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Urban carbon transformations: unravelling spatial and inter-sectoral linkages for key city industries based on multi-region input–output analysis

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A B S T R A C T

With around 80% of global greenhouse gas emissions directly or indirectly attributed to cities, attempts to mitigate climate change impacts must seriously consider urban carbon transformations. Two challenges are currently constraining urban planning decisions around decarbonisation. Firstly, a lack of detailed knowledge about city-induced emissions occurring outside of the city boundary hampers the design of mitigation strategies that involves the city's 'hinterland'. Secondly, the complexity of interconnections between industries and regions located upstream or downstream the supply chain of urban economic activity makes it difficult to implement specific, effective and efficient decarbonisation policies. In this study, a multi-scale, multi-region input–output model with nested regions at city, state, nation and world level is employed to study the carbon footprints and the inter-sectoral linkages in terms of embodied carbon emissions of the two largest metropolitan areas of Australia, Melbourne and Sydney. The results show that imported emissions make up more than 50% of the city carbon footprints, with most of them attributable to goods (excluding food) and services (excluding electricity). This highlights the importance of promoting mitigation measures both within and outside of the city. The energy, mining and agriculture sectors – usually located outside of city boundaries – all have significant carbon linkage multipliers associated with city demand, indicating the need of pursuing carbon mitigation measures in these sectors. The linkage analysis pinpoints to crucial sectors that need to be targeted in future investments towards urban decarbonisation to minimise emissions and to maximise positive economic effects for urban and regional economies. The study also provides an improved understanding of the differences and similarities between Australia's two main cities. It is envisaged that this type of analysis will become increasingly relevant to other cities as the spatial resolution of multi-region input–output databases continues to improve.

1. Introduction

Cities are home to over half of the world's population (UN-HABITAT, 2011) and are engines of growth for national economies. About 80% of global GHG emissions can be attributed to urban activities, with more than 70% of energy now consumed in cities (World Bank, 2013). Crucially, it is cities that are currently leading the way to implementing greenhouse gas (GHG) mitigation strategies (Kousky and Schneider, 2003). Cities can contribute decisively to bridging the global emissions gap, boasting an emissions reduction potential of up to two-thirds of the impact of recent national policies and actions (C40, 2014). Significant commitments towards GHG reduction have already been made by cities around the world: 228 global cities, home to around 436 million people, have set GHG reduction goals and targets (C40 and Arup, 2014).

The challenge for cities lies in balancing sustained economic performance and social welfare with GHG emissions reduction. One necessary condition is a comprehensive accounting inventory of city GHG emissions. This must include emissions coming from within the city boundaries but also those that are 'out-of-boundary', i.e. occurring outside of the city but attributable to activities within the city (C40 et al., 2014; Wilshire and Doust, 2013). In addition to the territorial accounting perspective, the city carbon

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footprint has been suggested as a complementary, consumption-based GHG accounting approach (Chavez and Ramaswami, 2013; Kennedy et al., 2009; Wiedmann et al., 2015). Such an approach facilitates the identification and quantification of economic (sectoral) and spatial interconnections occurring in the supply chain of key economic sectors, defined as those where investment is likely to maximise both economic growth and carbon mitigation.

A widely employed approach to estimating economic output and carbon emissions for different economic sectors is the input–output (IO) model developed by Leontief (1941). Carbon footprints based on IO models have already been estimated for several global cities (Wiedmann et al., 2015). However, only a handful of studies appear to have explicitly calculated local sectoral carbon intensities[1] (Chen et al., 2013; Feng et al., 2014; Minx et al., 2013). The majority of existing studies have instead made the assumption that local sectoral carbon intensities are equal to national sectoral intensities. This assumption is seen in both single-region IO models (Dias et al., 2014; Petsch et al., 2011; Vause et al., 2013) and multi-region models (Hermannsson and McIntyre, 2014). Other authors have attempted to obtain city-scale sectoral carbon intensities by combining national down-scaled input–output data with process-based data (Ala-Mantila et al., 2013, 2014; Larsen and Hertwich, 2009, 2010a,b). While this approach improves data quality, only the use of a sub-national multi-region input–output (MRIO) model with nested city-scale tables can achieve a more accurate representation of local specificities and interlinkages.

Most previous urban studies have focussed on carbon footprint accounting methodology and results whilst neglecting a more profound discussion of inter-sectoral economic interactions and their impact on GHG emissions. Within the framework of IO analysis, the classical multiplier method (Rasmussen, 1956) and the hypothetical extraction method (HEM) (Strassert, 1968) are two widely accepted methods to describe inter-sectoral relationships and identify key sectors. Based on these two methods, Miller and Blair (2009) summarised two types of economic effects exerted by one particular sector on other sectors can be measured: backward linkages (BLs), based on the Leontief inverse as suggested by Rasmussen (1956), and forward linkages (FLs), based on the Ghosh inverse (Chenery and Watanabe, 1958; Ghosh, 1958; Miller and Lahr, 2001; Miller and Blair, 2009). Increasingly, as a result of growing concerns over GHG mitigation, inter-sectoral linkage analysis is being used to investigate carbon emissions (Table A.1). In addition, analyzing the inter-sectoral linkages between cities, adjacent areas and national economies will allow a deeper understanding of urban carbon transformations.

Whilst the majority of previous linkage studies have used single-region IO analysis, similar measures may also be used to assess the types and intensities of spatial interdependence (spatial linkage) or connectedness in inter-regional or multi-regional models (Miller and Blair, 2009). Shao and Miller (1990) first presented a state-level multi-regional empirical study of the U.S. to assess the interregional interdependence structures. Okamoto and Ihara (2005) later used the classical multiplier method combined with structural decomposition analysis (SDA) to analyse the spatial structure of 8 Chinese regions. The remainder of past studies have focused on inter-country MRIO studies (Table A.2). Spatial linkages are thus considered an established tool for investigating spatial linkages at a national or regional scale. Nevertheless, the lack of complete MRIO datasets has hindered the development of spatial linkage applications to date, with single-region applications still more prevalent in economic and environmental applications. Spatial linkages are particularly useful for studying interconnections between the city and its hinterland. The present article demonstrates how these can be used in cases where cities have their own disaggregated IO data.

In this study, a novel application of linkage analysis is presented at different spatial scales encompassing city, regional, and national economic sector interactions. Both spatial and inter-sectoral linkages have been assessed to explore urban carbon transformations by means of a high-resolution MRIO model of Australia using Sydney and Melbourne as case studies. The results provide an indication as to which industries are the most promising sectors for future investment in the necessary urban transformation towards sustainability and also highlight interdependencies as well as differences and similarities between Australia's two main cities.

2. Methods and data

The Greater Capital City Statistical Area (GCCSA) boundaries, as published by the Australian Bureau of Statistics (ABS, 2011b), were adopted as the metropolitan city's boundary definition in this study (see Fig. A.1 in Appendix). It includes people living within the urban area of the city as well as people who regularly socialise, shop or work within the city, but live in small towns and rural areas surrounding the city. In 2009, our study period, Greater Melbourne, with a population of around 4 million made up 73.4% of the population of the state of Victoria and 3.4% (7693 km^2) of its area, while Greater Sydney, with a population of around 4.5 million represented 63% of the population of the state of New South Wales and 1.5% (12,138 km^2) of its area (ABS, 2011a).

"Since 1994, the Sydney economy has gradually transformed from having a manufacturing-based structure to the predominantly finance-based structure that it has today. Manufacturing decreased from about 15% of total industry value added in 1994 to 6% in 2014, while the financial industry grew from 9% in 1994 to 15% in 2014. The rest of industry value added is dominated by service sectors including professional services (9%), health care (6%), whole sale (5%), and other smaller service sectors. In a similar fashion, Melbourne's manufacturing decreased from 18% of total industry value added in 1994 to only 6% in 2014, while the financial industry made up more than 12% in 2014. The rest of industry value added is also mainly made up by service sectors, including professional services (9%), health care (7%), whole sale (5%), and other smaller service sectors (SGS-Economics & Planning, 2014)."

Both cities (as the central parts of the GCCSAs) have recently set their own carbon mitigation targets. The City of Melbourne committed to reduce GHG emissions by 10% below 2011 levels by 2018 in addition to becoming a carbon neutral city by 2020 (CoM, 2014), whereas the City of Sydney aims to reduce GHG emissions across the entire city by 24–32% below 2006 levels by 2030 (CoS, 2013). However, owing to the lack of out-of-boundary emissions accounting, there are no specific measures for embodied emissions or the total city carbon footprint.

As alluded to in the introduction, the best solution towards a more comprehensive carbon accounting framework for Australian cities is to create a multi-scale MRIO model (Bachmann et al., 2014) that allows for the integration of multiple spatial scales, including the city scale with interdependent local sectoral carbon intensities between regions. The Industrial Ecology Virtual Laboratory (IELab; www.ielab.info) is a platform for multi-scale MRIO data compilation with high spatial and sectoral detail. It allows for the flexible customisation of regions and sectors and their direct sectoral emissions (Lenzen et al., 2014). To create a city-scale, nested IO table the main information needed is data that specifically reflect

[1] The ratio of carbon emissions to economic output, commonly used as an indicator of how much carbon is directly or indirectly emitted per unit of sector output.