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Consequence CO_2 footprint analysis of circular economy scenarios in cities

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ABSTRACT

Cities concentrate a large amount of people and activities thus being responsible for large amounts of resources being consumed which generate significant impact footprints contributing to climate change both directly and indirectly. In the meantime, circular economy is seen a promising concept to improve resource efficiency. Circular economy strategies are an emerging and important paradigm that can have an important effect in reducing CO_2 emissions.

This study aims at evaluating how circular economy strategies can reduce CO_2 emissions in cities with different contexts to find similarities and differences between them. The studied cities are Beijing, Shanghai, Vienna, and Malmö.

A scenario analysis study is done for two scenarios: 1) Business-As-Usual scenario (BAU) and 2) Circular Economy scenario (CE) from year 2017–2050, using multi-regional input-output (MRIO) analysis. The most CO_2-intensive Exiobase sectors associated with downstream consumption in households and government were identified as CO_2 emission hotspots, and emission reduction targets were identified and applied to these sectors.

The main results from the study show that although Vienna and Malmö have applied sustainability strategies for quite some time, the results do not show that CE strategies work better in the European cities compared with Chinese cities. The results also suggest that the greatest potential and effectiveness in reducing consumption lies in the sectors of energy use and materials consumption for all cities. It can also be seen that CE scenarios have higher potential for CO_2 emissions reduction when compared to the BAU scenarios but the reduction level in Shanghai and Malmö is weaker compared to Vienna and Beijing, which indicates the effectiveness of current CE strategies in reducing Beijing and Vienna's emissions. It also suggests that for Shanghai and Malmö, more ambitious CE strategies should be considered. Finally, comparing the distribution of emissions among the four cities it can be seen that consumption of Beijing, Shanghai and Vienna relies highly on domestic production whilst Malmö is more dependent on international production.

1. Introduction

Resource consumption impacts ecosystems and causes sustainability issues in many forms, including increased greenhouse gas (GHG) emissions. From 1970 to 2017, with an average annual raw material demand growth from 7 tons to over 12 tons per capita, annual global materials extraction grew from 27 billion tons to 92 billion tons, and this accelerated global resource use creates increasingly negative impacts on the environment and human health (Oberle et al., 2019).

To improve human well-being and mitigate stress on the environment, it is important to reduce natural resource consumption and to use them more efficiently. Cities typically hold most of the country's population and gross domestic product (GDP) and are the center of industries and commerce (Swilling et al., 2013). This leads to cities also having the largest consumption footprints for most resources which are associated with direct and indirect GHGs, greatly impacting the social

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and natural environment, and as such are commonly targeted in sustainability policies (Kalmykova et al., 2016; United Nations Environment Programme, 2013; World Bank, 2010). Therefore, it is essential to investigate how to use resources efficiently and how to reduce emissions at city scale (Kalmykova et al., 2016).

To improve resource efficiency and reduce emissions, circular economy (CE) strategies are an emerging and important paradigm (Martins and Castro, 2020). The CE concept is based on three principles: 1) eliminating waste and pollution, 2) circulating products and materials at their highest value, and 3) regenerating nature (Ellen Macarthur Foundation, n.d.,). CE strategies can reduce raw material use and hence minimize waste generation (Andersen, 2007; Su et al., 2013). Although, it is not yet clear what is the impact of the implementation of Circular Economy for CO_2 emissions reduction, several studies point out for an effective reduction with the potential for reducing to two thirds (Cantzler et al., 2020). Applying CE strategies in cities could theoretically have a large impact on reducing CO_2 emissions.

Since there are several ways to apply CE strategies to make an impact on resource use, different scenarios can be created and simulated to: 1) reflect the characteristics of cities, 2) analyze potential future developments and 3) compare the outcomes of different assumptions (Odegard and Van der Voet, 2014; Panel et al., 2011; Rothman, 2008; Schanes et al., 2019).

A number of methods exist for assessing the impacts of resource consumption, including the IPAT model (i.e. Impact as a factor of Population, Affluence, and Technology) (Ehrlich and Holdren, 1971) and economic input-output (IO) analysis (Leontief, 1970). A model based on IO analysis provides an approach to simulate the impacts of specific policies or strategies from a macroeconomic perspective (Liu et al., 2018). This feature makes it a good way to assess the impacts of CE strategies on resource consumption and environmental pressures. This has been confirmed at city level as well: Ramaswami et al. (2011) and Baynes and Wiedmann (2012) compared several approaches to account the GHG emissions and assess urban environmental sustainability, and consumption-based approach based on economic IO analysis which can provide the most rigorous estimate and is useful in analyzing changes in consumption policies.

Several studies have used both scenario analysis and IO tables to investigate the impacts of circular economy strategies at country level. For example, waste management, resource efficiency, and product lifetime extension were modelled by Donati et al. (2020) on Exiobase at the global level. Wiebe et al. (2019) developed circular economy scenarios projected to 2030 using multi-regional input-output (MRIO) tables based on Exiobase to compare the environmental impacts to a business-as-usual scenario at a global level. They found that the adoption of circular economy measures decreased global material extraction including fossil fuels. Another example of a country-level study is by Palm et al. (2019) who quantified the environmental impacts of final consumption in Sweden at the national level by integrating national input-output, trade and environmental statistics into the MRIO data of Sweden on Exiobase. The results indicated the importance of addressing consumption-based impacts.

At city-level, material footprints have been analyzed by MRIO in some studies but they were not linked to carbon emissions (Jiang et al., 2019; Jin et al., 2021). There is also some literature that calculated consumption-based carbon emissions or carbon footprint for multiple cities, but mostly focused on the emissions analysis of a specific year and did not include scenario modelling (Chen et al., 2017; Fry et al., 2018; Minx et al., 2013; Moran et al., 2018; Wiedmann et al., 2021). Koide et al. (2021) used an input-output approach to set up scenarios to model the consumption-based carbon footprint reduction pathways at Japanese cities, provide scientific support for policy development and stakeholder actions.

When it comes to modeling the emission reduction potentials of CE strategies at city level, the POCACITO project by Harris et al. (2020) developed a future business-as-usual scenario and a low carbon scenario for European cities and quantified the GHG emission footprint using Exiobase MRIO models. Christis et al. (2019) quantified the consumption-based carbon footprint of households in Brussels based on MRIO data from Exiobase combined with regional IO data. In their study, the carbon footprint reduction potentials of different circular economy strategies were quantified and discussed as well. Paiho et al. (2021) quantified the energy and carbon emissions impacts of a former industrial area in Espoo, Finland, by analyzing a set of transportation, energy, and food circular targets through scenario analysis. Del Borghi et al. (2022) compared four cities in Bogota, Colombia; Genoa and Milan, Italy; and Glasgow, UK, from a consumption perspective for energy, mobility, and built environment sectors with respect to the carbon emission impacts of circular interventions.

Although MRIO analysis has been used to model future emissions at national scale and evaluate the global impacts of a future circular economy, city-level studies with scenario modelling remain limited (Christis et al., 2019; Del Borghi et al., 2022; Harris et al., 2020; Paiho et al., 2021). Furthermore, there seems to be few studies comparing these results from city-level studies between different countries or across continents (Del Borghi et al., 2022).

Building on the relevant studies mentioned above, the aim of this study is to quantify and compare resource consumption and climate impacts from applying CE strategies scenarios in different types of cities in different contexts, and to find similarities and differences between them. To have a global comparison, two continents were included, and four different cities were identified as case studies: Beijing and Shanghai in China, Vienna in Austria and Malmö in Sweden. These choices were based on differences in sustainability awareness and strategies. Vienna and Malmö have applied sustainability strategies for quite some time. For example, Vienna adopted its first "Climate Protection Program" (KliP I) in 1999. Meanwhile, Beijing and Shanghai are facing significant environmental issues due to rapid urban growth and have begun recently to apply sustainability strategies to address them. Furthermore, the cities vary in size and climate impacts, as discussed later in this article.

2. Methodology

2.1. Background and overview

The sections below describe the methodology used in this study (Fig. 1). The whole process can be divided into two parts, one for scenario generation to understand the benefits of CE implementation which is used for consequence CO_2 footprint analysis (based on the results from scenario generation).

For scenario generation, the first step was to choose the resource types to be analyzed leading to the identification of resource use drivers and variables. Time series of resources use data (in resource units, e.g., L of water) for the four cities were collected and used to extrapolate the consumption for base trends in 2050. Two scenarios were generated from the base trends results combining quantitative targets defined with the support of the IPAT model (Ehrlich and Holdren, 1971). Resource consumption in physical units was transformed in monetary units to compute the Input-Output (IO) Tables for the four cities.

The IO table computed in the scenario generation phase is used to generate Multi-Regional Input Output (MRIO) Tables for the four cities to evaluate CO_2 emission reductions. The Exiobase dataset was used to generate the MRIO tables and to calculate CO_2 emissions in 2050. The CO_2 emission hotspots of industry processes were identified by the data from Exiobase and corresponding emission reduction targets in 2050 were collected and applied. Full details on the methodology can be found in the report by Liu (2022).

2.2. Case study cities

All four case study cities face sustainability challenges due in large part to their high and/or increase in population. All of them try to address the challenges with urban sustainability strategies, with variations in the chosen measures, focus areas and ambition levels. The key figures for the four case study cities are compared below in Table 1, Table 2 and Table 3. Among them, Table 2 shows a comparison of key figures for the study cities in BAU and CE scenarios in 2050, that can be compared to Table 1 which shows the used key figures for the base year, 2017.

Beijing is the capital and the second-largest city in China, and the political and cultural centre of the country. The rapid growth of the economy in Beijing has led to issues such as air pollution, insufficient urban infrastructure services, extensive consumption of resources and energy, and reliance on external inputs (Song et al., 2015; Yang et al., 2020).To address these issues, Beijing has set the goal of becoming an eco-city by 2035 and a model of sustainable development for mega-cities by 2050 (Beijing Municipal Commission of Planning and Natural Resources, 2018), which consist of various sustainability strategies.

Shanghai is known as the largest city in China and is a centre of finance, trade and technology innovation, facing challenges such as population expansion, air and water pollution, and waste generation (Department of State, 2017; Lu et al., 2016). To deal with the issues of global warming, lack of ecological space and the deterioration of environmental quality, Shanghai aims to promote green and low-carbon development, improve the service quality of municipal infrastructure, and increase the ability to cope with disasters (Shanghai Municipal Government, 2018).

Vienna is the capital and largest city of Austria, and is the cultural, economic, and political center of the country. Almost one fourth of Austria's population (1.9 million) live in Vienna. In the city strategy until 2030, Vienna aims to be a smart and healthy metropolis. Furthermore, the Smart City Wien is an ongoing program until 2050 focusing on e.g. urban planning, CE strategies, and increasing eco-mobility (City of Vienna, n.d.; Eurostat, 2022).

Malmö is the third largest city in Sweden and is the fastest growing of the country's major cities. With a history in industry, today Malmö is considered a cosmopolitan city with strong connections to the neighboring Danish capital, Copenhagen, and together the two greater city regions account for 27% of the combined GDP of Sweden and Denmark. The fast population growth causes sustainability challenges, and Malmö has taken on several sustainability policy goals (Malmö Stad, 2022a; 2022b).

Table 1
A comparison of key figures of the four case study cities: Beijing (Beijing Municipal Bureau of Statistics, 2021; IEA, 2016), Shanghai (Department of State, 2019; Shanghai Municipal Bureau of Statistics, 2021), Vienna (Bundesministerium für Landwirtschaft Regionen und Tourismus, 2021; City of Vienna, 2021b; Statistik Austria, 2020), and Malmö (Malmö, 2019; Malmö Stad, 2021; SCB, 2020, SCB, 2021). The data in the table are from 2017 (base year of scenario analysis), except for GDP data in Beijing (from 2020), Vienna (2021) and Malmö, 2019. Currency conversion rates are based on Oct 11, 2022. Household water use for Vienna is approximated based on Vienna's total water use and Austria's household water use.

	Population (1000s)	GDP (Euro/capita)	Area (km^2)	Household energy use (kWh/capita)	Household water use (m^3/capita)
Beijing, China	21 707	23 696	16 411	6199	84
Shanghai, China	24 183	22 346	6341	4076	43
Vienna, Austria	1868	50 400	415	6507	18*
Malmö, Sweden	334	51 546	157	5982	58

* Vienna's household water use was calculated by multiplying the total water use with the share of household consumption in Austria's total water use.

2.3. Scenario generation

Two scenarios to analyze the potential effects of sustainable strategies on resource use and CO_2 emissions were developed: 1) Business-As-Usual (BAU): based on current resource use reduction targets sourced from the four cities plans and policies, and 2) Circular Economy (CE): based on ambitious resource use reduction targets that would result from the application of CE strategies, sourced from reference literature in CE research and publications.

The resource use scenarios were developed by extrapolating the resource use from the base year of 2017 to future resource use in 2050. Based on the Urban Metabolism concept (Wolman, 1965), three types of resources were considered: 1) Water, 2) Energy, and 3) Material, while the considered drivers of consumption in society were 1) Household, 2) Transport, and 3) Public sector (referred to as *societal categories*). The modelling of material consumption was limited to households only, given that data on material consumption in the public sector and transport from the Oxford Economics were very limited. The data (Oxford Economics, 2020) only included consumer spending of food, beverages, clothing, household textile etc. and other household goods.

2.3.1. Data collection and target identification

Water, energy and material use data were collected in physical units for all four cities over a time series ranging from 2001 to 2019 then extrapolated to 2050. Water and energy use data were sourced mainly from government statistics: Beijing (Beijing Municipal Bureau of Statistics, 2021), Shanghai (Shanghai Municipal Bureau of Statistics, 2021), Vienna (City of Vienna, 2021a), Malmö (Malmö, 2021; SCB, 2020)). The calculation of material consumption was based on Oxford Economics data on consumer expenditure of goods and services at the city level, in million Euro based on 2015 prices, from the year 2000 extrapolated to 2035 (Oxford Economics, 2020), as well as material price data in financial units (SEK/kg) which were based on prices in Sweden (Whetstone et al., 2020). This set of material price data were used for all four cities due to the lack of information for the other cities.

Targets and strategies were identification for the BAU and CE scenarios based on the specific cities governmental and sectoral planning documents, reports, and literature in relevant sectors. This included city master plans, circular economy development plans, and other relevant studies. In sectors where targets were missing, studies with similar characteristics from reference organizations were considered. At this stage of the study, only targets that affect consumption were included, i.e., the aggregated IO sectors of <D> *Electricity, gas and steam,* <E> *Water and waste management,* <G> *Wholesale and retail trade,* and <H> *Transport* (as explained below on the IO economic modelling). The targets used in the scenarios modelling are fully described in Appendix C.

2.3.2. IPAT modelling

The IPAT model was applied to generate the scenarios to assess the environmental impact of human activities (Ehrlich and Holdren, 1971):

$$I = P \times A \times T \quad (2.1)$$

I: Environmental impact (i.e. CO_2 emission in this study)
P: Population of the year (base year: 2017; scenario year:2050)
A: Affluence (unit: resource consumption per person)
T: Technology (unit: impact per unit of resource consumption)

The resource use scenarios represent the Population × Affluence (absolute consumption). The different targets and strategies from each scenario affected either absolute consumption or per capita affluence which could be combined with population changes. For example, to calculate the total water expenditure (P × A) for household sector in Beijing in BAU scenario, the total household water use is calculated by the total water use in the base year (2017) combined with the change rate (−0.214659686) based on the BAU target to 2035. Since the target

Table 2
A comparison of key figures for the four case study cities in 2050: Beijing, Shanghai, Vienna, and Malmö. The data in the table are from BAU and CE scenario analysis).

		BAU 2050		CE2050	
	Population (1000s)	Household energy use (kWh/capita)	Household water use (m^3/capita)	Household energy use (kWh/capita)	Household water use (m^3/capita)
Beijing, China	23 000	13 723	62	5115	39
Shanghai, China	25 000	6914	55	5826	39
Vienna, Austria	2185	3999	20	1786	13
Malmö, Sweden	466	5224	48	4513	31

Table 3
Median values of employment per economic sector during 2003–2017. Data for Vienna is for whole of Austria during 2009–2017 (Herlaar et al., 2020).

	Beijing, China	Shanghai, China	Vienna, Austria	Malmö, Sweden
Agriculture	6%	4%	5%	3%
Industry	20%	38%	26%	20%
Service	74%	56%	70%	77%

was up to 2035, no decrease between 2035 and 2050 was assumed and the result was used for household water per person in 2050. The calculation processes for all scenarios in four cities with details are described in Appendix D. The consumption results of scenarios were converted to the monetary unit by economic modelling with IO tables for further environmental impact assessment by MRIO analysis. The Technology variable in the IPAT equation (impact per unit of resource consumption), is represented by the CO_2 emission vector described in Section 2.4.

2.3.3. IO tables computation

City level IO tables for the base year (2017) were used to compute IO tables for 2050 for the different scenarios generated. The IO tables for Beijing and Shanghai were collected from official data at city level, while the tables for Vienna and Malmö were obtained from Fath et al., 2023's method. All the tables were aggregated into 17 sectors (corresponding to the first level of the NACE structure) using the Flegg's Location Quotient (FLQ) method (Flegg and Tohmo, 2014). All sectors with their full and short names are in Appendix A.

The relevant IO sectors in the aggregated IO table were identified for each resource for each societal category modelled. The sectors were *<D> Electricity, gas and steam, <E> Water and waste management, <G> Wholesale and retail trade,* and *<H> Transport* for *energy, water, materials and transport*.

The absolute change in resource consumption between the base year 2017 (the most recent year with available data) and the scenario year of 2050 (in alignment with global climate ambitions (UN, 2022)) was calculated based on the share of each sector in IO tables that was associated with the type of resource modelled. The share represents the amount of resources affected in the overall corresponding sector (in monetary units). The share was then used to calculate the unit price for the corresponding resource type in 2017. Considering the unit price, inflation, and the modelling results together, the resource use in monetary units was calculated, providing a new amount to the share of the sector which takes into account the changes of consumption resulting from different scenarios. Afterwards, the new values for the affected share of the sector was combined with the remaining unchanged share. A new total for the sector in 2050 was calculated. For example, the consumption of final goods considered in material consumption in households (see Appendix B) is about 52% (the affected share) of the total value of household consumption of sector *<G> Wholesale and retail trade*. Thus, the change in material consumption in the scenarios was applied to 52% of the value of the sector, then the remainder of the sector's value (48%) that was unaffected by the scenario was added back. Finally, adjustments are made for population and inflation change, while holding all other factors constant.

2.4. Modeling of CO_2 emissions for production hotspots

2.4.1. Multi-regional input-output table computation

To quantify CO_2 eq. emissions resulting from the scenarios defined (BAU and CE), data for the base year (2017) in Exiobase 3 was used for the environmentally extended MRIO analysis. Exiobase is a global, detailed Multi-Regional Environmentally Extended Supply-Use Table (MR-SUT) and Input-Output Table (MR-IOT) and it harmonizes data from over 40 countries including 162 industries (Stadler et al., 2021). The global production system was simplified by aggregating the CO_2 eq. footprint into the following regions: Austria, Sweden, rest of Europe, United States, China, and rest of the world (RoW). In this case, Europe, the United States and China were selected as large economies in different regions and the countries where the case cities are located were also selected for subsequent analysis. Each city was also disaggregated into the case study city and the rest of the country to consider the impact of domestic transactions.

2.4.2. Identification of production hotspots for CO_2 emissions

The most CO_2-intensive production sectors in relation to the production of each type of resource consumed were identified as production hotspots. This process was based on identifying the sectors in the supply chains for each country, where case study cities are located, and each type of resource considered (water, energy and materials). A ranking of the identified sectors, based on their global CO_2 emissions contribution, was made. For example, for materials, some of the sectors in the supply chains are: food and non-alcoholic beverages, textiles, retail/wholesale. By definition, hotspot sectors are those sectors that represent at least 75% of all emissions of that type of resource in each country.

Production hotspots were identified as follows: First, the industry process subsectors from 162 sectors in Exiobase related to different resources/drivers were selected. CO_2 emissions of the selected industry processes were calculated based on the transactions data in intermediate matrix and the CO_2 vector and ranked in descending order. A selection cut-off was applied after the cumulative emissions reached 75% of total emissions. Finally, the 162 subsectors in Exiobase were aggregated into the 17 sectors defined for the cities IO tables to connect with the resource consumption scenarios. For example, for energy consumption in Sweden, some of the identified production subsectors were: Production of electricity by coal and Production of electricity by gas. After calculation and sorting, 15 subsectors in different regions of the World, according to the MRIO aggregation, comprised the top 75% of emissions and these subsectors were aggregated in *<D> Electricity, gas and steam* and *<B> Mining and quarrying.* These two sectors accounted for 17% and 83% respectively of the total hotspots. The list of hotspot sectors can be found in section 3.3.

2.4.3. Identification of emission reduction targets for production hotspots

Based on literature about reducing CO_2 emissions using technological advances and other improvements, emission reduction targets for the selected production hotspots were identified and applied to quantify the CO_2 emission changes from 2017 to 2050. For example, a target was found stating that adopting clean energy technologies such as heat pumps, solar thermal heating and low-carbon district energy systems can reduce energy use by 50% in steam and water supply (IEA, 2022c). While geographical relevance was considered as much as possible during the collection of emission reduction targets, most of the targets were generic (i.e., not specific to a particular city or country). Full details on the emission reduction targets can be found in the Appendix C in supplementary material.

2.5. Consequence CO_2 footprint computation

Resource consumption scenarios amounts and upstream production hotspots emissions were used to calculate the consequence CO_2 footprint in the case study cities. The Leontief inverse formula was used to calculate CO_2 emissions to include the full life cycle based on the MRIO table (Leontief, 1970):

$$e = b \times [I_m - A_m]^{-1} \times f \tag{2.2}$$

e: Environmental impact (i.e. CO_2 emission in this study)
b: CO_2 emission vector
I_m: Identity matrix
A_m: Intermediate coefficient matrix
$[I_m - A_m]^{-1}$: Leontief inverse
f: Final demand vector

The MRIO framework including the region aggregation and disaggregation is shown in Fig. 2. The intermediate coefficient matrix was calculated based on the regions aggregation and disaggregation data from Exiobase and city-level input-output tables, and the final demand vector was obtained directly from the results of the scenario modelling described above in section 2.3. The intermediate matrix was aggregated into the same 17 sectors used in scenario modelling to match the final result vector.

To compare the CO_2 emissions of different scenarios and the differences between CO_2 reduction strategies, two CO_2 emission vectors were used. The first was the 2017 vector obtained directly from Exiobase, and the other was the 2050 vector calculated based on emission reduction targets applicable to hotspots. Finally, the consumption-based CO_2 footprint was calculated and the distribution of CO_2 emissions for the study cities in the 17 sectors, including their emissions footprint in the different regions were obtained.

2.6. Assumptions and limitations

The assumptions and limitations in this study span different aspects that need to be considered. Among them, the fact that specific CE targets for the four cities are partially missing. This is due to the varying awareness and importance of the circular economy in the cities. However, they were supplemented by targets for similar cities or global targets. For more details see Appendix C in Supplementary Information. Additionally, due to the lack of information for the price data for products in Beijing, Shanghai and Vienna, the material price data in financial units (SEK/kg) for Sweden was used for all four cities (Whetstone et al., 2020).

Regarding the consequence footprint analysis, the major assumption is that the same characteristics of national economies will be maintained from the base year (2017) to 2050 and the IO tables of base year will be used to calculate the transaction ratios and compute the CO_2 emissions in 2050.

To include domestic imports within the respective countries of the case study cities, the intermediate matrices of countries were disaggregated based on Exiobase tables which were complemented with national statistical data from China, and various data sources for Vienna

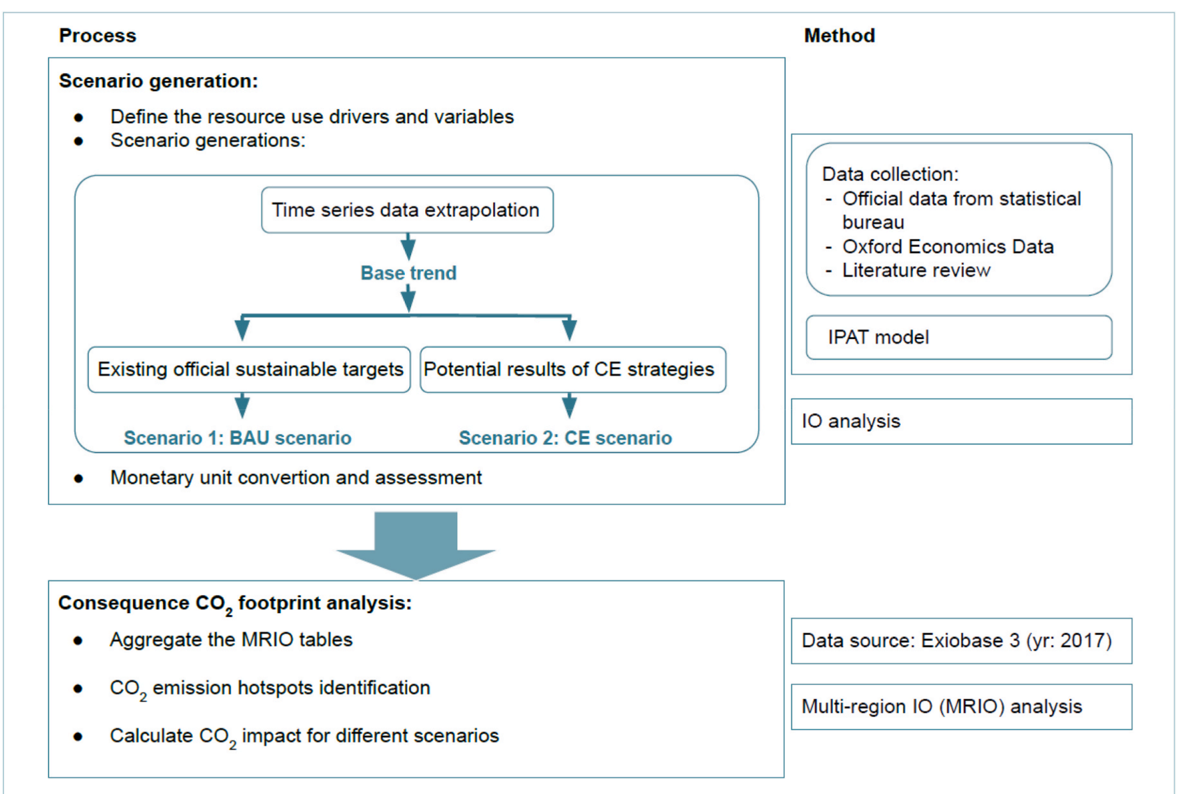


Fig. 1. Conceptual framework of the study, including processes and methods.

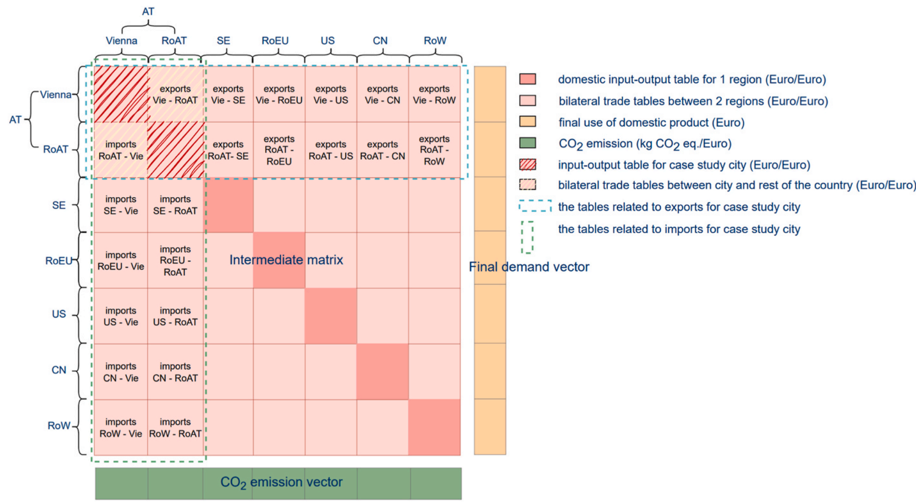


Fig. 2. The framework of the disaggregated MRIO table for case study city (Vienna as an example).

based on the Harmonized System (HS) coding classification. However, this process was made only for foreign imports. The domestic imports are calculated as the remaining transactions between the total final consumption (for each group, i.e., households, government, investment) subtracted by the consumption of goods/services produced in the city and the foreign imports. The difference in method estimations between these different databases may lead to negligible negative values in the intermediate matrix, which were assumed to be 0 in this study. Direct imports from other countries to household consumption were not considered.

There were no supplementary data for Malmö's domestic import, so the transaction relations of Malmö with other regions were assumed to be the same as Sweden's transactional relations with other regions and the domestic transactions were excluded. This can lead to lower emissions than expected in Malmö. Finally, it should be noted that the aggregation of data from 162 industries to 17 sectors can cause some data inaccuracies.

3. Resource consumption scenarios and hotspot analysis

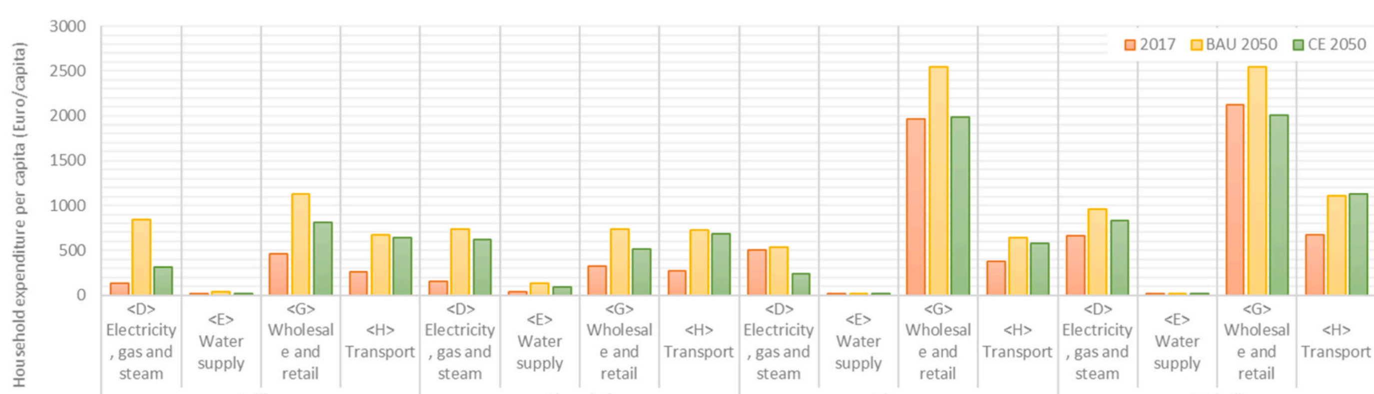
In this section, the results of the resource consumption scenario modelling and the hotspot analysis are provided. First, the results of the resource consumption scenario modelling are provided for each city (section 3.1), followed by the identification of emission hotspots (section 3.2) and finally the results of applying emission reduction targets to the hotspot sectors (section 3.3).

3.1. Resource consumption scenarios

Fig. 3 below presents a comparison of resource consumption scenarios for households (expressed in Euro per capita).

In total, compared with the BAU scenarios, the CE scenarios reduce household expenditure around 20 475 million Euro for Beijing, 10 515 million Euro for Shanghai, 2011 million Euro for Vienna, and 297 million Euro for Malmö, respectively. Especially in sector <D> *Electricity, gas and steam*, the CE scenario impacts are significant. For Beijing, they result in a reduction of more than 12 000 million Euro which accounts for over 50% of the total reduction, while in Vienna the resulting reduction is about 649 million Euro which is nearly one third of the total reduction. When comparing the per capita values between the cities, the expenditures in the Chinese cities are more evenly distributed between the affected sectors, while expenditures in sector <G> *Wholesale and retail* in the European cities are distinctively high.

As shown in Fig. 3, household expenditures focus more on sectors <D> *Electricity, gas and steam*, <G> *Wholesale and retail* and <H> *Transport*. In the affected sectors of nearly all cities, both BAU and CE scenarios for 2050 have a higher total consumption than the year 2017, which is mostly due to population growth and inflation. A side-by-side



	Beijing				Shanghai				Vienna				Malmö			
	<D> Electricity, gas and steam	<E> Water supply	<G> Wholesale and retail	<H> Transport	<D> Electricity, gas and steam	<E> Water supply	<G> Wholesale and retail	<H> Transport	<D> Electricity, gas and steam	<E> Water supply	<G> Wholesale and retail	<H> Transport	<D> Electricity, gas and steam	<E> Water supply	<G> Wholesale and retail	<H> Transport
2017	135,8281	16,82821	460,4828	260,5966	155,3241	36,53472	319,6516	266,9346	507,3191	14,24302	1966,088	381,6164	659,4671	14,02739	2120,054	670,3474
BAU 2050	841,0752	34,99174	1129,66	668,6	736,9468	129,8276	738,6704	721,2892	536,5434	21,15791	2542,861	644,1357	961,4439	16,96615	2541,68	1102,821
CE 2050	313,5183	21,76652	806,1339	642,6822	620,9884	91,202	512,004	681,9344	239,66	20,84219	1989,69	574,3384	830,5468	16,42925	2011,069	1127,261

Fig. 3. Household expenditures (Euro per capita) in the affected sectors in Shanghai, Beijing, Vienna and Malmö.

comparison of the two 2050 scenarios can better show how different strategies and targets impact resource consumption. The reduction from BAU to CE scenarios can be seen most clearly in sectors <D> and <G>.

Regarding expenditure changes in the public sector, the total savings were significantly smaller compared to household consumption, at 1.94 million Euro in Vienna and 0.27 million Euro in Malmö, which is 0.1% of the total savings in both Vienna and Malmö.

3.2. Identification of emission hotspots

In total, 67 emission hotspots were identified for China, 119 hotspots for Austria, and 125 hotspots for Sweden. The subsectors that make up the hotspot sectors and their contribution to the total hotspot emissions were assessed, to identify areas in which the biggest impact in emissions reduction can be made. A detailed list of hotspot sectors and subsectors can be found in Appendix E. Fig. 4 shows the distribution and concentration of CO_2 emissions of hotspots in different sectors.

For all cities, the hotspot sectors were identified to be *<A> Agriculture, <B> Mining and quarrying, <C> Manufacturing, <D> Electricity, gas and steam, <E> Water supply, <F> Construction, <G> Wholesale and retail, <H> Transport, <N> Specialist activities* and *<S> Entertainment* (see Fig. 4). In China, hotspot emissions were concentrated on sectors *<A>, <B>, <C>, <D>,* and *<H>*. While in European countries, the quantity of hotspot sectors was higher and included all 10 sectors identified, which indicates that the hotspots distribution of China is simpler than in European countries.

For water and energy, all hotspots in China belonged to sector *<D> Electricity, gas and steam*, while for Austria and Sweden, the hotspots for water were more complicated, including sectors *<B> Mining and quarrying, <C> Manufacturing and <D> Electricity, gas and steam*, among others. Meanwhile, for energy in Europe, the hotspots were focused on sectors *<C> Manufacturing and <D> Electricity, gas and steam*. The distribution of hotspot attribution is different in these two sectors (more than 90% for sector <D> in Austria and less than 20% for the same sector in Sweden) which may be due to the different energy mix in the two countries (IEA, 2022a, 2022d).

For transport, the hotspots have a more decentralized distribution. For China, the presence of sector *<A> Agriculture* in the transport hotspot category indicates that livestock-related agricultural transportation is a notable hotspot in transport emissions. However, sectors *<C> Manufacturing and <D> Electricity, gas and steam* still contribute to nearly 90% of emissions, which together comprise the largest impact to transport emissions. For Austria and Sweden, the sectors *<C> Manufacturing* and *<H> Transport* account for a significant percentage (over 30% and around 50% respectively for Austria and over 50% and over 30% respectively for Sweden). Future investigations could focus on sector *<H> Transport* to trace back and identify the specific sources of emissions.

For materials, sector *<A> Agriculture* has the highest CO_2 emission hotspots of all three countries. The proportion of sector <A> is higher in European countries (over 70% for Austria and over 95% for Sweden). This indicates that the amount of CO_2 emissions from agriculture and livestock play a critical role in the emissions of daily consumption downstream, especially for developed countries. But it should be noted that the hotspots sectors of materials in this study are only related to the production of final material goods – e.g., the production of beverages, textiles, retail/wholesale. Further upstream industry processes such as heavy industry production were not included.

3.3. Emission reduction targets in hotspot sectors

In total, 12, 13, and 11 emission reduction targets were identified respectively for China, Austria, and Sweden. Fig. 5 presents the results of emissions changes when emission reduction targets are applied to the hotspots.

Sector *<D> Electricity, gas and steam* has the highest emissions, reaching around 8800 tons CO_2 eq./million Euro in China and around 5000 tons CO_2 eq./million Euro in the US and RoW combined, although there is a significant reduction from 2017 to 2050. For China, the reduction is around 4000 tons CO_2 eq./million Euro (almost 45%). For Austria, the emissions reduce from 486 to 322 tons CO_2 eq./million Euro, and for Sweden from 414 to 271 tons CO_2 eq./million Euro, which

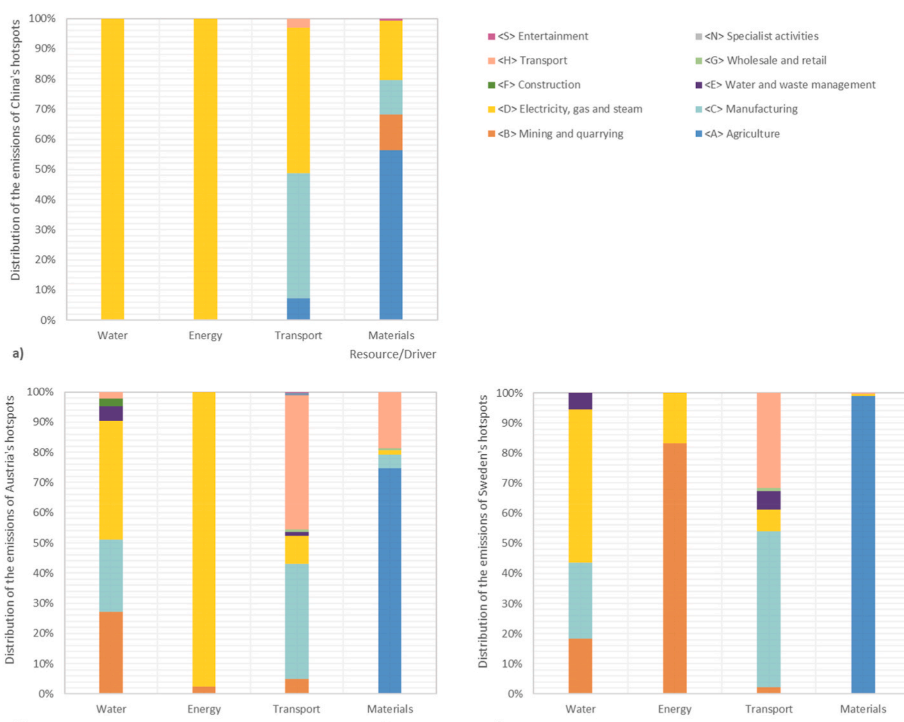


Fig. 4. The distribution of hotspot sectors at country level.a) China, b)Austria and c) Sweden.

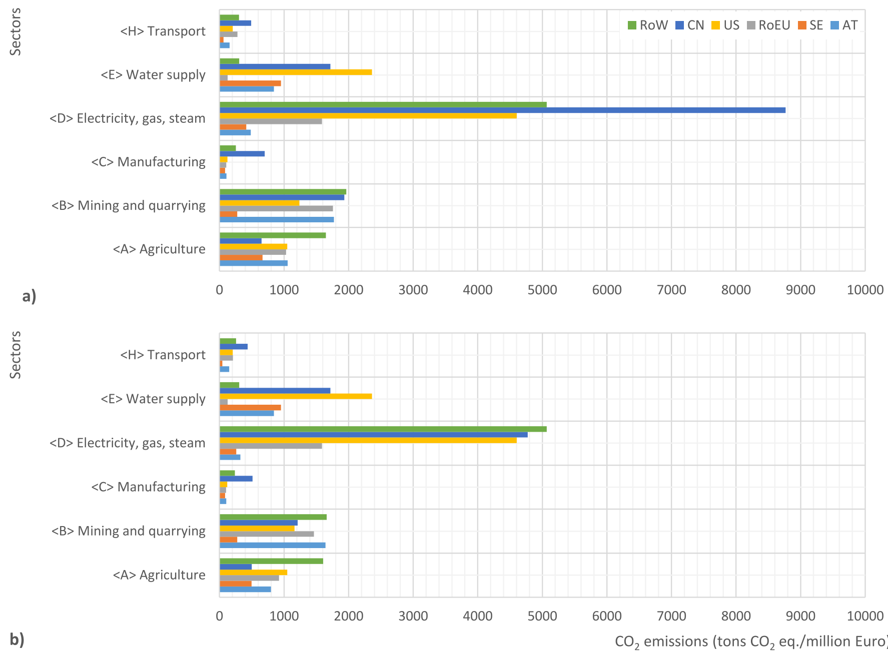


Fig. 5. The CO_2 emissions intensity of key hotspot sectors by region (tons CO_2 eq./million Euro) in; a) 2017 b) 2050 (with the application of emission reduction targets).

at around 35% are both lower than the 45% reduction in China. The emissions of sector <D> *Electricity, gas and steam* in other regions do not change due to the absence of emission reduction targets and hotspots.

The emissions of sectors <A> *Agriculture* and <B> *Mining and quarrying* are reduced to some extent for all regions. For sector <E> *Water supply*, due to the lack of emission reduction targets, there is no change in emissions from 2017 to 2050. For sectors <C> *Manufacturing* and <H> *Transport*, the emissions in 2017 are already low, at an average of 230 and 250 tons CO_2 eq./million Euro for all regions, respectively. However, some emissions reduction is still possible, as for example a reduction from 64 to 44 tons CO_2 eq./million Euro was obtained in sector <H> in Sweden.

4. Consequence CO_2 footprint of cities

In this section, the results of the consequence CO_2 footprint of the case study cities are presented. These represent the CO_2 emissions from both the resource consumption scenarios and their associated hotspot

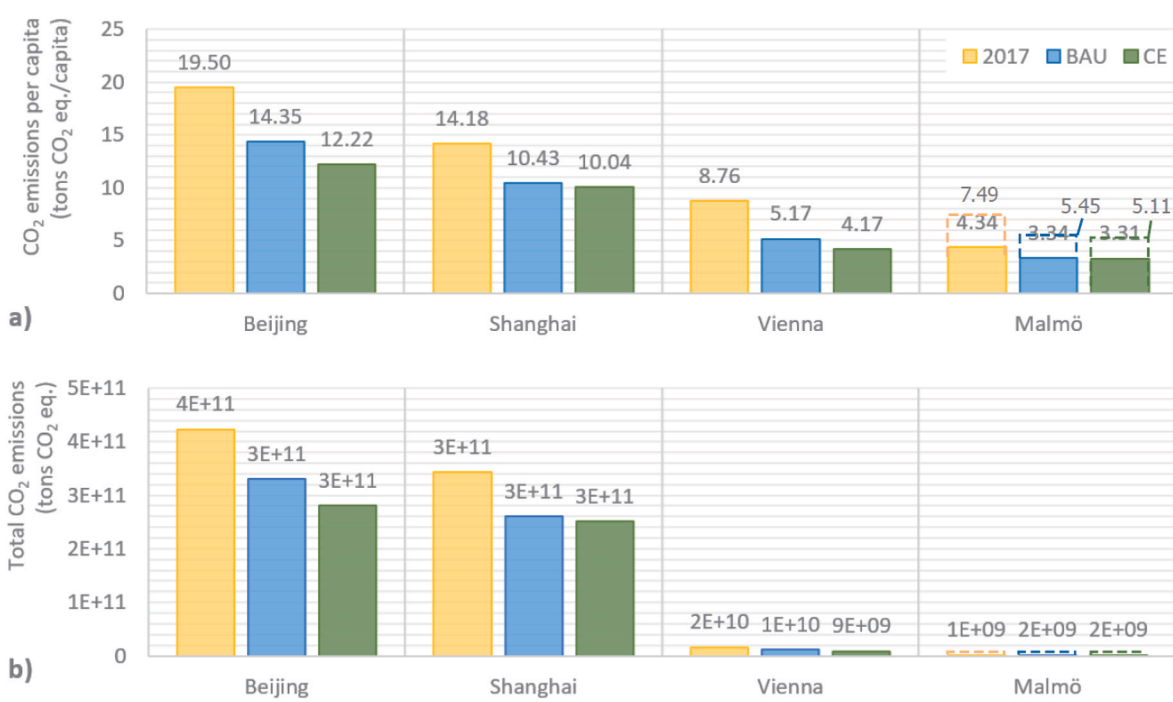


Fig. 6. The per capita (a) and total (b) CO_2 emissions in the case study cities in different scenarios (tons CO_2 eq./capita; tons CO_2 eq.). The dashed lines for Malmö indicate approximations.

sectors. The results are presented in terms of the total emissions for each city (section 4.1), distribution of emissions for each city by key sectors (section 4.2), and distribution of emissions for each city by their CO_2 footprint in different regions (section 4.3).

4.1. Total CO_2 emissions

The modelled resource consumption shows a reduction in CO_2 emissions from 2017 to 2050 in all cities in the BAU scenario, and even more so in the CE scenario. Fig. 6 shows the per capita emissions and the total for each city in each scenario.

In general, the estimation of the emissions in Malmö was lower than expected because domestic transactions could not be included. This was addressed by using the proportions of the emissions related to domestic transactions in Vienna, which account for nearly 42%, 39%, 35% in the base year, BAU and CE scenarios respectively. These figures were then used to approximate the emissions of Malmö including domestic transaction-related emissions, resulting in 2.50×10^9, 2.54×10^9 and 2.38×10^9 tons CO_2 eq. for total emissions and 7.49, 5.4, and 5.11 tons CO_2 eq./capita respectively for base year (2017), BAU and CE.

The change in emissions per capita for the CE scenario is greater in the European cities than the Chinese cities. For example, the change in Vienna is over 50% (from 8.76 tons CO_2 eq./capita in base year to 4.17 in CE) while the change in Beijing is 37% (from 19.5 tons CO_2 eq./capita in base year to 12.22 in CE) and the change in Shanghai is 29% (from 14.18 tons CO_2 eq./capita in base year to 10.04 in CE). This suggests that there is still a gap between the performance of European and Chinese cities in reducing emissions and that European cities perform better in reducing emissions when their emissions are already lower. One reason can be that when comparing the extrapolation of resource use between the cities, the growth of resource use is slower in the European cities. For example, the growth of clothing and footwear in material use in Vienna increases by 56.8% from 2017 to 2050 while in Beijing the increase is 163%.

Comparing cities of similar regions, in China the emissions per capita in Beijing are higher than in Shanghai in all scenarios (14.35 tons CO_2 eq./capita in BAU and 12.22 in CE in Beijing compared to 10.43 in BAU and 10.04 in CE in Shanghai). The emissions reduction from BAU to CE is greater in Beijing (15%) than Shanghai (4%). For the European cities, it would be inappropriate to compare the emissions between Vienna and Malmö due to the lack of data for Malmö.

4.2. Distribution of CO_2 emissions by key sectors

This section presents the CO_2 emissions data per capita for each city presented by key sectors. As shown in Fig. 7, the distribution of emissions is concentrated mostly on the sectors *<C> Manufacturing* and *<D> Electricity, gas, and steam*, followed by the remaining sectors which are presented as one group.

For all cities, the sum of emissions in sectors *<C> Manufacturing* and *<D> Electricity, gas and steam* account for over 50% of the city's total emissions. Meanwhile, the emissions of these sectors tend to decrease in all scenarios, and more so in the CE scenario. In terms of changes in the share of emissions, the share of sector <D> decreases while the share of sector <C> increases slightly. In Beijing for example, the share of sector <D> decreases from 47% (base year) to 46% (−1%) (BAU) and 38% (−9%) (CE), while the share of sector <C> increases from 29% (base year) and 29% (+0%) (BAU) to 33% (+4%) (CE). This indicates that the reduction of emissions in sector <D> is more significant than in sector <C>. But this pattern is not the same in Malmö, since there were only three emission reduction targets for sector <D> while there were nine targets for sector <C>. Another reason can be that renewable energy sources already accounted for a high percentage of total energy supply (for example, in 2017 the renewable energy mix in Sweden comprised at least 75% (IEA, 2022d), thus the feasibility to further reduce the emissions from energy is perhaps becoming marginal.

The combined proportion of hotspot emissions in sectors *<C> Manufacturing* and *<D> Electricity, gas and steam* in the Chinese cities are higher (over 70% for both cities) than in the European cities (around 60% for Vienna and 55% for Malmö), which indicates that consumption in Beijing and Shanghai relies more on manufacturing and energy than in Vienna and Malmö. It suggests that the composition of consumption-based CO_2 emissions in European cities is more complex and varied. This could be because these cities have shifted further from a production/industrial economy to a service economy as well as being relatively advanced in implementing sustainability efforts in the sectors *<C> Manufacturing* and *<D> Electricity, gas and steam*.

4.3. Regional distribution of CO_2 emission footprint

The distribution of CO_2 emissions in the case study cities in the different scenarios is shown in Fig. 8, categorized by sector and the regions in which the emissions are released due to the city's consumption (i.e., both final consumption in the cities and its associated CO_2 emission footprint in hotspot sectors).

Comparing the distribution of emissions across regions, for Beijing, Shanghai and Vienna, CO_2 emissions are concentrated mainly in the city and the country in which the city is located. In the base year, these combined national emissions in China account for 91% and 89% for Beijing and Shanghai respectively, and 77% for Vienna in Austria. Although these shares decrease slightly in the scenarios, the same pattern holds. However, for Malmö, the CO_2 emissions are more decentralized. Malmö's consumption footprint in China is high (32% for base year) and slightly lower than the emissions in Malmö itself (33% for base year); the emissions in RoW are high as well, followed by the emissions in RoEU. The differences in distribution of emissions across

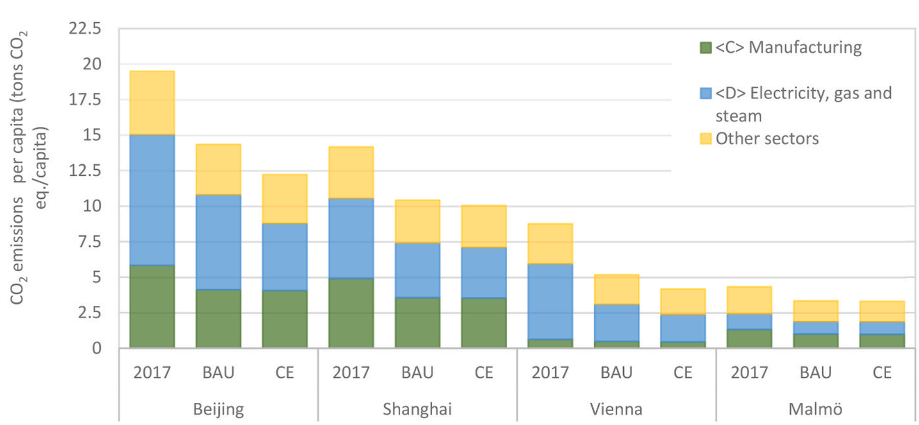


Fig. 7. CO_2 emissions distribution by sectors in the case study cities for the different scenarios (tons CO_2 eq./capita).

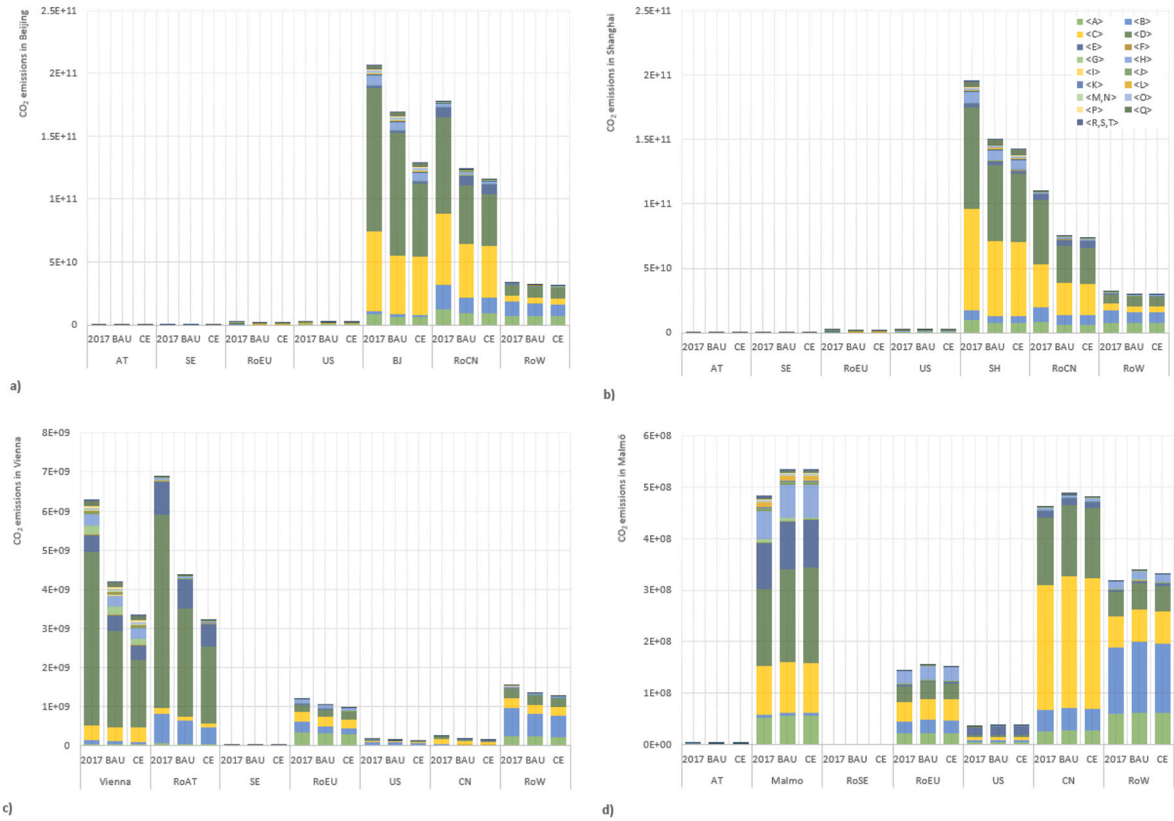


Fig. 8. CO_2 emissions distribution by sector in the case study cities in the different scenarios and associated upstream emissions footprint in the different regions; case study cities: a) Beijing; b) Shanghai; c) Vienna; d) Malmö.

regions may be attributed to differences in the cities' reliance on imports (see section 5 Discussion).

For national emissions, the Chinese cities themselves take up a larger proportion of the emissions than their footprint in the rest of the country (for Beijing, 49% in the city and 42% in RoCN; for Shanghai, 57% in the city and 32% in RoCN). In the case of Vienna, the emissions are slightly higher in the rest of Austria than in city itself (39% in Vienna and 42% in RoAT). And for Malmö, there are no data for the emissions in the rest of Sweden.

At the same time, for the national emissions in Chinese cities, both sectors <C> *Manufacturing* and <D> *Electricity, gas and steam* have a high share of about 80% in total in the city and about 70% in the RoCN, like the pattern of sectoral shares of total emissions presented in section 4.2. Vienna's emissions in Austria are more concentrated in sector <D> (around 70%), and <C> has a lower share (below 10%), since a significant portion of sector <C>-based emissions are distributed in other regions of Europe and the rest of the world.

The local emissions of Malmö are concentrated in sectors <C> and <D> as well, while the contribution of sectors <A> *Agriculture,* <E> *Water supply* and <H> *Transport* are notable (11%, 19%, and 11% respectively for base year). Malmö's emissions footprint in China are concentrated on sector <C> (over 50%) and <D> (around 20%). This is in line with the significance of China as a global supplier of manufacturing. Sector <B> *Mining and quarrying* is the highest emission sector (around 30%) for Malmö's consumption-based emissions in RoW. This is related to the fact that Russia is among the biggest supplier of raw material resources and belongs to the RoW region in this study (IEA, 2017).

For the Chinese cities, CO_2 emissions based on sector <A> *Agriculture* are accounted for in all emission regions, while for Vienna, agriculture-related emissions seem to be largely outside of Austria, concentrated in the rest of Europe and the rest of the world.

For Vienna and Malmö, the emissions of sector <E> *Water supply* account for a higher share of their respective national emissions (for example, 14% and 17%, respectively in CE) compared with the Beijing and Shanghai for China (4% and 3%, respectively in CE).

It is also worth mentioning that for Vienna and Malmö, the emissions related to sector <M,N> *Specialist activities* are low but observable (for example, 0.6% and 0.3%, respectively in CE), while for Chinese cities, this part of emissions is even lower.

5. Discussion

5.1. Resource consumption scenarios

In the resource consumption scenarios, the study found that household expenditure was mainly spent on energy, wholesale and retail, and transport for all four cities. This result is reasonable because energy, food production and transportation were considered to be basic needs for all citizens (Paiho et al., 2021), which also aligns with the results that mobility and food were always the two most important consumption categories (Ivanova et al., 2016). However, in terms of expenditure per capita, expenditure on wholesale and retail in European cities was significantly higher than in Chinese cities. The importance of wholesale and retail comes as no surprise, as it is generally believed that higher GDP is associated with higher final demand (Harris et al., 2020).

In terms of the absolute volume of resource consumption, sectors <D> *Electricity, gas and steam,* and <G> *Wholesale and retail* have a great potential to reduce consumption when CE strategies are applied. As for sectors <G> and <H>, collecting additional impact targets, such as targets for other materials groups other than only food, would allow for more accurate modelling and the ability to capture the full potential for reduced consumption in these two sectors.

The resource consumption scenarios were the basis of the consequence CO_2 footprint analysis. In the generation of the scenarios, the ability of the cities to reach the objectives identified in the targets was assumed to be true. Therefore, the likelihood of its implementation or success were not discussed in this study. It should be noted that this may lead to an overestimation of the final outcome in practice should barriers to policy implementation arise. Furthermore, due to the lack of targets related to materials, the true potential of reducing material consumption was likely not fully reflected in the scenarios. Similar studies such as those by Donati et al. (2020) and Wiebe et al. (2019) showed that CE approaches can reduce global material extraction and fossil fuels, and by extension reduce emissions. In this study, the only materials-related target was a country-level food reduction target from the UN Environment Programme, which is not a specific target for the case study cities and may not reflect the food structure of Chinese cities, resulting in less accurate modelling results.

5.2. Hotspot analysis

The distribution of hotspots in European cities is more complicated than in Chinese cities, in that they occur further downstream in the tertiary sectors such as services. This corresponds with research by Ivanova et al. (2016) in which consumption in tertiary sectors is strongly driven by household income, and in an emerging economy, the percentage of carbon emissions of tertiary sectors is lower for different materials and drivers, and CO_2 emissions from water and energy value chains in Chinese cities are almost entirely concentrated in the electricity-based energy industry. For Vienna, the electricity, gas and steam industry plays a notable role in water and energy value chains. Austria's energy sources, mainly oil, gas and coal (IEA, 2022a) contributes to this pattern. The consumption of gas and liquid fuels generated a considerable carbon footprint during production and usage phase (Christis et al., 2019). Reducing emissions from power generation, for example by changing the source of electricity, can have a significant impact on reducing emissions from the consumption of water and energy. For Malmö, the mining and quarrying industry becomes the largest part in energy value chains. The reason for this may be that nuclear energy, Sweden's main source of energy (IEA, 2022d), emits low amounts of CO_2, which amplifies the share of CO_2 emissions from the extraction of oil, which still accounts for a certain share of energy sources. In the sectors of materials and transport, efforts for mitigating emissions should be directed towards all sectors included in the value chain but the efforts put on agriculture may gain more effects for material use due to its high proportion among the materials hotspots. A more ambitious CE strategy for food consumption can be a pathway to reducing agricultural emissions, considering that agriculture and food production are closely linked, and that food products has long been considered to have the highest footprint (Tukker et al., 2016).

For a number of hotspots in China, Austria and Sweden, no emission reduction targets were found due to the complexity of the manufacturing industry and data constraints, which may lead to an underestimation of the CO_2 reduction effect, especially in from the production perspective. Looking further upstream to find emission hotspots from more industrial processes and collecting their emission reduction targets may be a way to improve the model's accuracy in the future.

5.3. Consequence CO_2 footprint analysis

The results of Vienna in the base year (2017) align with the results from Schmid's study (2020) and Moran et al.'s study (2018). Malmö's results are in the same magnitude as the results in the Swedish Konsumtionskompassen (Stockholm Environment Institute, 2022). The CO_2 emissions per capita in BAU scenarios for all cities decreased significantly compared with the base year. All Chinese and European cities plan to take measures to reduce their CO_2 footprint. Compared to the BAU scenarios, the emissions reduction in CE scenarios is greater but the reduction level in Shanghai and Malmö is weaker compared to the other two cities. This indicates that more ambitious CE strategies are needed in these two cities in the future, perhaps in other sectors not covered in this study. Most efforts aim at relative decoupling of GHG emissions from the economy. A strong CE scenario could result in absolute decoupling that actually reduces overall consumption.

The CO_2 emissions concentrated on <*C*> *Manufacturing* and <*D*> *Electricity, gas and steam* aligns with the high expenditure of sector <*G*> *Wholesale and retail* in the resource consumption scenarios and the high share of energy-related hotspots in sector <D> on the production side. This reflects the correlations between consumption, production and energy use, in line with the findings of Harris (2016). The proportions of CO_2 emissions of manufacturing and energy sectors in the European cities are lower than in the Chinese cities, which is attributed to the higher share of renewable energy in Europe (IEA, 2022a, 2022b, 2022d).

The distribution of total city emissions by region shows that the consumption of Beijing, Shanghai and Vienna rely highly on domestic production. On the other hand, over half of the CO_2 emissions based on the consumption of Malmö lie outside of Sweden, indicating a greater dependence on international production. This is due to several factors, most probably mainly the following three: service-focused industry (Herlaar et al. (2020) and Forslid (2022)), relatively low emission factor nordic electricity mix, 70.8 g CO2e/kWh in the manufacturing industry (SMED, 2021). Malmö has made a shift to a service-focused industry extremely fast, and these industries often consume more energy than other emission-inducing resources. Due to the low emission factor for energy, the emissions of Malmö's economy are relatively low. Our results are comparable with the study by Ivanova et al. (2016) in which indirect domestic impacts accounted for 92% of the total footprint of China and the indirect foreign impacts accounted for more than 50% of the total footprint of Sweden.

5.4. Comparison with similar studies

Compared to the base year, the CO_2 reduction of CE scenarios achieves 37% in Beijing, 29% in Shanghai, over 50% in Vienna and 24% in Malmö. Among them, the emission reduction in Vienna is very close to the study in another European city, Brussels (Christis et al., 2019), in which the CE strategies on food, mobility and housing can reduce 25%, 18% and 7% of Brussel's carbon footprint respectively and 51% in total compared with the data in 2010. It is worth mentioning that in this study, the specific numerical changes brought by CE were based on assumptions of cash-out costs' reduction potential rather than from specific CE strategy targets of resources. This indicates that the current CE strategies for Vienna are justified and promising. The results of a similar study related to Malmö were different, in the post carbon scenario to 2050 of Harris et al.'s study (2020), the consumption-based GHG emissions per capita in eight of the ten case studies cities in Europe increased, including Malmö. This may be due to the scenario modelling, since in Harris and colleagues' study (2020) , it was assumed that an increase in GDP resulted in an increase in final demand rather than calculating the resource demand changes themselves. However, they also confirmed that the post carbon scenario can reduce about 8% emissions compared with BAU scenario.

The studies of emission reduction potential based on scenario modelling in Beijing and Shanghai have mostly focused on analyzing the potential for changes in the energy mix from industrial perspective, making it inappropriate to compare with other existing studies directly (Feng and Zhang, 2012; Li et al., 2010; Wang et al., 2020; Yu et al., 2015). However, this study complements the reduction potential of households to reduce emissions from different resources and provides decision support for the urban transition to CE strategies.

5.5. Effect of CE targets on CO_2 footprint

Compared to Shanghai and Malmö, the CO_2 reduction of the CE scenario in Beijing and Vienna is more substantial on top of the reduction already achieved in the BAU scenario. With a reduction rate of over 10%, this indicates that the current CE strategies have been very effective in reducing Beijing and Vienna's emissions, and that the reduction impacts are more notable within their respective countries. For Shanghai and Malmö, more ambitious CE strategies should be considered.

A significant proportion of the emissions based on consumption in Malmö are outside of Sweden, comparable to results from Palm et al. (2019). This can be challenging to address from within the city. The change of consumption habits can be an option, such as the adoption of circular consumption models, resource efficiency and product life extension, as also found in Skånberg and Svenfelt's study (2021) on backcasting sustainability scenarios in Sweden. However, without the domestic imports data of Malmö, the CO_2 emissions reduction within Sweden cannot be analyzed for the footprint analysis of Malmö. In the future, increasing the completeness of data can improve the accuracy and reliability of results.

Both the planning and the implementation of specific CE goals need more development in all the cities. In general, the results indicate that the greatest potential and effectiveness in reducing consumption lies in the sectors of energy use and materials consumption. Monetary savings with the chosen CE targets can also be significant.

5.6. Assumptions and limitations

Despite having some potentially significant limitations the work in this study is relevant since it provides new information about the CE role in terms of climate reduction potential in different cities and how different and similar they might be. Additionally, insight on what is the progress towards CE and how much impact it might have is also of relevance.

The partially missing CE targets in case study cities were supplemented by targets for similar cities or global targets. The CO_2 reduction potential was presented based on circular economy strategies of comparable cities that are considered to be achievable in the case study cities as well. This demonstrates both the potential for CO_2 emission reduction and provides a pioneering experience that the city can refer towards the development of a specific CE strategy.

Compared with Chinese cities, the city-level IO table data of Vienna and Malmö was rare and related work was still in progress. Our study combined several data sources trying to complete the analysis at city level which brought uncertainties because of different classification forms and structures for each database. However, this article still provides results to compare the CO_2 emission reduction potential of CE strategies in different cities based on the data sources currently available. This result can be improved by the ongoing MRIO-project within Statistics Sweden (Tillväxtanalys, 2021) in the future to obtain more accurate estimation.

6. Conclusion

The research herein combines material footprint analysis and MRIO to provide a novel look at the greenhouse gas emissions at the city-level, specifically comparing four cities across China and Europe under Business as Usual and Circular Economy scenarios. Although Vienna and Malmö have applied sustainability strategies for quite some time, the results do not show that CE strategies work better in all European cities compared with Chinese cities.

Comparing the household expenditure of the BAU and CE scenarios, the energy, and wholesale and retail sectors have a great potential to reduce consumption when CE strategies are applied for all four cities. And the expenditure per capita on wholesale and retail in European cities was significantly higher than in Chinese cities, which indicates these two European cities have a greater capability to reduce consumption from wholesale and retail perspective in the future.

Regarding CO_2 emissions, the emissions reduction in CE scenarios is greater compared to the BAU scenarios but the reduction level in Shanghai and Malmö is weaker compared to the other two cities. This indicates that the current CE strategies have been very effective in reducing Beijing and Vienna's emissions, and for Shanghai and Malmö, more ambitious CE strategies should be considered. Meanwhile, comparing among the four cities, the distribution of emissions indicates that the consumption of Beijing, Shanghai and Vienna rely highly on domestic production whilst Malmö is more dependent on international production.

The results suggest that the greatest potential and effectiveness in reducing consumption lies in the sectors of energy use and materials consumption for all cities, which are the future directions where CE policies can have a greater impact and work toward absolute decoupling of resource use and emissions. In the future, the results of this study can be refined by tracing further upstream to identify more significant upstream emissions hotspots and devising strategies to reduce the impacts in those sectors.

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 is partially confidential

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.clpl.2023.100045.

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