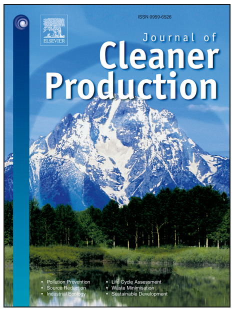
Journal Pre-proof



Low carbon cities in 2050? GHG emissions of European cities using production-based and consumption-based emission accounting methods

Steve Harris, Jan Weinzettel, Andrea Bigano, Albin Källmén

PII: S0959-6526(19)34076-4

DOI: https://doi.org/10.1016/j.jclepro.2019.119206

Reference: JCLP 119206

To appear in: *Journal of Cleaner Production*

Received Date: 8 November 2018

Revised Date: 17 October 2019

Accepted Date: 6 November 2019

Please cite this article as: Harris S, Weinzettel J, Bigano A, Källmén A, Low carbon cities in 2050? GHG emissions of European cities using production-based and consumption-based emission accounting methods, *Journal of Cleaner Production* (2019), doi: https://doi.org/10.1016/j.jclepro.2019.119206.

Low carbon cities in 2050? GHG emissions of European cities using production-based and consumption-based emission accounting methods.

Steve Harris[a]*, Jan Weinzettel[b], Andrea Bigano[c,d] and Albin Källmén[a].

a. IVL Swedish Environmental Research Institute. Aschebergsgatan 44, 411 33 Göteborg. steve.harris@ivl.se

b. Charles University, José Martího 407/2, 162 00 Prague 6, Czech Republic. Jan.Weinzettel@czp.cuni.cz

c. Fondazione Eni Enrico Mattei (FEEM), Corso Magenta, 63, 20123 – Milano, Italy (previous institution)

d. "Present address" CMCC Foundation Centro Euro-Mediterraneo sui Cambiamenti Climatici, Università Ca' Foscari Venezia, RFF-CMCC European Institute on Economics and the Environment, Via Felice Casati 39, I-20124 Milano, Italy. andrea.bigano@cmcc.it

* Corresponding author.

Abstract

The role of cities and their stakeholders in creating a sustainable low carbon society is becoming increasingly critical. Cities and their supply chains are responsible for almost 80% of the global energy consumption and over 60% of greenhouse gas emissions (GHG). It is expected that by 2050 seventy percent of the global population will be living in urban areas. However, in general cities still quantify and report only their production-based GHG emissions and fail to account for their supply chains. There has been much less focus on the GHG emissions associated with consumption in cities, including household and government consumption.

This paper compares the production-based GHG accounting method with the consumption-based method for ten European cities. This is performed for a base year (2010) and two divergent future scenarios for 2050, a business-as-usual (BAU) scenario and a post carbon (PC2050) scenario. The PC2050 scenario was created by city stakeholders in the framework of the European research project POCACITO in (2014-2016). Consumption-based emissions are calculated using the EXIOBASE multi-regional input-output model.

Compared to 2010, both BAU and PC2050 scenarios show significant decreases for production-based emissions, falling 31% and 68% respectively. However, during this period consumption-based emissions increase for eight cities, rising 33% and 35% respectively. This occurs despite the modelled improvements in global production efficiency for 2050 and the significant production-based reductions under the PC2050 scenarios. The increase in consumption-based emissions is primarily linked to rising GDP and a corresponding increase in spending and consumption, which override the local and global efficiency improvements.

Hence the results highlight a notable disparity between the traditional focus on production-based accounting and consumption-based accounting. This suggests that future city actions should extend their focus on addressing the impact of consumption in addition to local energy production and emissions. It also suggests that city stakeholders are generally underestimating the impact of consumption and the responses required.

Keywords: carbon footprint, production-based accounting, consumption-based accounting, sustainable city, EE-MRIO.

1 Introduction

It is well documented that the world's population is becoming increasingly urbanised, and that by 2050 more than 66% of people could be living in urban areas[1] (UN, 2014). Europe is already highly urbanised with 74% of the population living in urban areas, with an expected increase to 80% by 2050 (UN, 2014). Globally, cities are responsible for over 78% of the global energy consumption and over 60% of greenhouse gas (GHG) emissions. This is due to their socio-economic strength and related consumption (UN Habitat, 2016; C40 Cities, 2018). They are also responsible for 85% of Gross Domestic Product (GDP; Gouldson et al., 2015a) and are therefore of critical importance in addressing climate change and sustainability (C40 Cities, 2018).

Cities have made notable progress in attempting to reduce GHG emissions with initiatives such as the Covenant of Mayors that has over 7000 signatories from EU cities (CoM, 2018) and C40 Cities that includes over 90 global megacities (C40 Cities, 2018a). There are three ways that cities can report their GHG emissions. Territorial-based accounting systems cover the emissions produced by activities within city borders and jurisdiction, whilst production-based accounting (PBA) can include emissions related to economic activities of households and companies whose operations may lie outside the city borders (EEA, 2013). Conversely, consumption-based accounting (CBA) includes upstream emissions from the production of all products and services consumed by citizens regardless of where production occurs (EEA. 2013). However, reporting of GHG emissions from cities is currently almost entirely focussed on territorial or production-based GHG emissions (Dahal and Niemelä, 2017).

The importance of consumption-based emissions is increasingly highlighted in the literature (C40 Cities, 2018b; Dahal and Niemela, 2017; Sudmant et al. 2018) and by the emergence of standards such PAS 2070 (BSI, 2013). This is because the activities and consumption of cities induce significant quantities of GHG emissions outside the boundaries of the city (Chen et al., 2016; Minx et al., 2013). Focussing only on territorial or production-based emissions may lead to emission reductions being offset by carbon leakage where carbon intensive activities are outsourced (Jiborn et al., 2018). For example, when embodied GHG emissions in imports are considered, Annex I countries do not meet their targets of the Kyoto Protocol (Kanemoto et al., 2014; Peters et al., 2011). Therefore, not only are cities increasingly the root of emissions, they are viewed as the "core of climate change mitigation" (Zhifu et al., 2019).

Gouldson et al. (2015b) note that there is less research on GHG emissions from cities compared to research performed at the national and international level. Nonetheless, there is a growing list of literature on production-based emissions of cities (Kennedy et al. 2009; Kennedy et al. 2010; Glaeser and Kahn 2010; Bi et al. 2011). In addition, the literature that examines the carbon footprint or consumption-based emissions of cities is increasing (e.g. Jones and Kammen 2013; Lin et al. 2015; Minx et al. 2013; Feng et al. 2014). Recent work by Moran et al. (2018) used the Eora multi-region input-output (MRIO) database to help estimate carbon footprints for 13,000 cities.

The difference from using PBA and CBA methods has also been examined in recent studies. Meng et al. (2017) compared the production- and consumption-based emissions for the Chinese megacities: Beijing, Shanghai, Tianjin and Chongqing. Whilst, Sudmant et al. (2018) compared the two accounting methods for cities in China, the UK and the US, finding that per capita income and population density are closely linked to consumption-based emissions levels. They found that for most cities consumption-based emissions were higher than production-based emissions. This is supported by

[1] As the UN (2014) note, there is currently no global definition for urban settlement, which varies widely across countries. The UN used data based on the concept of urban agglomeration or the population within the administrative boundaries of the cities.

Feng et al (2014) who found that 48%-82% of emissions were consumption-based for four Chinese megacities; Chen et al. (2017) calculated 50% for Sydney and Melbourne, whilst C40 Cities (2018b) obtained an average of 60% for 79 global cities. The remaining emissions arise from activities within the city boundaries such as heating, electricity generation and transport.

Few studies have used MRIO or similar methods to model future emissions of cities. However, MRIO has been used to estimate future consumption impacts at a national level (Scott et al., 2013), and also the global implications of a future circular economy (Wiebe et al., 2019). Liu et al. (2018) used Environmentally-Extended Input-Output Simulation to model production- and consumption-based GHG mitigation policies for a Canadian industrial region. Production-based policies were found to result in larger GHG emissions reductions for primary industries, whereas consumption-based policies were more effective for industries at the end of industrial supply chains. In related research, Hertwich et al. (2015) combine life-cycle assessment input-output data to model 2030 and 2050 scenarios for the global energy system based on renewable energy. They demonstrated that the higher material inputs to supply the global electricity needs in 2050 were manageable and would result in significant reductions in environmental impacts such as GHG emissions, freshwater ecotoxicity, eutrophication and particulate-matter exposure.

A further challenge is how to model the impacts of future city development strategies on GHG emissions and the complex socio-economic and ecological systems (Heinonen et al. 2015). Scenario analysis and backcasting techniques are two approaches that can form the basis to analyse possible future scenarios (Swart et al., 2004). Scenario analysis has evolved since the 1950's as a methodology to analyse future sustainability pathways and aid strategic decision making (Schoemaker, 2004 and Swart et al., 2004). Backcasting involves the definition of a desired future and ways that this can be achieved. "It is thus explicitly normative, involving working backwards from a particular desired future end-point to the present in order to determine the physical feasibility of that future and what policy measures would be required to reach that point" (Robinson 1990). In terms of sustainability science, scenarios can be described as "coherent and plausible stories, told in words and numbers, about the possible co-evolutionary pathways of combined human and environmental systems" (Swart et al. 2004).

The aim of this paper is to compare PBA and CBA for a base year and two future 2050 scenarios, for ten European cities. The future scenarios compared are a Business-as-Usual (BAU) and a post-carbon 2050 (PC2050) scenario, the latter developed by city stakeholders. To our knowledge this is the first research to use and compare PBA and CBA (using MRIO) for both current and future scenarios of cities. It seeks to answer the following research questions:

1. What are the GHG emissions of the cities using PBA and CBA for 2010 and the future scenarios: BAU and PC2050?
2. How do the GHG emissions compare across the cities using the two accounting methods?
3. Are the post-carbon strategies developed by the city stakeholders effective at reducing GHG emissions for 2050?

2 Methodology

2.1 Background and overview

This study covers ten European cities: Barcelona, Copenhagen, Istanbul, Lisbon, Litoměřice, Malmö, Milan, Turin, Rostock and Zagreb. These were selected to provide a diverse mix of city population sizes ranging from 24,000 to 13.9 million inhabitants, from different European geographic regions (see Table 1 for an overview of key city figures). In addition, they were participants in the EU Post

Carbon Cities of Tomorrow (POCACITO) project where this research was performed (POCACITO, 2014). A main aim of POCACITO was to assess the sustainability implications of a post-carbon strategy and resultant scenario, compared to BAU.

Table 1: Key figures for the municipalities of the cities (for years 2012)

	Population (000's)	GDP (EUR)	Energy use (GWh)	GHG/Capita (TCO_2e)
Barcelona, Spain	1,600	37,347	16,782	2.7
Copenhagen, Denmark	559	63,000	8,366	5.0
Istanbul, Turkey	13,900	9922	15,570	2.7
Lisbon, Portugal	548	48,000	10,786	7.1
Litoměřice, Czech Republic	24	11,800	366	5.7
Malmö, Sweden	313	45,000	7,759	5.0
Milan, Italy	1,324	51,754	28,167	6.0
Rostock, Germany	203	30,678	3,776	4.1
Turin, Italy	902	30,716	18,841	5.7
Zagreb, Crotia	793	18,645	11,300	3.2

Source: Harris et al. 2016a.

The sections below describe the methodology. First the city model and its key components are presented. Understanding the recent trends of the key components related to GHG emissions formed the basis to model future scenarios and their GHG emissions. Next the PBA and CBA methods are described, followed by the scenario modelling. Further detail can be found in the supplementary material and Harris et al. (2016b).

2.2 City emissions model

Cities are complex dynamic systems with multiple interrelated variables that affect each other (Feng et al., 2013). These include variables related to energy demand and production, but also socio-economic development and even behavioural aspects (Feng et al., 2013). For our city model, we divide the variables into two categories. The first consists of the main variables that have a direct bearing on energy GHG emissions: energy use and energy sources. Whilst the second group contain related variables that have a direct influence on the main variables: population, GDP, transport model split and energy efficiency of buildings. This is illustrated in Figure 1. This is in line with Feng et al. (2013) who developed a system dynamics model using the same key components to simulate the development of energy consumption and GHG emissions for Beijing.

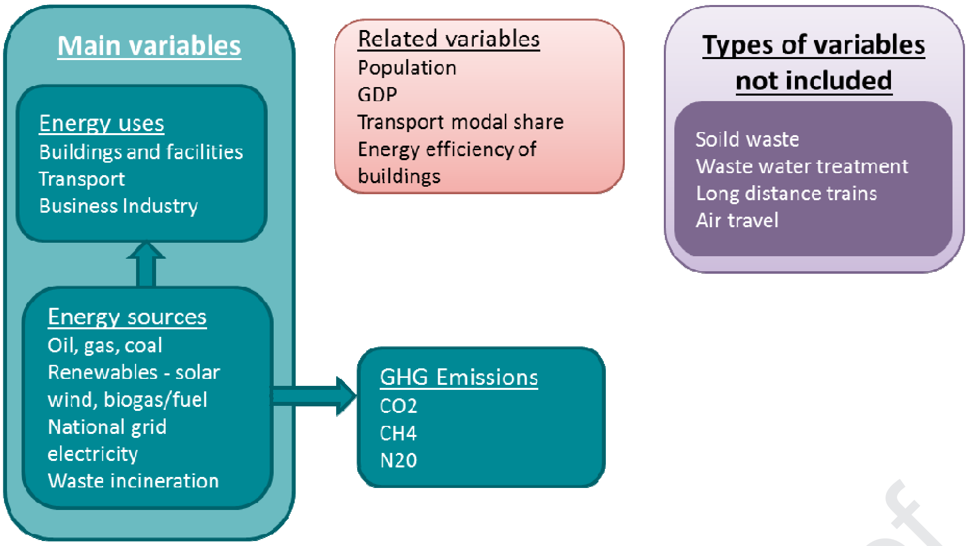


Figure 1; Illustration of the main variables on GHG emissions, the related variables and the variables that were not included in the model

An initial sustainability assessment of each city was conducted as part of the POCACITO project on 22 key sustainability performance indicators and their recent trends (typically over 10-15 years; see Selada et al. 2015). This yielded significant data and provided information on recent and ongoing sustainability projects within the cities, which served as a background to help develop the scenarios. Table 2 provides further information on the key indicators for the components and the data sources.

Table 2: City components, indicators and data sources for the analysis of recent trends

COMPONENT	KEY ASPECTS/INDICATORS	MAIN DATA SOURCES FOR RECENT TREND ANALYSIS
GHG Emissions and Energy	Energy demand – by sector: transport, municipality and public services, residential, business/services and industry. Energy production - source of energy including: national grid electricity, local produced electricity and renewables, GHG emission – calculated from the energy production were available for most cities.	GHG emissions and energy reports from the individual cities (references provided in supplementary data). In addition, reports from the Covenant of Mayors (CoM, 2018). Selada et al. 2015
Population	Population of municipality Population of greater metropolitan area Population trends	Country specific statistical sources and reports from the city municipalities (Selada et al. 2015). Oxford Economics, (2015) provided population data at the greater metropolitan region.
Transport	Energy demand Modal split City transport policy and projects (e.g. to increase public transport share)	Data on total energy used by the transport sector and the modal split breakdown and trends were obtained from Selada et al. (2015) (which was based on individual city reports).
Housing and building	Share of final energy demand for residential and service sectors City wide development policies and projects. Trend in developing or promoting energy efficient buildings.	Information on the status and share of energy efficient buildings was derived from Selada et al. 2015. This report also provided information
GDP	GDP GDP per capita for greater metro region	Selada et al. (2015) Oxford Economics (2015)
Business and Industry	Industry and service share of GDP (growth or decline). Changes in industry structure – e.g. reduction of car production industry in Turin	Selada et al. (2015). Municipality reports from each city also provided further information and are listed in the supplementary material

2.3 Production- and consumption-based accounting methods

2.3.1 Production-based accounting

The most consistent and robust data for cities is available at the municipality level which is therefore the focus for the production-based energy and GHG emissions calculations and modelling. The methodology follows the Global Protocol for Community-Scale Greenhouse Gas Emissions Inventories, which was developed from the GHG Protocol (GPC, 2014). The system boundary for the production-based GHG emissions comprises Scope 1 GHG emissions derived from sources located within the city boundaries (including CO_2, CH_4 and N_2O) and Scope 2 from grid-supplied energy, including those that cross city boundaries. This consists of emissions from activities within the city boundaries that include heating and electricity production (used in housing and buildings), transport, industry and waste incineration. It does not include Scope 3 emissions (e.g. from the production of oil and gas) because this would be consumption-based accounting. In addition, we do not include emissions from water, waste or agriculture, fugitive emissions, forestry or land use changes, as no consistent data across the cities was available. In addition, these are not included in GHG emission reports published by the cities.

For those cities that had less consistent or robust data available, we supplemented data with national energy production and consumption trends, as well as industry profile changes and population and GDP growth.

2.3.2 Consumption-based accounting

Consumption-based accounting “captures direct and life cycle GHG emissions for all goods and services consumed by residents of a city, i.e. GHG emissions are allocated to the final consumers of goods and services, rather than the original producers of those GHG emissions” (BSI, 2013). The assessment boundary includes “GHG emissions arising from production of goods and services consumed by households, government and business capital investment within the city boundary, regardless of location of production” (BSI, 2013).

To quantify the consumption-based emissions of cities we combine household expenditure surveys (containing final demand of households) and government expenditure data, with Environmentally Extended Multi-Regional Input-Output analysis (EE-MRIO) (Millward-Hopkins et al., 2017). Combining household consumption with government expenditure data provides the maximum coverage for final demand categories (Ivanova et al., 2015). Local industrial production is included as it is contained in the consumption of households and governments; and what is not included, is associated with export to another region. EE-MRIO is widely used to calculate upstream environmental impacts resulting from the complete production chains of products, using the following matrix equation (Leontief, 1970) (equation 1):

$$\boldsymbol{FP} = \boldsymbol{F}(\boldsymbol{I} - \boldsymbol{A}) - 1\boldsymbol{y} \tag{1}$$

Where FP is the resulting footprint of products included in vector “y”, F is the intensity matrix containing environmental stressors for each economic sector per unit of sector output (rows are environmental stressors and columns are economic sectors), I is an identity matrix, A is the input technological coefficient matrix containing inputs of products per unit of sector output and y is a vector of final use products, which was replaced by city specific household consumption data from the household expenditure survey for each city.

Several MRIO databases exist that enable the calculation of consumption-based emissions. We utilise the EXIOBASE database derived from the European product-by-product EE-MRIO table (Eurostat 2008) established under the EU funded CREEA project (Wood et al., 2015). This was chosen due to its high product resolution (200 product groups) and because it was specifically designed for environmental analysis. Household consumption data was obtained from local authority data sources for Milan and Turin (ISTAT, 2015) and from Oxford Economics (2015) for the remaining cities (purchased under a confidential commercial license). Data for government expenditure was derived from Agenzia per l' Italia digitale (2015) for Italy. For the remaining cities, data contained in EXIOBASE on national government spending was scaled down to represent the city populations.

2.4 Scenario modelling

2.4.1 Scenario development and modelling of production-based BAU

For each of the key components, the BAU modelling was performed through linear extrapolation of the recent trends and modified by consideration of the qualitative influencing variables. The relationship between these factors is illustrated in Figure 2.

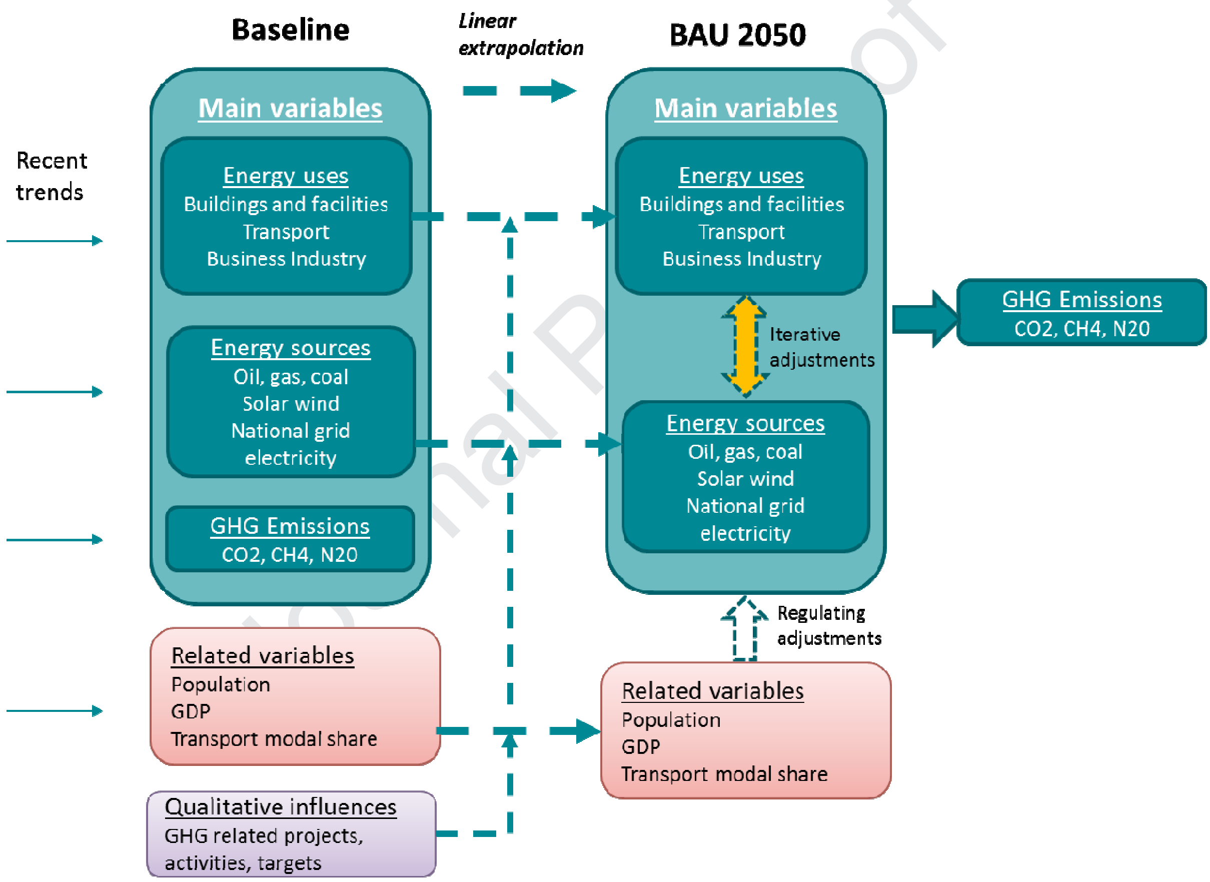


Figure 2: Scenario modelling structure for linear extrapolation of recent trends to BAU 2050

Therefore, each key component was first calculated using linear extrapolation and then adjusted based on a careful review of the following factors:

1. Qualitative influences – the evidence that current and ongoing policies and projects were inducing changes to (or likely to) energy use and GHG emissions.
2. Related variables – how have other factors influenced the current developments and recent trends. For example: effects of immigration on population growth, or migration from the city centre to surrounding suburbs; and changes to the energy consumptions of industry sectors. These types of factors were identified in the comprehensive indicators assessments

performed for each city. Therefore, "regulating adjustments" were made where appropriate to incorporate these effects.

3. Interaction of indicators – how trends influence each other and correlation between indicators. For instance, has the increase in energy demand followed population growth? Or is a reduction in energy demand due to a decrease in energy-intensive manufacturing caused by a growing service sector, or the result of the financial crisis)? It was also necessary to make "Iterative adjustments" to ensure the production and demand of energy was balanced.

For national energy sources, demands and GHG emissions in 2050 we used Capros et al., (2015) (this is based on the PRIMES model). Population projections to 2030 for the greater metropolitan areas were obtained from Oxford Economics (2015) and extended to 2050 using linear extrapolation. Other assumptions are documented in the supplementary material.

2.4.2 Modelling of PC2050 scenario and production-based emissions

The quantification of PC2050 is based on qualitative scenarios developed by city stakeholders as part of the EU POCACITO project Breil et al. (2015b). A series of three workshops were held in each city with local stakeholders to create a post-carbon 2050 vision and perform a back-casting exercise to develop strategies, actions and milestones (Breil et al., 2015a). The average composition of local stakeholder groups in the first two workshops is show in Figure 3.

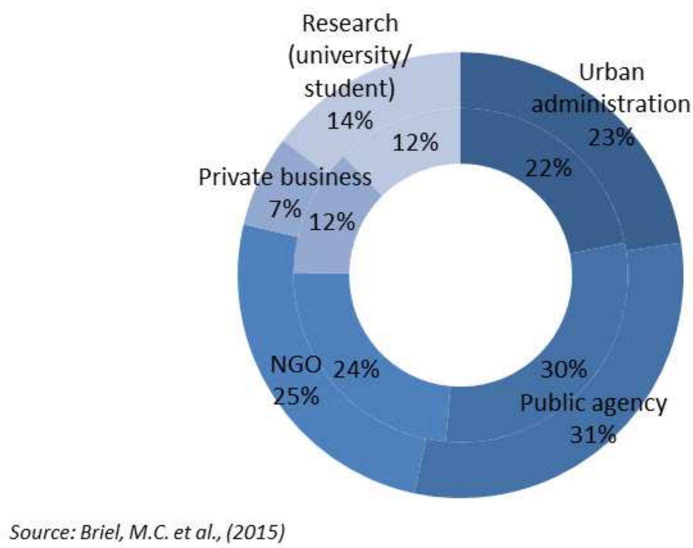


Figure 3: Stakeholder types at first (inner circle) and second (outer circle) workshop

The PC2050 scenarios were quantified by adjusting the key components of the BAU scenario based on an interpretation the ability of the PC2050 targets and actions to reduce energy use and emissions (see Table 11 of supplementary information). The Shared Socioeconomic Pathways (SSP's) produced for the IPCC fifth assessment report published in 2014 (IIASA, 2014) were used to calculate the difference between BAU and PC2050 for population and GDP change (Breil et al., 2014). Further information on the assumptions for calculating the PC2050 projections of each component can be found in upplementary material (Section 1.2).

2.4.3 Modelling of BAU 2050 in EXIOBASE

To model the 2050 scenarios in EXIOBASE the three main blocks of the MRIO databases, the input coefficients, environmental extensions and final demand, were manually adjusted to account for expected 2050 changes. To facilitate this, the MRIO dataset for the global production system was aggregated into 13 broad regions; one each for the countries of the participant cities (except for Zagreb, which is part of a broader region Rest of World (RoW)– Europe within Exiobase v2) and four rest of the world regions (Japan, Rest of EU, Norway and Switzerland; BRICS; US; and RoW). We assumed that with increasing levels of globalization, the efficiency of the country-specific technologies will converge. Because the future trading relationships (where countries obtain different materials and components) between countries is difficult to predict, we assume this remains constant for the purposes of the modelling. These assumptions align with other leading (Hertwich et al. 2015).

Each of the regions has a direct input (technological) coefficient matrix consisting of 200 products that stipulates how much of one product is required to produce another product. For the 2050 scenarios each product was adjusted to account for expected changes (based on the best available projections for factors such as resource efficiency of production and energy use (e.g. from IEA, (2015) and Capros et al. (2014)). The environmental intensity matrices, which represents the emission profiles for the 200 products and for each region, were subsequently adjusted using the same methodology.

The final demand of households in the BAU scenario was based on projections purchased from Oxford Economics to 2030 (Oxford Economics, 2015). This dataset was extrapolated to 2050 by assuming that the basic trend projected to 2030 for each product type would continue. Further adjustments were then made to the energy profile of the cities to align with the energy profile obtained from the production-based modelling.

2.4.4 Modelling of PC2050 in EXIOBASE

For the PC2050 scenario, we used the same underlying production system used in the BAU modelling, assuming that the global production systems outside the cities are the same. Total final demand of all products was adjusted based on the difference in the ratio of GDP for BAU and PC2050 for each city. Therefore, it is assumed that the Kaya identity is consistent in each of the scenarios (Kaya et al. 1997) (equation 2):

$$F = P \times \frac{G}{P} \times \frac{E}{G} \times \frac{F}{E} \qquad (2)$$

Where, F is total CO2 emissions, P is population, G is GDP, E is energy consumption. In other words, we assume that an increase in GDP results in an increase in final demand. After distributing the final demand amongst the product groups, the final energy demand was further refined to reflect the share of energy sources modelled in the production-based modelling. The final demand of the non-energy products was then adjusted for the main products where there was an anticipated difference in final demand between BAU and PC2050. This interpretation was based on an examination of the sustainability assessment of the scenarios (detailed in Harris et al. 2016). Adjustments were made by assuming that a *moderate change* from BAU to PC2050 results in a 25% variation and a *substantial change* means 50% variation (see supplementary material for further information).

3 Results

This section is divided into three parts. First, the key components of the city model and the developed scenarios are presented to compare the current trajectory of the cities (BAU) with PC2050. Next, we present the production-based results, followed by the consumption-based results.

3.1 City model extrapolation

The modelling results for the key components of the two scenarios compared to the current (2010) values are shown in Figure 4. Figure 4(a) shows that the population increases under both BAU and PC2050 for most cities, apart from Litoměřice where a small decrease in population occurs (500 less residents). Population and GDP are generally higher in PC2050 than BAU. Whilst all cities experience GDP increases under both scenarios, there is a wide variation for PC2050 compared to the base year (from just 17% for Turin up to 194% for Istanbul). These changes reflect the use of the Shared Socioeconomic Pathways (IIASA 2015) as background scenarios for population and GDP.

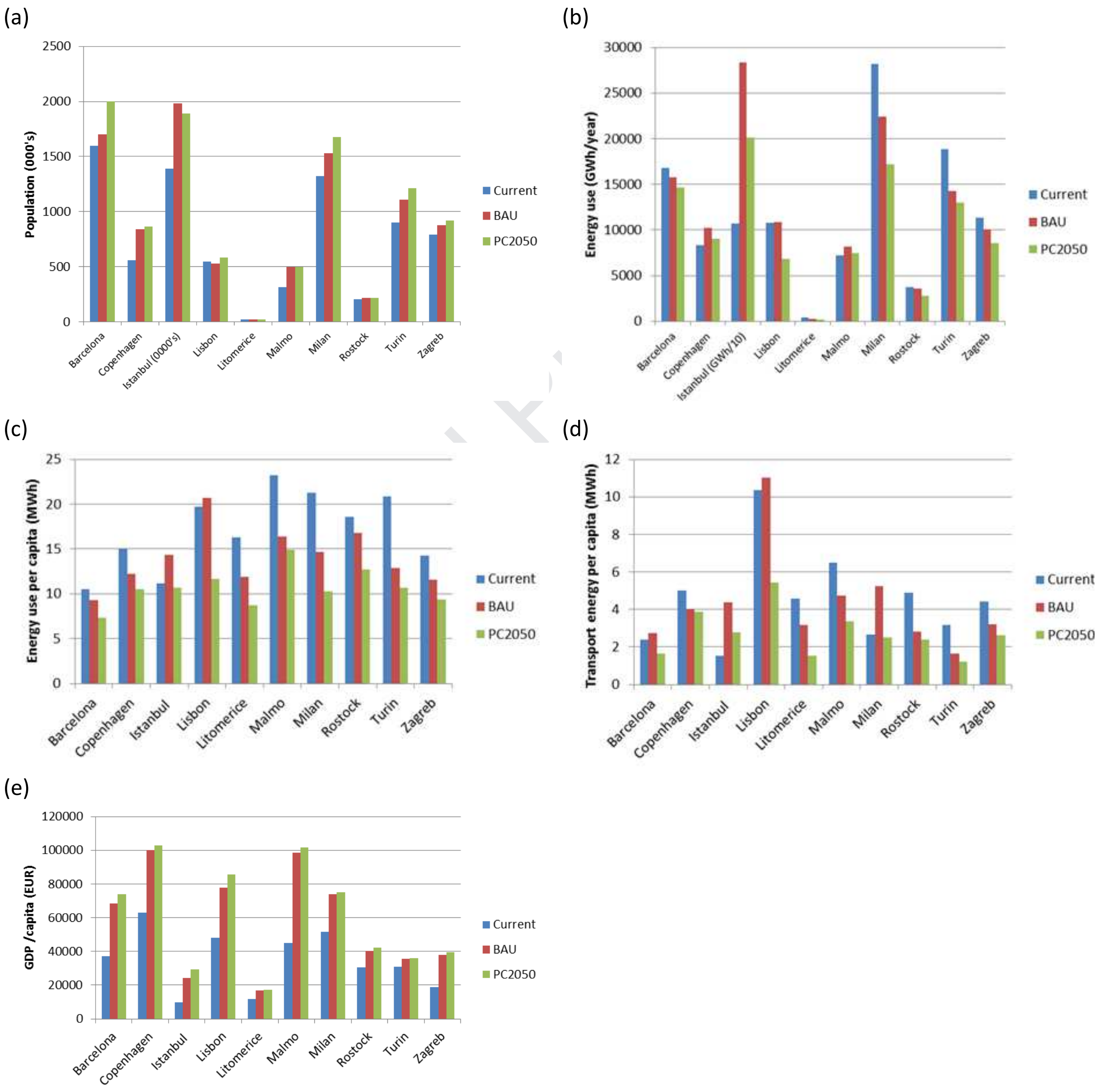


Figure 4: Scenario modelling results of the main elements for the ten case study cities for current, BAU 2050 and PC 2050. (a) Population. (b) Energy consumption. (c) Energy use per capita. (d) Transport energy per capita. (e) GDP per capita.

Under BAU total energy use (Figure 4.b) increases for four of the cities (Copenhagen, Lisbon, Istanbul and Malmö) and three cities under PC2050 (Copenhagen, Istanbul and Malmö), because of the population increases. However, energy use per capita (Figure 1.c) declines in all cities under the PC2050 scenario. There is also a decrease in energy use per capita under BAU for all cities except Barcelona, Istanbul and Lisbon.

3.2 Production-based accounting

3.2.1 GHG emissions per capita

Figure 5 shows that the production-based emissions per capita decrease considerably under BAU (except for Istanbul), but much more under PC2050. Barcelona, Copenhagen and Litoměřice have the lowest per capita emissions under PC2050, with 0.35, 0.18, and 0.36 tCO_2e per capita/year, respectively. These cities are also the leading performers under BAU, with Copenhagen showing the lowest GHG emissions at 0.7 tCO_2e per capita/year. Under PC2050, the other cities are between 1 to 2 tCO_2e per capita (except Istanbul and Turin).

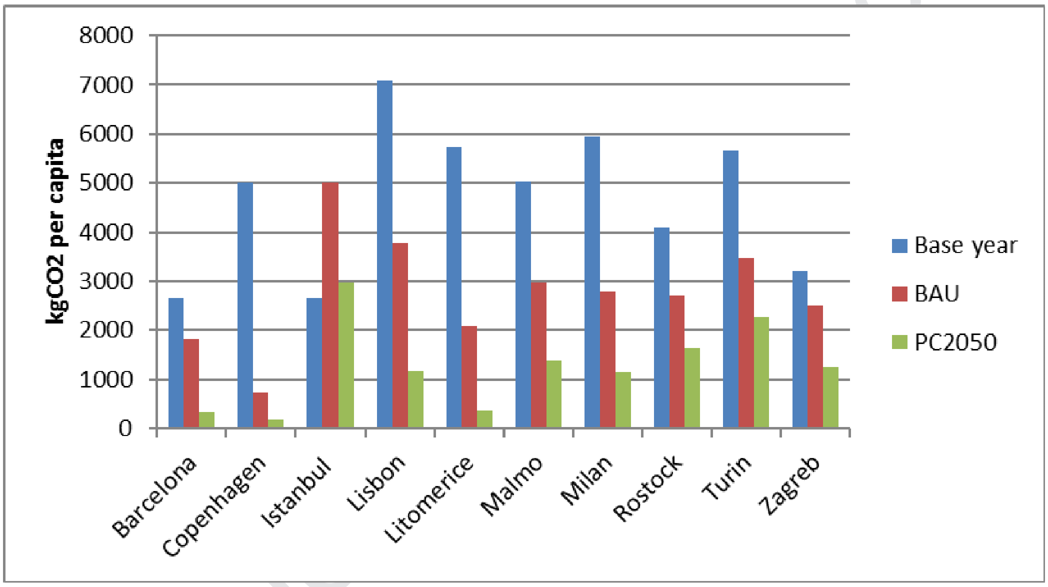


Figure 5: Production-based GHG emissions per capita for base year, BAU and PC2050 scenarios

3.2.2 Economic output per unit of GHG emissions

A key indicator to assess a transition to a green economy of a nation or city is economic output per environmental impact (UNEP, 2013). Figure 6 shows that the GHG emissions per unit of GDP (Euros) is expected to improve under BAU and vastly improve under PC2050, for all cities. If the indicator is inverted (to obtain GDP generated per GHG emission) the leading performer under PC2050 is clearly Copenhagen, which generates 581 Euro/ $kgCO_2e$ compared to 9.9 Euro/ $kgCO_2e$ for Istanbul (which is similar to the current level for Milan and Malmö).

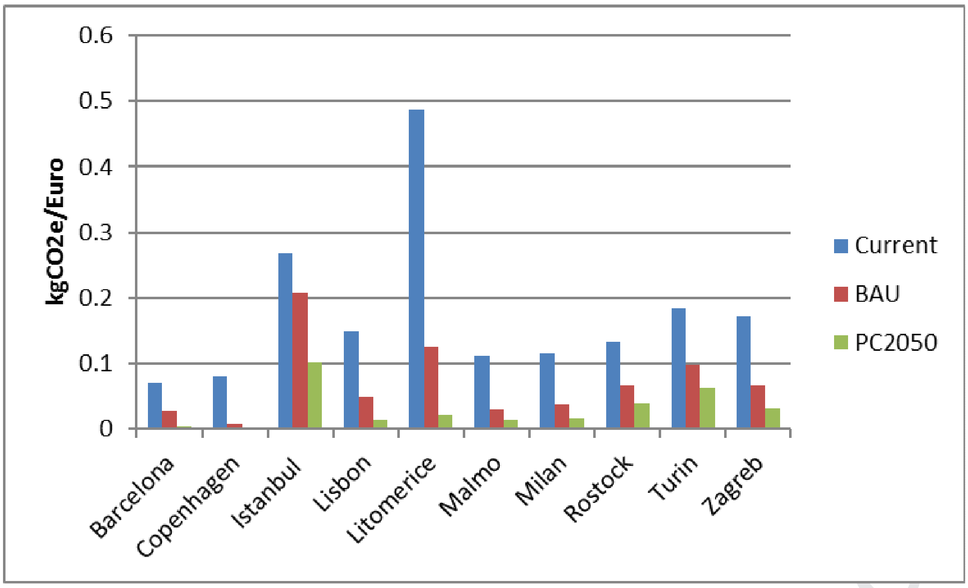


Figure 6: Production-based GHG emissions per unit of GDP (Euro)

3.3 Consumption-based accounting

3.3.1 Consumption-based emissions compared to production-based emissions

The consumption-based accounting results (Figure 7) show increases in GHG emissions per capita for eight of the cities under BAU and PC2050, which is linked to increasing affluence that results in increased consumptio. Milan and Turin are the only cities for which slight decreases are expected. The highest absolute emissions per capita in 2007 occur in Zagreb, due to high coal and gas usage as energy sources; the lowest in Istanbul, primarily due to lower affluence (and therefore household spending). In PC2050, Zagreb remains the highest, with Copenhagen next highest followed closely by Istanbul.

Figure 7 also provides a comparison of the production-based emissions with the consumption-based emissions. It highlights that whilst production-based emissions are generally decreasing from the base year to BAU, and further in PC2050, consumption-based emissions are increasing. In the base year, 48% of the total emissions are derived from production-based emissions, but this is reduced to 22% in BAU and only 9% under PC2050.

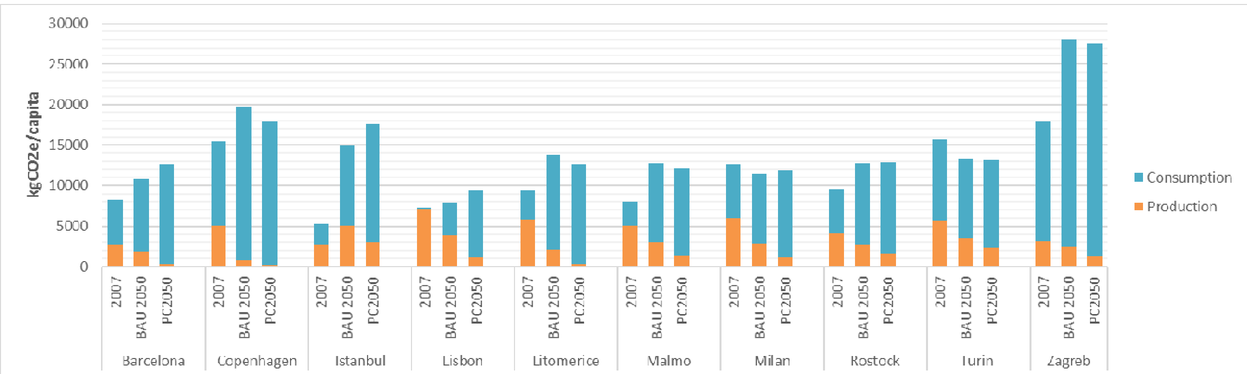


Figure 7: Comparison of production- and consumption-based GHG emissions per capita for 2007, BAU and PC2050

3.3.2 Contribution of product groups to GHG emissions

For the analysis, the products were grouped into six main groups based on the purpose of consumption: food, housing, electricity and heat fuels, transport fuels, equipment and services, other goods (goods not otherwise included), and other services (services not otherwise included). Four cities are selected for closer analysis based on their contrasting characteristics, with differences in population, affluence and energy profile. The contribution of the product groups to the overall GHG emissions for each of the scenarios is shown in Figure 8.

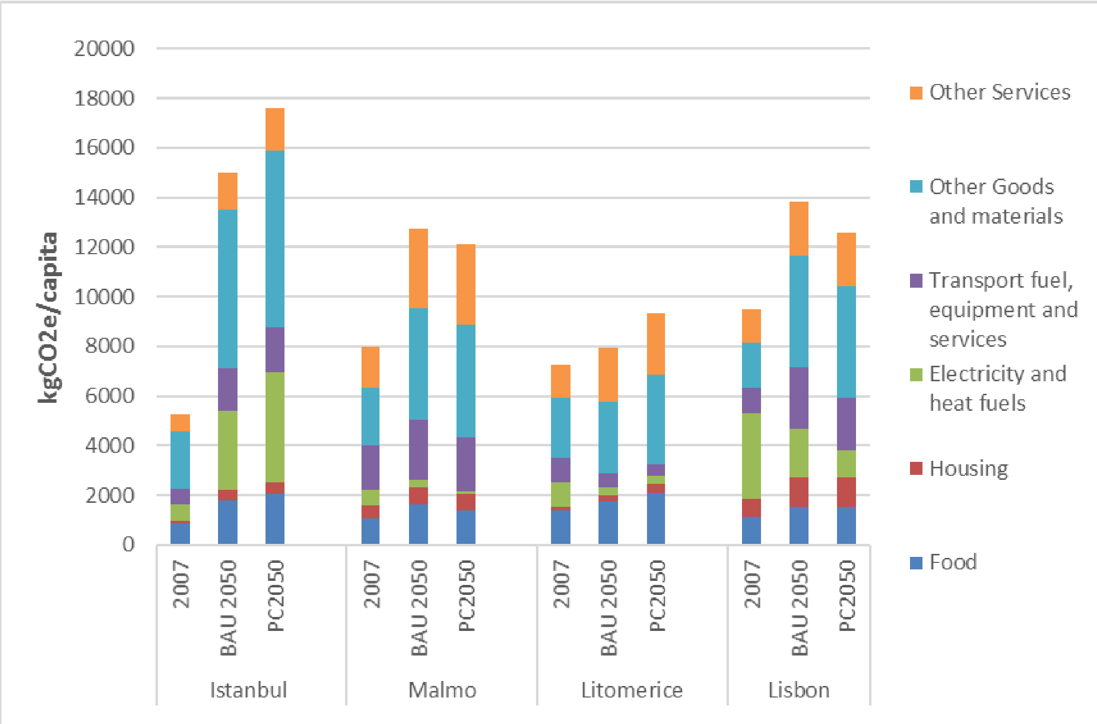


Figure 8: Contribution of product groups to GHG emissions for the scenarios of four cities

Despite Istanbul having the lowest emissions of any city in 2007, there are strong increases for electricity use, transport, and other goods and materials, again linked to rising affluence. Litoměřice and Lisbon both display significant reductions in electricity use from 2007 to BAU and further in PC2050, due to a shift to a renewable energy supply. The increase in Lisbon's transport emissions is because the population continues to move to the outer suburbs increasing the need for transport.

There are similar increases in "other services" and "other goods and materials" which represent an increasing share of total GHG emissions for all cities. It can also be seen that food emissions increase from 2007 for the future scenarios, although for Malmö and Lisbon is less for PC 2050 than BAU. This is due to actions in the PC2050 scenarios for sustainable local food production.

3.3.3 Economic analysis of consumption-based emissions

Finally, Figure 9 shows the consumption-based GHG emissions per Euro of GDP, which is considerably higher than for the production-based GHG emissions across the scenarios. The current average consumption-based GHG emissions per Euro of GDP is 0.42 kgCO2e/Euro, compared to 0.18 kgCO2e/Euro when considering production-based emissions. Under PC2050, the gap widens, and the difference is even more startling with an average of 0.03 and 0.34 kgCO2e/Euro for production-and consumption-based emissions, respectively.

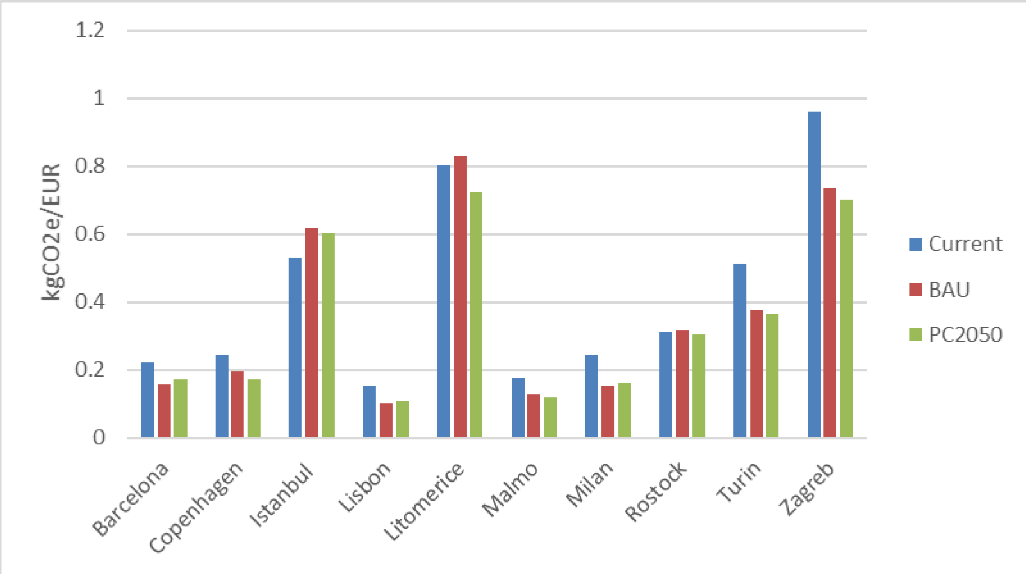


Figure 9: Consumption-based GHG emissions per unit of GDP (Euro)

4 Discussion

This research has sought to compare the use of two different GHG emission accounting methods: production-and consumption-based. To achieve this, our methodology was applied to ten European cities, for the base year, BAU and PC2050 scenarios. This section discusses the main findings within the overall structure of the research questions, looking first at the results of the base year of the cities, before discussing the stakeholder generated visions and strategies and finally the GHG emissions of the future scenarios.

4.1 Base year

1) On average consumption-based emissions are twice as big as production-based emissions

For the base year production-based emissions are on average 52% of the consumption-based emissions. This is comparable to Mi et al (2019) who found consumption-based emissions account for 50% or more of the total GHG emissions for Chinese cities (with a similar range of 4 to 25 tCO_2e).

Among the ten cities analysed, Lisbon is an exception with a larger share of production-based emissions. Hence Lisbon can be described as a “producer” city, whilst the others are “consumer” cities with a large proportion of consumption-based emissions (Sudamt et al., 2019; Mi et al., 2019). This supports other research that shows that Western cities are primarily consumer cities, whilst regions such as China have a higher share of producer cities (Sudamt et al., 2019).

The economic analysis shows that the cities with a larger service sector, Copenhagen, Barcelona, Milan and Malmö, generate less production-based emissions per Euro of GDP. Due to their high GDP they also perform well for their consumption-based emissions per Euro of GDP.

2) "Other goods and services" represent the largest share of consumption-based emissions

The analysis of the six product groups for consumption-based emissions shows that the contribution of food across the cities is similar, but the share of electricity and transport fluctuates. In general, food, housing and electricity account for half of the total emissions, whilst "other services" and "other goods and materials" account for the other half. Since the latter two categories are related to consumable goods and services, this emphasises the importance of consumption resulting linked to disposal income.

4.2 Stakeholders strategies and actions

3) The stakeholder visions and actions have potential to significantly reduce production-based emissions

Overall, the PC2050 scenarios showed significant reductions in production-based emissions, down to 0.7 tCO2e per capita/year for Copenhagen, and most cities less than 1.5 tCO2e per capita/year. This is primarily the result of actions on energy production (renewable based), transport and building efficiency. However, under PC2050 scenarios, consumption-based emissions increase for most cities. This is partly because only few actions were proposed by the stakeholders that focus on the wider system related to consumption-based emissions. When we consider the PC2050 scenarios generated from the visions and back-casting workshops within the POCACITO project, nearly all cities had a production-based focus – focusing on transport, energy sources and to a lesser extent housing and buildings.

The workshops consisted of a broad cross-section of stakeholders and it is not possible to connect the individual stakeholders to the strategic actions and targets. It is apparent however, that the focus is on traditional responses, related to production-based accounting, which is consistent with the approach of many cities globally (Erickson and Tempest, 2014). Two limitations should also be noted. It was challenging to maintain a consistent profile of stakeholders throughout the workshop series and the stakeholders did not review the report on strategic visions after the workshop series.

4.3 BAU and PC2050 scenarios

Total energy demand increased for four cities, Copenhagen, Lisbon, Istanbul and Malmö, under BAU, reflecting the recent trends and the modelling technique of linear extrapolation. The energy increases occur for different reasons but are linked strongly with affluence and population growth. In Istanbul, increasing affluence and population leads to a significant increase in energy demand. However, Lisbon's BAU energy use remains similar to the base year, with a high transport energy share due to the population moving to the suburbs and an increasing use of car transport.

In the PC2050 scenarios, energy use is around 10 MWh per capita/year for the majority of cities, with Barcelona being the lowest at 6.8 MWh per capita/year. This suggests that energy efficiency improvements are required for most cities, even though the associated production-based GHG emissions are reduced.

4) In 2050 production-based emissions decrease (apart from Istanbul) whilst consumption-based emissions increase (for 8 out of 10 cities). The gap between PBA and CBA widens.

Compared to the base year, the average production-based emissions are 31% lower for BAU and 68% lower for PC2050. The leading performers, Barcelona, Copenhagen and Litoměřice, all have strong actions for the reduction of fossil fuels, with a focus on geothermal for Litoměřice, solar for Barcelona and wind and biofuels for Copenhagen. Istanbul is the only city with a rise under BAU, which illustrates the risk for rapidly growing cities, with rising incomes, to develop in ways that could embed high GHG emissions (Sudmant et al., 2018). This phenomenon is known as “weak leakage” where emissions concentrate in specific places due to lower costs (Peters et al., 2011). However, Istanbul’s PC2050 production-based emissions are 41% lower than BAU due to the stakeholder actions proposed under PC2050.

Consumption-based emissions increase markedly for most cities under BAU and PC2050, with an average increase of 33% and 35%, respectively. The only exceptions are Milan and Turin, both displaying a slight decrease, due to more modest increases in GDP per capita. At the same time, the share of average production-based emissions reduces from 48% for the base year of to only 9% in PC2050. This highlights the growing importance of consumption-based emissions.

The high increase in consumption-based emissions for Istanbul under both scenarios reflects findings shown in other research regarding increasing affluence in cities from less developed regions. Sudmant et al., (2017) noted that projections for Chinese urban areas suggest massive potential for growth of consumption-based emissions. This would be in addition to the current production-based emissions if production volume and associated emissions remains the same. Considering the number of rapidly growing cities worldwide, particularly in Asia, consumption is a major challenge for national and global emission targets. Research has consistently shown a strong link between income and consumption-based emissions (Hertwich and Peters, 2009; Moran et al., 2018). In contrast however, Scott and Barrett (2015) forecast falling consumption-based emissions in the UK.

5) Economic analysis based on PBA suggests future decoupling, but CBA is less convincing.

There is a marked reduction in production-based emissions per Euro of GDP for the future scenarios compared to the current year (Figure 6), with an average of 0.18 kgCO_2e/Euro in the base year reducing to and 0.03 kgCO_2e/Euro in PC2050. This suggests a decoupling of emissions from economic growth. However, during the same period the average consumption-based emissions per Euro of GDP only reduced from 0.41 to 0.34, despite considerable GDP increases (Figure 7 and Figure 9). This suggests a relative decoupling although is the result of a strong rise in GDP, as consumption-based emissions increase considerably

6) The product groups “other services” and “other goods and materials” increase their share of total emissions

The consumption-based emissions for the product groups “other services” and “other goods and materials” rise under both scenarios and represent an increasing share of total emissions (Figure 8). These categories essentially capture consumable goods and services, supporting the notion that consumption-based emissions rise due to increased affluence and spending.

Litoměřice highlights that despite significant reductions in the more locally controllable emissions (electricity and heating fuels, and transport), total emissions rise in both 2050 scenarios due to increased overall spending in food, “other goods and materials” and “other services”. Lisbon reduces electricity and heating impacts but fails to reduce transport and housing due to the population moving from the city centre to the greater metropolitan region.

4.4 Strategies for the reduction of consumption-based emissions

The product groups of housing, electricity and transport can be considered as being under local control, but under the 2050 scenarios still have a high combined contribution to consumption-based emissions. If we also include food, (since food products can possibly be produced locally or close to a city) then 40-50% of GHG emissions could potentially be reduced by means of local improvements. Indeed, food production could involve more locally produced food, grown in a more circular fashion, whereby nutrients from the city (e.g. composted food waste residue) are reused to grow more food. As to housing, transport and buildings, action could involve reuse of materials (e.g. in roads) and use of more sustainable fuels such as through electrification in transport. Electricity's impact can be reduced by fostering generation based on local renewable energy sources, as well as local storage for peak periods.

Cities are growing in power and are in a unique position to mobilise and influence local actors (Sudmant et al., 2018). There are two overall approaches, capturing the full value of imported components and materials through the circular economy, and fostering action in the supply chain (Pettersson and Harris 2016; Sudmant et al., 2018). The former can be stimulated by cities through the implementation of simple responses such as repair cafes, and exchange locations for used goods (Mont et al., 2018), through to supporting innovative circular economy companies that refurbish, remanufacture or recycle (EMF, 2014; Pettersson and Harris 2016). The sharing economy, such as car sharing (Martin and Shaheen, 2016), office sharing and tool sharing also has the potential to contribute to reduced consumption.

Reducing food waste has been suggested as being much less expensive but as effective in reducing overall emissions (considered from a consumption perspective) as retrofitting buildings or upgrading transport systems (Millward-Hopkins et al., 2017). In Sweden and other parts of Europe, some of the value of food waste is captured through biogas production and use in transport (with the nutrient packed residue used as fertiliser). Product and resource efficiency standards (Kagawa et al. 2013) impact on embedded emissions, and similarly efficiency standards can be applied to buildings and infrastructure. Finally, cities can reduce the need for consumption impact through the urban planning process, in terms of the city's form, function and distances (Mi et al., 2019).

5 Conclusion

This paper aimed to compare the difference in GHG emissions for ten European case study cities under two 2050 scenarios, BAU and PC2050. Specifically, we aimed at understanding how much of a difference a near-zero carbon vision and the related set of actions would make on both production-based and consumption-based emissions.

The analysis suggests that the primary goal for the city visions and scenarios, which is the creation of low- or zero-carbon societies, would not be achieved under BAU or PC2050 for most of the case study cities, even considering only production-based emissions. Under BAU, only Copenhagen would emit under 1 tCO_2e per capita, with the highest emissions reaching 5 tCO_2e per capita in Istanbul. Most cities would remain in the range of 2-4 tCO_2e per capita, which indicates significant room for improvement for the energy efficiency measures of the PC2050 scenarios for most cities. This could be achieved by embedding an energy efficiency approach in policy making that fosters concerted action on transport, buildings, appliances and on the planning of infrastructure. Lowering the energy demand would subsequently reduce the requirements for installed capacity of renewable energy and its storage.

The consumption-based emissions are a cause for concern, with projected emissions increasing under both BAU and PC2050 for eight of the ten cities. From a baseline average of 11 tCO_2e per capita, the consumption-based emissions increase to an average of 14.6 tCO_2e per capita and 14.8 tCO_2e per capita for BAU and PC2050 respectively. This is primarily linked to rising GDP and a corresponding increase in spending and consumption that was modelled in the MIRO analysis. Our modelling results suggest that the expected technological and associated efficiency increases of the global production systems (accounted for in the model) would not compensate for the emissions associated with increased consumption expenditure.

Hence the results highlight a notable disparity between the traditional focus on production-based emission (and local impacts) and those consumption-based emissions. Analysis that considers only our production-based results would conclude that an almost absolute decoupling has occurred, with major decrease in GHG emissions and a rising GDP. However, the consumption-based analysis shows significant increases in GHG emissions. This suggests that the focus of future actions should also be placed on addressing consumption within the city and the related production systems, in addition to local energy production and emissions.

The application of the EE-MRIO framework and database to model future scenarios is challenging and involves some uncertainties. One improvement therefore could be to strengthen the modelling of the background global production model of the database and develop a method for uncertainty analysis. The adjustments of each production matrix and environmental intensities needed to be performed manually and separately, and therefore a sensitivity analysis could not be performed within the scope of the project.

In conclusion, the study suggests that most emissions are outside of the European cities that were studied. This finding however, does not necessarily imply that the city cannot control these emissions, because research is beginning to address these issues, e.g. with circular economy and sharing solutions. However, it does suggest that a sole focus on zero production-based emissions in European cities will not make a significant impact on future GHG emissions. Further research to identify and support consumption-based actions is urgently required considering that ongoing choices in city planning and development may be embedded for decades.

Acknowledgements

The research leading to this paper received funding from the European Union Seventh Framework Programme for research (FP7 SSH.2013.7.1-1: Post-carbon cities in Europe: A long-term outlook under the grant agreement n°613286). We would like to thank two anonymous reviewers for their comments and suggestions that led to a significant improvement to this paper.

6 References

Agenzia per l' Italia digitale, 2015. Presidenza del Consiglio dei Ministri, Website: www.soldipubblici.gov.it.

Breil, M., Bigano, A., Cattaneo, C., Ridgway, M., Tuerk, A., Lettmayer, J.R., Fujiwara, N., Dupas, S., 2014. Definition of Storylines for the Framing of Urban Scenarios. Definition of Storylines for the Framing of Urban Scenarios. Report D4.1 for the POCACITO FP7 project. Website (visited 14/01/2016): http://pocacito.eu/sites/default/files/D4_1_Storylines_for_urban_scenarios.pdf

Breil, M., Cattaneo, K., Johnson, K., 2015a. Qualitative Scenario Building for Post-carbon Cities. https://pocacito.eu/sites/default/files/D4_4_Qualitative_Scenario_Building_for_Post_Carbon_Cities.pdf, pp. 1-49.

Breil, M., Johnson, K., Jensen, A., Baycan, T., Aygun, A., Lombardi, P., Staricco, L., Knoblauch, D., Albrecht, S., Kordić, Z., Pašičko, R., Vlašić, S., Ljungkvist, H., Eriksson, E., Harris, S., Núñez Ferrer, J., Infelise, F., Selada, C., Mendes, G., Almeida, A., Škopková, H., Havránek, M., 2015b. Report on Stakeholder Workshop. Post Carbon Visions and Qualitative Scenarios for the Case Study Cities. https://pocacito.eu/sites/default/files/D4_2_Report_on_Stakeholder_Workshops_rev-final_0.pdf, pp. 1-192.

BSI, 2013. PAS 2070 Specification for the assessment of greenhouse gas emissions of a city. Direct plus supply chain and consumption-based methodologies. Published by BSI Standards Limited 2013.

C40 Cities, 2018a. Website visited 06/07/2018: https://www.c40.org/about

C40 Cities, 2018b. Consumption based GHG emissions of C40 cities. March 2018. Available (06/07/2018): https://www.c40.org/researches/consumption-based-emissions

Capros, P., et al. 2014. EU Energy, Transport and GHG Emissions. Trends to 2050. Reference scenario 2013. Report for the Directorate-General for Energy, the Directorate-General for Climate Action and the Directorate-General for Mobility and Transport, European Commission.

Chen, G., Hadjikakou, M., Wiedmann, T., 2017. Urban carbon transformations: unravelling spatial and inter-sectoral linkages for key city industries based on multi-region input–output analysis. Journal of Cleaner Production 163, 224-240.

Chen, G., Wiedmann, T., Hadjikakou, M., Rowley, H., 2016. City Carbon Footprint Networks. Energies 9(8).

Covenant of Mayors, 2016. Covenant of Mayors for Climate & Energy. Website (visited 27/11/2016): http://www.covenantofmayors.eu/index_en.html

Dahal, K., Niemelä, J., 2017. Cities' Greenhouse Gas Accounting Methods: A Study of Helsinki, Stockholm, and Copenhagen. Climate 5(2), 31.

EEA. European Union CO2 Emissions: Different Accounting Perspectives; European Environment Agency: Publications Office of the European Union, Luxembourg, 2013.

EMF, 2014. Towards the circular economy. Accelerating the scale-up across global supply chains, Ellen MacArthur Foundation: 80.

Erikson, P., Tempest, K., 2014. Advancing climate ambition: How city-scale actions can contribute to global climate goals. Stockholm Environment Institute. Working Paper No. 2014-06

Eurostat, 2008. Eurostat Manual of Supply, Use and Input-Output Tables (European Communities, Luxembourg).

Feng, Y.Y., Chen, S.Q., Zhang, L.X., 2013. System dynamics modeling for urban energy consumption and CO2 emissions: A case study of Beijing, China. Ecological Modelling 252, 44-52.

Feng, K., Hubacek, K., Sun, L., Liu, Z., 2014. Consumption-based CO2 accounting of China's megacities: the case of Beijing, Tianjin, Shanghai and Chongqing. Ecol. Indic. 47, 26–31.

Galli, A., Wiedmann, T., Ercin, E., Knoblauch, D., Ewing, B., Giljum, S., 2012. Integrating Ecological, Carbon and Water footprint into a "Footprint Family" of indicators: Definition and role in tracking human pressure on the planet. Ecological Indicators, Volume 16, 2012, Pp.100-112.

Gouldson, A., Colenbrander, S., Sudmant, A., Godfrey, N., Millward-Hopkins, J., Fang, W., Zhao, X., 2015a. Accelerating Low-Carbon Development in the World's Cities. A New Climate Economy contributing paper for Seizing the Global Opportunity: Partnerships for Better Growth and a Better Climate. London and Washington, DC. http://2015.newclimateeconomy.report/misc/working-papers/.

Gouldson, A., Colenbrander, S., Sudmant, A., McAnulla, F., Kerr, N., Sakai, P., Hall, S., Papargyropoulou, E., Kuylenstierna, J., 2015b. Exploring the economic case for climate action in cities. Global Environmental Change, 35, pp. 93-105.

GPC, 2014. Global Protocol for Community-Scale Greenhouse Gas Emission Inventories. An Accounting and Reporting Standard for Cities.

Harris, S., Bigano, A., Briel, M., Jensen, A., Knoblauch, D., Schlock, M., Albrecht, S., Škopková, H., Havránek, M., Ljungkvist, H., Nunez, J., Staricco, L., Baycan, T., Aygun, A., Kordić, Z., Pašičko, R., Vlašić, S., 2015. Systemic Characteristics of the Case Study Cities. Applying the Sensitivity Model. Deliverable D5.1 for the POCACITO project. Available at: www. pocacito.eu

Harris, S., Breil, M., Bigano, A., Knoblauch, D., Schock, M., Škopková, H., Nunez Ferrer, J., Selada, C., Silva, C., Staricco, L., Jensen, A., Kordić, Z., Baycan, T., 2016a. Quantification of the case study cities. POCACITO project report D5.2, available at: www.pocacito.eu.

Harris, S., Weinzettel, J., Levin, G., Zanderson, M., Petterson, A., Bigano, A., Breil, M, 2016b. Sustainability Impacts of Post-Carbon Cities. POCACITO project report D5.3, available at: www.pocacito.eu.

Heinonen, J., Horvath, A., Junnila, S., 2015. Environmental assessments in the built environment: crucial yet underdeveloped. Environmental Research Letters, Vol. 10, No. 3.

Hertwich, E.G., Peters, G.P., 2009. Carbon Footprint of Nations: A Global, Trade-Linked Analysis. Environmental Science & Technology 43(16), 6414-6420.

Hertwich, E.G., Gibon, T., Bouman, E.A., Arvesen, A., Suh, S., Heath, G.A., Bergesen, J.D., Ramirez, A., Vega, M.I., Shi, L., 2015. Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies. Proceedings of the National Academy of Sciences 112(20), 6277.

IEA, 2015. IEA World Energy Outlook 2015. Visited 19/09/2018. https://www.iea.org/publications/freepublications/publication/WEO2015.pdf

IIASA, 2014. "Climate Change & Socioeconomic Development." Climate Change & Socioeconomic Development. http://www.iiasa.ac.at/web/home/resources/publications/IIASAMagazineOptions/ClimateChange.en.html.

IIASA, 2014. Supplementary Note for the SSP Data Sets. IIASA. https://secure.iiasa.ac.at/web-apps/ene/SspDb/static/download/ssp_suplementary%20text.pdf.

IIASA, 2015. SSP Scenario Database. Website (visited: August 2016): http://www.iiasa.ac.at/web/home/research/researchPrograms/Energy/SSP_Scenario_Database.html

ISTAT, 2015. Indagine sulle spese delle famiglie. Italian Household Consumption Expenditure survey. Website: https://www.istat.it/it/archivio/71980

Ivanova, D., Stadler, K., Steen-Olsen, K., Wood, R., Vita, G., Tukker, A., Hertwich, E.G., 2016. Environmental Impact Assessment of Household Consumption. Journal of Industrial Ecology 20(3), 526-536.

Jiborn, M., Kander, A., Kulionis, V., Nielsen, H., Moran, D.D., 2018. Decoupling or delusion? Measuring emissions displacement in foreign trade. Global Environmental Change 49, 27-34.

Jones, C., Kammen, D., 2013. Spatial distribution of US Household carbon footprints reveals suburbanization undermines greenhouse gas benefits of urban population density Environ. Sci. Technol. 48, 895–902.

Kagawa, S., Hubacek, K., Nansai, K., Kataoka, M., Managi, S., Suh, S., Kudoh, Y., 2013. Better cars or older cars? Assessing CO2 emission reduction potential of passenger vehicle replacement programs. Global Environ. Change 23, 1807e1818.

Kanemoto, K., Moran, D., Lenzen, M., Geschke, A., 2014. International trade undermines national emission reduction targets: New evidence from air pollution. Global Environmental Change 24, 52-59.

Kaya, Y., Keiichi, Y., 1997. Environment, energy, and economy: strategies for sustainability. Tokyo [u.a.]: United Nations Univ. Press. ISBN 9280809113.

Kennedy, C., Steinberger, J., Gasson, B., Hansen, Y., Hillman, T., Havranek, M., Pataki, D., Phdungsilp, A., Ramaswami, A., Mendez, G.V., 2009. "Greenhouse Gas Emissions from Global Cities." Environmental Science & Technology 43(19): 7297-7302.

Kennedy, C., Steinberger, J., Gasson, B., Hansen, Y., Hillman, T., Havranek, M., Pataki, D., Phdungsilp, A., Ramaswami, A., Mendez, G.V., 2010. "Methodology for inventorying greenhouse gas emissions from global cities." Energy Policy 38(9): 4828-4837.

Leontief, W., 1970. Environmental Repercussions and Economic Structure - Input - Output Approach. Review of Economics and Statistics 52, 262-271.

Liu, L., Huang, G., Baetz, B., Zhang, K., 2018. Environmentally-extended input-output simulation for analyzing production-based and consumption-based industrial greenhouse gas mitigation policies. Applied Energy 232, 69-78.

Martin, E., Shaheen, S., 2016. Impacts of Car2go on vehicle ownership, modal, shift, vehicle miles travelled, and greenhouse gas emissions: An analysis of five North American cities.: 26.

Meng, J., Mi, Z., Yang, H., Shan, Y., Guan, D., Liu, J., 2017. The consumption-based black carbon emissions of China's megacities. J. Clean. Prod., 161 (2017), pp. 1275-1282

Mi, Z., Zheng, J., Meng, J., Zheng, H., Li, X., Coffman, D.M., Woltjer, J., Wang, S., Guan, D., 2019. Carbon emissions of cities from a consumption-based perspective. Applied Energy 235, 509-518.

Millward-Hopkins, J., Gouldson, A., Scott, K., Barrett, J., Sudmant, A., 2017. Uncovering blind spots in urban carbon management: the role of consumption-based carbon accounting in Bristol, UK. Regional Environmental Change 17(5), 1467-1478.

Minx, J., Baiocchi, G., Wiedmann, T., Barrett, J., Creutzig, F., Feng, K., Förster, M., Pichler, P.-P., Weisz, H., Hubacek, K., 2013. Carbon footprints of cities and other human settlements in the UK. Environmental Research Letters 8(3), 035039.

Mont, O., Plepys, A., Whalen, K., Nussholz, J., 2018. Business model innovation for a Circular Economy. A report from the International Institute for Industrial Environmental Economics, Lund University. https://mistrarees.se/custom/uploads/2018/05/MISTRA-REES-Drivers-and-Barriers-Lund-2.pdf

Moran, D., Kanemoto, K., Jiborn, M., Wood, R., Többen, J., Seto, K.C., 2018. Carbon footprints of 13 000 cities. Environmental Research Letters 13(6), 064041.

Oxford Economics, 2015. Household consumption data from 1992 to 2030 for ten European cities. Confidential data obtained on a commercial basis.

Peters, G.P., Minx, J.C., Weber, C.L., Edenhofer, O., 2011. Growth in emission transfers via international trade from 1990 to 2008. Proceedings of the National Academy of Sciences 108(21), 8903.

Petterson, A., Harris, S., 2016. Circular Cities. Opportunities to Support A Circular Economy in Cities. POCACITO Policy Brief No.4, December 2016. Website (visited: 15/05/2019): https://pocacito.eu/sites/default/files/POCACITO PolicyBrief_No-4_Circular_Economy_in_Cities1612.pdf

POCACITO, 2014. POCACITO in a nutshell. Website (visited: 15/05/2019): https://pocacito.eu/about

Robinson, J.B., 1990. "Futures under Glass: A Recipe for People Who Hate to Predict." Futures 22 (8): 820–42.

Schoemaker, P.J.H., 2004. Forecasting and scenario planning: the challenges of uncertainty and complexity. In: D.J. Koehler, N. Harvey (Eds.), Blackwell Handbook of Judgment and Decision Making, Blackwell Publishing Ltd., Malden, MA, USA (2004), pp. 274–296.

Scott, K., Owen, A., Barrett, J., 2013. Estimating emissions associated with future UK consumption patterns. Report submitted to the Committee on Climate Change, June 2013.

Scott, K., Barrett, J., 2015. An integration of net imported emissions into climate change targets. Environmental Science & Policy 52, 150-157.

Sudmant, A., Gouldson, A., Millward-Hopkins, J., Scott, K., Barrett, J., 2018. Producer cities and consumer cities: Using production- and consumption-based carbon accounts to guide climate action in China, the UK, and the US. Journal of Cleaner Production 176, 654-662.

Swart, R.J., Raskin, P., Robinson, J., 2004. The problem of the future: sustainability science and scenario analysis. Global Environmental Change, Vol. 14 (2004) 137–146.

UNEP, 2013. City-level decoupling. Urban resource flows and the governance of infrastructure transitions. A Report of the Working Group on Cities of the International Resource Panel. Swilling M., Robinson B., Marvin S. and Hodson M.

UN Habitat, 2011. Hot Cities: battle-ground for climate change. http://mirror.unhabitat.org/downloads/docs/E_Hot_Cities.pdf

UN Habitat, 2016. Climate Change. https://unhabitat.org/urban-themes/climate-change/

Wiebe, K.S., Harsdorff, M., Montt, G., Simas, M.S., Wood, R., 2019. Global Circular Economy Scenario in a Multiregional Input–Output Framework. Environmental Science & Technology.

Wood, R., Stadler, K., Bulavskaya, T., Lutter, S., Giljum, S., De Koning, A., Kuenen, J., Schütz, H., Acosta-Fernández, J., Usubiaga, A., Simas, M., Ivanova, O., Weinzettel, J., Schmidt, H.J., Merciai, S., Tukker, A., 2015. Global Sustainability Accounting—Developing EXIOBASE for Multi-Regional Footprint Analysis. Sustainability 7(1).