient estimates for each region within the database. For the 43 non-UK nations, emissions-output coefficients are taken from the WIOD-consistent Environmental Accounts, while for GCR and the rUK we initially assume that sectoral emissions-output coefficients are the same, i.e. the emissions-coefficient for sector i in GCR and RUK is the same.

4. Results

We can now illustrate the results from our method using data for Glasgow City Region within the UK. We begin by describing the results of the city-nation-global extended MRIO accounts under the production- and consumption-based carbon accounting perspectives, including both the ACF and PCF. We then looking at the impact of alternative emissions intensities, specifically the calculation of sectoral CO2 emissions-intensity (i.e. kTCO2 per £million) for Glasgow City Region (and rest of the UK) industries respectively.

4.1. Production- and consumption-based carbon accounts

Table 3 shows the results of our three measures of carbon emissions for Glasgow City Region using the disaggregated MRIO accounts. The Production-based Carbon Accounts, showing emissions generated in the city from industry activity and fossil fuel use within the city boundary – PBCA – reveal a total of 3703.2 kTCO2 in 2014.

Our two metrics of footprints report higher values than the PBCA. First, the Areal Carbon Footprint (ACF) – the global emissions driven by the total consumption demand in the city is 6500.5 kT CO_2, which is 76% greater than the PBCA. Recall, that this is comprised both of emissions in GCR, and emissions outwith the region, both from imports (and their associated emissions in production) and from the (global) supply chains for goods which are consumed in the GCR.

Our second GCR footprint measure is the Personal Carbon Footprint, which captures only the global emissions associated with GCR household demand, and so excludes other GCR final demand, including Government, Non-Profit Institutions Serving Households (NPISH) and Investment. The PCF is 4575.0 kT CO2, is 29.6% lower than the ACF. This is a larger difference between the ACF and PCF than that previously found (see Section 2.3 above) and perhaps reflects Glasgow's greater share of public sector activities compared to the rest of the UK.[5]

Recall that under th CBCA approaches, we ascribe carbon emissions to GCR consumption based on the location of production (irrespective of production, and including through the global supply chain) which is then consumed in GCR. Fig. 1 shows the breakdown of Glasgow City Region consumption emissions by country (both for the ACF and the PCF). We can note that the broad pattern across countries is similar in each case, with the PCF always smaller for each country, reflecting that PCF encompasses only some elements of GCR final demand while the ACF includes all GCR final demand, which is in line with the results in Table 1.

The geographic pattern shows that under both metrics, consumption within the GCR primarily supports emissions in the GCR and RUK: these two areas comprise a total of 53.1% and 56.0% of each footprint metric respectively. Outside of the UK, emissions in the rest of the World area constitute 14.0% of all emissions associated with GCR consumption (on both metrics), with China the fourth highest area, providing 9.3 and 8.3% respectively of all of GCR consumption-based emissions. Other noticeable areas providing more than 2% of Glasgow footprint emissions are the USA, Russia, Germany and India.

An interesting question is the extent to which local emissions are related to local consumption – that is, how much emissions within the GCR are associated with the spending on goods which are produced within that same area. MRIO frameworks are ideal for looking at this question, as we can disentangle the location of consumption from the location of production explicitly in these frameworks. To show the location of emissions in the PCF, we split the vector of spending by GCR households into two elements: 1) the spending made by GCR Households locally in GCR, with imports by country/industry outside GCR set to zero, and 2) spending by GCR Households outside the GCR, with spending in the GCR set to zero. The results of this are shown in Fig. 2 below (note that in total these will sum to the 4575 kT CO2 shown in Table 1).

This shows clearly that GCR emissions under the PCF are largely coming from the consumption of GCR goods. While there are some emissions in GCR from the consumption of goods produced outside of GCR (i.e., in GCR Households' imports), these are minuscule (only 2 kT CO2 out of a total of 1922 kT CO2 for emissions related to imports). GCR Households' spending in GCR however generates significant emissions in the rest of the UK: recall that we have separated direct household imports to GCR here, so all these emissions are coming through the production of intermediate inputs taking place outside GCR which go into items purchased by GCR consumption in GCR.

4.2. CBCAs vs PBCA under alternative emissions intensities

We have to this point used the emissions-output coefficients for each sector/nation from that sectors (in that nations) emissions divided by that sector's (in that nations) sectoral output, e.g. $e_i^i = ep_i^i / x_i^i$. We have made the assumption that each sector in GCR and RUK has the same emissions-output intensity as the same sector in the UK.

The specific link between economic activity and emissions at a sectoral level in GCR and RUK is unknown, but this relationship will be

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[5] Government spend in Glasgow City Region is 12.9% of total output compared with 11.7% for the UK as a whole.

Table 2
Schematic of multi-regional IO and data sources/calculations.

		Intermediate demand			Final demand			Gross Output
		GCR	Rest of UK	Rest of World	GCR	Rest of UK	Rest of World	
Intermediate production	Glasgow City Region (GCR)	FLQ's based on sectoral employment	Balancing item (exports)	GCR proportion of UK WIOD exports based on output	Use LQ's to scale UK demand	Balancing item (exports)	GCR proportion of UK WIOD exports based on output	GCR GVA estimates, then covert to output using national ratios
	Rest of UK	Balancing item (imports)	UK intermediates – GCR intermediate production – Inter-regional trade	RUK proportion of UK WIOD exports based on output	Balancing item (imports)	UK final demand – GCR final demand	RUK proportion of UK WIOD exports based on output	UK row total for sector i *minus* GCR row total for sector i.
	Rest of world	GCR proportion of UK WIOD imports based on output	RUK proportion of UK WIOD imports based on output	WIOD	GCR proportion of UK WIOD imports based on output	RUK proportion of UK WIOD imports based on output	WIOD	WIOD
Primary inputs	GCR	GCR Proportion of UK inputs based on output	–	–	GCR Proportion of UK inputs based on output	–	–	Row total
	Rest of UK	–	GCR Proportion of UK inputs based on output	–	–	GCR Proportion of UK inputs based on output	–	Row total
	Rest of world	–	–	WIOD	–	–	WIOD	Row total
	Gross inputs	GCR GVA estimates, then covert to output using national ratios	UK row total for sector i *minus* GCR row total for sector i.	WIOD	GCR Proportion of UK inputs based on population	RUK Proportion of UK inputs based on population	WIOD	WIOD
Emissions		Dependant on assumptions (see section 4)		WIOD	–	–	–	

Table 3
Production- and Consumption footprint metrics for Glasgow City Region, 2014.

	CO_2 emissions, kT
Production-Based Carbon Accounts	3703.2
Areal Carbon Footprint	6500.5
Personal Carbon Footprint	4575.0

Source: Authors calculations.

critical for the results of MRIO footprint analysis. Given the lack of any certainty, we set out four possible options below, relating to publicly available information on energy use and emissions at the sectoral level within the UK (and which could reasonably be used to represent the emissions from production in Glasgow).

Our starting option – which has been used in the analysis to this point - is to assume that emissions-output coefficients are the same for each sector in GCR and UK (and by extension RUK), thus we the emissions

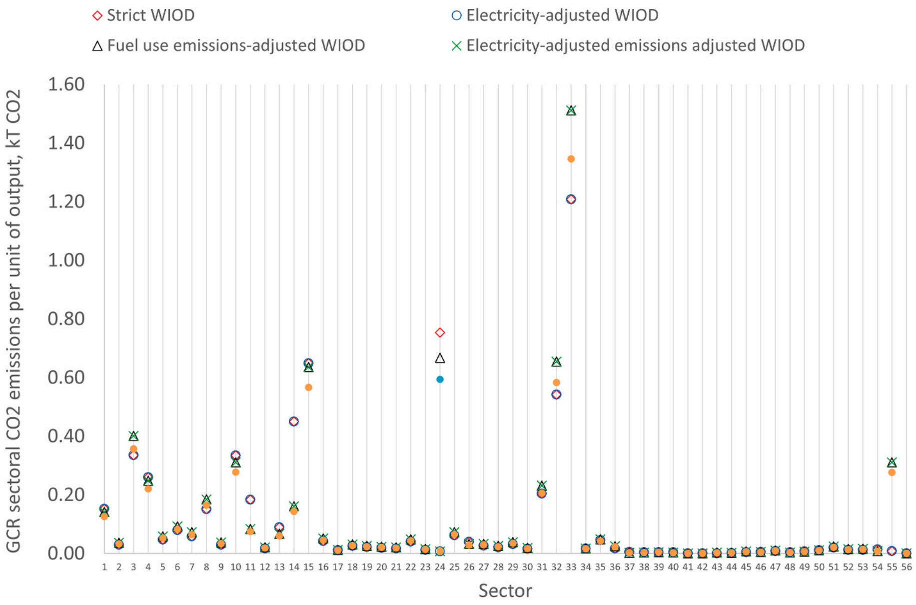

Fig. 1. ACF and PCF emissions by country in 2014, kT CO2.
Source: Authors' calculations.

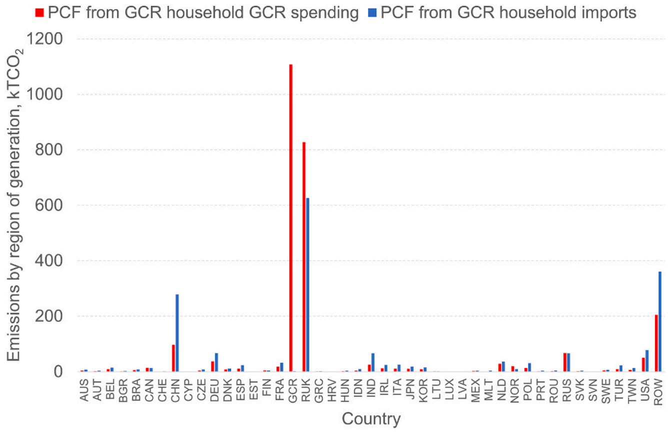

Fig. 2. PCF emissions from spending in GCR and spending on imports, kT CO$_2$.
Source: Authors' calculations.

intensity (CO2 per £ of output) for sector *i* for the UK from WIOD for sector *i* in both Glasgow and the rest of the UK, e.g. $e_i^{UK} = e_i^{GCR} = e_i^{RUK}$. This gives us our first case, which we term as the "*strict WIOD*" option.

Our second option, brings in some local knowledge on the nature of electricity industry in the GCR accounts. We know – as Hermannsson and McIntyre (2014) noted – that the nature of activity in the electricity sector in Glasgow is very different that in the rest of Scotland. The emissions in the electricity sector in the WIOD accounts will reflect not only those from generation activities but also the other activities of electricity, including transmission, distribution and supply. Glasgow has a high share of the headquarters and main office activities of companies active in electricity, including Scottish Power, and thus a significant employment in electricity industry, but has no large scale (fossil) electricity generation within the city. For this reason, the emissions in the GCR electricity sector in GCR is likely to be significantly lower than those given by the strict application of the WIOD emissions-output coefficient. If such data were available in the WIOD, we would ideally like to replace the (calculated) emissions intensity for the Electricity sector in GCR with the average emissions intensity for non-generation element of electricity. However, as there is no disaggregation between generation and non-generation elements in the WIOD accounts, we calculate and take an emissions-output coefficient for Service sectors in the UK WIOD and use this for the GCR electricity sector in our second option. We term this the "*electricity-adjusted WIOD*" option.

So far we have not used any other emissions information than that which comes from the WIOD. However, in the UK, we have official statistics on emissions by industrial sector derived from sectoral fuel use. Our third option uses these to better reflect the differences in emissions intensities between sectors in the two regions. This would capture any differences in the emissions-intensity of production within a sector for each region, for instance, if the Manufacturing sector in GCR has a more emissions-intensive product or process than the same sector in the rest of the UK.

Our first step is to calculate sectoral emissions in GCR and RUK, which we do by using output shares between each region, i.e., for sector *i* in GCR:

$$ep_i^{GCR} = e_i^{UK}\frac{x_i^{GCR}}{x_i^{UK}} \tag{8}$$

An alternative emissions-output coefficient can be calculated as the relationship between emissions and output at the sectoral level (i.e. $e_i^{GCR} = ep_i^{GCR}/x_i^{GCR}$). Replacing superscript GCR with RUK in equation (8) we can find the emissions and emissions coefficients for all sectors in RUK. However, when we apply this we find that there is a difference between total UK sectoral production emissions from ONS and WIOD for 2014. (Total WIOD emissions for the UK sum to 367,461 kT CO2, while ONS total emissions are 327,355 kT CO2). Perhaps this is due to differences in the methodologies by which these metrics are constructed in each case, and the use of nation or sector-specific values. To reconcile this within the current framework, we want to preserve the consistency with the WIOD dataset, and so a scalar is applied to raise all sectors emissions by the required amount so that the total UK emissions is the same in each case (i.e., the sum of emissions from all *i* industries for both GCR and RUK). In practice this means that while we have preserved the integrity of total UK emissions, if we add together the sum of emissions in GCR and RUK for a specific sector these no longer match to the total for that sector in the UK.[6] This is our third case, which we term "*fuel use emissions-adjusted*" option.

Our fourth option repeats the same difference between options 1 and 2, by replacing the emissions allocated to GCR electricity sector from the "fuel use emissions-adjusted" case with those calculated using an emissions-coefficient estimated from GCR Service sectors in option 3. Again, this reflects the differences in activity between the Electricity sector in GCR and the RUK areas. This makes our fourth case, which we term "*electricity adjusted fuel use emissions-adjusted*" option.

Across all options, total emissions in the UK are constant. All emissions-intensities for sectors/nations outside the UK are left unchanged in each case from those given in 2014 WIOD. For the UK, moving from option 1 to option 2, or from option 3 to option 4, total sectoral emissions in both GCR and RUK are unchanged, but any increase (decrease) in emissions in one sector in either GCR or RUK means that there needs to be a corresponding decrease (increase) in the same sector in the other region, and the recalculation of region/sector emissions-output coefficients.

Fig. 3 sets out the emissions intensity of GCR industries under each of the four cases. Along the horizontal axis we have the 56 industrial activities identified in each nation in WIOD, while the vertical axis shows the emissions per unit of output (i.e., kT CO2 per £million). We can see that for some sectors and options, the sectoral coefficient varies significantly, but for others there is little variation across the options. For instance, sectors 34 to 56, largely covering service sectors (both private and public) have very little variation across the four options, while Primary, Manufacturing and Utilities both contain sectors with higher coefficients and also have different values depending upon the option

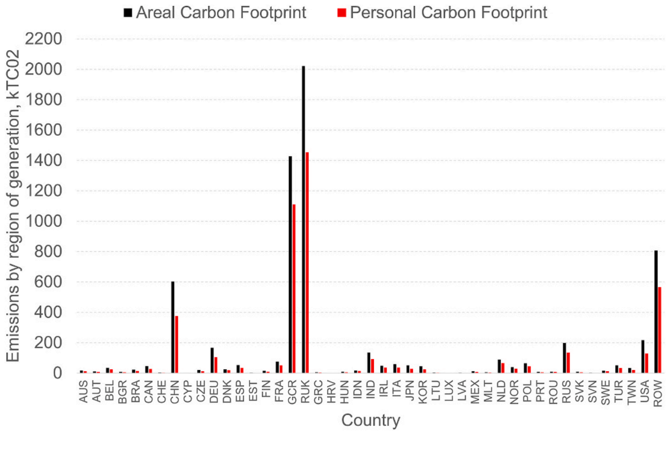

Fig. 3. Emissions-output coefficients (kT CO2 per £m) for each sector in GCR under four options.
Source: Authors calculations.

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[6] One additional option could be to use the fuel-use estimated values for GCR and RUK from the UK, but this would mean that total UK emissions would be different from those in WIOD.

used.

Within the non-Service sectors (we look at the Electricity sector (number 24) next) we can identify three kinds of sectors. First, we have those sectors which have relatively low emissions-output coefficients and where there is little change under the alternative options. This includes sectors 5–7, 9, 16–23 and 25 to 30. Second, we have those sectors where there is some variation depending on whether we are using option 1 ("strict WIOD") or 3 ("fuel-use emissions-adjusted") and where the emissions intensity increases in this move to the third option. (Recall that in options 2 and 4, only the Electricity sector emissions coefficient changes relative to options 1 and 3). These include sector 3 ("Fishing and Aquaculture") and 31 to 33 ("Land transport and transport via pipelines", "Water transport" and "Air transport"). Third, we have those where the emissions-intensity reduces in option 3 relative to option 1, specifically sectors 1 ("Crop and animal production"), 4 ("Mining and quarrying"), 10 ("Manufacturing of coke and refined petroleum products"), 13 ("Manufacturing of rubber and plastic products") and 14 ("Manufacture of other non-metallic mineral products").

We can see the impact of our adjustment for the Electricity sector in GCR by looking at the values for sector 24 ("Electricity, gas, steam and air conditioning supply"). The unadjusted values, corresponding to those from options 1 and 3, give the sector an emissions-intensity of 0.75 kT CO2 and 0.67 Kt CO2 in these two cases, giving this sector in GCR the second highest value of all industries, behind only "Air Transport" (33). The adjustment from option 1 to option 2 reduces this emissions intensity by 99.06%, while the move from option 3 to 4 reduces it by 98.86%.

We are interested in understanding whether the different calculations of sectoral emissions change the overall level of emissions associated with production and consumption activities in GCR. Table 4 sets out these key results, showing (in the second and third columns) the Production-Based Carbon Accounts (PBCA) and the Areal Carbon Footprint (ACF) for Glasgow under each of the four alternatives options for the calculations of emissions in GCR and RUK. The final column in Table 4 shows the ratio between the two metrics for each option showing the extent to which the ACF is larger or smaller than the PBCA.

Looking at the totals first, depending on the assumptions about emissions intensities, the PBCA can vary from 1977.1 (in the "electricity-adjusted WIOD" case) to 3703.2 kT CO2 ("Strict WIOD"), so that the simple step of replacing the emissions from the Electricity sector cuts territorial emissions to 53% of their previous value. There is a smaller reduction in production-based emissions as we move from option 3 and 4.

Under the ACF perspective, a much smaller range of outcomes is found, with the smallest metric (in the "electricity-adjusted fuel use-adjusted" case) 90% of the highest value (again in the "Strict WIOD" case). This smaller range is explained given that the move from option 1 to 2, or 3 to 4 only changes the emissions intensities for GCR production, which is only part of the emissions driven by GCR consumption.

5. Discussion

Our results show the value of an MRIO perspective on understanding emissions by cities from perspectives. In this section we discuss the practical challenges in implementing our approach and embedding these metrics into guiding policy decisions. We set these out on the domains of timeliness, data quality and completeness, and how the different perspective would show the consequences of policy actions.

Table 4

Glasgow emissions, production- and consumption-based carbon accounting perspectives, 2014, $KtCO_2$.

	PBCA	ACF	ACF/PBCA
Strict WIOD	3703.2	6500.5	1.76
Electricity-adjusted WIOD	1977.1	5896.6	2.98
Fuel use emissions adjusted WIOD	3657.3	6428.4	1.75
Electricity-adjusted fuel use-adjusted WIOD	2133.5	5895.3	2.76

Source: Authors calculations.

First, the nature of economic accounts is that these bring together data from a wide range of economic surveys, and primary economic data, and so generally feature a lag between the period to which they relate and their publication. Our illustration is undertaken for the year 2014 as this is the latest data to which WIOD accounts are currently available – which provide MRIO with emissions at the sectoral level for a high number of countries and with high industrial detail. Other economic accounts do exist, however this lag between years and publication is a feature which limits the practical application of these metrics for short-term analysis. The EU's recent FIGARO accounts, for instance, in 2021 published a set of accounts for the EU and its major trading partners (plus the rest of the world) spanning the period between 2010 and 2019.

These lags are perhaps tolerable if the metrics of consumption and production-based carbon accounts are required only for academic interest or consideration of a static picture of the relationship between countries. Should cities or regions choose to implement emissions metrics that employ consumption-based perspectives – such as San Francisco which has set a target of reducing (relative to 1990 levels) sector-based (i.e., inventory) emissions by 61% by 2030 *and* consumption-based emissions by 40% over the same period (San Francisco Department of the Environment, 2021) then a shorter lag between the end of the period and publication would be more useful.

Second, all analysis at the global scale requires a huge amount of information, some of which must come from national/local data providers, but which must then be reconciled with data from other national providers for other countries. Any process of standardisation is therefore likely to lead to differences emerging between the purportedly same metrics (such as total CO2 emissions from industrial production). We see that there is a gap of over 11% between this single metric for the UK for instance. Our illustrative alternative assumptions show that changing one emissions intensity – such as the emissions from Electricity in GCR – can impact significantly on the production emissions metric at the sub-national level. A major benefit for policymakers of our framework is that the method can be used – when there are updates to the global MRIO accounts - to provide regular updates on the drivers of city emission under both production- and consumption-emissions. These insights can support transparent emissions accounting as well as identifying the areas most appropriate for emissions policies under the target used by the city. For these methods to become genuinely useful for policy applications, there is a need to ensure that data quality improves, both in its timeliness and in reflecting the (measured) experience at the national and local level. It might be possible to introduce location specific emissions from real-time measurements and associate these to local economic activity (e.g., Moran et al., 2020). These appear to set out the possibility of a huge and rapid improvement in this area both for the accuracy of results in reflecting local emissions (and moving away from the use of national averages) and in the timeliness of emissions measures.

Third, our analysis covers only one (important) element of global and local emissions: those from fuel use in production sectors. Omitted from this analysis are direct emissions from household consumption (e.g., use of household fuels in heating and cooking) or emissions from private transport. At the local level, transport emissions will occur within the boundary of the city, and so contribute to territorial emissions. These will reflect vehicle use but will also reflect the nature of the vehicle fleet (whether electric, hybrid or petrol/diesel), the layout of streets and neighbourhoods, and also the relationships between places of work/social/entertainment and residence, so will be highly geographically focused within a city. These emissions will become a more important factor for a city's emissions where progress on decarbonisation "static" energy consumption (e.g., electricity use in buildings) has been made.

Fourth, there is naturally interest in showing the consequences of policies for measures of emissions. Such could be critical for building and maintaining support for the range of interventions introduced, demonstrating the these had desired effects, such as reductions in emissions. An interesting contribution to this point comes from Ramaswami et al. (2021) who note that there are a range of methodologies and approaches for urban carbon accounting, which policymakers need to be aware of to set appropriate targets and identify the policy actions through which those can be achieved.

Our framework suggests a way in which MRIO accounts can be used to provide emissions metrics on three of the four forms suggested by Ramaswami et al. (2021). Their territorial source-based accounting perspective is akin to our Production-based metric, for example. They note how this measure would not be able to identify changes in emissions from some specific policies which cities might introduce, such as building insulation programmes, where the electricity savings from reduced losses would reduce electricity production (and thus emissions) outside of the city, where electricity generation would occur. Ramaswami et al. (2021)'s consumption-based footprint measure on the other hand, while useful for showing the consequences of policies to reduce energy consumption by households, would not encompass non-household demands, or businesses serving external markets. These suggest that urban policymakers would be well served by a range of indicators against which urban emissions could be tracked – including those from local measures as well as IO frameworks - to ensure that local actions were consistent with emissions reductions not only locally, but also at national and global scales.

6. Conclusions

Cities are increasingly the focus of policy ambition to reduce emissions, however there does not exist any consensus on city-level carbon accounting and existing metrics for emissions measurements are often incomplete below the national level. Furthermore, analysis of emissions in its own silo – as if these are disconnected from economic activity and fuel use – prevents a more complete understanding of the economic-emissions system. Linking emissions to multiregional input output (MRIO) accounts is a well-established technique which lets sub-national areas understand both the economic nature of emissions as well as understand emissions from production as well as consumption perspectives.

In this paper, we provide a methodology through which analysts can simultaneously estimate the territorial emissions (i.e., the emissions of a city or its production-based carbon accounts) and those on a consumption-based perspective, including its Areal (ACF) and Personal Carbon Footprint (PCF)) can be identified from. These metrics of emissions accounts are then found via the appropriate disaggregation of a city-region within the disaggregation of the World Input Output Database (WIOD). This framework makes use of economic data at the sub-national level, offering scope for the methodology to be employed by sub-national geographies across the world where such data exist. The benefit for sub-national policy makers is that the framework will estimate regional emissions linked to economic activity, which then can be adapted into an appraisal model to measure both the environmental and economic consequences of regional policy decisions.

Illustrating our framework for Glasgow (Scotland) in 2014 we find that Glasgow has a Production-Based Carbon emissions of 3703 kT CO2. This is lower than both the ACF (6500 kT CO2) and the PCF (4575 kT CO2) indicating that Glasgow consumption generated net emissions outwith its own boundaries. We know that the emissions metrics of footprints will be sensitive to alternative assumptions about the emissions-intensity of sectors. When we employ alternative assumptions about the nature of emissions-intensity in Glasgow and the rest of the UK we find that this finding - that GCR's territorial emissions are always lower than its consumption emissions – is not affected by the specific assumptions made.

As well as describing how the proposed framework maps to existing emissions accounting, we have highlighted some of the challenges in implementing MRIO techniques to understanding emissions at the sub-national levels to provide a benchmark for policy analysis. However, while the approach as outlined here provides useful insights, there are three useful ways in which the practical aspects of the approach can be extended. First, the analysis has focused on economic activity and emissions, but we have not incorporated employment at the sectoral level. Putting emissions alongside employment could help to identify key sectors not only for emissions, but also those sectors which are important for economic and emissions outcomes and so tell a richer story about these links. Second, a time series of tables within an MRIO framework could be used in Structural Decomposition Analysis. This could help to understand the factors which contributed to changes in emissions over time, and so highlight the space for such changes to contribute to future emissions changes. In the context of a city emissions analysis, the import of electricity from the wider hinterland will mean that the decarbonisation of large-scale electricity generation (outwith the city) will contribute to apparent reductions on the city's emissions on a Consumption basis. Third, the developed environmentally-extended MRIO accounts could be used as the initial dataset for Computable General Equilibrium analysis of the economic and emissions impacts of policies, to identify the spillover impacts of policies developed in one region/nation on others, or the distribution of impacts for common policies across countries and sectors.

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CRediT authorship contribution statement

Grant Allan: Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Supervision, and, Project administration. **Kevin Connolly:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing. **Aditya Maurya:** Methodology, Software, Formal analysis, Investigation, Data curation, Writing – original draft, and, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2023.139323.

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