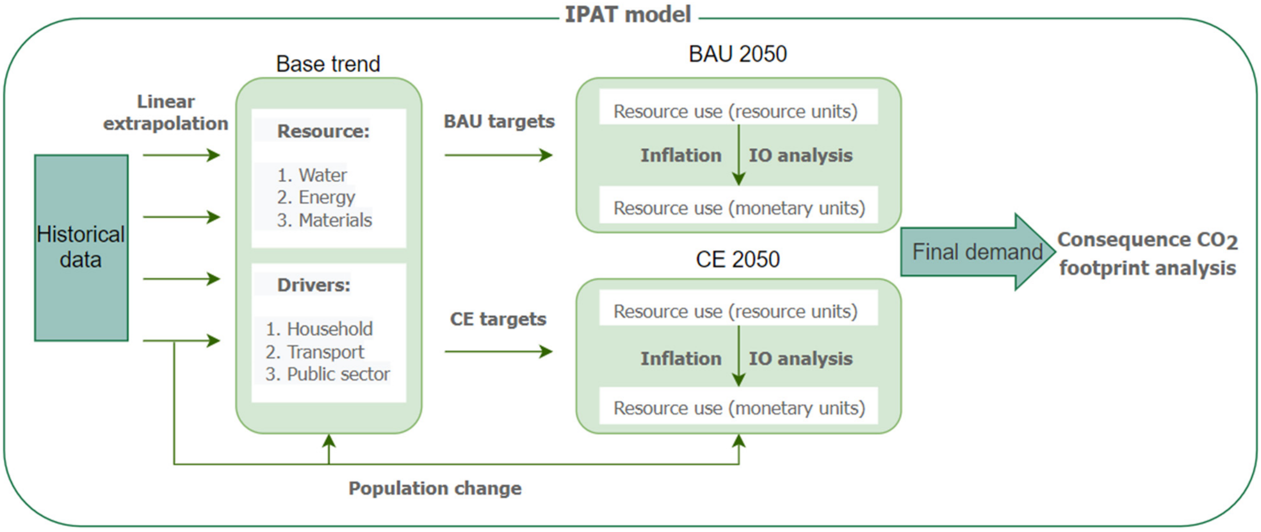


# Consequence footprint analysis of benefits of CE scenario for cities

## Case study for Beijing and Shanghai

Master's thesis in Master's Programme Infrastructure and Environmental Engineering

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DEPARTMENT OF ARCHITECTURE AND CIVIL ENGINEERING

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2022
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MASTER'S THESIS ACEX30

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ABSTRACT

To reduce resource use in cities and relieve environmental pressure, circular economy (CE) strategies are widely mentioned and gradually applied. To quantify and evaluate the impacts of CE strategies for urban development in both resource use and $CO_2$ emission perspectives, this study evaluates resource consumption and environmental impacts (focusing on $CO_2$ emissions) with CE strategies and how much they can reduce the $CO_2$ emission for the study cities, Shanghai and Beijing, by scenarios generation (Business-As-Usual (BAU) scenario and Circular Economy (CE) scenario) and MRIO analysis.

CE scenarios reduce around 10515 million Euro household expenditure in total for Shanghai and around 20475 million Euro household expenditure for Beijing compared with BAU scenarios. For the environmental impacts, the $CO_2$ emission per capita can be reduced by 37% and the total $CO_2$ emission can be reduced by 34% from 2017 in Beijing. The $CO_2$ emission per capita for Shanghai can be reduced by 28% and the total $CO_2$ emission can be reduced by 26%. It is worth mentioning that compared to Shanghai, the $CO_2$ reduction of the CE scenario in Beijing is substantial on top of the reduction already achieved by the BAU scenario.

The results indicate that for the collected targets and plans, the CE strategies are more effective for Beijing to reduce resource consumption and $CO_2$ emission. For Shanghai, the effect on emission reduction is not significant, and more ambitious CE strategies should be considered in the future.

Key words: circular economy, scenario, MRIO, $CO_2$ footprint

# Contents

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Göteborg, Sweden, 2022

Yiwen Liu

# Notations

**Roman upper case letters**

| | |
|---|---|
| $A$ | Affluence (unit: consumption per person) |
| $A_m$ | Intermediate coefficient matrix |
| $I$ | Environmental impact (i.e. $CO_2$ emission in the thesis) |
| $I_m$ | Identity matrix |
| $[I_m - A_m]^{-1}$ | Leontief inverse |
| $P$ | Population |
| $S_i$ | The imports matrix from region a to study city (Million Eur) |
| $S_a$ | The coefficient intermediate matrix of region a (Million Eur/ Million Eur) |
| $S_e$ | The exports matrix from study city to region a (Million Eur) |
| $S_{city}$ | The coefficient intermediate matrix of study city (Million Eur/ Million Eur) |
| $T$ | Technology (unit: impact per unit of consumption) |
| $W_i$ | Diagonal matrix of imports value of study city (Million Eur) |
| $W_e$ | Diagonal matrix of exports value of study city (Million Eur) |

**Roman lower case letters**

| | |
|---|---|
| $b$ | $CO_2$ emission vector |
| $e$ | Environmental impact (i.e. $CO_2$ emission in the thesis) |
| $f$ | Final demand vector |

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# 1 Introduction

This chapter describes the background of this thesis, including the importance of resource use and environmental impacts evaluation in cities and the research status. The introduction of case study cities is also presented. The aim and scope are presented.

## 1.1 Background

Resource consumption impacts the ecosystems and increases the concerns of sustainability. In the first decade of the 21st century, with the annual average material demand growth from 7 tons to over 12 tons per capita, the annual global materials extraction grew from 27 billion tons to 92 billion tons, the accelerated global resource use brings increasingly negative impacts on the environment and human health (Bringezu et al., 2017; Oberle et al., 2019). To advance human well-being with a sustainable approach, it is important to reduce the resource consumption, make natural resources more efficient and find a way to reduce the environmental pressure.

To improve resource efficiency and reducing emissions, the CE strategies in different aspects are considered to be a trending paradigm that plays an important role (Martins & Castro, 2020). The circular economy (CE) concept is proposed as another economic system compared with the traditional unsustainable linear material and energy flow model (Korhonen et al., 2018; MacArthur, 2013). In this way, the CE strategies can reduce the raw materials use and hence minimize the amount of discharged waste (Andersen, 2007; Su et al., 2013).

It is imperative to focus on how to save resources and reduce emissions at the city scale (Kalmykova et al., 2016). As large human settlements, cities have the majority of the population with most of GDP and are the center of industries, commerce, and policies, which are responsible for the consumption of most of the resources and greatly influence the social and natural environment (Kalmykova et al., 2016; Swilling et al., 2013).

To analyse the resource use flows of cities, the concept of urban metabolism is proposed and widely researched. The concept of urban metabolism was conceived by Wolman and is used to present the consumption, growth of resources and energy, and the production of waste during different processes in cities (Kennedy et al., 2007; Wolman, 1965). Within the urban metabolism field, the main proposals are to analyse the materials and energy flows throughout a city, to quantify greenhouse gas emissions and to support authorities' decisions by these evaluations (Kennedy et al., 2011). So with the information of the resource transformation within cities, urban metabolism provides a comprehensive framework to understand and find approaches to achieve urban sustainable targets (Conke & Ferreira, 2015; Hoornweg et al., 2012).

To analyse the resource use with different strategies within urban metabolism, scenario analysis is a widely-used way to reflect the characteristics of the cities, analyse potential future developments and compare between different assumptions (Odegard & Van der Voet, 2014; Panel et al., 2011; Rothman, 2008; Schanes et al., 2019). It is worth mentioning that this approach focuses on the current situation and assumptions about future challenges, rather than making predictions (Jarke et al., 1998; Schwartz, 2012). There are different ways to categorize scenarios and within the environmental field, the U.N. Intergovernmental Panel on Climate Change (IPCC) provides a set of archetypes. IPCC groups the existing scenarios in the review of global future scenarios which consider qualification dimensions e.g. socio-economic dimension with technological and environmental dimensions. The scenarios are clustered into 1) Pessimistic scenarios, 2) Current trends scenarios, 3) High-tech optimist scenarios and 4) Sustainable development scenarios based upon whether general conditions deteriorate, no significant change from current conditions, or conditions improve (Morita et al., 2001; Rothman, 2008).

Life cycle assessment (LCA), material flow analysis (MFA), and input-output analysis (IO analysis) are three frameworks constructed for urban metabolism studies (Kennedy et al., 2011; Zhang, 2013). Among the researches on different frameworks to urban metabolism, there are many studies that have taken a scenario development approach.

Spielmann et al. (2005) analysed the climate change scores and nitrogen dioxide scores for the transport system in Switzerland using prospective LCA method. They developed four scenarios to maximise the diversity of alternatives and assessed which option performed considerably better. Prospective LCA combining with scenarios is always used to analyse the improvement of environmental performance for early stage technologies in a product, for instance, Nordelöf et al. (2014) compared the different technologies for electric vehicles and Edwards et al. (2004) analysed the energy consumption and greenhouse gas emissions for different automotive fuel pathways. However, considering that LCA is a method used to assess the environmental impact of a product or service throughout its life cycle, these studies with this approach are limited to a product or service level not city level (Corona et al., 2019; Spielmann et al., 2005). MFA provides another perspective to analyse the urban metabolism which focuses more on the material flow and makes it easier to understand the paths that resources take through an defined system (Corona et al., 2019). With scenario development, the battery outflows from electric vehicles including the metals and other expected materials from years 2015 to 2040 were analysed by MFA (Richa et al., 2014). And MFA is always used to track the input, output and storage of specific materials. Gerst (2009) analysed the global copper cycle from 2000 to next 100 years with 4 scenarios based on two scenario themes, degree of globalization and degree of environmental consciousness. Another study analysed the flows and stocks of platinum for automobile industry in China from 2009 to 2019 and evaluated the platinum demand from 2020 to 2050 for two scenarios related to environmental goals (Zhang et al., 2021).

Different with LCA and MFA, IO analysis is used to describe and analyse the environmental and economic impacts between different sectors by monetary units (Corona et al., 2019). For sustainable urban development, IO analysis provides a top-down approach at a macro scale and linking resource use, emissions and economy makes it more intuitive for the stakeholders to understand the economic impact and the relevance between resources and the economy (Corona et al., 2019). An Environmentally-Extended Input-Output Simulation (EEIOS) model has been developed to analyse the efficiency of emission reduction policies in Canada by 28 scenarios from both the production and consumption sides (Liu et al., 2018). Hertwich et al. (2015) presented a scenario-based hybrid LCA-MRIO model to analyse the global energy system change with renewable energy from 2010 to 2050.

The model based on the 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 impact of CE strategies on resource consumption and environmental pressures. Wiebe et al. (2019) developed circular economy scenarios projected to 2030 using MRIO based on Exiobase for increased recycling, repair, resource efficiency and remanufacturing, and compared the environmental impacts with a business as usual scenario at the global level. They found that the adoption of circular economy measures decreased global material extraction including fossil fuels. Although MRIO has been used to model the future emissions at national scale and evaluate global impacts of a future circular economy, there still are few city-level studies (Harris et al., 2020; Scott et al., 2013; Wiebe et al., 2019). The POCACITO project documented by Harris et al. (2020) developed two scenarios, business as usual scenario and low carbon scenario, for European cities to 2050 and quantified the GHG emissions for both scenarios. The research concentrated more on emissions both consumption-based and production-based. The consumption-based emissions were calculated using Exiobase MRIO models. They found that there was a significant difference in the results between production-based accounting (a more traditional focus) and consumption-based accounting, where consumption-based emissions were generally much higher than production-based emissions.

This thesis focuses on the evaluation of resource consumption and environmental impacts (especially $CO_2$ emissions) with CE strategies and how it benefits sustainable urban development on city level. The case study cities chosen in this thesis are Shanghai and Beijing. Combined with the scenarios generation and MRIO analysis, the efficiency of the application of strategies with/without CE for sustainable urban development are analysed.

## 1.2 Case study

### 1.2.1 Shanghai

Located at 31° 14′ N, 121° 29′ E with a land area of 6340.5 $m^2$, Shanghai has 24.88 million resident populations and the GDP of 3870 billion yuan by the end of 2020 (Department-of-State, 2019; Shanghai-Municipal-Bureau-of-Statistics, 2021). Known as The largest mega-city in China, Shanghai is the centre of international economy, finance, trade, shipping, science and technology innovation facing challenges such as population expansion, air and water pollution, waste generation (Department-of-State, 2017; Lu et al., 2016). It is vital for such a large city to find a sustainable way to develop and build a more resilient and liveable environment in a long-term plan.

Shanghai has the goal of comprehensive, coordinated and sustainable development (Shanghai-Municipal-Government, 2018). To deal with the trends of global warming and climate extremes, and the challenges of lack of ecological space and the deterioration of environmental quality, Shanghai targets to promote green and low-carbon development, improve the guarantee ability and service level of municipal infrastructure, and increase the ability and resilience of cities to cope with disasters (Shanghai-Municipal-Government, 2018). Comprehensively reducing carbon emissions, rationalizing and optimizing the energy structure, reducing energy consumption and developing green transportation are parts of the targets of Shanghai's master plan from 2017-2035 (Shanghai-Municipal-Government, 2018).

Some research was made to analyse the metabolic characteristics and sustainable status of Shanghai. Lu et al. (2016) used the MuSIASEM approach from the socio-economic perspective to analyse the urban metabolism of Shanghai from 2001 to 2013 based on land use as the fund. And they also used this framework to compare the metabolic characteristics of Shanghai, Tokyo, London and Paris and evaluate the sustainable performance of each city (Han et al., 2018). Zhang et al. (2018) did research to build up a metabolism framework on the industrial ecosystem level to assess the urban sustainability and analyse the construction metabolism in Shanghai from 2004 to 2014. Besides, the circular economy development of Shanghai from 2005 to 2014 was mentioned in comparative assessment research which affirmed the availability of circular economy in reducing resource consumption and environmental pollution (Guo et al., 2017). Most of the research focused on past achievements. Although there is an old study which projects the energy demand and $CO_2$ emission of Shanghai from 2006 to 2020 following the IPCC guidelines with two scenarios, one based on base trend without any policies and the other based on basic policies (Li et al., 2010). There is still a gap in the thorough circular economy implementation analysis based on the urban metabolism field of Shanghai for long-term future development. And the study about how circular economy fosters sustainable development of Shanghai can provide references for the transformation of mega-cities' development in the future.

### 1.2.2 Beijing

Beijing is the capital of China, famous as the political and cultural center of the country, a world-famous ancient capital and a modern international city. As the second largest Chinese city, in 2020, the GDP of Beijing is 3610 billion yuan with 21.89 million resident populations (Beijing-Municipal-Bureau-of-Statistics, 2021). The rapid growth of the economy in Beijing brings problems such as air deterioration, insufficient urban infrastructure services, and extensive consumption of resource and energy (Yang et al., 2020). Besides, Beijing has the problem of resource scarcity and the requirements of production and daily life rely on external inputs (Song et al., 2015). Due to these vulnerabilities, sustainable urban development pathways are critical for Beijing.

Beijing has the concept of building a world-class harmonious and liveable city, and has set the goal of becoming an eco-city by 2035, when the "big city disease" will be significantly treated, and by 2050, Beijing would achieve the target to be a model of sustainable development for mega-cities (Beijing-Municipal-Commission-of-Planning-and-Natural-Resources, 2018). To mitigate and adapt to climate change, Beijing plans to protect and restore natural ecosystems, maintain biodiversity, and enhance ecosystem services, while strengthening sustainable management of natural resources and enhancing urban resilience (Beijing-Municipal-Commission-of-Planning-and-Natural-Resources, 2018).

The research about urban metabolism of Beijing was made. Zhang et al. (2014) used flow analysis and utility analysis from ecological network theory, combining monetary IO tables to compile physical IO tables which accounted for ecological elements, to discuss the characteristics of Beijing's metabolic system and provide a scientific basis for more sustainable urban development of Beijing. And for the literature that has focused on the analysis of energy and environmental issues in Beijing, IO tables were commonly used, especially for the $CO_2$ emission analysis (Guo et al., 2012; Zhou et al., 2010). Scenarios were used to analyse the future trends of Beijing's urban development. Feng and Zhang (2012) used three scenarios: business-as-usual (BAU), basic-policy (BP) and low-carbon (LC) for energy demand, energy structure and carbon emission analysis of Beijing from 2007 to 2035 to find out which model and policies are most eco-friendly. Another study has focused on the impacts of urban land use changes for the sustainable urbanization from 2015 to 2035 based on status quo scenario (SQ) and urban planning development scenario (UPD) (Xu et al., 2019). For CE strategies, the research mostly focused on how to describe the practice and progress of CE development in Chinese cities (Fan & Fang, 2020; Guo et al., 2017). Combining the

CE strategies and sustainable urban development, and using scenarios to describe the future potentials and evaluate the environmental impacts, for Beijing, can provide a valuable reference for sustainable urban development with CE as the development model and strategy.

## 1.3 Aim and research questions

The thesis aim is to evaluate the resource use reduction potentials of implementing circular economy strategies in Shanghai and Beijing in 2050 and assess the $CO_2$ emission impacts.

In order to assess the $CO_2$ emission impact of CE strategies, it is important to evaluate the influence of resource use on different strategies and compare the differences efficiently. To find a proper way to assess the impact and benefits, the following research questions are proposed to be addressed:

1. “What are the strategies that can be put in place to affect consumption and production in a CE perspective?”

2. “How much resource is reduced by applying CE strategies in 2050 to final demand?”

3. “What are the emission hotspots of the production stage for different resources and how much potential do they have to reduce emissions in terms of production side?”

4. “How much $CO_2$ emission can be offset with the application of CE strategies?”

## 1.4 Scope

This thesis addresses the reduction potentials and impacts of resource use and $CO_2$ emission for CE strategies applying in mega-cities in China, with case studies focused on Shanghai and Beijing.

The assessment focuses on the consumption side of the case study cities at first because the consumption needs trigger the productive activities including the productive activities outside the cities’ territories (Christis et al., 2019; Ramaswami et al., 2012). And there is research that shows the consumption-based emissions in four megacities in China including Shanghai and Beijing were much larger than the production-based emissions (Meng et al., 2017). Through the global supply chain, the consumption in Shanghai and Beijing can impact the resource use and $CO_2$ emission globally by productive activities all over the world. The productive activities within and without the cities’ territories should be used together to measure the cities’ resource use and environmental impacts (Christis et al., 2019; Satterthwaite, 2008). The final consumption of cities is the sum of household consumption (including rural household consumption and urban household consumption) and government consumption excluding the capital formation and inventory increase and export, that can link to CE strategies directly. The consumption analysis is based on the consumption data within the whole selected year.

The main focus of the thesis is to quantify and evaluate the impacts of CE strategies for urban development in both resource use and $CO_2$ emission perspectives. The strategies and targets that cannot be converted quantitatively are not taken into account. This may lead to an underestimation of the effect of CE strategies on reducing resource use and $CO_2$ emissions.

# 2 Methodology

The methodology chapter describes the methods used to reach the research aim step by step. The general workflow and methods are shown in Figure 2.1. The IPAT model is used to generate the scenarios and the IO analysis combining with the scenario can assess the resource use changes in monetary units. With the scenario modelling results and the database Exiobase, MRIO analysis is used to evaluate the reduction of $CO_2$ emission with different strategies.

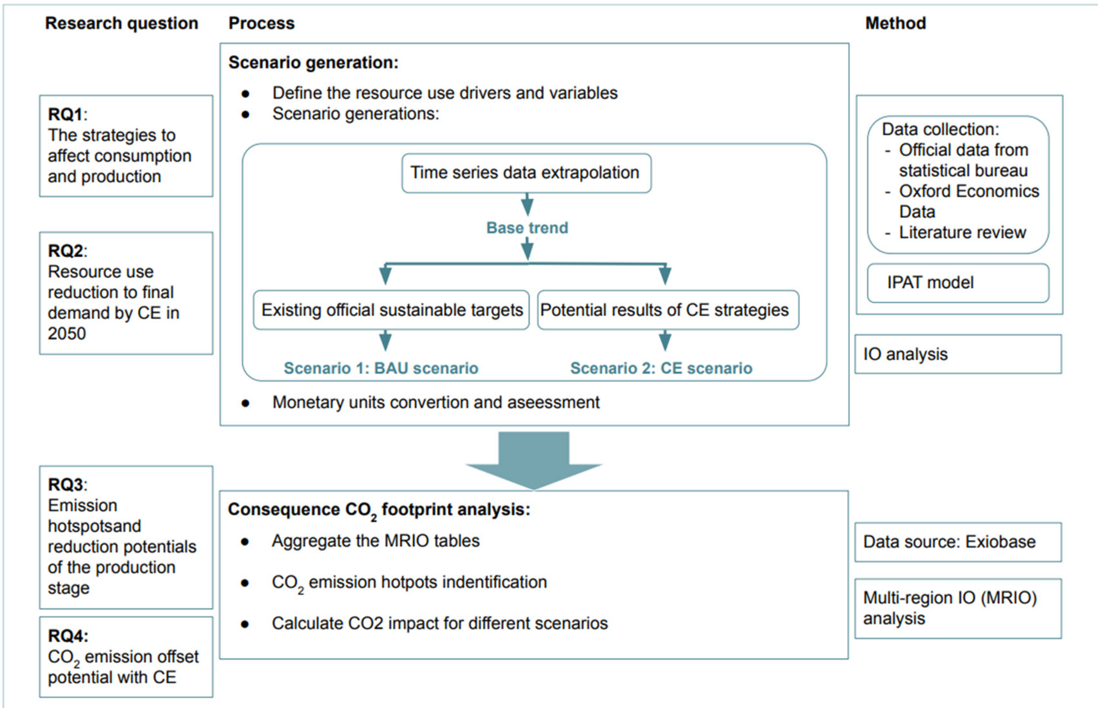



*Figure 2.1 Conceptual framework of methods*

## 2.1 Scenario modelling

To analyse and evaluate the resource consumption reduction potentials in 2050, two scenarios are developed to describe the potential effects of different sustainable strategies on resource use and $CO_2$ emission:

Business-As-Usual (BAU2050) scenario: BAU2050 scenario is based on the current resource consumption and the future sustainable urban development plan. Most strategies and targets are from the official plans with existing sustainability targets from different cities' municipalities.

Circular Economy (CE2050) scenario: CE2050 scenario describes the potential future of less resource use and less $CO_2$ emission that would result from CE strategies application. The targets are the reference figures from CE research and publications.

The development of scenarios will be made by analysing the current trends in the urban system with linear extrapolation and future assumptions based on the quantitative plans and targets embedded the population change, and the units of results should be the resource units at first (i.e. L of water, kWh energy and kg materials). The conceptual model of scenario modelling is shown as Figure 2.2. IPAT model is used to build up scenarios with resource units. Then when the scenarios are modelled by input-output

(IO) analysis, the scenarios are converted to financial units for modelling and the results reflect the changes of final consumption of case study cities in different scenarios. The results of final demand will be used to evaluate $CO_2$ emission in consequence footprint analysis which is explained in Chapter 2.2.

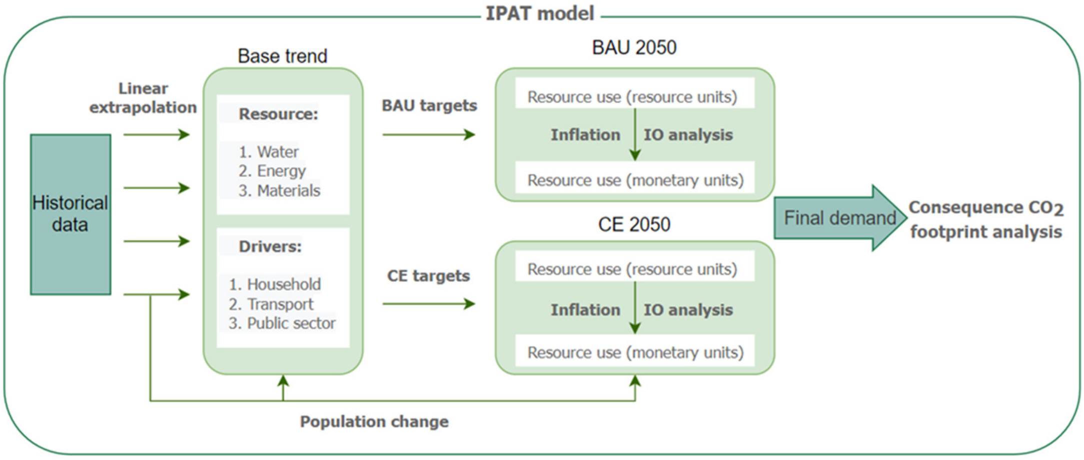



*Figure 2.2 Conceptual model of scenario modelling*

### 2.1.1 IPAT model

The IPAT model is applied to assess the environmental impact of human activities. The equation (Environmental Impact = Population × Affluence × Technology) aligns the population and the environmental damage and provides an understandable framework to measure the driving force of environmental impacts (Harrison & Pearce, 2000). The equation is described as equation (2.1):

$$I = P \times A \times T \tag{2.1}$$

$I$ : Environmental impact (i.e. $CO_2$ emission in the thesis)

$P$ : Population

$A$ : Affluence (unit: consumption per person)

$T$ : Technology (unit: impact per unit of consumption)

In the scenario generation, the scenario results focus on the Affluence (consumption per person) and the Population × Affluence (absolute consumption). The different strategies from each scenario affects the consumption. The total control target affects absolute consumption; the per capita control target affects the Affluence in IPAT equation, and this value in combination with changes of population affects absolute consumption. And for the environmental impact assessment, the consumption results of scenarios are converted to the monetary unit (Eurostat) by modelling with IO tables. The environmental impact can be calculated by the final consumption results combining with the consequence $CO_2$ footprint analysis using MRIO analysis which is described in detail in Chapter 2.2.

### 2.1.2 Model structure

The developed scenarios in this thesis consider the resource consumption in Shanghai and Beijing. The time period of the analysis spans the years 2017 to 2050, with 2017 as the base year. This thesis analyses three basic types of resources: 1) Water, 2) Energy and 3) Materials. The main drivers are 1) Household, 2) Transport and 3) Public sector which are key societal categories.

Considering the characteristics of different resource, the sectors are split into subsectors in the model. For the resource Material, the household sector includes 8 subsectors based on the material sectors in Oxford Economics Data: 1) food and non-alcoholic beverages per year, 2) alcoholic beverages, tobacco and narcotics per year, 3) clothing and footwear per year, 4) furnishings, household equipment and routine household maintenance per year, 5) health per year, 6) information and communication per year, 7) recreation, sport, and culture per year, 8) personal care, social protection and miscellaneous goods per year. The driving factor Transport is divided into two subsectors including private transport and public transport.

### 2.1.3 Data collection and targets screening

The time-series data is collected to know the resource consumption by years and prepare for extrapolating the trend to assume the resource consumption results by the scenario year in the future. The data sources and timeline information about the time series data are shown in Table 2.1.

*Table 2.1 The sources of time series data for Shanghai and Beijing*

| City | Resources | Time series | Data sources |
|---|---|---|---|
| Shanghai | Water | 2010-2019 | Shanghai Statistical Yearbook (Shanghai-Municipal-Bureau-of-Statistics, 2021) |
| | Energy | 2010-2019 | Shanghai Statistical Yearbook (Shanghai-Municipal-Bureau-of-Statistics, 2021) |
| | Materials | 2000-2035 | Oxford Economics Data (Oxford-Economics, 2020) |
| Beijing | Water | 2001-2019 | Beijing Water Authority |
| | Energy | 2010-2020 | Beijing Statistical Yearbook (Beijing-Municipal-Bureau-of-Statistics, 2021) |
| | Materials | 2000-2035 | Oxford Economics Data (Oxford-Economics, 2020) |

The data of water and energy is from the official government's statistical documents at the municipality level which focus on the consumption-based resource use including the Statistical Yearbook and other relevant reports. The household consumption data for materials is from Oxford Economics, that provides the consumer expenditure of goods and services at the city level from the year 2000 projected to 2035 (Oxford-Economics, 2020).

The strategies and targets used in BAU and CE scenarios are located through the government and sector planning documents, reports and global research and literature in relevant sectors, including the City's Master Plan, City's Infrastructure Development Plan, Circular Economy Development Plan and other relevant studies. If there are missing targets in a key modelling sector, studies of locations with similar characteristics or authoritative references will be sought to fill in the information. It is worth noting that the targets selected here only consider those affecting consumption; strategies where technological advances only affect emissions are not included here, but will be considered in consequence $CO_2$ footprint analysis in Chapter 2.2.

### 2.1.4 Scenario quantification

As the Figure 2.2 shows, for base trend, the time-series resource consumption data before the base year 2017 is used to extrapolate the trend to 2050 for different resources by societal categories linearly. The data used to draw the treadlines is the total resource consumption per year and the equations of the trendlines are used to project figures to 2050 regardless of the R-value. The resource consumption per unit is the total resource consumption value divided by the population of the corresponding year and the unit values and the absolute values of the resource consumption are used to calculate the change rates respectively.

For BAU and CE scenarios, the quantitative target are screened out to model at what affects the resource consumption. When modelling the efficiency of BAU and CE strategies, the rate of change is considered only once within a limited time frame. In this way, the scenario results in 2050 are calculated by the values of base year 2017 multiplied by the change rate from each target. And the unit values and the absolute results of resource consumption are used to compare with the values of the base year 2017 to get the respective change rates.

The framework of base trend and BAU scenarios quantification can be described as Table A.1 in Appendix. The CE scenario quantification is followed the same framework.

### 2.1.5 Economic modelling using IO tables

An IO table is always used to analyse the economic impacts and provide an approach to calculate the resource use and environmental impacts in economies (Chen & Chen, 2011; Corona et al., 2019). In this thesis, IO tables are used to assess the resource use changes in monetary units focusing on the changes of final demand.

There are 42 sectors in official IO tables from Shanghai and Beijing. To simplify the analysis and reduce the data complexity, the 42 sectors in official IO tables for Chinese cities are aggregated to 17 sectors which are shown below in Table 2.2. These 17 sectors are chosen as a common structure corresponding to the 1-digit structure of CPA2 2008 due to the unavailability of some secondary regional data for a finer-grained level based on Nikita and Sjoerd's method (Nikita & Sjoerd, 2022).

*Table 2.2 The aggregation sectors for IO tables*

| | Sector code | Sector name |
|---|---|---|
| 0 | <A> | Agriculture, forestry and fishing |
| 1 | <B> | Mining and quarrying |

| | | |
|---|---|---|
| 2 | <C> | Manufacturing |
| 3 | **<D>** | **Electricity, gas, steam and air conditioning supply** |
| 4 | **<E>** | **Water supply; sewerage, waste management and remediation activities** |
| 5 | <F> | Construction |
| 6 | **<G>** | **Wholesale and retail trade; repair of motor vehicles and motorcycles** |
| 7 | **<H>** | **Transportation and storage** |
| 8 | <I> | Accommodation and food service activities |
| 9 | <J> | Information and communication |
| 10 | <K> | Financial and insurance activities |
| 11 | <L> | Real estate activities |
| 12 | <M,N> | Professional, scientific and technical activities; Administrative and support service activities |
| 13 | <O> | Public administration and defence; compulsory social security |
| 14 | <P> | Education |
| 15 | <Q> | Human health and social work activities |
| 16 | <R,S,T> | Arts, entertainment and recreation; Other service activities; Activities of households as employers; undifferentiated goods- and services-producing activities of households for own use |

To calculate the total expenditure of different resources in 2017, the relevant IO sectors in the aggregated IO tables are identified. All the relevant sectors in the scenario modelling are bolded in Table 2.2. The total expenditure of relevant sector is the total expenditure including the rural and urban household expenditure and public expenditure of corresponding resources in 2017 converted from 10000 yuan to million Euro.

To calculate the total expenditure of different resources in 2050, the inflation rate needs to be considered. In the thesis, the inflation rate is assumed as the cumulative rate based on the average historical inflation rate from China Future Inflation Calculator (Official Inflation Data, 2022). When assuming the rate of inflation after 2022, the average historical inflation rate listed on this website is used. With this rate, the average inflation rate from 2017 to 2050 can be calculated by this calculator. Here, the average inflation rate is 4.13% per year, producing a cumulative price increase of 279.71% between 2017 and 2050. And due to the fact that the data source of materials --- Oxford Economics Data already included the inflation, steps performed to consider inflation are not calculated in the economic modelling of material consumption.

When calculating the total expenditure of different resources in 2050, the relevant sector can be divided as affected sector and unaffected sector. To calculate the affected sector, the subsectors within the relevant sector is considered, and the percentage of the corresponding resource consumption in the identified sector will be assumed. The results of share percentage multiplied by the total expenditure of relevant sector are the expenditure of corresponding resources in 2017. Then the unit price in 2017 is calculated by corresponding expenditure of resources in 2017 divided by the absolute value of resource consumption in 2017. Considering the inflation, the unit price in 2050 is calculated by multiplying unit price in 2017 by the inflation rate. Then the total expenditure of affected sector is calculated by the absolute value of resource use in 2050 from different scenarios multiplying the unit price in 2050. The expenditure of unaffected sector in 2017 is the same as the total expenditure of relevant IO sector in 2017 minus the affected sector in 2017. The expenditure of unaffected sector in 2017 multiplying the inflation rate is the expenditure of unaffected sector in 2050. Adding the expenditure of affected and unaffected sectors in 2050 together can get the total expenditure of corresponding resources in 2050.

To make it easier to understand the calculation process, here is an example. The relevant IO sector for energy of transport is sector <H> transport and storage. And the percentage of the transport including public and private transport which is affected part in sector <H> is estimated to be 18.674 % of the whole sector expenditure in Shanghai scenario (3.92 % public transport and 14.75 % private transport) in 2017. So first, we assume that the share of affected parts of the sectors is the same in 2017 and in 2050 in both BAU and CE scenarios. And then the unit price embedded the inflation would be used to multiply the absolute resource consumption with different scenarios. The remaining share, for example 81.326% in the case of sector <H> in Shanghai scenario, is only affected by inflation. So, in conclusion, the total expenditure in sector <H> is therefore calculated in the following way in both BAU and CE scenarios:

Total expenditure of <H>

= Affected sector + Unaffected sector

= Affected sector: {[(Total expenditure of <H> 2017 × 3.92 %)/ absolute resource use of public transport 2017] × inflation rate × absolute resource use of public transport 2050 (BAU or CE) + [(Total expenditure of <H> 2017 × 14.75 %)/ absolute resource use of private transport 2017] × inflation rate × absolute resource use of private transport 2050 (BAU or CE)} + Unaffected sector: {[Total expenditure of <H> 2017 × (1-3.92 % -14.75 %)] × inflation rate}

The framework of economic modelling is described as Table A.2 in Appendix. And the specific modelling steps are detailed in Appendix II.

## 2.2 Consequence $CO_2$ footprint analysis

To evaluate the impacts of $CO_2$ emission with different strategies, especially for CE application in 2050, and to connect the emissions to the whole world within and without the case study cities, multi-regional Input-Output (MRIO) analysis is used.

The process of Consequence $CO_2$ footprint analysis is shown as Figure 2.3. The Exiobase is chosen as MRIO database. The total expenditure results from scenario modelling will be used to calculate the $CO_2$ emission. The results of $CO_2$ emission calculation should be in unit kg $CO_2$ eq.

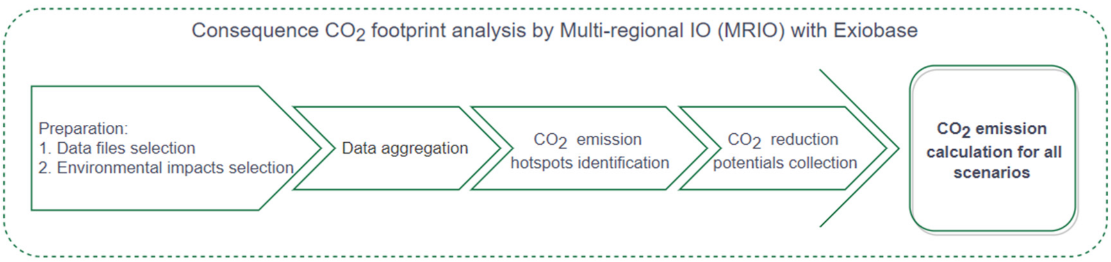



*Figure 2.3 The process of consequence $CO_2$ footprint analysis*

### 2.2.1 Multi-regional Input-Output (MRIO) analysis with Exiobase

Exiobase is a database with global and detailed environmentally extended multi-regional Input-Output (EE-MRIO) tables which presents the economic and environmental data and describes the relationships between global economy and their environmental consequences (Stadler et al., 2018). For monetary form of Exiobase, the data are about 47 regions, 200 products and 163 industries, that makes it accurate, thorough and suitable for environmental impacts analysis.

Using MRIO to model the scenarios, three blocks including intermediate matrix, environmental extension ($CO_2$ emission in this thesis) and final demand. The framework is shown as Figure 2.4. The details of data aggregation and calculation are shown in Chapter 2.2.2.

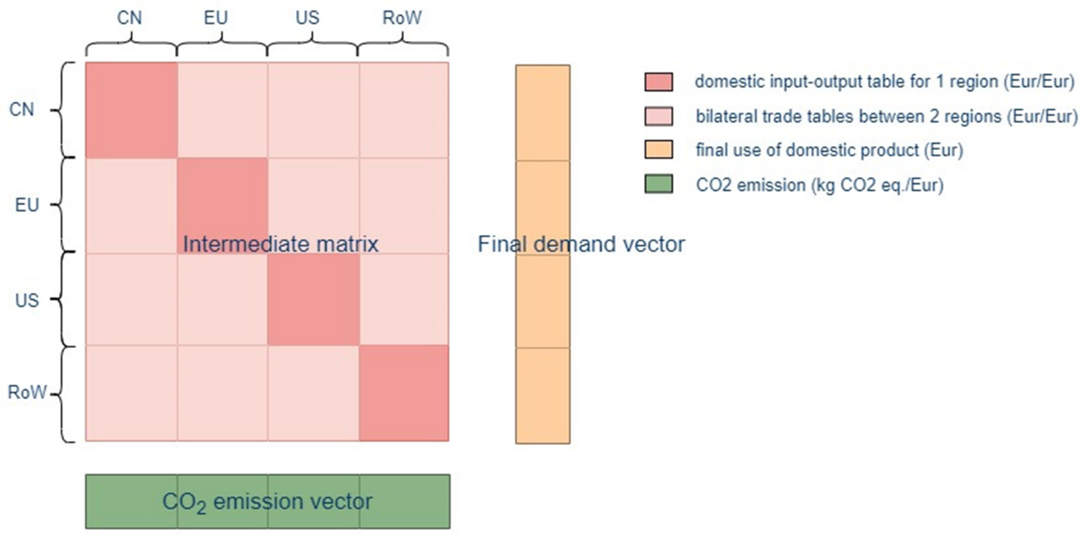



*Figure 2.4 The framework of multi-regional Input-Output (MRIO) table*

### 2.2.2 Data aggregation and disaggregation

To simplify the global production system, all the documents related to $CO_2$ footprint analysis are aggregate into 4 regions, Europe (Edwards et al.), the United States (US), China (CN) embedded the case study cities and rest of the world (RoW).

After identifying the hotspots, the 163 industries in all the documents will be aggregated to 17 sectors same with IO table analysis in scenario modelling to connect the scenario results and the MRIO analysis process.

Moreover, the internal imports of the country where the study city is located into are taken into consideration, to enable a more complete analysis on the consumption side. To consider the transaction flows within the country, the CN region is disaggregated into study city and rest of China (RoCN), shown as Figure 2.5.

To disaggregate the CN intermediate matrix, the national IO table of Beijing and Shanghai are used as a supplement for Exiobase. The main equations used for calculation are:

$$S_i = S_a \times w_i \tag{2.2}$$

$S_i$ : The imports matrix from region a to study city (Million Eur)

$S_a$ : The coefficient intermediate matrix of region a (Million Eur/ Million Eur)

$W_i$ : Diagonal matrix of imports value of study city (Million Eur)

$$S_e = S_{city} \times W_e \tag{2.3}$$

$S_e$ : The exports matrix from study city to region a (Million Eur)

$S_{city}$ : The coefficient intermediate matrix of study city (Million Eur/ Million Eur)

$W_e$ : Diagonal matrix of exports value of study city (Million Eur)

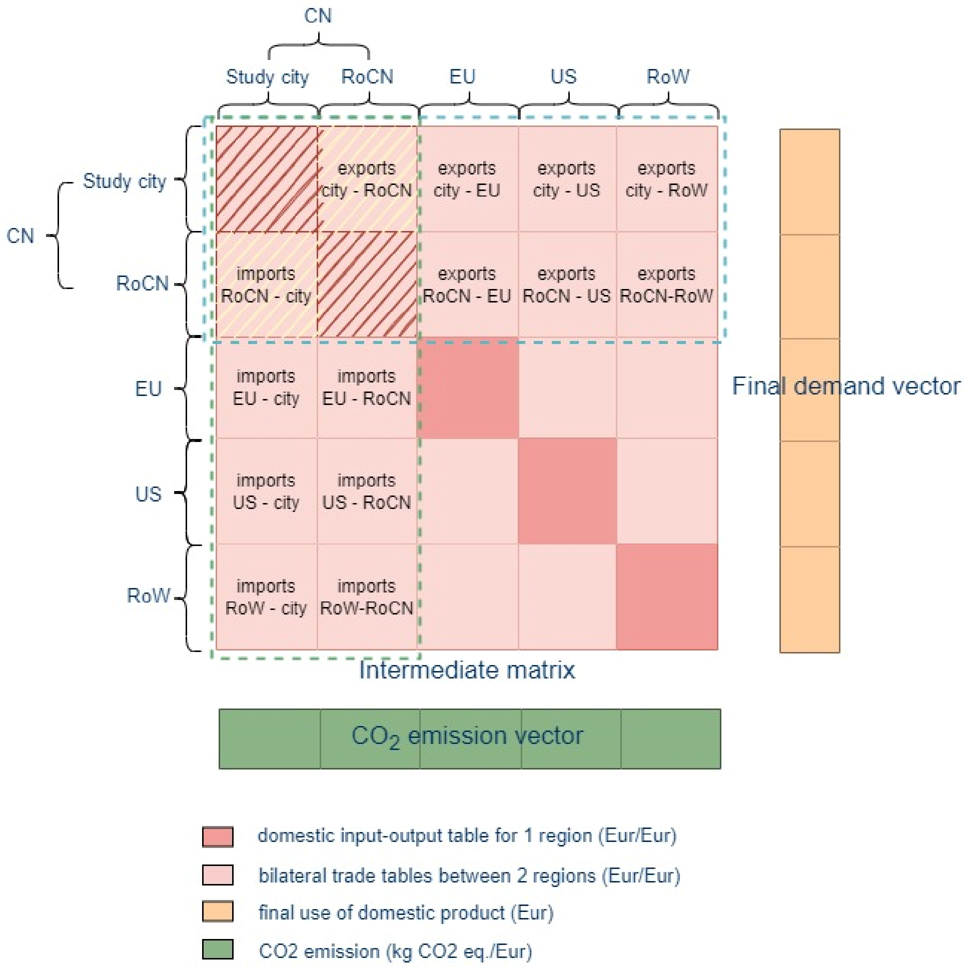



*Figure 2.5 The disaggregated MRIO table for study city*

Before the disaggregation, the RoCN intermediate matrix (absolute value) is calculate by intermediate matrix CN - intermediate matrix of study city. Then the same relationship is used to calculate the total output for RoCN to calculate the RoCN intermediate matrix (coefficient).

With all the coefficient matrix, the imports and exports matrix can be calculated with equations (2.2) and (2.3). It is important to be mentioned here that the import-export relationship (intermediate matrix) for the rest of the world outside of China and the study cities is approximately understood to be equal to the import-export relationship (intermediate matrix) between these regions and China, and this part of the data comes from Exiobase. And at the same time, these parts' imports and exports matrix for study cities is calculated aggregated as one region --- Rest of World (without China) and is split to three regions used here (EU, US, RoW) by the proportion of these original matrix. The matrix for RoCN use the original matrix to minus the matrix for study.

To help to understand easily, here is an example for disaggregation of Beijing:

1. Calculate the imports matrix CN to Beijing: coefficient intermediate matrix RoCN (CN-Beijing) * absolute internal imports values matrix (diagonal matrix);

2. Calculate the exports matrix Beijing to CN: coefficient intermediate matrix Beijing * absolute internal exports values matrix (diagonal matrix);

3. Calculate the imports matrix EU, US, RoW to Beijing: coefficient intermediate matrix (aggregated 3 regions to CN) * absolute international imports values matrix (diagonal matrix). Here assumes the intermediate matrix (Rest of World to CN) ≈ the intermediate matrix (Rest of World to Beijing);

4.Then disaggregate the imports matrix EU, US, RoW to Beijing by proportion. The proportion can be calculated by the absolute value intermediate matrix (EU, US, RoW to CN respectively)/ absolute value intermediate matrix (aggregated 3 regions to CN);

5. The imports matrix EU, US, RoW to RoCN respectively = The imports matrix EU, US, RoW to CN - the imports matrix EU, US, RoW to Beijing respectively;

6. Use the same method to disaggregate the exports matrix into Beijing and RoCN;

7. Organize the new intermediate matrix with absolute values. Calculate the new coefficient matrix.

### 2.2.3 Hotspots and reduction potentials identification

The $CO_2$ emission vector combined with the intermediate matrix which reflects the transaction for whole world is used to trace back the life chain of different industries. In order to analyse the $CO_2$ emission of different industry processes, the focus is on the industries that have the greatest impact on sectors impacted by the scenarios for Chinese cities and is referred to as the emission hotspot. To identify the hotspots, the industries connected to water, energy, transport and materials directly of 163 industries in Exiobase are chosen. The specific industries are shown in Table 2.3. For water, there is only one industry related; while the energy, transport and materials have 16, 8 and 20 industry process respectively.

*Table 2.3 The industries in Exiobase with corresponding resources*

| Sector | Industry process in Exiobase | Sector | Industry process in Exiobase |
|---|---|---|---|
| Water | Collection, purification and distribution of water (41) | Transport | Inland water transport |
| Energy | Production of electricity by coal | | Air transport (62) |
| | Production of electricity by gas | Material | Processing of meat cattle |
| | Production of electricity by nuclear | | Processing of meat pigs |
| | Production of electricity by hydro | | Processing of meat poultry |

| | | | |
|---|---|---|---|
| | Production of electricity by wind | | Production of meat products nec |
| | Production of electricity by petroleum and other oil derivatives | | Processing vegetable oils and fats |
| | Production of electricity by biomass and waste | | Processing of dairy products |
| | Production of electricity by solar photovoltaic | | Processed rice |
| | Production of electricity by solar thermal | | Sugar refining |
| | Production of electricity by tide, wave, ocean | | Processing of Food products nec |
| | Production of electricity by Geothermal | | Manufacture of beverages |
| | Production of electricity nec | | Manufacture of fish products |
| | Transmission of electricity | | Manufacture of tobacco products (16) |
| | Distribution and trade of electricity | | Tanning and dressing of leather; manufacture of luggage, handbags, saddlery, harness and footwear (19) |
| | Manufacture of gas; distribution of gaseous fuels through mains | | Manufacture of wearing apparel; dressing and dyeing of fur (18) |
| | Steam and hot water supply | | Manufacture of textiles (17) |
| Transport | Manufacture of motor vehicles, trailers and semi-trailers (34) | | Manufacture of furniture; manufacturing n.e.c. (36) |
| | Manufacture of other transport equipment (35) | | Sale, maintenance, repair of motor vehicles, motor vehicles parts, motorcycles, motor cycles parts and accessoiries |
| | Transport via railways | | Retail sale of automotive fuel |
| | Other land transport | | Wholesale trade and commission trade, except of motor vehicles and motorcycles (51) |
| | Transport via pipelines | | Retail trade, except of motor vehicles and motorcycles; repair of personal and household goods (52) |
| | Sea and coastal water transport | | |

The $CO_2$ emission of industry processes selected are calculated and industrial processes were ranked in descending order of emissions, with a cut-off of 75% of emissions, and the top 75% of industrial processes were defined as emission hotspots. However, for some industrial processes with overly concentrated emissions, such as the largest emission subsectors that can reach more than 50% of the total emissions and the top two subsectors that have a combined emission of nearly 90%, the 75% cut-off is not appropriate. In these cases, 90% of the total emissions is used as the cut-off. In this study, 90% is used for water and energy and 75% is for transport and materials.

To assume the $CO_2$ emission vector for 2050, the reduction potentials of these hotspots are taken into consideration. The reduction potentials are from literature and reports about emissions reduction with technological advances and other improvements. When collecting the reduction potentials, the regions of the emission hotspots should be taken into account which would impact the reduction level.

### 2.2.4 $CO_2$ footprint calculation

To calculate the $CO_2$ emission, the general formula based on the Leontief inverse is used:

$$e = b \times [I_m - A_m]^{-1} \times f \qquad (2.3)$$

$e$ : Environmental impact (i.e. $CO_2$ emission in the thesis)

$b$ : $CO_2$ emission vector

$I_m$ : Identity matrix

$A_m$ : Intermediate coefficient matrix

$[I_m - A_m]^{-1}$ : Leontief inverse

$f$ : Final demand vector

To compare the $CO_2$ emission of different scenarios and the differences between $CO_2$ reduction technologies, there will be two $CO_2$ emission vectors. The first one is vector of 2017 directly from Exiobase and the other will apply $CO_2$ reduction potentials to 2050. The $CO_2$ emission for 2017 will be calculated with $CO_2$ emission vector of 2017 from Exiobase. And when considering the $CO_2$ emission reduction potentials in 2050, the $CO_2$ emission for two scenarios will be calculated with $CO_2$ emission vector of 2050 with reduction ratio of different industries.

The intermediate matrix is organized by the method and steps mentioned in Chapter 2.2.2 and the identity matrix is the a matrix of the same size as intermediate matrix with the diagonal values of 1 and the remaining values of 0. $[I_m - A_m]^{-1}$ is known as Leontief inverse to reflect the total requirements.

The final demand vector is from the economic modelling results of scenario generation in Chapter 2.1 with 17 sectors.

With all these blocks, the consumption-based $CO_2$ footprints are calculated and the distribution of $CO_2$ emissions for the study cities in 14 sectors in different regions can be presented directly.

## 2.3 Assumptions and limitations

In this study, different assumptions were made in order to perform the modelling. The objectives of different reports and studies as qualitative targets are considered achievable, both in scenario modelling and $CO_2$ emission reduction, and the inability to reach the objectives was not considered and discussed in this study. This may lead to an overestimation of the final outcome of the policy in practice. Meanwhile, the scenarios and assumptions made in these documents are considered to hold in this study as well. Besides, the gap in targets information leads to the introduction of some reference studies to fill in, which may lead to some deviation of the modelling results from the development of the city and needs to rely on the development of subsequent research in related fields to improve the accuracy and precision in the future. Different reference choices can lead to partially different results.

In consequence footprint analysis, the 163 industries are aggregated to 17 sectors by the corresponding classification references in Exiobase. For these industries which match with several sectors, they are split equally according to the number of corresponding sectors according to that there is no information on specific allocation percentages. And the transaction flow is considered to be unchanged.To include the impact of imports within China on the emissions of the study cities, IO tables for the two study cities from the national statistical data are introduced as a complement to Exiobase. The gap between these two databases may lead to some small negative values in intermediate matrix which are assumed to be 0 in this study. The choice of database can lead to different results, and the results of this study can only represent the analysis based on Exiobase as well as Chinese national statistics, and along with the error caused by the differences in information between the two databases.

# 3 Results and discussion

This chapter presents the results of this project which answer the proposed research questions. The Chapter 3.1 is related to the research questions one and two, and the Chapter 3.2 is related to the third and fourth research questions.

## 3.1 Scenario modelling

### 3.1.1 Strategies for Scenarios

The specific objectives and targets are shown as Table 3.1.

*Table 3.1 The targets and strategies for Scenarios modelling*

| City | Resources | Targets | Data sources |
|---|---|---|---|
| BAU Scenario | | | |
| Shanghai | Water | By 2035, the total annual water consumption will be controlled at 13.8 billion cubic meters. | Shanghai master plan 2017-2035 (Shanghai-Municipal-Government, 2018) |
| | Energy | 1) By 2035, the public transport proportion of all-mode travels in the city will be about 40%.<br>2) The proportion of individual motorized traffic trips in the main urban area is reduced to less than 18%. | Shanghai master plan 2017-2035 (Shanghai-Municipal-Government, 2018) |
| Beijing | Water | The total annual water consumption in the city is about 3.82 billion cubic meters, to be controlled within 4.3 billion cubic meters by 2020, and the total water consumption to meet national requirements by 2035. The city's total annual production and domestic water consumption during the "14th Five-Year Plan" period will be controlled to within 3 billion cubic meters. | Beijing master plan 2016-2035 (Beijing-Municipal-Commission-of-Planning-and-Natural-Resources, 2018); Beijing Major Infrastructure Development Plan for the 14th Five-Year Plan Period (Beijing-Municipal-Government, 2022) |
| | Energy | 1) By 2020 the proportion of green travel in the city from the status quota 70.7% to more than 75%, by 2035 not less than 80%; by 2020 the proportion of bicycle travel is not less than 10.6%, by 2035 not less than 12.6%.<br>2) By 2020, the proportion of private vehicle trips and the average intensity of trips will be reduced by 10%-15%, and by 2035, the rate of reduction will be no less than 30%. | Beijing master plan 2016-2035 (Beijing-Municipal-Commission-of-Planning-and-Natural-Resources, 2018) |
| CE Scenario | | | |

| | | | |
|---|---|---|---|
| Shanghai | Water | We can all use 30 percent less water by installing water-efficient fixtures and appliances. | US EPA (EPA, 2017) |
| | Energy | 1) For Transport:<br>2050: new modal split: strong increase in the share of PT [public transport] (55%); significant decrease in the share of MIT (<10%) and changed vehicle fleet.<br>2) For Household:<br>By 2025, …the energy consumption per unit GDP will be reduced by 13.5% compared with 2020. | 1) For Transport: (Gassner et al., 2021)<br>2) For Household: "Fourteen Five" Circular Economy Development Plan, 2020 (National-Development-and-Reform-Commission, 2020) |
| | Materials | For Food and non-alcoholic beverages:<br>Most of the food waste (4.1 million tonnes or 61 percent) is avoidable and could have been eaten had it been better managed. | (UN-Environment-Programme, n.d.) |
| Beijing | Water | By 2025, …the water consumption per unit GDP will be reduced by 16% compared with 2020. | "Fourteen Five" Circular Economy Development Plan, 2020 (National-Development-and-Reform-Commission, 2020) |
| | Energy | 1) For Transport:<br>2050: new modal split: strong increase in the share of PT [public transport] (55%); significant decrease in the share of MIT (<10%) and changed vehicle fleet.<br>2) For Household:<br>By 2025, …the energy consumption per unit GDP will be reduced by 13.5% compared with 2020. | 1) For Transport: (Gassner et al., 2021)<br>2) For Household: "Fourteen Five" Circular Economy Development Plan, 2020 (National-Development-and-Reform-Commission, 2020) |
| | Materials | For Food and non-alcoholic beverages:<br>Most of the food waste (4.1 million tonnes or 61 percent) is avoidable and could have been eaten had it been better managed. | (UN-Environment-Programme, n.d.) |

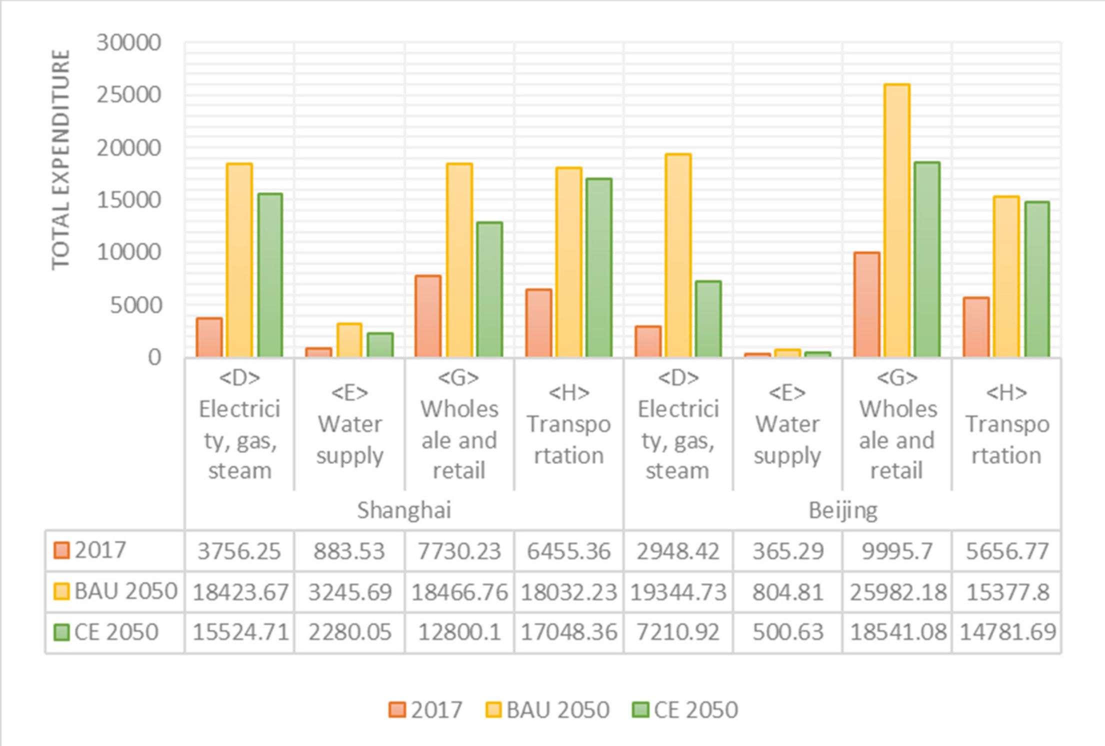
For BAU scenarios, the targets focus on the resources of water and energy for both cities. For both Shanghai and Beijing, there is a lack of information about the targets of materials. The water targets are general targets about the total annual water consumption which includes household consumption, public consumption and industrial consumption as well. The total annual water consumption target of Beijing in

2035 is 3 billion cubic meter which is much more ambitious than the target of Shanghai. But when considering the population of each city, the value of water consumption per capita may show different results. The targets for energy are mostly about the shared model of transport.  For Shanghai, the plans clearly state the requirements for the percentage of public transport --- the public transport proportion of all-mode travels in the city will be about 40%. For Beijing, there is no clear ratio requirement for public transport, the plan is more about green travel including cycling and walking requirements, but the percentage of public transport can be calculated by the ratio of different modes of travel. For private transport, Shanghai's target is directly the change in the share of private transport by 2035, while Beijing's target is the change in the rate of reduction, which makes it impossible to directly compare these two targets to see which one is more ambitious.

For CE scenarios, the targets focus on all three resources of water, energy and materials for both cities. Due to the lack of information on CE targets, some of the targets were collected from studies on places with similar characteristics to the study city or from relatively authoritative reference documents. For Shanghai, the water target is based on the reference from US EPA due to the lack of ambitious targets for water; for Beijing, this target is based on the Circular Economy development plan. The target of Shanghai is based on technical applications that make it easy to calculate and simulate. The target of Beijing is about the water consumption per unit GDP which makes this target calculation requires more data such as GDP forecasts for different years, etc. Meanwhile, this is a goal for the next five years and may require a reasonable extrapolation to a more long-term time approach. For energy targets, both cities have the targets for transport based on the reference of Vienna related to transport shared model and the household energy targets are general targets about the energy consumption per unit GDP. Vienna's study of the share model is consistent with the way traffic in the city is analysed, which makes it a good reference. Compared with the BAU target for transport in Shanghai (40% for public transport and 18% for private transport), the most ambitious target in the reference is chosen as the CE target (55% for public transport and 10% for private transport). The same objective makes the changes in energy consumption of cities more based on the city's own characteristics, such as changes in population and energy consumption structure in base year 2017. And the gap of material targets still exits. The targets for materials are only about the sector food and non-alcoholic beverages from UN Environment Programme. This target is not a specific target for Chinese cities and may conflict with the food structure of Chinese cities, resulting in less accurate model results regarding materials.

### 3.1.2 City model results

The scenario modelling results from consumption side only affect the sectors <D> electricity, gas, steam and air conditioning supply, <E> water supply; sewerage, waste management and remediation activities, <G> wholesale and retail trade; repair of motor vehicles and motorcycles and <H> transportation and storage. And the results in million Euro unit are shown in Figure 3.1.




| | Shanghai <D> Electricity, gas, steam | Shanghai <E> Water supply | Shanghai <G> Wholesale and retail | Shanghai <H> Transportation | Beijing <D> Electricity, gas, steam | Beijing <E> Water supply | Beijing <G> Wholesale and retail | Beijing <H> Transportation |
|---|---|---|---|---|---|---|---|---|
| 2017 | 3756.25 | 883.53 | 7730.23 | 6455.36 | 2948.42 | 365.29 | 9995.7 | 5656.77 |
| BAU 2050 | 18423.67 | 3245.69 | 18466.76 | 18032.23 | 19344.73 | 804.81 | 25982.18 | 15377.8 |
| CE 2050 | 15524.71 | 2280.05 | 12800.1 | 17048.36 | 7210.92 | 500.63 | 18541.08 | 14781.69 |

*Figure 3.1 The Household expenditure of sectors affected in Shanghai and Beijing (Million EUR)*

From the figure, it can be seen that the household expenditure focuses more on the sectors <D>, <G> and <H>. Both scenarios for 2050 have a higher consumption than in 2017, regardless of the target for resource consumption, which is due to population growth and inflation. A side-by-side comparison of the two 2050 scenarios can eliminate this aspect and better show how different strategies and targets have different impacts on resource consumption.

Compared between these sectors, the reduction trends from BAU scenarios to CE scenarios can be seen most clearly in sectors <D> electricity, gas, steam and air conditioning supply and <G> wholesale and retail trade; repair of motor vehicles and motorcycles for both cities. For Shanghai, CE strategies have the most effect on reducing household expenditure in sector <G>; for Beijing, the highest degree of decline can be observed in sector <D> and followed by sector <G>. For the big influence of sector <D>, the reason is that in the scenarios, the target about energy is considered to impact 100% of sector <D>, making the change very visible at the level of this sector. And the difference in the magnitude of the change between Beijing and Shanghai for the same target in sector <D> is due to the fact that the unit GDP-based target is subject to different effects depending on the local GDP forecast. The scenario impacts more than 50% of sector <G> which leads to significant reduction from BAU scenario to CE scenario. When comparing the change of sector <G> from 2017 to BAU scenario to CE scenario, the magnitude of the change is the same because the food-based target is directly about the material unit.

In total, the CE scenarios reduce around 10515 million Euro household expenditure for Shanghai and around 20475 million Euro household expenditure for Beijing compared with BAU scenarios. For Beijing, the sector <D> reduces more than 12000 million Euro which accounts for more than 50% of the total reduction. This indicates that in our scenario, for the collected targets and plans, the CE strategy is more useful for Beijing to reduce resource consumption, where sector <D> plays a greater role, indicating that there is the greatest potential and effectiveness in reducing energy use.

After discussing the general pattern, the results for each sector are discussed separately. From the figure, for sector <D> in both cities, the household expenditure of BAU scenarios is the highest one, while the results of CE scenario decrease to some extent but are still higher than the values of 2017. This is due to the fact that CE targets are more challenging than BAU's, while population growth and inflation will lead to higher resource consumption in absolute terms in 2050. In 2017, the household expenditure of sector <D> in Shanghai is higher than in Beijing, however, the increasing rate from 2017 to 2050 for BAU scenario of Shanghai is lower which makes the household expenditure of Beijing higher in BAU scenario 2050. And comparing the results for CE scenarios, the values for Beijing is much lower and the decline from BAU to CE scenario is greater that is more than half. It can be said that the CE strategies have led to a decline in household expenditure for sector <D> in both cities, with the effect being more pronounced in Beijing.

For sector <E>, in general, the household expenditure of sector <E> in Shanghai is much higher than expenditure in Beijing in either scenario. And the increasing rate from 2017 to 2050 of BAU scenario of Shanghai is much higher as well. Although the CE scenario decreases by almost 1000 million Euro compared with the BAU scenario in Shanghai, the absolute value of household expenditure in CE scenario is still much higher than Beijing which makes the reduction level not sufficient. This is because Shanghai's BAU target is a limit on the growth of water consumption, not a target to reduce it, and at the same time, Shanghai's target value is much higher than Beijing's.

For sector <G> of all scenarios, the household expenditure in Beijing is higher than Shanghai. And the increasing rates from 2017 to 2050 in both scenarios in Beijing are higher than Shanghai. Although the CE scenario decreases around 7500 million Euro for Beijing from BAU scenario, the absolute value of household expenditure for CE scenario is still higher than the result for BAU scenario in Shanghai. Both BAU scenarios and CE have the same target for both cities, while inflation is the same, which leads to consumption values that are only affected by base consumption values and population growth.

For sector <H> transportation and storage, same as the other sectors, the BAU scenario has the highest value of household expenditure and the results in 2017 are the lowest. Compared with BAU scenarios, the CE scenarios also decrease the values of household expenditure, however, the degree of decline is very slight, especially when compared to the growth rate from 2017 to 2050 of BAU scenario. This may be due to the fact that the reduction in private transport will be accompanied by an increase in public transport energy consumption, while the small proportion of both components in the sector <H> leads to the fact that a change in the target has little impact on the change in resource consumption.

In terms of the absolute volume of resource consumption, sectors <D>, <G> and <H> have a greater potential to reduce consumption. In this case, the potential of sector <D> is already reflected in the scenario modelling, and the subsequent need for more reduction in consumption side can only make the CE strategy more ambitious. As for sectors <G> and <H>, collecting additional impact targets within more sectors like targets for other materials not only food would allow for more accurate modelling and capture the full potential for reduced consumption in these two sectors.

## 3.2 Consequence $CO_2$ footprint analysis

### 3.2.1 $CO_2$ hotspots identification

The distribution of hotspots for different resources shows different patterns, as shown in Figure 3.2. The details of the specific subsector hotspots corresponding to each sector are shown in Table A.3 in Appendix.

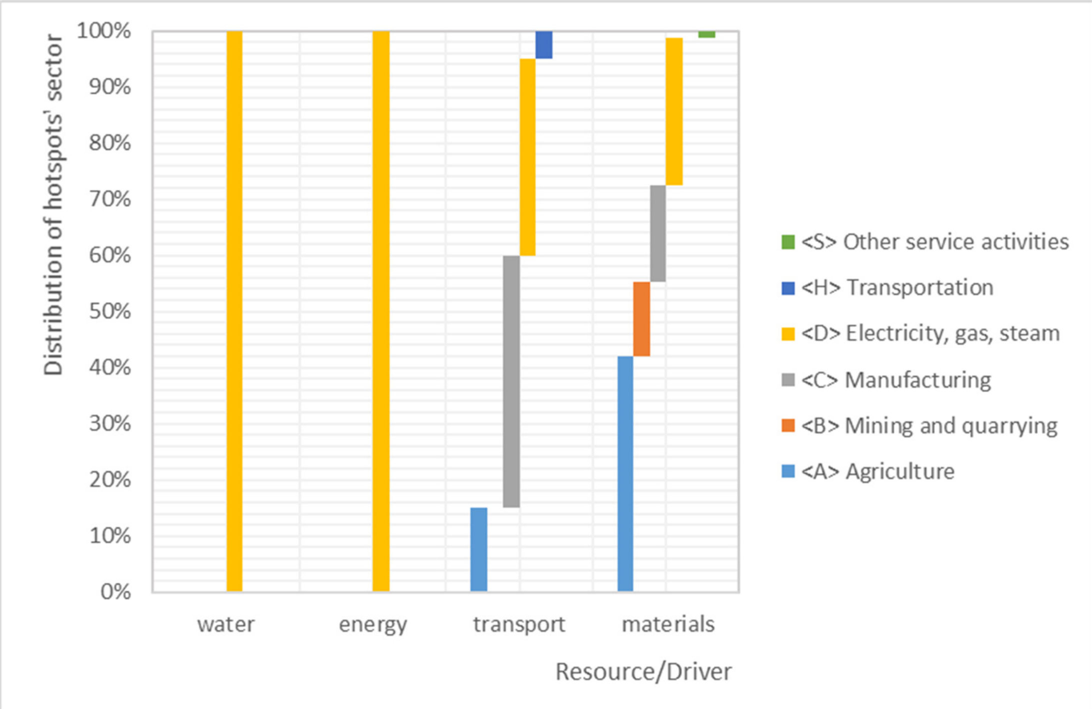



*Figure 3.2 Distribution of hotspots for different resources/drivers*

For the production sectors selected related to the resources or drivers, the hotspots are concentrated on the sectors <A>, <B>, <C>, <D>, <H> and <S>. For water and energy, all the hotspots belong to sector <D>, with emissions from these two resource hotspots accounting for 90% of total emissions. It presents that for these two resources, the $CO_2$ emissions are almost entirely concentrated in the electricity-based energy industry. Reducing emissions from power generation, such as by changing the source of electricity, can have a significant impact on reducing emissions from the consumption of these two resources. Different with the resources water and energy of which the hotspots are highly concentrated on one sector, the transport and materials have more decentralized distribution. Among the scattered hotspots, there are still a certain percentage of hotspots belonging to sector <D>, which makes sector <D> the largest emitter for consumption based on the resources and drivers chosen in this study. The sector <C> has the second highest number of hotspots after sector <D> and most of them are related to the manufacture of steel, rubber and other components for automobile production. The presence of sector <A> in the transportation hotspot category indicates that livestock-related agricultural transportation is a hotspot that cannot be ignored in transportation emissions. The hotspots of sector <H> consider the overall emission value of a type of transport mode which is very complex and can be trace more back to identify more fundamental industrial processes. For materials, sector <A> has the most $CO_2$ emission hotspots and followed by the sector <D>. This indicates that the amount of $CO_2$ emissions from agriculture and livestock is too large to ignore, and it plays a very critical role in the emissions of daily consumption. Sector

<B> appears for the first time in the hotspot of materials which indicates that during the production process of materials, the mining and quarrying about the energy and raw materials contributes to emissions that cannot be ignored. Sector <S> appears because there is a hotspot corresponding to two sectors, one of which is <S>. The hotspot is divided equally into sectors that account for 50% of each sector. The average split here are based on assumptions made to facilitate data processing due to the absence of data on the proportion of different sectors, which may lead to some bias in the results, such as a high proportion of sector <S>.

Analysing the overall hotspot distribution, sector <D> contributes the largest amount of $CO_2$ emissions, followed by sectors <A> and <C>. This means that these three sectors have the greatest potential to reduce emissions, and the same proportion of reduction potential in these sectors can lead to more absolute reductions in emissions.

The Figure 3.3 combined with Table 3.2 shows the distribution of hotspots location and the specific information for hotspots outside China.

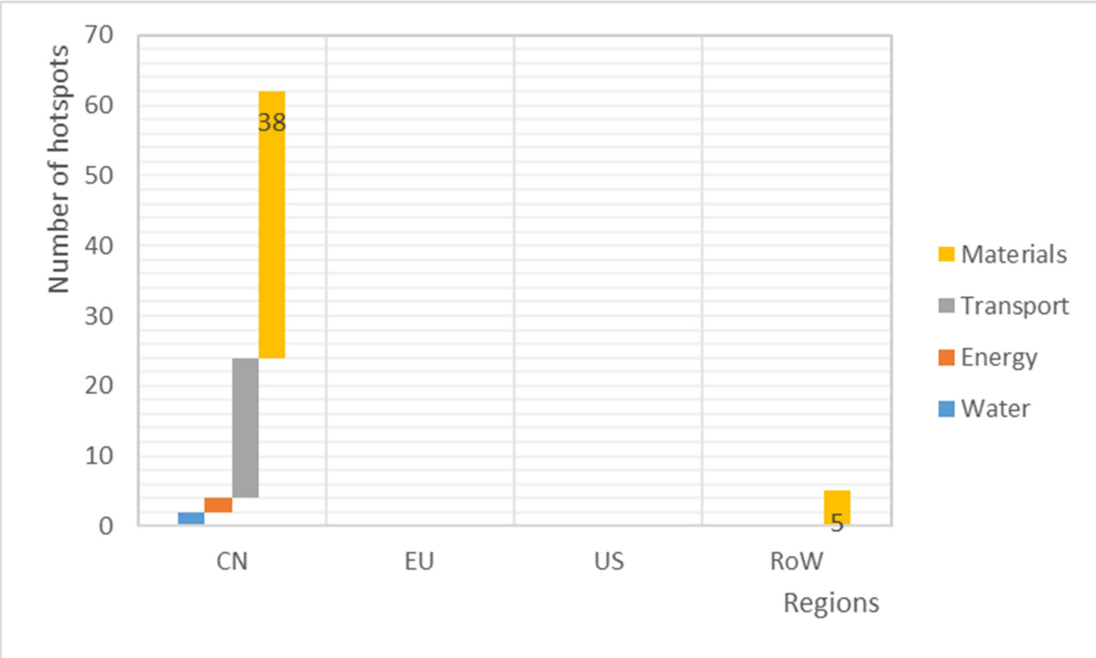



*Figure 3.3 Distribution of hot spots in different regions*

*Table 3.2 The information on hotspots in RoW*

| Hotspot subsector | Sectors | Number |
|---|---|---|
| Extraction of natural gas and services related to natural gas extraction, excluding surveying | <B> Mining and quarrying | 3 |
| Cultivation of oil seeds | <A> Agriculture | 1 |
| Cultivation of vegetables, fruit, nuts | <A> Agriculture | 1 |

Most of $CO_2$ hotspots identified are focused on China where the production process takes place. It presents that regarding the consumption of water, energy, transport and materials, the emissions of the production processes relied on are concentrated locally in China, and due to data limitations, it is not possible to distinguish the emissions of study cities from other regions. Meanwhile, it can be seen that the number of hotspots for transport and materials are much larger, which is because the differences in emissions per hotspot of these two are not large, resulting in a high number of hotspots. For water and energy, the excessive concentration of emissions leads to low number of hotspots. For the materials resource with the highest number of hotspots, there are five of them located in RoW and three of them belongs to sector <B>. In addition to the large demand for various raw materials that need to be extracted in the process of material production, this is also related to the fact that this region is among the world leaders in resource extraction (IEA, 2017). China is also a major mineral extracting country, but the emissions for hotspots in sector <B> are not as much as the emissions from this part of RoW. This may be due to the high unit emissions from the mining of RoW, or it may be due to the fact that this part of the material production process relies mainly on imports for its needs, while Chinese mining provides for exports. RoW also has two hotspots for sector <A>, but it is a very small part compared to the hotspots in China. It is also worth noting that no emission hotspots are located in Europe or the United States for the four selected industry-related resources or drivers.

### 3.2.2 $CO_2$ emission hotspots reduction potentials

There are 12 targets for $CO_2$ emission change potential related to hotspots identified. Most of them are global targets, including the potential for change of 52 emission hotspots (The same subsector hotspot in the same region is counted by the number of occurrences). There are also 10 hotspots for which the emission change potential was not found to be a suitable target due to time and data, mainly focusing on the manufacture hotspots, which may lead to an underestimation of the $CO_2$ reduction effect in these two regions. Due to the complexity of the manufacturing industry, emissions reduction potential is difficult to collect, and tracing back further to find emission hotspots from more fundamental industrial processes and collecting reduction potential of them may be a way to improve model's accuracy in the future. The specific emission change potentials corresponding to each hotspot and their references are shown in Table A.4 in the Appendix.

Quantifying the potential for emission changes in different hotspots allows the $CO_2$ emissions in different sectors from 2017 to 2050 to be analysed. Figure 3.4 shows the $CO_2$ emission (tons $CO_2$ eq./ Million Eur) of different sectors at the same scale in 2017 and 2050 respectively. A visual comparison of the histograms shows the extent of the change in $CO_2$ emissions per million euros. Since the emission hotspots associated with the regions where the study cities are located only exist in China and RoW, Figure 3.4 only analyses the $CO_2$ emission changes in these two regions.

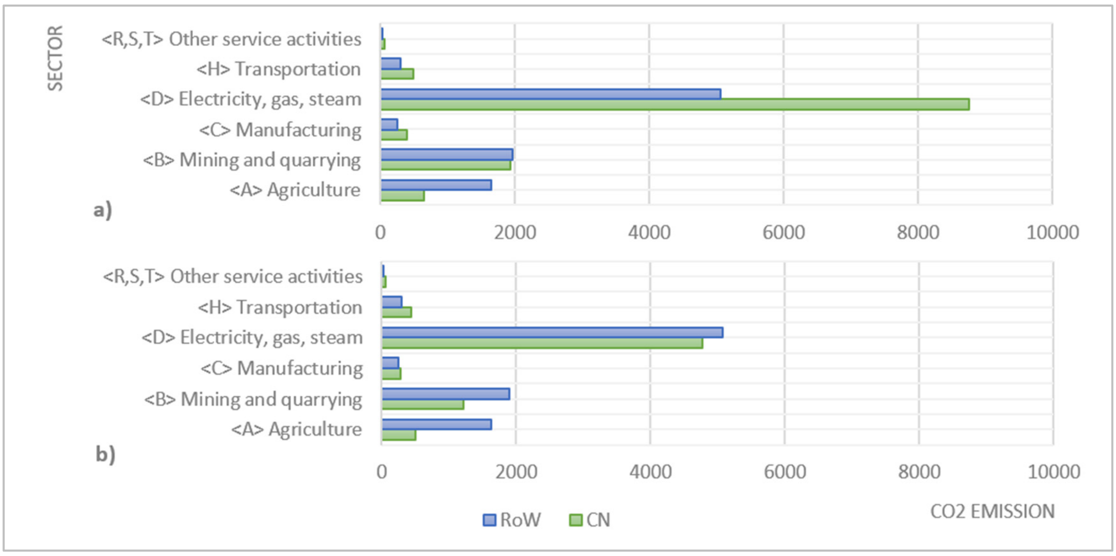



*Figure 3.4 The $CO_2$ emission of different sectors in 2 regions (tons $CO_2$ eq./Million Eur); a) 2017 b) 2050*

Sector <D> has the highest unit emissions, while it can also be seen to have a significant reduction from 2017 to 2050. For CN, the reduction is round 4000 tons $CO_2$ eq./ Million Eur. The reduction of CN is close to 50%, as the fact that its hotspots are more concentrated in sector <D> than other regions, and also to its high emissions base in 2017. The emissions of sector <D> for region RoW do not change is due to the absence of hotspots associated with sector <D>.

As the second highest emission sector, the reduction of emissions in sector <B> is less significant. For CN, the reduction is about 700 tons $CO_2$ eq./ Million Eur, while for RoW, the reduction is even harder to see with the naked eye. This is related to the small base of emissions relative to sector <D>, but more so to the fact that for sector <B> mining and quarrying, the identified hotspot "Extraction of natural gas and services related to natural gas extraction, excluding surveying" does not have a very significant reduction. Emissions from sector <A> follow sector <B> closely, with unit emissions decreasing in each region but less significantly. It can be seen that the reduction of CN is about 150 tons $CO_2$ eq./ Million Eur and the RoW still have the potentials to reduce more.

For sectors <C> and <H> of CN, the emissions in 2017 are already low compared to other sectors, while unit emission reductions in 2050 for these sectors are not significant due to the small number of hotspots and the lack of reduction potential targets. For sectors <C>, <H> and <R, S, T> of RoW and sector <R, S, T> of China, the $CO_2$ emissions do not change because of no hotspots and lack of reduction potential respectively.

### 3.2.3 $CO_2$ emissions analysis

As can be seen in the Figure 3.5, for both cities, both BAU and CE scenarios show some degree of decrease in $CO_2$ emissions compared to 2017. Overall, Beijing has higher emissions per capita than Shanghai, and even the emissions in the BAU scenario are higher than those in Shanghai in 2017. But this pattern does not apply on total $CO_2$ emissions, due to the fact that in the 2050 scenario, Beijing's population is lower than Shanghai's. This result shows a different outcome from similar previous studies. In the study of Mi et al. (2016) about consumption-based emissions in Chinese cities, Shanghai's total emissions in 2007 were larger than Beijing's. Feng et al. (2014) also found the same pattern. A comparison of raw data was conducted and the differences that Beijing's imports and exports were half of Shanghai's in 2007, while they were nearly double Shanghai's in 2017 were found. This suggests that there have been some changes in the structure of production and consumption in the two cities, leading to a change in the relative relationship of the total consumption-based emissions of these two cities. It is also important to mention that in this study both direct and indirect emissions are calculated but no distinction is made between direct consumption and emissions due to imports. This differs from related studies, but here the scope of the emissions footprint is expanded beyond the domestic emissions of China.

For Beijing, the $CO_2$ emission per capita decreases 3.99 tons $CO_2$ eq. comparing the BAU scenario and 2017. Comparing the two scenarios, it can be concluded that CE is another 2.11 tons lower than the BAU scenario. Different with the great improvement of Beijing, the emission per capita of Shanghai decreases by 2.99 tons $CO_2$ eq. from 2017 to BAU, and the CE scenario only decreased by 0.38 tons $CO_2$ eq. compared to the BAU scenario. The CE strategy is highly effective in reducing Beijing's emissions, more than half of the amount already reduced in the BAU scenario. However, for Shanghai, the CE strategy seems to have a very limited effect, as the reduction in emissions on the basis of the BAU scenario is very small, but the cumulative emissions are also significant, reaching $1 \times 10^{10}$ tons $CO_2$ eq. However, the return-on-input ratio of the CE strategy may be controversial in Shanghai.

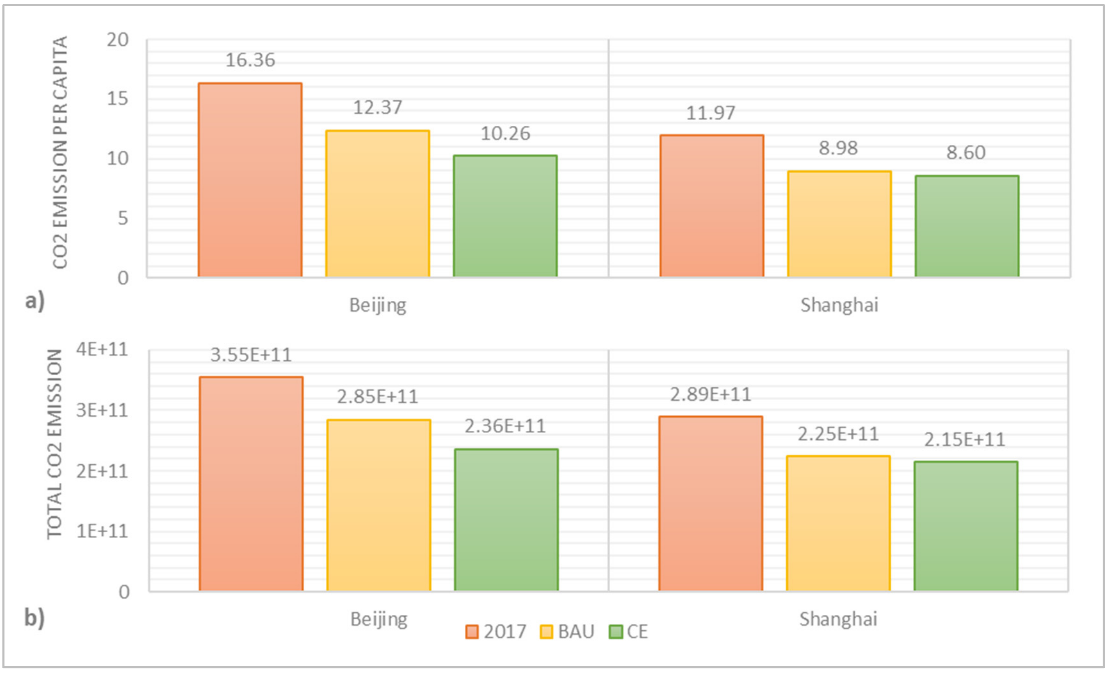



*Figure 3.5 The $CO_2$ emission for different scenarios; a) $CO_2$ emission per capita unit: tons $CO_2$ eq./capita; b) total $CO_2$ emission unit: tons $CO_2$ eq.*

Figure 3.6 and Figure 3.7 show two stacked charts, one for the absolute values of emission and one for the distribution of 17 sectors in 5 regions for both Beijing and Shanghai. From the figures, it is clear that the emissions of both Beijing and Shanghai are concentrated on China, with RoW following behind.

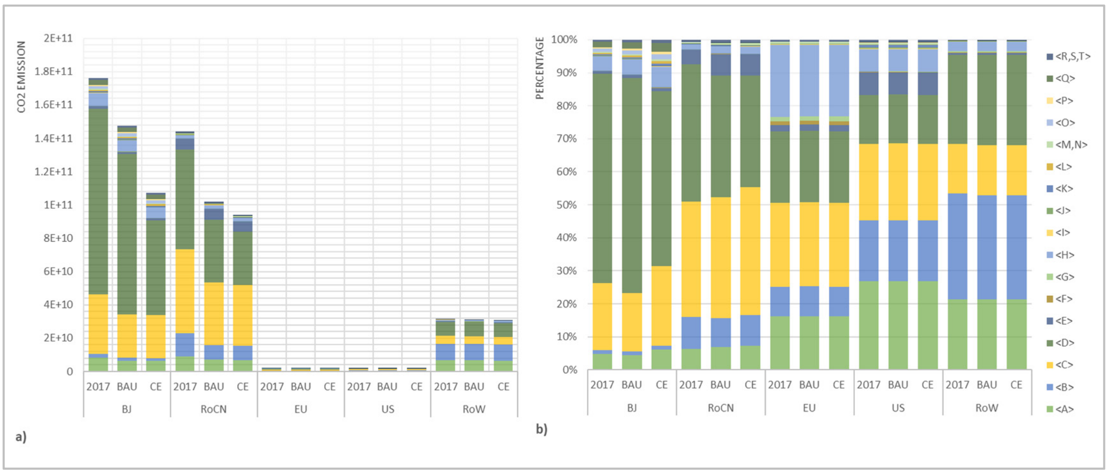



*Figure 3.6 Production-based $CO_2$ emissions linked to consumption in Beijing; unit: a) tons $CO_2$ eq.; b) distribution percentage)*

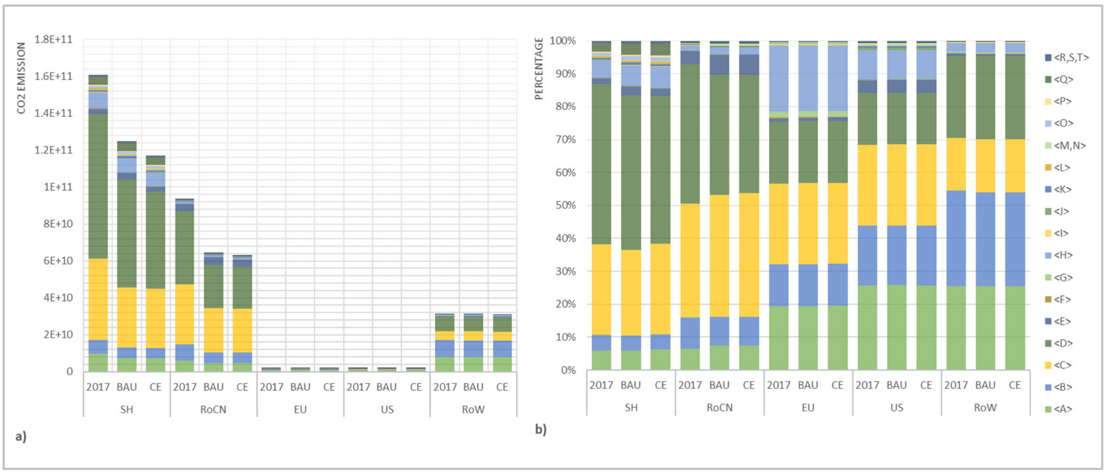



*Figure 3.7 Production-based $CO_2$ emissions linked to consumption in Shanghai; unit: a) tons $CO_2$ eq.; b) distribution percentage)*

Comparing the emission of Beijing and Shanghai within China, the difference in emissions between the two cities in their own cities is not significant, with Shanghai being slightly lower; in other areas of China than the cities studied themselves, Beijing's emissions are significantly higher than Shanghai's and are in the same order of magnitude as its own city's, while Shanghai's emissions from this part are only close to half of its own city's emissions. This suggests that household and public consumption in Beijing is more dependent on production from other parts of China than in Shanghai. Meanwhile, it can be seen that for emissions in Beijing, the reduction from the BAU to CE scenario is greater than the reduction from 2017 to the BAU scenario; for the rest of China, the reduction from 2017 to the BAU scenario is much greater than the reduction from BAU to CE. It shows that the CE strategy has been very effective in reducing Beijing's local emissions. For Shanghai, neither in Shanghai nor in the rest of the China, the emission reduction of CE scenario from the BAU scenario is not more than the 2017 to BAU scenario. This is consistent with the general pattern shown in Figure 3.5.

And for distribution of different sectors, the distribution of the two cities in different regions is similar. For study cities themselves, the emissions are concentrated on sector

<D> which accounts for about 50% and followed by the sector <C> with around 20%. Sector <D> has a relatively higher share in Beijing. For rest of China, the importance of sector <C> and sector <D> becomes almost equal. For RoW, sectors <A>, <B> and <D> become the largest emitting sectors, and the emission of sector <C> is following but not that important as it in other regions. For EU, the emission of sector <H> becomes visible.

It can also be seen that the decrease of $CO_2$ emission for scenarios is focused more on sector <D>. Meanwhile, the reduction in emissions from sector <D> is accompanied by less significant changes in emissions from other sectors, resulting in a higher share of emissions from other sectors in the scenario model.

# 4 Conclusion

Two scenarios (Business-As-Usual (BAU2050) and Circular Economy (CE2050)) are developed to compare the resource consumption differences between the conventional situation and an ambitious circular economy situation for Beijing and Shanghai. Afterwards, the MRIO analysis is used to evaluate the $CO_2$ offset of implementing circular economy strategies.

The development of scenarios is made by analysing the current trends in the urban system, and the plans and targets. The targets used for BAU are more accurate and from local official documents; CE's strategy is more lacking, citing studies from multiple locations around the world. In China, the field of specific CE goals and implementation planning needs more development. Referring to the CE strategies of cities with similarities may be a good approach. Due to the scenario modelling results, the CE scenarios reduce around 10515 million Euro household expenditure for Shanghai and around 20475 million Euro household expenditure for Beijing compared with BAU scenarios. Although both scenarios for 2050 have a higher consumption than in 2017, due to population growth and inflation. It presents, for the collected targets and plans, the CE strategies are more useful for Beijing to reduce resource consumption. For Beijing, the sector of electricity reduces most from BAU to CE scenarios; while for Shanghai, the sector of wholesome and retail reduces most. It indicates that there is the greatest potential and effectiveness in reducing energy use and materials consumption.

The sector of electricity contributes the largest amount of $CO_2$ emissions, followed by sectors of agriculture and manufacturing. This means that most of emission hotspots of China for water, energy, transport and materials are concentrated on these three sectors and they have the greatest potential to reduce emissions. And most of the hotspots are located in China with rest of them belonging to RoW. It indicates that the $CO_2$ emission hotspots of China are local basically. The $CO_2$ emission of sector of electricity has the most significant reduction from 2017 to 2050. which is around 4000 tons $CO_2$ eq./ Million Eur for China. The reduction is close to 50%. Other sectors with reduction potential all have lower reduction results compared to the energy sector. However, the reduction potential of manufacturing sector may be underestimated due to the lack of reduction potential targets of hotspots belong to it.

Combing with the consumption reduction results from scenarios modelling and the reduction potentials for production industries, the $CO_2$ emission per capita can be reduced by 37% and the total $CO_2$ emission can be reduced by 34% from 2017 in Beijing. In Shanghai, the $CO_2$ emission per capita can be reduced by 28% and the total $CO_2$ emission can be reduced by 26%. Meanwhile, compared to Shanghai, the $CO_2$ reduction of the CE scenario in Beijing is still very considerable on top of the reduction already achieved by the BAU scenario, indicating that the current CE strategies are already able to reduce Beijing's emissions very well. However, for Shanghai, more ambitious CE strategies should be considered.

# References


Andersen, M. S. (2007). An introductory note on the environmental economics of the circular economy. *Sustainability science*, *2*(1), 133-140.

Beijing-Municipal-Bureau-of-Statistics. (2021). *Beijing Statistical Yearbook*. http://nj.tjj.beijing.gov.cn/nj/main/2021-tjnj/zk/indexch.htm

Beijing-Municipal-Commission-of-Planning-and-Natural-Resources. (2018). *Beijng's master plan*. Retrieved from http://ghzrzyw.beijing.gov.cn/zhengwuxinxi/zxzt/bjcsztgh20162035/202001/t20200102_1554613.html

Beijing-Municipal-Government. (2022). *Beijing Major Infrastructure Development Plan for the 14th Five-Year Plan Period*. Retrieved from http://fgw.beijing.gov.cn/fgwzwgk/zcgk/ghjhwb/wnjh/202203/t20220303_2692058.htm

BJTRC. (2018). *Beijing transport 2018 annual report*.

Bringezu, S., Ramaswami, A., Schandl, H., O'Brien, M., Pelton, R., Acquatella, J., Ayuk, E., Chiu, A., Flanegin, R., & Fry, J. (2017). Assessing global resource use: A system approach to resource efficiency and pollution reduction. *IRP Reports*.

Chen, G., & Chen, Z. (2011). Greenhouse gas emissions and natural resources use by the world economy: ecological input–output modeling. *Ecological Modelling*, *222*(14), 2362-2376.

Christis, M., Athanassiadis, A., & Vercalsteren, A. (2019). Implementation at a city level of circular economy strategies and climate change mitigation–the case of Brussels. *Journal of Cleaner Production*, *218*, 511-520.

Conke, L. S., & Ferreira, T. L. (2015). Urban metabolism: Measuring the city's contribution to sustainable development. *Environmental pollution*, *202*, 146-152.

Corona, B., Shen, L., Reike, D., Carreón, J. R., & Worrell, E. (2019). Towards sustainable development through the circular economy—A review and critical assessment on current circularity metrics. *Resources, Conservation and Recycling*, *151*, 104498.

Delevingne, L., Glazener, W., Grégoir, L., & Henderson, K. (2020). Climate risk and decarbonization: What every mining CEO needs to know. *McKinsey Insights*.

Department-of-State. (2017). *Approval of the State Council on the Shanghai Urban Master Plan*. Central People's Government of the People's Republic of China. http://www.gov.cn/zhengce/content/2017-12/25/content_5250134.htm

Department-of-State. (2019). *Direct local access – Shanghai*. Central People's Government of the People's Republic of China. http://www.gov.cn/guoqing/2019-02/13/content_5365290.htm

Edwards, R., Mahieu, V., Griesemann, J.-C., Larivé, J.-F., & Rickeard, D. J. (2004). Well-to-wheels analysis of future automotive fuels and powertrains in the European context. *SAE transactions*, 1072-1084.

EPA, U. (2017). *Office of Wastewater Management*. https://19january2017snapshot.epa.gov/www3/watersense/about_us/facts.html

Eurostat. (2018). *METADATA: Classification of Individual Consumption by Purpose (COICOP), 2018 version*. https://ec.europa.eu/eurostat/ramon/nomenclatures/index.cfm?TargetUrl=LST_NOM_DTL&StrNom=COICOP_2018&StrLanguageCode=EN&IntPcKey=43894885&StrLayoutCode=HIERARCHIC

Fan, Y., & Fang, C. (2020). Circular economy development in China-current situation, evaluation and policy implications. *Environmental impact assessment review*, *84*, 106441.

FAO. (2022). *Assessment of greenhouse gas emissions and mitigation potential, Food and Agriculture Organization of the United Nations*. https://www.fao.org/gleam/results/en/

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. *Ecological Indicators*, *47*, 26-31.

Feng, Y., & Zhang, L. (2012). Scenario analysis of urban energy saving and carbon abatement policies: a case study of Beijing city, China. *Procedia Environmental Sciences*, *13*, 632-644.

Gassner, A., Lederer, J., Kovacic, G., Mollay, U., Schremmer, C., & Fellner, J. (2021). Projection of material flows and stocks in the urban transport sector until 2050–A scenario-based analysis for the city of Vienna. *Journal of Cleaner Production*, *311*, 127591.

Gerst, M. D. (2009). Linking material flow analysis and resource policy via future scenarios of in-use stock: An example for copper. *Environmental science & technology*, *43*(16), 6320-6325.

Guo, B., Geng, Y., Ren, J., Zhu, L., Liu, Y., & Sterr, T. (2017). Comparative assessment of circular economy development in China's four megacities: The case of Beijing, Chongqing, Shanghai and Urumqi. *Journal of Cleaner Production*, *162*, 234-246.

Guo, S., Shao, L., Chen, H., Li, Z., Liu, J., Xu, F., Li, J., Han, M., Meng, J., & Chen, Z.-M. (2012). Inventory and input–output analysis of CO2 emissions by fossil fuel consumption in Beijing 2007. *Ecological Informatics*, *12*, 93-100.

Han, W., Geng, Y., Lu, Y., Wilson, J., Sun, L., Satoshi, O., Geldron, A., & Qian, Y. (2018). Urban metabolism of megacities: A comparative analysis of Shanghai, Tokyo, London and Paris to inform low carbon and sustainable development pathways. *Energy*, *155*, 887-898.

Harris, S., Weinzettel, J., Bigano, A., & Källmén, A. (2020). Low carbon cities in 2050? GHG emissions of European cities using production-based and consumption-based emission accounting methods. *Journal of Cleaner Production*, *248*, 119206.

Harrison, P., & Pearce, F. (2000). *AAAS atlas of population & environment*. Univ of California Press.

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), 6277-6282.

Hoornweg, D. A., Campillo, G., Expert, C. C., Linders, D., Platform, U. K., Saldivar-Sali, A. N., Bermudo, G. C., & Sugar, L. (2012). Mainstreaming Urban Metabolism: Advances and Challenges in City Participation. *Sixth Urban Research and Knowledge Symposium 2012*.

IEA. (2016). *Unit converter and glossary*. https://www.iea.org/reports/unit-converter-and-glossary

IEA. (2017). *World Energy Outlook 2017*. https://iea.blob.core.windows.net/assets/4a50d774-5e8c-457e-bcc9-513357f9b2fb/World_Energy_Outlook_2017.pdf

IEA. (2021a). *Heating*. https://www.iea.org/reports/heating
IEA. (2021b). *World Energy Outlook 2021*. https://www.iea.org/reports/world-energy-outlook-2021
IEA. (2022a). *Chemicals*. https://www.iea.org/reports/chemicals
IEA. (2022b). *Oil and Natural Gas Supply*. https://www.iea.org/reports/oil-and-natural-gas-supply
IEA. (2022c). *Steel*. https://www.iea.org/reports/steel
IMO. (2019). *IMO's work to cut GHG emissions from ships, International Maritime Organization*. https://www.imo.org/en/MediaCentre/HotTopics/Pages/Cutting-GHG-emissions.aspx
Jarke, M., Bui, X. T., & Carroll, J. M. (1998). Scenario management: An interdisciplinary approach. *Requirements Engineering*, *3*(3), 155-173.
Kalmykova, Y., Rosado, L., & Patrício, J. (2016). Resource consumption drivers and pathways to reduction: economy, policy and lifestyle impact on material flows at the national and urban scale. *Journal of Cleaner Production*, *132*, 70-80.
Kennedy, C., Cuddihy, J., & Engel‐Yan, J. (2007). The changing metabolism of cities. *Journal of industrial ecology*, *11*(2), 43-59.
Kennedy, C., Pincetl, S., & Bunje, P. (2011). The study of urban metabolism and its applications to urban planning and design. *Environmental pollution*, *159*(8-9), 1965-1973.
Korhonen, J., Honkasalo, A., & Seppälä, J. (2018). Circular economy: the concept and its limitations. *Ecological Economics*, *143*, 37-46.
Li, L., Chen, C., Xie, S., Huang, C., Cheng, Z., Wang, H., Wang, Y., Huang, H., Lu, J., & Dhakal, S. (2010). Energy demand and carbon emissions under different development scenarios for Shanghai, China. *Energy Policy*, *38*(9), 4797-4807.
Li, Y., Wang, B., Xie, Y., & Zhu, L. (2020). Cost and potential for CO2 emissions reduction in China's petroleum refining sector—A bottom up analysis. *Energy Reports*, *6*, 497-506.
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.
Lu, Y., Geng, Y., Qian, Y., Han, W., McDowall, W., & Bleischwitz, R. (2016). Changes of human time and land use pattern in one mega city's urban metabolism: a multi-scale integrated analysis of Shanghai. *Journal of Cleaner Production*, *133*, 391-401.
MacArthur, E. (2013). Towards the circular economy. *Journal of industrial ecology*, *2*(1), 23-44.
Martins, F. F., & Castro, H. (2020). Raw material depletion and scenario assessment in European Union–A circular economy approach. *Energy Reports*, *6*, 417-422.
Meng, J., Mi, Z., Yang, H., Shan, Y., Guan, D., & Liu, J. (2017). The consumption-based black carbon emissions of China's megacities. *Journal of Cleaner Production*, *161*, 1275-1282.
Mi, Z., Zhang, Y., Guan, D., Shan, Y., Liu, Z., Cong, R., Yuan, X.-C., & Wei, Y.-M. (2016). Consumption-based emission accounting for Chinese cities. *Applied energy*, *184*, 1073-1081.
Morita, T., Robinson, J., Alcamo, J., Nakicenovic, N., & Riahi, K. (2001). Greenhouse gas emission mitigation scenarios and implications.
National-Development-and-Reform-Commission. (2020). *"Fourteen Five" Circular Economy Development Plan*. Retrieved from

https://www.ndrc.gov.cn/xxgk/zcfb/ghwb/202107/P020210707324072693362.pdf
Nikita, S., & Sjoerd, H. (2022). *Regionalizing input-output tables and environmentally extended accounts for Vienna and Malmö*
Nordelöf, A., Messagie, M., Tillman, A.-M., Ljunggren Söderman, M., & Van Mierlo, J. (2014). Environmental impacts of hybrid, plug-in hybrid, and battery electric vehicles—what can we learn from life cycle assessment? *The International Journal of Life Cycle Assessment*, *19*(11), 1866-1890.
Oberle, B., Bringezu, S., Hatfield-Dodds, S., Hellweg, S., Schandl, H., Clement, J., Cabernard, L., Che, N., Chen, D., & Droz-Georget, H. (2019). Global resources outlook 2019: natural resources for the future we want.
Odegard, I., & Van der Voet, E. (2014). The future of food—Scenarios and the effect on natural resource use in agriculture in 2050. *Ecological Economics*, *97*, 51-59.
Oxford-Economics. (2020). Consumer spending, real, Euros - goods and services. Malmo, Vienna, Beijing and Shanghai.
Panel, I. R., Consumption, U. N. E. P. S., & Branch, P. (2011). *Decoupling natural resource use and environmental impacts from economic growth*. UNEP/Earthprint.
Ramaswami, A., Chavez, A., & Chertow, M. (2012). Carbon footprinting of cities and implications for analysis of urban material and energy flows. *Journal of industrial ecology*, *16*(6), 783-785.
Richa, K., Babbitt, C. W., Gaustad, G., & Wang, X. (2014). A future perspective on lithium-ion battery waste flows from electric vehicles. *Resources, Conservation and Recycling*, *83*, 63-76.
Rothman, D. S. (2008). A survey of environmental scenarios. *Environmental Futures: The Practice of Environmental Scenario Analysis*, 37-65.
Satterthwaite, D. (2008). Cities' contribution to global warming: notes on the allocation of greenhouse gas emissions. *Environment and urbanization*, *20*(2), 539-549.
SCCTPI. (2018). *Shanghai comprehensive transportation annual report 2017*.
Schanes, K., Jäger, J., & Drummond, P. (2019). Three scenario narratives for a resource-efficient and low-carbon Europe in 2050. *Ecological Economics*, *155*, 70-79.
Schwartz, P. (2012). *The art of the long view: planning for the future in an uncertain world*. Currency.
Scott, K., Owen, A., & Barrett, J. (2013). Estimating emissions associated with future UK consumption patterns. *A report for the UK committee on climate change*.
Shanghai-Municipal-Bureau-of-Statistics. (2021). *Shanghai Statistical Yearbook (2021)*. http://tjj.sh.gov.cn/tjnj/20220309/0e01088a76754b448de6d608c42dad0f.html
Shanghai-Municipal-Government. (2018). *SHANGHAI MASTER PLAN 2017-2035*. https://www.shanghai.gov.cn/newshanghai/xxgkfj/2035001.pdf
Song, T., Cai, J., Xu, H., Deng, Y., Niu, F., Yang, Z., & Du, S. (2015). Urban metabolism based on emergy and slack based model: A case study of Beijing, China. *Chinese Geographical Science*, *25*(1), 113-123.
Spielmann, M., Scholz, R., Tietje, O., & Haan, P. d. (2005). Scenario modelling in prospective LCA of transport systems. Application of formative scenario analysis (11 pp). *The International Journal of Life Cycle Assessment*, *10*(5), 325-335.

Stadler, K., Wood, R., Bulavskaya, T., Södersten, C. J., Simas, M., Schmidt, S., Usubiaga, A., Acosta‐Fernández, J., Kuenen, J., & Bruckner, M. (2018). EXIOBASE 3: Developing a time series of detailed environmentally extended multi‐regional input‐output tables. *Journal of industrial ecology*, *22*(3), 502-515.

Su, B., Heshmati, A., Geng, Y., & Yu, X. (2013). A review of the circular economy in China: moving from rhetoric to implementation. *Journal of Cleaner Production*, *42*, 215-227.

Sun, D.-Q., Yi, B.-W., Xu, J.-H., Zhao, W.-Z., Zhang, G.-S., & Lu, Y.-F. (2018). Assessment of CO2 emission reduction potentials in the Chinese oil and gas extraction industry: From a technical and cost-effective perspective. *Journal of Cleaner Production*, *201*, 1101-1110.

Swilling, M., Robinson, B., Marvin, S., Hodson, M., & Hajer, M. (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.

UN-Environment-Programme. (n.d.). *Worldwide food waste*. https://www.unep.org/thinkeatsave/get-informed/worldwide-food-waste

van Hooijdonk, T., & Hettinga, K. (2015). Dairy in a sustainable diet: a question of balance. *Nutr Rev*, *73*(S1), 48-54.

Whetstone, A., Kalmykova, Y., Rosado, L., & Lavers Westin, A. (2020). Informing sustainable consumption in urban districts: A method for transforming household expenditures into physical quantities. *Sustainability*, *12*(3), 802.

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*, *53*(11), 6362-6373.

Wollenberg, E., Richards, M., Smith, P., Havlík, P., Obersteiner, M., Tubiello, F. N., Herold, M., Gerber, P., Carter, S., & Reisinger, A. (2016). Reducing emissions from agriculture to meet the 2 C target. *Global change biology*, *22*(12), 3859-3864.

Wolman, A. (1965). The metabolism of cities. *Scientific American*, *213*(3), 178-193.

World-Intellectual-Property-Organizaton. (2001). *International Classification of Goods and Services: Part II With the list of goods and services in class order.* (8th ed.).

Xu, Q., Zheng, X., & Zheng, M. (2019). Do urban planning policies meet sustainable urbanization goals? A scenario-based study in Beijing, China. *Science of the Total Environment*, *670*, 498-507.

Yang, Z., Yang, H., & Wang, H. (2020). Evaluating urban sustainability under different development pathways: A case study of the Beijing-Tianjin-Hebei region. *Sustainable Cities and Society*, *61*, 102226.

Yu Hao, Y. R., Zhang Yuejun, & Wang Shouyang. (2013). Study on energy demand and environmental emissions of urban passenger transportation - A case study of Beijing. *Journal of Beijing University of Technology (Social Science Edition)*, *15(5)*.

Zhang, Y. (2013). Urban metabolism: A review of research methodologies. *Environmental pollution*, *178*, 463-473.

Zhang, Y., Liu, Y., Lv, H., Chen, S., & Li, S. (2021). Dynamic analysis of platinum material flows and stocks with hybrid MFA method aiming to carbon neutral targets of automotive industry in China. *Environmental Pollutants and Bioavailability*, *33*(1), 194-205.

Zhang, Y., Lu, W., Tam, V. W.-Y., & Feng, Y. (2018). From urban metabolism to industrial ecosystem metabolism: A study of construction in Shanghai from 2004 to 2014. *Journal of Cleaner Production*, *202*, 428-438.

Zhang, Y., Zheng, H., Fath, B. D., Liu, H., Yang, Z., Liu, G., & Su, M. (2014). Ecological network analysis of an urban metabolic system based on input–output tables: Model development and case study for Beijing. *Science of the Total Environment*, *468*, 642-653.

Zhou, S., Chen, H., & Li, S. (2010). Resources use and greenhouse gas emissions in urban economy: ecological input–output modeling for Beijing 2002. *Communications in Nonlinear Science and Numerical Simulation*, *15*(10), 3201-3231.

# Appendix

*Table A.1 Framework for scenarios quantification*

| Resource | Category | Base year 2017 | | Base trend 2050 | | | | BAU 2050 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Resource use per unit | Resource use, absolute value | Resource use per unit | Resource use, absolute value | Rate of change per unit | Rate of change, absolute | Description of change | Description of calculation | Resource use per unit | Resource use, absolute value | Rate of change per unit | Rate of change, absolute |
| Water | Household | | | | | | | | | | | | |
| Energy | Transport | | | | | | | | | | | | |
| Material | Public sector | | | | | | | | | | | | |

*Table A.2 Framework for economic modelling*

| Resource | Category | Relevant IO sector | | IO sector 2017 | Affected sector | | | | Unaffected sector | | IO sector 2050 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Associated IO FD category and sector for resource use | % Share of sector for resource use | Total expenditure of IO Sector 2017 (million EUR) | Expenditure of resource in sector 2017 (million EUR) | Unit price 2017 (million EUR/resource) | Unit price 2050 w/ inflation (million EUR /resource) | Expenditure of resource in sector 2050 w/ inflation (million EUR) | Unaffected sector: Expenditure 2017 (million EUR) | Unaffected sector: Expenditure 2050 w/ inflation (million EUR) | Total expenditure of Whole IO Sector 2050 (million EUR) |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Water | Household | | | | | | | | | | |
| Energy | Transport | | | | | | | | | | |
| Material | Public sector | | | | | | | | | | |

*Table A.3 The corresponding hotspots and their places for each sector*

| Sector related to scenarios | Subsector | Hotspot Region | Hotspot |
|---|---|---|---|
| Water | Collection, purification and distribution of water (41) | CN | Production of electricity by coal |
| | Collection, purification and distribution of water (41) | CN | Steam and hot water supply |
| Energy | Distribution and trade of electricity | CN | Production of electricity by coal |
| | Transmission of electricity | CN | Production of electricity by coal |
| Transport | Manufacture of motor vehicles, trailers and semi-trailers (34) | CN | Production of electricity by coal |
| | Manufacture of other transport equipment (35) | CN | Manufacture of basic iron and steel and of ferro-alloys and first products thereof |
| | Manufacture of motor vehicles, trailers and semi-trailers (34) | CN | Manufacture of basic iron and steel and of ferro-alloys and first products thereof |
| | Manufacture of other transport equipment (35) | CN | Production of electricity by coal |
| | Other land transport | CN | Petroleum Refinery |
| | Manufacture of other transport equipment (35) | CN | Steam and hot water supply |
| | Manufacture of motor vehicles, trailers and semi-trailers (34) | CN | Steam and hot water supply |
| | Air transport (62) | CN | Production of electricity by coal |

| | | | |
|---|---|---|---|
| | Other land transport | CN | Pigs farming |
| | Sea and coastal water transport | CN | Sea and coastal water transport |
| | Sea and coastal water transport | CN | Pigs farming |
| | Other land transport | CN | Production of electricity by coal |
| | Transport via railways | CN | Petroleum Refinery |
| | Manufacture of motor vehicles, trailers and semi-trailers (34) | CN | Casting of metals |
| | Other land transport | CN | Meat animals nec |
| | Manufacture of other transport equipment (35) | CN | Manufacture of gas; distribution of gaseous fuels through mains |
| | Manufacture of motor vehicles, trailers and semi-trailers (34) | CN | Manufacture of motor vehicles, trailers and semi-trailers (34) |
| | Manufacture of motor vehicles, trailers and semi-trailers (34) | CN | Manufacture of rubber and plastic products (25) |
| | Manufacture of other transport equipment (35) | CN | Manufacture of other transport equipment (35) |
| | Manufacture of other transport equipment (35) | CN | Manufacture of fabricated metal products, except machinery and equipment (28) |
| Material | Processed rice | CN | Cultivation of paddy rice |
| | Manufacture of textiles (17) | CN | Chemicals nec |
| | Manufacture of fish products | CN | Production of electricity by coal |
| | Processing of dairy products | CN | Raw milk |
| | Manufacture of textiles (17) | RoW | Extraction of natural gas and services related to natural gas extraction, excluding surveying |
| | Processing of Food products nec | CN | Production of electricity by coal |

| | | | |
|---|---|---|---|
| | Processing of Food products nec | CN | Cultivation of cereal grains nec |
| | Processing of Food products nec | CN | Cultivation of vegetables, fruit, nuts |
| | Manufacture of textiles (17) | CN | Cultivation of plant-based fibers |
| | Manufacture of furniture; manufacturing n.e.c. (36) | RoW | Extraction of natural gas and services related to natural gas extraction, excluding surveying |
| | Processing of meat cattle | CN | Cattle farming |
| | Processing of Food products nec | CN | Pigs farming |
| | Processing of meat pigs | CN | Pigs farming |
| | Tanning and dressing of leather; manufacture of luggage, handbags, saddlery, harness and footwear (19) | CN | Production of electricity by coal |
| | Production of meat products nec | CN | Meat animals nec |
| | Manufacture of wearing apparel; dressing and dyeing of fur (18) | RoW | Extraction of natural gas and services related to natural gas extraction, excluding surveying |
| | Processing vegetable oils and fats | CN | Cultivation of oil seeds |
| | Manufacture of textiles (17) | CN | Manufacture of textiles (17) |
| | Manufacture of beverages | CN | Production of electricity by coal |
| | Manufacture of wearing apparel; dressing and dyeing of fur (18) | CN | Production of electricity by coal |
| | Manufacture of furniture; manufacturing n.e.c. (36) | CN | Manufacture of furniture; manufacturing n.e.c. (36) |
| | Retail trade, except of motor vehicles and motorcycles; repair of personal and household goods (52) | CN | Steam and hot water supply |
| | Processing vegetable oils and fats | RoW | Cultivation of oil seeds |
| | Manufacture of textiles (17) | CN | Cultivation of wheat |

| | | | |
|---|---|---|---|
| | Manufacture of beverages | CN | Cultivation of wheat |
| | Tanning and dressing of leather; manufacture of luggage, handbags, saddlery, harness and footwear (19) | CN | Mining of coal and lignite; extraction of peat (10) |
| | Tanning and dressing of leather; manufacture of luggage, handbags, saddlery, harness and footwear (19) | CN | Steam and hot water supply |
| | Tanning and dressing of leather; manufacture of luggage, handbags, saddlery, harness and footwear (19) | CN | Tanning and dressing of leather; manufacture of luggage, handbags, saddlery, harness and footwear (19) |
| | Manufacture of textiles (17) | CN | Extraction of natural gas and services related to natural gas extraction, excluding surveying |
| | Processing of meat poultry | CN | Poultry farming |
| | Manufacture of furniture; manufacturing n.e.c. (36) | CN | Manufacture of basic iron and steel and of ferro-alloys and first products thereof |
| | Manufacture of wearing apparel; dressing and dyeing of fur (18) | CN | Steam and hot water supply |
| | Manufacture of furniture; manufacturing n.e.c. (36) | CN | Manufacture of fabricated metal products, except machinery and equipment (28) |
| | Processing of Food products nec | RoW | Cultivation of vegetables, fruit, nuts |
| | Processing of Food products nec | CN | Manufacture of gas; distribution of gaseous fuels through mains |
| | Production of meat products nec | CN | Production of electricity by coal |
| | Tanning and dressing of leather; manufacture of luggage, handbags, saddlery, harness and footwear (19) | CN | Cattle farming |
| | Manufacture of wearing apparel; dressing and dyeing of fur (18) | CN | Manufacture of textiles (17) |

*Table A.4 The reduction potentials of hotspots*

| **Hotspot region** | **Hotspots subsector** | **num ber** | **reduction potential in 2050** | **Change ratio** | **Reference** |
|---|---|---|---|---|---|
| CN | Production of electricity by coal | 13 | In the APS, coal use falls significantly after 2030, notably in China, and global demand in 2050 is half of 2020 levels. | -50% | (IEA, 2021b) |
| CN | Steam and hot water supply | 6 | To be in line with the Net Zero Scenario, the share of clean energy technologies such as heat pumps, solar thermal heating, low-carbon district energy systems and biomass boilers, needs to exceed 80% of new heating equipment sales by 2030.<br>Alongside building envelope improvements, deployment of these low-carbon high-efficiency heating technologies would help reduce average global heating energy intensity by around 4% annually in the next decade. The combined effects of efficiency improvements, fuel-shifting and power sector decarbonisation would reduce buildings' heating-related emissions by over 50% by 2030. | -50% | (IEA, 2021a) |
| CN | Manufacture of basic iron and steel and of ferro-alloys and first products thereof | 3 | The direct $CO_2$ intensity of crude steel production has decreased slightly in the past few years, but efforts need to be accelerated to get on track with the pathway in the Net Zero Emissions by 2050 Scenario. In contrast to the minor annual improvements in the last decade, the $CO_2$ intensity in the Net Zero Scenario falls by around 3% annually on average between 2020 and 2030. | -30% per year for ten years | (IEA, 2022c) |
| CN | Petroleum Refinery | 2 | It was determined that the contribution of technologies to emissions reduction was approximately 32.5% of the total $CO_2$ emissions when there was no ETS. | -32.5% | (Li et al., 2020) |
| CN | Pigs farming | 4 | Emissions reduction from the livestock sector can be achieved by reducing production and consumption, by lowering emission intensity of production, or by a combination of the two. GLEAM does not evaluate the potential of reduced consumption of livestock products. Mitigation potential estimates in GLEAM are based on the wide gap in emission intensities that exists on a global and regional scale and within production systems and agro-ecological regions. The estimation for mitigation is around 33 percent, or about 2.5 gigatonnes $CO_2$-eq, with respect to the baseline scenario. | -33% | (FAO, 2022) |

| | | | | | |
|---|---|---|---|---|---|
| CN | Sea and coastal water transport | 1 | The IMO Initial Strategy on the reduction of GHG emissions from shipping sets key ambitions. This is a policy framework. The main goals are:<br>Cut annual greenhouse gas emissions from international shipping by at least half by 2050, compared with their level in 2008, and work towards phasing out GHG emissions from shipping entirely as soon as possible in this century.<br>The Initial GHG Strategy envisages a reduction in carbon intensity of international shipping (to reduce $CO_2$ emissions per transport work), as an average across international shipping, by at least 40% by 2030, pursuing efforts towards 70% by 2050, compared to 2008. | -50% | (IMO, 2019) |
| CN | Casting of metals | 1 | | | |
| CN | Meat animals nec | 2 | Emissions reduction from the livestock sector can be achieved by reducing production and consumption, by lowering emission intensity of production, or by a combination of the two. GLEAM does not evaluate the potential of reduced consumption of livestock products. Mitigation potential estimates in GLEAM are based on the wide gap in emission intensities that exists on a global and regional scale and within production systems and agro-ecological regions. The estimation for mitigation is around 33 percent, or about 2.5 gigatonnes $CO_2$-eq, with respect to the baseline scenario. | -33% | (FAO, 2022) |
| CN | Manufacture of gas; distribution of gaseous fuels through mains | 2 | Oil and natural gas currently satisfy more than half of global energy demand. In the Net Zero Emissions by 2050 Scenario, oil and gas demand falls by around 15% by 2030, but emissions from oil and gas supply drop by almost 55%. | -15% | (IEA, 2022b) |
| CN | Manufacture of motor vehicles, trailers and semi-trailers (34) | 1 | | | |
| CN | Manufacture of rubber and plastic products (25) | 1 | | | |

| | | | | | |
|---|---|---|---|---|---|
| CN | Manufacture of other transport equipment (35) | 1 | | | |
| CN | Manufacture of fabricated metal products, except machinery and equipment (28) | 2 | | | |
| CN | Cultivation of paddy rice | 1 | The resulting scenarios indicate that a preliminary goal for agricultural non-$CO_2$ emissions mitigation by 2030 to stay within the 2 °C limit is 0.92–1.37 $GtCO_2e$ yr−1 or about 1 $GtCO_2e$ yr−1. This is an annualized, not cumulative, goal. The target assumes an allowable emissions budget of 6.15–7.78 $GtCO_2e$ yr−1 for agriculture in 2030. The goal represents an 11–18% reduction relative to the scenarios' respective 2030 business-as-usual baselines. | -14.5% | (Wollenberg et al., 2016) |
| CN | Chemicals nec | 1 | Chemical sector emissions need to peak in the next few years and decline towards 2030 to get on track with the Net Zero Scenario. The sector's emissions decline in this scenario by about 15% relative to current levels by 2030, despite strong growth in demand for its outputs. | -15% | (IEA, 2022a) |
| CN | Raw milk | 1 | As discussed previously, an in-crease from 704 to 1077 million tons of milk by 2050 could theoretically be obtained by fewer cows with greater productivity, which could potentially reduce the average GHG emissions per kilogram of milk by more than 40%. | -40% | (van Hooijdonk & Hettinga, 2015) |
| RoW | Extraction of natural gas and services related to natural gas extraction, excluding surveying | 3 | Oil and natural gas currently satisfy more than half of global energy demand. In the Net Zero Emissions by 2050 Scenario, oil and gas demand falls by around 15% by 2030, but emissions from oil and gas supply drop by almost 55%. | -15% | (IEA, 2022b) |

| | | | | | |
|---|---|---|---|---|---|
| CN | Cultivation of cereal grains nec | 1 | The resulting scenarios indicate that a preliminary goal for agricultural non-$CO_2$ emissions mitigation by 2030 to stay within the 2 °C limit is 0.92–1.37 $GtCO_2e$ yr−1 or about 1 $GtCO_2e$ yr−1. This is an annualized, not cumulative, goal. The target assumes an allowable emissions budget of 6.15–7.78 $GtCO_2e$ yr−1 for agriculture in 2030. The goal represents an 11–18% reduction relative to the scenarios' respective 2030 business-as-usual baselines. | -14.5% | (Wollenberg et al., 2016) |
| CN | Cultivation of vegetables, fruit, nuts | 1 | The resulting scenarios indicate that a preliminary goal for agricultural non-$CO_2$ emissions mitigation by 2030 to stay within the 2 °C limit is 0.92–1.37 $GtCO_2e$ yr−1 or about 1 $GtCO_2e$ yr−1. This is an annualized, not cumulative, goal. The target assumes an allowable emissions budget of 6.15–7.78 $GtCO_2e$ yr−1 for agriculture in 2030. The goal represents an 11–18% reduction relative to the scenarios' respective 2030 business-as-usual baselines. | -14.5% | (Wollenberg et al., 2016) |
| CN | Cultivation of plant-based fibers | 1 | The resulting scenarios indicate that a preliminary goal for agricultural non-$CO_2$ emissions mitigation by 2030 to stay within the 2 °C limit is 0.92–1.37 $GtCO_2e$ yr−1 or about 1 $GtCO_2e$ yr−1. This is an annualized, not cumulative, goal. The target assumes an allowable emissions budget of 6.15–7.78 $GtCO_2e$ yr−1 for agriculture in 2030. The goal represents an 11–18% reduction relative to the scenarios' respective 2030 business-as-usual baselines. | -14.5% | (Wollenberg et al., 2016) |
| CN | Cattle farming | 2 | Emissions reduction from the livestock sector can be achieved by reducing production and consumption, by lowering emission intensity of production, or by a combination of the two. GLEAM does not evaluate the potential of reduced consumption of livestock products. Mitigation potential estimates in GLEAM are based on the wide gap in emission intensities that exists on a global and regional scale and within production systems and agro-ecological regions. The estimation for mitigation is around 33 percent, or about 2.5 gigatonnes $CO_2$-eq, with respect to the baseline scenario. | -33% | (FAO, 2022) |
| CN | Cultivation of oil seeds | 1 | The resulting scenarios indicate that a preliminary goal for agricultural non-$CO_2$ emissions mitigation by 2030 to stay within the 2 °C limit is 0.92–1.37 $GtCO_2e$ yr−1 or about 1 $GtCO_2e$ yr−1. This is an annualized, not cumulative, goal. The target assumes an allowable emissions budget of 6.15–7.78 $GtCO_2e$ yr−1 for agriculture in 2030. The goal | -14.5% | (Wollenberg et al., 2016) |

| | | | | | |
|---|---|---|---|---|---|
| | | | represents an 11–18% reduction relative to the scenarios' respective 2030 business-as-usual baselines. | | |
| CN | Manufacture of textiles (17) | 2 | | | |
| CN | Manufacture of furniture; manufacturing n.e.c. (36) | 1 | | | |
| RoW | Cultivation of oil seeds | 1 | The resulting scenarios indicate that a preliminary goal for agricultural non-$CO_2$ emissions mitigation by 2030 to stay within the 2 °C limit is 0.92–1.37 $GtCO_2e$ yr−1 or about 1 $GtCO_2e$ yr−1. This is an annualized, not cumulative, goal. The target assumes an allowable emissions budget of 6.15–7.78 $GtCO_2e$ yr−1 for agriculture in 2030. The goal represents an 11–18% reduction relative to the scenarios' respective 2030 business-as-usual baselines. | -14.5% | (Wollenberg et al., 2016) |
| CN | Cultivation of wheat | 2 | The resulting scenarios indicate that a preliminary goal for agricultural non-$CO_2$ emissions mitigation by 2030 to stay within the 2 °C limit is 0.92–1.37 $GtCO_2e$ yr−1 or about 1 $GtCO_2e$ yr−1. This is an annualized, not cumulative, goal. The target assumes an allowable emissions budget of 6.15–7.78 $GtCO_2e$ yr−1 for agriculture in 2030. The goal represents an 11–18% reduction relative to the scenarios' respective 2030 business-as-usual baselines. | -14.5% | (Wollenberg et al., 2016) |
| CN | Mining of coal and lignite; extraction of peat (10) | 1 | To stay on track for a global 2°C scenario, all sectors would need to reduce $CO_2$ emissions from 2010 levels by at least 50 percent by 2050. To limit warming to 1.5°C, a reduction of at least 85 percent would likely be needed. Mining companies' published emission targets tend to be more modest than that, setting low targets, not setting targets beyond the early 2020s, or focusing on emission intensity rather than absolute numbers | -50% | (Delevingne et al., 2020) |
| CN | Tanning and dressing of leather; manufacture of | 1 | | | |

| | | | | | |
|---|---|---|---|---|---|
| | luggage, handbags, saddlery, harness and footwear (19) | | | | |
| CN | Extraction of natural gas and services related to natural gas extraction, excluding surveying | 1 | The carbon emission reduction potential in the Chinese oil and gas extraction industry in 2050 can reach 16.71 million tons in the case of all low-carbon technologies available, and the decrease rate can be as high as 14.3%. | -14.3% | (Sun et al., 2018) |
| CN | Poultry farming | 1 | Emissions reduction from the livestock sector can be achieved by reducing production and consumption, by lowering emission intensity of production, or by a combination of the two. GLEAM does not evaluate the potential of reduced consumption of livestock products. Mitigation potential estimates in GLEAM are based on the wide gap in emission intensities that exists on a global and regional scale and within production systems and agro-ecological regions. The estimation for mitigation is around 33 percent, or about 2.5 giga tonnes $CO_2$-eq, with respect to the baseline scenario. | -33% | (FAO, 2022) |
| RoW | Cultivation of vegetables, fruit, nuts | 1 | The resulting scenarios indicate that a preliminary goal for agricultural non-$CO_2$ emissions mitigation by 2030 to stay within the 2 °C limit is 0.92–1.37 $GtCO_2e$ $yr^{-1}$ or about 1 $GtCO_2e$ $yr^{-1}$. This is an annualized, not cumulative, goal. The target assumes an allowable emissions budget of 6.15–7.78 $GtCO_2e$ $yr^{-1}$ for agriculture in 2030. The goal represents an 11–18% reduction relative to the scenarios' respective 2030 business-as-usual baselines. | -14.5% | (Wollenberg et al., 2016) |

# Appendix II

## A. The steps for material consumption modelling

The modelling of material consumption was limited to households only, given that data on material consumption in the public sector and transport is very limited. For households, the calculation of material consumption (household goods, in kg) was based on Oxford Economics data on consumer expenditure of goods and services at the city level, in million EUR based on 2015 prices, from the year 2000 projected to 2050 (Oxford-Economics, 2020), and material price data in financial units (kr/kg) which is based on prices in Sweden (Whetstone et al., 2020).

Both data sources use COICOP sector classifications (though at different levels of detail). The calculation method was the same for all four cities. Given limited time and resources, only one source on material price data was used.

Specifically, the calculation method is summarized as follows.

**Step 1: Adapting Oxford Economics consumer expenditure data**

First, the COICOP sectors in the Oxford Economics consumer expenditure data was classified as either goods or services based on the International Classification of Goods and Services produced by the World Intellectual Property Organization (World-Intellectual-Property-Organizaton, 2001). Sectors that included both goods and services (i.e. COICOP groups 056 "Routine household maintenance goods and services" and 131 "Personal care goods and services") were halved based on the assumption that 50% of the value is assigned to goods and the rest to services.

The Oxford Economics data consisted only of the COICOP sector descriptions and not the codes. As such, the COICOP grouping codes were assigned to the descriptions based on the COICOP sector classification version of 2018 (Eurostat, 2018).

**Step 2: Adapting material cost data**

The material cost data collected by (Whetstone et al., 2020) consisted of prices in Swedish krona per kg of specific products classified by specific COICOP product codes. In this step, the specific COICOP product groups for each line of the material price data set were aggregated and assigned to the COICOP grouping codes identified in Step 1. For example, COICOP product code “U0111101 Rice” and “U0111201 Crispbread” in the material price data were aggregated and assigned to COICOP group “011 Food” in the Oxford Economics data.

The following price data were missing: COICOP group “024 Narcotics", “0814 Audio-visual, photographic and information processing equipment" and “097 Newspapers, books and stationery" and as such were excluded from the remainder of the calculations.

**Step 3: Calculating the average material price by COICOP group in EUR/kg**

After aggregated the relevant products into the appropriate COICOP group, the average material cost was calculated for each group. Price data in Swedish krona was converted to Euros based on the exchange rate published by the European Central Bank in 2021. The final average material price figures per COICOP group was obtained in EUR/kg.

**Step 4: Calculating materials consumed in kg**

This was calculated by dividing the material prices (in EUR/kg) by consumer expenditure (in million EUR). A conversion was made from million EUR to EUR. The final figures obtained are materials consumed in kg for each COICOP product group per year from 2000 to 2050.

**Step 5: Graphing trends in material consumption (in kg) until 2050**

For each COICOP product group, the consumption trend is projected by graphing a linear trendline from 2000 to 2050. The equations of the trendlines were obtained and used for calculating Household material consumption in 2050 for each city.

## B. Shanghai

### Basic data

| | **Basic data** |
|---|---|
| **Item** | **Calculation method, assumptions and data sources** |
| City Population | City population in the base year (2017): 24,183,300 (Shanghai-Municipal-Bureau-of-Statistics, 2021)<br><br>City population data in 2050: 25,000,000 (Shanghai-Municipal-Government, 2018). The target for population management is to keep the population around 25 million and considering the past target achievement rate is high enough, this population target is assumed to be achieved. |

### Base trend

| | | **Base trend** |
|---|---|---|
| **Societal category** | **Resource** | **Calculation method, assumptions and data sources** |
| Household | Water | **Calculation of water use per person in the base year (2017)**: Calculated by total "Water use by household" in 2017 divided by 2017 population. Converted from 100 Mm3 to m3. (Shanghai-Municipal-Bureau-of-Statistics, 2021)<br><br>**Calculation of water use per person in 2050**: Calculated by total "Water use by household" extrapolated to 2050 divided by 2050 population. The extrapolation is calculated using the equation of a linear trendline (y=0.1017x-194.64, R2=0.7589) drawn on total water use per year in Shanghai for households from 2010 to 2019. Converted from 100 Mm3 to m3 (Shanghai-Municipal-Bureau-of-Statistics, 2021(Shanghai-Municipal-Government, 2018 #38)). |
| | Energy | The data on energy consumption by households in Shanghai is the living consumption sector including urban and rural household consumption (Shanghai-Municipal-Bureau-of-Statistics, 2021).<br><br>**Calculation of energy use per person in the base year (2017)**: Calculated by total "Energy consumption (Living Consumption)" in 2017 divided by 2017 population. Converted from TCE to MWh to kWh (Shanghai-Municipal-Bureau-of-Statistics, 2021) |

| | | |
|---|---|---|
| | | **Calculation of energy use per person in 2050**: Calculated by total "Energy consumption by Living Consumption" extrapolated to 2050 divided by 2050 population. The extrapolation is calculated using the equation of a linear trendline (y=2,175,294.94x-4,286,504,042.87, R2=0.81) drawn on total energy use per year in Shanghai for households from 2010 to 2019. Converted from TCE to MWh to kWh (Shanghai-Municipal-Bureau-of-Statistics, 2021). |
| | Materials | **Calculation of material use per person in base year (2017):** Based on the materials consumption calculations explained in Subchapter A, the figure for material consumption in kg for 2017 was obtained for each COICOP product group, then divided by the city population in 2017.<br>**Calculation of material use per person in 2050:** For each COICOP product group, the material consumption trendlines were used to estimate material consumption in kg in 2050. The trendline equations are as follows:<br>Food and non-alcoholic beverages: y=927.05x-1,835,568.70 R=0.94<br>Alcoholic beverages, tobacco and narcotics: y= 331.63x-664,003.10 R=0.98<br>Clothing and footwear: y=34.32x-68,565.54 R=0.98<br>Furnishings, household equipment and routine household maintenance: y=199.68x-399,728.99 R=0.96<br>Health: y=20.50x-41,106.57 R=0.95<br>Information and communication: y=0.94x-1,874.39 R=0.96<br>Recreation, sport and culture: y=15.71x-31,524.99 R=0.95<br>Personal care, social protection and miscellaneous goods: y=2.82x-5,633.14 R=0.97 |
| Public sector | Water | Considering the different sectors of water use, assume that the water consumption by public = the total water consumption – water consumption by household – water consumption by industry<br>**Calculation of water use per person in the base year (2017):** Calculated by total "Water use by public" in 2017 divided by the city population in 2017. Converted from 100 Mm3 to m3. (Shanghai-Municipal-Bureau-of-Statistics, 2021)<br>**Calculation of water use per person in 2050:** Calculated by total "Water use by public" extrapolated to 2050 divided by 2050 population. The extrapolation is calculated using the equation of a linear trendline (y=0.0986x-189.37, R2=0.2709) drawn on total water use per year in Shanghai for public sector from 2010 to 2019. Converted from 100 Mm3 to m3 (Shanghai-Municipal-Bureau-of-Statistics, 2021(Shanghai-Municipal-Government, 2018 #38)). |

| | | |
|---|---|---|
| Transport | Energy | The data of energy consumption by the transport sector in Shanghai is for a big sector including transport, warehousing, post and communications which accounts for around 22%. Compared with the proportion of transportation energy consumption in China (17%), there is no big difference between these proportions which means we can assume this sector is almost the energy consumption for transportation (Shanghai-Municipal-Bureau-of-Statistics, 2021).<br><br>The energy consumption for public and private transport has used the proportion of energy consumption to multiply the total energy consumption by the transport sector respectively. The proportions of private and public transport energy consumption are 79% and 21% respectively (SCCTPI, 2018).<br><br>**Calculation of energy use per person in the base year (2017)**: Calculated by total "Energy consumption (Transportation, Warehousing, Post and Communications" in 2017 divided by 2017 population. Converted from TCE to MWh to kWh (Shanghai-Municipal-Government, 2018 #38(IEA, 2016 #100)).<br><br>**Calculation of energy use per person in 2050**: Calculated by total “Energy consumption by Transportation, Warehousing, Post and Communications” extrapolated to 2050 divided by 2050 population. The extrapolation is calculated using the equation of a linear trendline (y=5,569,588.67x-11,039,428,921.41, R2=0.82) drawn on total energy use per year in Shanghai for households from 2010 to 2019. Converted from TCE to MWh to kWh (Shanghai-Municipal-Government, 2018(IEA, 2016 #100)). |

**BAU scenario 2050**

| | | **BAU** |
|---|---|---|
| **Societal category** | **Resource** | **Calculation method, assumptions and data sources** |
| Household | Water | **Calculation of water use per person in 2050 based on BAU scenario**: The absolute value of resource use is calculated by the total water use in the base year (2017) multiplied by the change rate (0.316793893) based on the step-wise trend target from 2017 to 2035. Assume that the absolute value from 2035 to 2050 would keep stable. Calculated by the absolute value of resource use in 2050 divided by the 2050 population (National-Development-and-Reform-Commission, 2020). |
| | Energy | **Calculation of energy use per person in 2050 based on BAU scenario**: Same with the values from the base trend |
| | Materials | **Calculation of material use per person in 2050 based on BAU scenario**: Same with the values from the base trend |
| Public sector | Water | **Calculation of water use per person in 2050 based on BAU scenario**: The absolute value of resource use is calculated by the |

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| | | total water use in the base year (2017) multiplied by the change rate (0.316793893) based on the step-wise trend target from 2017 to 2035. Assume that the absolute value from 2035 to 2050 would keep stable. Calculated by the absolute value of resource use in 2050 divided by the 2050 population (Statistics., #103). |
| Transport (public) | Energy | **Calculation of energy use per person in 2050 based on BAU scenario**: Due to the target based on the model share with different transport, the equations below are used to calculate the new energy use:<br>For the base year 2017, Energy consumption (public) = Proportion of public transport energy consumption × Total energy consumption by the transport sector = Energy use per person (public) × Population of Shanghai = Total travel volume (trips) × Proportion of public travel volume × Energy use per trip (public).<br><br>The energy use per trip (public) =3887.86kWh<br><br>Then we assume the energy use per trip for both private and public transport will not change. New energy consumption per person(public) = [Energy use per trip × Proportion of the transport way × New total travel volume (= Total travel volume / Population ratio × new population)]/ new population<br><br>Population ratio = Total travel volume / Population and the ratio is stable for years, so we use the average value from 2017 which is 1.35 here (SCCTPI, 2018). |
| Transport (private) | Energy | **Calculation of energy use per person in 2050 based on BAU scenario**: Due to the target based on the model share with different transport, the equations below are used to calculate the new energy use:<br>For the base year 2017, Energy consumption (private) = Proportion of private transport energy consumption × Total energy consumption by the transport sector = Energy use per person (private) × Population of Shanghai = Total travel volume (trips) × Proportion of private travel volume × Energy use per trip (private).<br><br>The energy use per trip (private) =24038.36kWh<br><br>Then we assume the energy use per trip for both private and public transport will not change. New energy consumption per person (private) = [Energy use per trip × Proportion of the transport way × New total travel volume (= Total travel volume / Population ratio × new population)]/new population<br><br>Population ratio = Total travel volume / Population and the ratio is stable for years, so we use the average value from 2017 which is 1.35 here(SCCTPI, 2018). |

**CE scenario 2050**

| | | CE |
|---|---|---|
| **Societal category** | **Resource** | **Calculation method, assumptions and data sources** |
| Household | Water | **Calculation of water use in 2050 based on CE scenario**:<br>Combined with the fact that the lack of circular economy target in Shanghai and considering that the description from US EPA "using 30% less water by installing water-efficient fixtures and appliances" (EPA, 2017), we assume that in base trend, these water-efficient fixtures were not installed and in CE scenario in 2050, the target of 30% less water use would be achieved.<br><br>The value of water use per person is calculated by the water use per person in the base year (2017) multiplied by the change rate (decrease 30%) based on the step-wise trend target from US EPA. Then the absolute value of water use is calculated by the value of water use per person multiplied by the population in 2050. |
| | Energy | **Calculation of energy use in 2050 based on CE scenario**:<br>Every five years, the circular economy development plan would have a target for the reduction proportion of energy use. The latest one mentioned: "By 2025, ……the energy consumption per unit GDP will be reduced by 13.5% compared with 2020." (National-Development-and-Reform-Commission, 2020)<br><br>Collect the target for every five-year circular economy development plan, and extrapolate the trend to get the reduction rate further. And calculate the absolute resource use of 2050 based on the step-wise targets per 5 years:<br><br>Absolute resource use 2050<br>= ((the absolute resource use of 2020 / (GDP of 2020 × city's average proportion of domestic GDP) × total reduction rate 2020- 2050) × (GDP prediction of 2050 × city's average proportion of domestic GDP)<br>In which:<br><br>Total reduction rate 2020-2050<br>= (1-reducation rate 2020-2025) × (1-reducation rate 2025-2030) × (1-reducation rate 2030-2035) × (1-reducation rate 2035-2040) × (1-reducation rate 2040-2045) × (1-reducation rate 2045-2050)<br><br>Then the value of energy use per person is calculated by the absolute value of energy use divided by the population in 2050. |
| | Materials | **Calculation of material use in 2050 based on CE scenario**:<br>For the group "Food and non-alcoholic beverages", the target is concluded by two studies from UNEP that 61% of food waste is avoidable (UN-Environment-Programme, n.d.). It is ambitious enough here to apply in the CE scenario.<br><br>The value of "Food and non-alcoholic beverages" material use per person is calculated by the "Food and non-alcoholic beverages" material use per person in the base year (2017) multiplied by the change rate (decrease 61%) based on the step- |

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| | | wise trend target from UNEP. Then the absolute value of "Food and non-alcoholic beverages" material use is calculated by the value of "Food and non-alcoholic beverages" material use per person multiplied by the population in 2050. |
| Public sector | Water | **Calculation of water use in 2050 based on CE scenario**: Combined with the fact that the lack of circular economy target in Shanghai and considering that the description from US EPA "using 30% less water by installing water-efficient fixtures and appliances" (EPA, 2017), we assume that in base trend, these water-efficient fixtures were not installed and in CE scenario in 2050, the target of 30% less water use would be achieved.<br><br>The value of water use per person is calculated by the water use per person in the base year (2017) multiplied by the change rate (decrease 30%) based on the step-wise trend target from US EPA. Then the absolute value of water use is calculated by the value of water use per person multiplied by the population in 2050. |
| Transport | Energy | **Calculation of energy use in 2050 based on CE scenario**: Due to the lack of targets for transport in CE scenario, considering that the target from Vienna is also based on transport model share and it is suitable for CE scenario, the target used here is the target that "the modal shares of public and private transport are 55 % and 10 %, respectively in 2050".<br>Then calculate the energy use for transport by the same way used when we calculated it for BAU scenarios.<br><br>The energy use per trip (private) = 24038.36 kwh<br>The energy use per trip (public) = 3887.86 kwh<br><br>We assume the energy use per trip for both private and public transport will not change. New energy consumption per person (private/public) = [Energy use per trip × Proportion of the transport way × New total travel volume (= Total travel volume / Population ratio (1.35) × new population)]/new population |

## IO table sections for BAU and CE

| **Societal category** | **Resource** | **Calculation method, assumptions and data sources** |
|---|---|---|
| Household | Water | **Calculation of total expenditure of water relevant IO sector 2017:** The associated IO FD category and sector is Household Final Demand of Sector <E>. The total expenditure of water relevant IO sector 2017 is the total value of urban and rural household consumption from <E> in Shanghai IO table 2017. Converted from CNY to EUR.<br>**Calculation of total expenditure of water relevant IO sector 2050**: There is no waste management and sewage in disaggregated table, and the value of <E> sector is the same as the subsector called water production and supply. Thus assume 100% of <E> is for water consumption.<br>• Affected sector: Calculated resource in sector 2017 by multiplying total expenditure of water relevant IO sector 2017 |

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| | | and the share percentage of the sector for resource use. Calculated unit price 2017 by absolute value of resource use 2017 divided by the resource in sector 2017. Calculated the unit price 2050 by multiplying unit price 2017 by the inflation rate. Then calculated the resource in sector 2050 by the absolute value of resource use 2017 multiplying the cumulative rate of absolute change and inflation rate.<br>• Unaffected sector: Calculated the unaffected expenditure 2017 by expenditure of water relevant IO sector 2017 minus the affected expenditure 2017. Calculated unaffected expenditure 2050 by expenditure of water relevant IO sector 2017 multiplying the inflation rate.<br>Calculated the total expenditure of water relevant IO sector 2050 by adding affected expenditure 2050 and unaffected expenditure 2050. |
| | Energy | **Calculation of total expenditure of energy relevant IO sector 2017:** The associated IO FD category and sector is Household Final Demand of Sector <D>. The total expenditure of water relevant IO sector 2017 is the total value of urban and rural household consumption from <D> in Shanghai IO table 2017. Converted from CNY to EUR.<br>**Calculation of total expenditure of energy relevant IO sector 2050**: The value of <D> sector is the same as the sum of subsectors called electricity, steam and hot water production and supply, and gas production and supply. Thus assume 100% of <D> is for energy consumption.<br>• Affected sector: Same with the household water sector<br>• Unaffected sector: Same with the household water sector<br>Calculated the total expenditure of energy relevant IO sector 2050 by adding affected expenditure 2050 and unaffected expenditure 2050. |
| | Materials | **Calculation of total expenditure of material relevant IO sector 2017:** The associated IO FD category and sector is Household Final Demand of Sector <G>. The total expenditure of water relevant IO sector 2017 is the total value of urban and rural household consumption from <G> in Shanghai IO table 2017. Converted from CNY to EUR.<br>**Calculation of total expenditure of material relevant IO sector 2050**: The value of <G> sector is the same as the sum of subsectors called wholesale and retail. Thus assume 63.3% of <G> which is the proportion of retail is for material consumption. Then for different subsectors under material sector, the proportion of affected sector <G> is calculated by the material breakdown and the sum is 63.3%<br>• Affected sector: Same with the household water sector<br>• Unaffected sector: Same with the household water sector<br>Calculated the total expenditure of material relevant IO sector 2050 by adding affected expenditure 2050 and unaffected expenditure 2050. |
| Public sector | Water | **Calculation of total expenditure of water relevant IO sector 2017:** The associated IO FD category and sector is Public Sector Final Demand of Sector <E>. The total expenditure of water relevant IO sector 2017 is the value of government consumption from <E> in Shanghai IO table 2017. Converted from CNY to EUR. |

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|---|---|---|
| | | **Calculation of total expenditure of water relevant IO sector 2050**: Same with the household water sector |
| Transport (public) | Energy | **Calculation of total expenditure of energy relevant IO sector 2017:** The associated IO FD category and sector is Household Final Demand of Sector <H>. The total expenditure of energy relevant IO sector 2017 is the total value of urban and rural household consumption from <H> in Shanghai IO table 2017. Converted from CNY to EUR.<br>**Calculation of total expenditure of energy relevant IO sector 2050**: The proportion of transportation is derived from subsector urban public transport and road transport for sector <H> from the IO table for China of 2017 which is 18.67%. Considering the proportion of public transport energy use, thus 18.67% of <E> × 21% is for public transportation energy consumption.<br>• Affected sector: Same with the household energy sector<br>• Unaffected sector: Same with the household energy sector<br>Calculated the total expenditure of energy relevant IO sector 2050 by adding affected expenditure 2050 and unaffected expenditure 2050. |
| Transport (Private) | Energy | **Calculation of total expenditure of energy relevant IO sector 2017:** The associated IO FD category and sector is Household Final Demand of Sector <H>. The total expenditure of energy relevant IO sector 2017 is the total value of urban and rural household consumption from <H> in Shanghai IO table 2017. Converted from CNY to EUR.<br>**Calculation of total expenditure of energy relevant IO sector 2050**: The proportion of transportation is derived from subsector urban public transport and road transport for sector <H> from the IO table for China of 2017 which is 18.67%. Considering the proportion of private transport energy use, thus 18.67% of <E> × 79% is for private transportation energy consumption.<br>• Affected sector: Same with the household energy sector<br>• Unaffected sector: Same with the household energy sector<br>Calculated the total expenditure of energy relevant IO sector 2050 by adding affected expenditure 2050 and unaffected expenditure 2050. |

## C. Beijing

### Basic data

| | **Basic data** |
|---|---|
| **Item** | **Calculation method, assumptions and data sources** |
| City Population | City population in the base year (2017): 21,707,000 (Beijing-Municipal-Bureau-of-Statistics, 2021)<br>City population data in 2050: 23,000,000 (Beijing-Municipal-Commission-of-Planning-and-Natural-Resources, 2018) The target for population management is to bring the population below 23 million and considering the past target achievement rate is high enough, |

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| | this population target is assumed to be achieved. |

## 2. Base trend

| | | Base trend |
|---|---|---|
| **Societal category** | **Resource** | **Calculation method, assumptions and data sources** |
| Household | Water | **Calculation of water use per person in the base year (2017)**: Calculated by total "Domestic Water" in 2017 divided by 2017 population. Converted from 100 Mm3 to m3.(Beijing-Municipal-Bureau-of-Statistics, 2021)<br>**Calculation of water use per person in 2050**: Calculated by total "Domestic Water" extrapolated to 2050 divided by 2050 population. The extrapolation is calculated using the equation of a linear trendline (y=0.4081x-805.01, R2=0.9733) drawn on total water use per year in Beijing for households from 2001 to 2019. Converted from 100 Mm3 to m3 (Beijing-Municipal-Bureau-of-Statistics, 2021). |
| | Energy | **Calculation of energy use per person in the base year (2017)**: Calculated by total "Residential consumption (Total Energy Consumption)" in 2017 divided by 2017 population. Converted from ton of SCE to GWh to kWh (IEA, 2016).<br>**Calculation of energy use per person in 2050**: Calculated by total "Residential consumption (Total Energy Consumption)" extrapolated to 2050 divided by 2050 population. The extrapolation is calculated using the equation of a linear trendline (y=5,465.59x-10,888,840.67, R2=0.98) drawn on total energy use per year in Beijing for households from 2000 to 2019. Converted from ton of SCE to GWh to kWh (IEA, 2016). |
| | Materials | **Calculation of material use per person in base year (2017):** Based on the materials consumption calculations explained in Subchapter A, the figure for material consumption in kg for 2017 was obtained for each COICOP product group, then divided by the city population in 2017.<br>**Calculation of material use per person in 2050:** For each COICOP product group, the material consumption trendlines were used to estimate material consumption in kg in 2050. The trendline equations are as follows:<br>• Food and non-alcoholic beverages: y=794.47x-1,579,462.47 R2=0.98<br>• Alcoholic beverages, tobacco and narcotics: y=372.81x-747,292.49 R2=0.99<br>• Clothing and footwear: y=38.79x-77,537.78 R2=0.97<br>• Furnishings, household equipment and routine household maintenance: y=281.24x-563,814.81 R=0.98<br>• Health: y=23.66x-47,473.19 R2=0.95<br>• Information and communication: y=0.98x-1,959.72 R2=0.98<br>• Recreation, sport and culture: y=12.50x-25,092.32 R2=0.95 |

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| | | • Personal care, social protection and miscellaneous goods: y=2.90x-5,808.50 R2=0.98 |
| Public sector | Water | Considering the different sectors of water use, assume that the water consumption by public is the same as the water use for the environment.<br>**Calculation of water use per person in the base year (2017):** Calculated by total "Water for the Environment" in 2017 divided by the city population in 2017. Converted from 100 Mm3 to m3. (Beijing-Municipal-Bureau-of-Statistics, 2021)<br>**Calculation of water use per person in 2050:** Calculated by total "Water for the Environment" extrapolated to 2050 divided by 2050 population. The extrapolation is calculated using the equation of a linear trendline (y=0.8305x-1663.8, R2=0.9075) drawn on total water use per year in Beijing for public sector from 2001 to 2019. Converted from 100 Mm3 to m3 (Beijing-Municipal-Bureau-of-Statistics, 2021). |
| Transport | Energy | The data of energy consumption by the transport sector in Beijing is for a big sector including transport, warehousing, post and communications which accounts for around 20%. Compared with the proportion of transportation energy consumption in China (17%), there is no big difference between these proportions which means we can assume this sector is almost the energy consumption for transportation (Beijing-Municipal-Bureau-of-Statistics, 2021).<br>The energy consumption for public and private transport has used the proportion of energy consumption to multiply the total energy consumption by the transport sector respectively. The proportions of private and public transport energy consumption are 81.81% and 18.19% respectively (Yu Hao, 2013).<br>**Calculation of energy use per person in the base year (2017)**: Calculated by total "Energy consumption (Transportation, Warehousing, Post and Communications" in 2017 divided by 2017 population. Converted from ton of SCE to GWh to kWh (IEA, 2016 #100).<br>**Calculation of energy use per person in 2050**: Calculated by total "Energy consumption by Transportation, Warehousing, Post and Communications" extrapolated to 2050 divided by 2050 population. The extrapolation is calculated using the equation of a linear trendline (y=3,605,870.93x-7,159,414,318.89, R2=0.86) drawn on total energy use per year in Beijing for households from 2010 to 2019. Converted from ton of SCE to GWh to kWh (IEA, 2016). |

## BAU scenario 2050

| | | **BAU** |
|---|---|---|
| **Societal category** | **Resource** | **Calculation method, assumptions and data sources** |
| Household | Water | **Calculation of water use per person in 2050 based on BAU scenario**: The absolute value of resource use is calculated by the total water use in the base year (2017) multiplied by the change |

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|---|---|---|
| | | rate (0.214659686) based on the step-wise trend target from 2016 to 2025 to 2035. Assume that the absolute value from 2035 to 2050 would keep stable. Calculated by the absolute value of resource use in 2050 divided by the 2050 population (Beijing-Municipal-Commission-of-Planning-and-Natural-Resources, 2018(Beijing-Municipal-Government, 2022 #65)). |
| | Energy | **Calculation of energy use per person in 2050 based on BAU scenario**: Same with the values from the base trend |
| | Materials | **Calculation of material use per person in 2050 based on BAU scenario**: Same with the values from the base trend |
| Public sector | Water | **Calculation of water use per person in 2050 based on BAU scenario**: The absolute value of resource use is calculated by the total water use in the base year (2017) multiplied by the change rate (0.214659686) based on the step-wise trend target from 2016 to 2025 to 2035. Assume that the absolute value from 2035 to 2050 would keep stable. Calculated by the absolute value of resource use in 2050 divided by the 2050 population (Beijing-Municipal-Commission-of-Planning-and-Natural-Resources, 2018(Beijing-Municipal-Government, 2022 #65)). |
| Transport (public) | Energy | The target for public transportation is about the proportion of green travel in which the proportion of green travel is not less than 80% by 2035 and the bicycle travel is not less than 12.6%. (Beijing master plan 2016-2035). Assume that the green travel increase focuses on the public transportation. Then the proportion of public transport increases to 37.4% [80%-12.6%(cycling)-30%(walking)] (BJTRC, 2018)<br>**Calculation of energy use per person in 2050 based on BAU scenario**: Due to the target based on the model share with different transport, the equations below are used to calculate the new energy use:<br>For the base year 2017, Energy consumption (public) = Proportion of public transport energy consumption × Total energy consumption by the transport sector = Energy use per person (public) × Population of Shanghai = Total travel volume (trips) × Proportion of public travel volume × Energy use per trip (public).<br><br>The energy use per trip (public) =1685.37kWh<br><br>Then we assume the energy use per trip for both private and public transport will not change. New energy consumption per person(public) = [Energy use per trip × Proportion of the transport way × New total travel volume (= Total travel volume / Population ratio × new population)]/new population<br>In which:<br>Population ratio = Total travel volume / Population and the ratio is stable for years, so we use the average value from 2017 to 2019 which is 1.82 here (BJTRC, 2018). |
| Transport (private) | Energy | **Calculation of energy use per person in 2050 based on BAU scenario**: Due to the target based on the model share with different transport, the equations below are used to calculate the new energy use:<br>For the base year 2017, Energy consumption (private) = Proportion of private transport energy consumption × Total energy consumption by the transport sector = Energy use per |

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| | | person (private) × Population of Shanghai = Total travel volume (trips) × Proportion of private travel volume × Energy use per trip (private).<br><br>The energy use per trip (private) =9885.58kWh<br><br>Then we assume the energy use per trip for both private and public transport will not change. New energy consumption per person (private) = [Energy use per trip × Proportion of the transport way × New total travel volume (= Total travel volume / Population ratio × new population)]/new population<br>In which:<br>Population ratio = Total travel volume / Population and the ratio is stable for years, so we use the average value from 2017 to 2019 which is 1.82 here (BJTRC, 2018). |

### CE scenario 2050

| | | CE |
|---|---|---|
| **Societal category** | **Resource** | **Calculation method, assumptions and data sources** |
| Household | Water | **Calculation of water use in 2050 based on CE scenario**: 'By 2025, ……the water consumption per unit GDP will be reduced by 16% compared with 2020(National-Development-and-Reform-Commission, 2020).<br><br>Collect the target for every five-year circular economy development plan, and extrapolate the trend to get the reduction rate further. And calculate the absolute resource use of 2050 based on the step-wise targets per 5 years:<br><br>Absolute resource use 2050<br>= ((the absolute resource use of 2020 / (GDP of 2020 × city's average proportion of domestic GDP) × total reduction rate 2020-2050) × (GDP prediction of 2050 × city's average proportion of domestic GDP)<br>In which:<br>Total reduction rate 2020-2050<br>= (1-reducation rate 2020-2025) × (1-reducation rate 2025-2030) × (1-reducation rate 2030-2035) × (1-reducation rate 2035-2040) × (1-reducation rate 2040-2045) × (1-reducation rate 2045-2050)<br>In Beijing, the reduction rate of 2015-2020 is 15%. Extrapolate the trend of rate to 2030 then keep stable to calculate the resource use value. So the absolute resource use 2050 is the same with the absolute resource use 2030.<br>Then the value of energy use per person is calculated by the absolute value of energy use divided by the population in 2050. |
| | Energy | **Calculation of energy use in 2050 based on CE scenario**: Every five years, the circular economy development plan would have a target for the reduction proportion of energy use. The latest one mentioned: “By 2025, ……the energy consumption per unit GDP will be reduced by 13.5% compared with 2020.” (National-Development-and-Reform-Commission, 2020) |

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|---|---|---|
| | | Collect the target for every five-year circular economy development plan, and extrapolate the trend to get the reduction rate further. And calculate the absolute resource use of 2050 based on the step-wise targets per 5 years:<br><br>Absolute resource use 2050<br>= ((the absolute resource use of 2020 / (GDP of 2020 × city's average proportion of domestic GDP) × total reduction rate 2020-2050) × (GDP prediction of 2050 × city's average proportion of domestic GDP)<br>In which:<br><br>Total reduction rate 2020-2050<br>= (1-reducation rate 2020-2025) × (1-reducation rate 2025-2030) × (1-reducation rate 2030-2035) × (1-reducation rate 2035-2040) × (1-reducation rate 2040-2045) × (1-reducation rate 2045-2050)<br><br>Then the value of energy use per person is calculated by the absolute value of energy use divided by the population in 2050. |
| | Materials | **Calculation of material use in 2050 based on CE scenario**: For the group "Food and non-alcoholic beverages", the target is concluded by two studies from UNEP that 61% of food waste is avoidable (UNEP). It is ambitious enough here to apply in the CE scenario.<br><br>The value of "Food and non-alcoholic beverages" material use per person is calculated by the "Food and non-alcoholic beverages" material use per person in the base year (2017) multiplied by the change rate (decrease 61%) based on the step-wise trend target from UNEP. Then the absolute value of "Food and non-alcoholic beverages" material use is calculated by the value of "Food and non-alcoholic beverages" material use per person multiplied by the population in 2050. |
| Public sector | Water | **Calculation of water use in 2050 based on CE scenario**: 'By 2025, ……the water consumption per unit GDP will be reduced by 16% compared with 2020 ("Fourteen Five" Circular Economy Development Plan, 2020).<br><br>Collect the target for every five-year circular economy development plan, and extrapolate the trend to get the reduction rate further. And calculate the absolute resource use of 2050 based on the step-wise targets per 5 years:<br><br>Absolute resource use 2050<br>= ((the absolute resource use of 2020 / (GDP of 2020 × city's average proportion of domestic GDP) × total reduction rate 2020-2050) × (GDP prediction of 2050 × city's average proportion of domestic GDP)<br>In which:<br>Total reduction rate 2020-2050<br>= (1-reducation rate 2020-2025) × (1-reducation rate 2025-2030) × (1-reducation rate 2030-2035) × (1-reducation rate 2035-2040) × (1-reducation rate 2040-2045) × (1-reducation rate 2045-2050)<br>In Beijing, the reduction rate of 2015-2020 is 15%. Extrapolate the trend of rate to 2030 then keep stable to calculate the resource |

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| | | use value. So the absolute resource use 2050 is the same with the absolute resource use 2030.<br>Then the value of energy use per person is calculated by the absolute value of energy use divided by the population in 2050. |
| Transport | Energy | **Calculation of energy use in 2050 based on CE scenario**: Due to the lack of targets for transport in CE scenario, considering that the target from Vienna is also based on transport model share and it is suitable for CE scenario, the target used here is the target that "the modal shares of public and private transport are 55 % and 10 %, respectively in 2050".<br>Then calculate the energy use for transport by the same way used when we calculated it for BAU scenarios.<br><br>The energy use per trip (private) = 9885.58kwh<br>The energy use per trip (public) = 1685.37kwh<br><br>We assume the energy use per trip for both private and public transport will not change. New energy consumption per person (private/public) = [Energy use per trip × Proportion of the transport way × New total travel volume (= Total travel volume / Population ratio (1.82) × new population)]/new population |

## IO table sections for BAU and CE

| Societal category | Resource | Calculation method, assumptions and data sources |
|---|---|---|
| Household | Water | **Calculation of total expenditure of water relevant IO sector 2017:** The associated IO FD category and sector is Household Final Demand of Sector <E>. The total expenditure of water relevant IO sector 2017 is the total value of urban and rural household consumption from <E> in Beijing IO table 2017. Converted from CNY to EUR.<br>**Calculation of total expenditure of water relevant IO sector 2050**: There is no waste management and sewage in disaggregated table, and the value of <E> sector is the same as the subsector called water production and supply. Thus assume 100% of <E> is for water consumption.<br>• Affected sector: Calculated resource in sector 2017 by multiplying total expenditure of water relevant IO sector 2017 and the share percentage of the sector for resource use. Calculated unit price 2017 by absolute value of resource use 2017 divided by the resource in sector 2017. Calculated the unit price 2050 by multiplying unit price 2017 by the inflation rate. Then calculated the resource in sector 2050 by the absolute value of resource use 2017 multiplying the cumulative rate of absolute change and inflation rate.<br>• Unaffected sector: Calculated the unaffected expenditure 2017 by expenditure of water relevant IO sector 2017 minus the affected expenditure 2017. Calculated unaffected expenditure 2050 by expenditure of water relevant IO sector 2017 multiplying the inflation rate.<br>Calculated the total expenditure of water relevant IO sector 2050 by adding affected expenditure 2050 and unaffected expenditure 2050. |

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| | Energy | **Calculation of total expenditure of energy relevant IO sector 2017:** The associated IO FD category and sector is Household Final Demand of Sector <D>. The total expenditure of water relevant IO sector 2017 is the total value of urban and rural household consumption from <D> in Beijing IO table 2017. Converted from CNY to EUR.<br>**Calculation of total expenditure of energy relevant IO sector 2050**: The value of <D> sector is the same as the sum of subsectors called electricity, steam and hot water production and supply, and gas production and supply. Thus assume 100% of <D> is for energy consumption.<br>• Affected sector: Same with the household water sector<br>• Unaffected sector: Same with the household water sector<br>Calculated the total expenditure of energy relevant IO sector 2050 by adding affected expenditure 2050 and unaffected expenditure 2050. |
| | Materials | **Calculation of total expenditure of material relevant IO sector 2017:** The associated IO FD category and sector is Household Final Demand of Sector <G>. The total expenditure of water relevant IO sector 2017 is the total value of urban and rural household consumption from <G> in Beijing IO table 2017. Converted from CNY to EUR.<br>**Calculation of total expenditure of material relevant IO sector 2050**: The value of <G> sector is the same as the sum of subsectors called wholesale and retail. Thus assume 63.3% of <G> which is the proportion of retail is for material consumption. Then for different subsectors under material sector, the proportion of affected sector <G> is calculated by the material breakdown and the sum is 63.3%<br>• Affected sector: Same with the household water sector<br>• Unaffected sector: Same with the household water sector<br>Calculated the total expenditure of material relevant IO sector 2050 by adding affected expenditure 2050 and unaffected expenditure 2050. |
| Public sector | Water | **Calculation of total expenditure of water relevant IO sector 2017:** The associated IO FD category and sector is Public Sector Final Demand of Sector <E>. The total expenditure of water relevant IO sector 2017 is the value of government consumption from <E> in Beijing IO table 2017. Converted from CNY to EUR.<br>**Calculation of total expenditure of water relevant IO sector 2050**: There is no waste management and sewage in disaggregated table, and the value of <E> sector is the same as the subsector called water production and supply. Thus assume 100% of <E> is for water consumption.<br>• Affected sector: Calculated resource in sector 2017 by multiplying total expenditure of water relevant IO sector 2017 and the share percentage of the sector for resource use. Calculated unit price 2017 by absolute value of resource use 2017 divided by the resource in sector 2017. Calculated the unit price 2050 by multiplying unit price 2017 by the inflation rate. Then calculated the resource in sector 2050 by the absolute value of resource use 2017 multiplying the cumulative rate of absolute change and inflation rate.<br>• Unaffected sector: Calculated the unaffected expenditure 2017 by expenditure of water relevant IO sector 2017 minus |

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| | | the affected expenditure 2017. Calculated unaffected expenditure 2050 by expenditure of water relevant IO sector 2017 multiplying the inflation rate.<br>Calculated the total expenditure of water relevant IO sector 2050 by adding affected expenditure 2050 and unaffected expenditure 2050. |
| Transport (public) | Energy | **Calculation of total expenditure of energy relevant IO sector 2017:** The associated IO FD category and sector is Household Final Demand of Sector <H>. The total expenditure of energy relevant IO sector 2017 is the total value of urban and rural household consumption from <H> in Shanghai IO table 2017. Converted from CNY to EUR.<br>**Calculation of total expenditure of energy relevant IO sector 2050**: The proportion of transportation is derived from subsector urban public transport and road transport for sector <H> from the IO table for China of 2017 which is 18.67%. Considering the proportion of public transport energy use, thus 18.67% of <E> × 18.19% is for public transportation energy consumption.<br>• Affected sector: Same with the household energy sector<br>• Unaffected sector: Same with the household energy sector<br>Calculated the total expenditure of energy relevant IO sector 2050 by adding affected expenditure 2050 and unaffected expenditure 2050. |
| Transport (Private) | Energy | **Calculation of total expenditure of energy relevant IO sector 2017:** The associated IO FD category and sector is Household Final Demand of Sector <H>. The total expenditure of energy relevant IO sector 2017 is the total value of urban and rural household consumption from <H> in Shanghai IO table 2017. Converted from CNY to EUR.<br>**Calculation of total expenditure of energy relevant IO sector 2050**: The proportion of transportation is derived from subsector urban public transport and road transport for sector <H> from the IO table for China of 2017 which is 18.67%. Considering the proportion of private transport energy use, thus 18.67% of <E> × 81.81% is for private transportation energy consumption.<br>• Affected sector: Same with the household energy sector<br>• Unaffected sector: Same with the household energy sector<br>Calculated the total expenditure of energy relevant IO sector 2050 by adding affected expenditure 2050 and unaffected expenditure 2050. |