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Title page

Supply-side carbon accounting and mitigation analysis for Beijing-Tianjin-Hebei urban agglomeration in China

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Highlights:

- The differences between three carbon accounting methods are visualized
- Income-based emissions of 14 cities for Beijing-Tianjin-Hebei urban agglomeration
- The heatmap of the supply-side emission patterns according to the city's characteristics
- Identify labour-intensive sectors through the labour-capital ratio
- The trade-off among carbon emissions, carbon efficiency and labour transfer

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Cities play an important role in controlling climate change. Previous 'city-scale studies' have investigated consumption-based emission accounting for demand-side mitigation analysis. However, to date very few studies have presented income-based emissions accounting for supply-side mitigation strategies at the level of an urban agglomeration. To fill this gap, this research begins by accounting for the income-based carbon footprint of the Beijing-Tianjin-Hebei (BTH) urban agglomeration. The 14 cities that make up the BTH region were grouped into 4 types in order to analyze the emission patterns of each and to identify both labour-intensive and carbon-efficient sectors. The results from this analysis are presented in a number of heatmaps, which show the emission patterns, labour-capital ratios and carbon efficiencies. The industry relocation among the 14 cities is then discussed with regards to the *Beijing-Tianjin-Hebei Coordinated Development Strategy*. The results indicate that: the service sector of Beijing, several mining sectors of resource-oriented cities, and the electricity production for all of the cities are the most carbon-intensive sectors from an income-based perspective; the labour-intensive sectors are typically carbon-efficient, and the combination of supply-side carbon emissions, carbon efficiency and labour-to-capital ratio helps identify the key sectors for providing policy-makers the direction of industrial adjustment and relocation.

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1. Introduction

Cities need to be a key area of focus if the world is to successfully reduce its carbon emissions. This is due to their ever-growing populations, energy use, and economic development. Carbon dioxide emissions from energy use in cities has been growing by 1.8% per year (versus 1.6% globally). This percentage will be maintained under business-as-usual scenarios up until the year 2030, with the share of global CO_2 from cities rising from 71 to 76 percent (IEA, 2009). Cities account for over 67 percent of energy-related global greenhouse gases, which is expected to rise to 74 percent by 2030 (IEA, 2008). Based on data from the United Nations, cities consume as much as 80 percent of energy production worldwide and account for a roughly equal share of greenhouse gas emissions in total (World Bank, 2010).

China, the biggest emitter country in the world, has developed an ambitious greenhouse gas (GHG) mitigation strategy. At COP21, the Chinese Government pledged to reduce carbon intensity by 60 - 65% from 2005 levels by 2030 (IEA, 2016). Urban development is a priority due to the amount of power that needs to be generated to keep cities running along with emission-intensive industries such as mining and manufacturing (Baeumler et al., 2012). China has continuously expanded its urban economies over the last 40-years, many of which have developed its urban agglomerations. The GDP of cities above prefectural level in 2016 totaled 76.9 trillion RMB, increasing by 15.9 percent for a constant price in comparison to 2012 (NBS, 2013a, 2017). A total of 58.52 percent of China's population lived in a city in 2017, up by 5.95 percent since the end of 2012 (NBS, 2013b, 2018). The growth in China's urban areas has led to concomitant increases in demand for energy and the coal-oriented energy mix which supplies them has meant they need to play a leading role in China's attempts to reduce its carbon emissions. A deeper understanding of Chinese cities' emission patterns is therefore essential for mitigation analysis and policy-making in this area.

The Beijing-Tianjin-Hebei (BTH hereafter) region, one of three economic growth poles in China, has become an urban agglomeration[1](Wang et al., 2017; Zhao et al., 2017). Its 14 cities including the capital Beijing, which is based in the Tianjin municipality, and the 11 cities from neighboring Hebei province and Dezhou in the Shandong province are all included in the *Beijing-Tianjin-Hebei Coordinated Development Strategy* (*BTH-Strategy*) (SCC, 2015). The primary goal of the *BTH-Strategy* is to transfer Beijing's non-capital functions[2] into neighborhoods to solve "big city disease" and support the economic growth of the rest of BTH region by relocating some industries (SCC, 2015; Government of Beijing, 2015, 2018a, 2018b). The 14 cities of the BTH region also shoulder the responsibility of emissions mitigation i.e. cutting 20.5% - 22.0% of carbon intensity between 2015-2020 (Government of Hebei, 2017; Government of Shandong, 2017; Government of Tianjin, 2016; SCC, 2016). Therefore, in order for these targets to succeed, accounting for the carbon emissions for the 14 cities and their

[1] The urban agglomeration is defined as "Highly integrated groups of cities that share common interest and fate", please see Fang and Yu, (2017).

[2] Non-capital function transfer is to remove Beijing's irrelevant sectors including the general manufacturing industry, regional logistics bases and wholesale markets, several educational and medical organizations and several administrative departments and non-profit service institutions.

industries, and balancing the mitigation and population growth are urgently needed for the BTH region.

Income-based carbon accounting from the supply-side perspective has not been analysed to the same degree when compared to consumption-based carbon accounting from the demand-side perspective (Lenzen and Murray, 2010; Rodrigues et al., 2010; Rodrigues and Domingos, 2008). Consumption-based accounting is a common allocation method that attributes emissions occurred in domestic and industries abroad to the final demand of household, government and business （Figure 1, a). It is linked to upstream emissions and measured by the Leontief demand-driven input-output model (Peters and Hertwich, 2008), also refer to other city-scale Leontief demand-driven input-output studies in Athanassiadis et al. (2018), Chen et al. (2017), Chen et al. (2018), Chen et al. (2016), Mi et al. (2016), Hu et al. (2016), Li et al. (2018), Lin et al. (2017), Pichler et al. (2017), Mi et al. (2019), etc.). In contrast, the income-based accounting uncovers the supply-chain emissions induced by primary input provided by economic agencies, and thus links with emitters (Figure 1, c) (Marques et al., 2012). It is measured by downstream emissions using the Ghosh supply-driven input-output model. The term 'income-based' aligns with the Gross Domestic Product (GDP) accounting from the income perspective, i.e., economic agencies who directly participate in the production obtaining their income in terms of the value added of industries. The income includes employee compensation (labor income), operating surplus and mixed income (capital income) and net taxes (i.e., taxes on production minus subsidies) (government income) (Miller and Blair, 2009). The Ghosh input-output model allocates emissions to the suppliers who provide the primary input for the downstream production through the supply-chain, rather than consumers who consume goods and services produced from the upstream production in the Leontief input-output model. Compared to demand-side mitigation policies on consumers, the supply-side mitigation emphasizes policies on suppliers of primary input who producing the industrial value added, thus focusing on the reforms of industry which suits the current top-down mitigation policies in China.

Previous studies have proved the effectiveness of the Ghosh model by quantifying the income-based emissions at global and regional scales. Marques et al. (2012) assessed the income-based emissions of 112 nations or regions based on the GTAP database. In a later study, Marques et al. (2013) chose 87 regions from the GTAP database to investigate how a region's income is derived from carbon emissions occurring abroad. Steininger et al. (2016) listed three accounting systems of 140 world regions using the GTAP database arguing that compiling multiple carbon accounts is the best option. Liang et al. (2017) constructed a time series of income-based emissions of 41 nations/regions using the WIOD database from 1995-2009. Liu and Fan (2017) suggested that income-based emissions accounting is a necessary complement for current common accountings and calculated 77 countries' income-based emissions using the Eora database. Zhang (2010) and Liang et al. (2016) chose China and the U.S. as a case studies, where they combined income-based emissions with Structural Decomposition Analysis (SDA) to identify the key factors for reducing carbon emissions. Zhang (2015) studied 30 provinces in China analyzing the provincial responsibility by combining income-based emissions under different principles. Xie et al. (2017) used China's interregional non-competitive input-output tables for 2007 and 2010, including 30 Chinese provinces, to estimate the amount of interprovincial carbon emission transfer from the supply-side perspective.

Income-based accounting also differs from the geographic production-based accounting (Figure1, b). Geographic production-based emissions (i.e. territorial emissions) are calculated by multiplying the data of activities with emission factors following the *IPCC guidelines* (see also city-scale studies conducted by Cai et al. (2018), Cai et al. (2018), Lombardi et al. (2018), Xu et al. (2018), Shan et al. (2018), Chen et al. (2017), Markolf et al. (2017), Shan et al. (2017), Shan et al. (2017), Ramachandra et al. (2015), Wang et al. (2014), Zhang et al. (2013), Zhang et al. (2013), Liu et al. (2012), Sugar et al. (2012), Wang et al. (2012), Xi et al. (2011), etc.). Geographic production-based accounting only takes the direct emissions of industry into account, it does not build the endogenous connection with the economy in the same way as income-based accounting, though they both focus on the producer's responsibility. Globally, the income-based footprint equals the geographic production-based emissions, which is the result of reallocation of the geographic production-based emissions according to the value added of the industry. The income-based footprint enables the reduction of industry's direct emissions through economic policies such as a carbon tax on industry's value added.

Previous studies indicate that urban carbon emissions closely correlate with GDP. Yin et al. (2015) found an inverted U-shaped curve exists between carbon emission and economic growth. Li et al. (2016) also supported this finding by conducting a provincial-level study. Alam et al.

(2016) demonstrated that CO_2 emissions decrease overtime when income increases, which is the case for China. However, Kang et al.'s (2016) results paint a different picture in the relationship between economic growth and CO_2 emissions, which showed an inverted-N trajectory, while Wang et al. (2015) and Zhou et al. (2017) suggested that economic development increases carbon emissions. In this study, we also explored the relationship between GDP and urban carbon emissions from supply-side perspective.

The income-based emissions of the 14 cities are important indicator for supply-side mitigation while the analysis of urban characteristics and their development stages would support the effective implementation of the *BTH-Strategy* (Chen et al., 2017; Fujii et al., 2017; Shan et al., 2018). In this study, the income-based emissions were first accounted for the 14 cities of BTH region. These cities were split into 4 types for the purpose of analyzing the sectoral emission patterns and identifying the labour-intensive and carbon-efficient sectors. The industry relocation among the 14 cities are then further discussed with regards to the *BTH-Strategy* and carbon mitigation policy.

2. Material and methods

2.1 Ghosh model

The supply-side input-output model was developed by Ghosh (Ghosh, 1958) as a supplement to the Leontief demand-driven input-output model (Leontief, 1936). Ghosh's input-output model is an allocation model with the column balance equation $\mathbf{x'=i'T+v}$, where $\mathbf{T}$

is the intermediate transaction matrix, **v** is the row vector of value added, **i** is a suitable unitary vector, and **x** is the total output.

The direct output coefficients **B** is calculated by dividing each row of **T** by the gross output of the sector associated with that row. Its matrix $\mathbf{B}=\hat{\mathbf{x}}^{-1}\mathbf{T}$, namely allocation coefficients, represents that the distribution of outputs of the original sectors. The outputs across all sectors of the economy show inter-industrial sectors buying input from the original sectors.

Using the column balance equation, we have $\mathbf{x}'=\mathbf{i}'\mathbf{T}+\mathbf{v}=\mathbf{i}'\hat{\mathbf{x}}\mathbf{B}+\mathbf{v}=\mathbf{x}'\mathbf{B}+\mathbf{v}=\mathbf{v}(\mathbf{I}-\mathbf{B})^{-1}=\mathbf{vG}$. The matrix **G** is called the Ghosh inverse, relating sectoral gross production to the primary inputs — a unit of value entering the inter-industry (supply chain) system at the beginning of the process. It is termed a supply inverse and measures the production values of sectors that come in the supply chain system caused by per unit of primary input in sectors (Miller and Blair, 2009).

Attaching the environmental satellite accounts to the supply chain system, the environmentally-extended Ghosh model can be shown as $\mathbf{Q}=\mathbf{vGq}$, where **Q** represents total carbon emissions and **q** is the sectoral emission intensity vector that is calculated by $\mathbf{q}=\mathbf{Q}\hat{\mathbf{x}}^{-1}$, indicating emissions caused by producing per unit of sectoral output. Accordingly, the vector **Gq** in the supply-side system represents the sectoral emission effects on total output throughout all the supply chain system associating with one unit of primary inputs in sectors. The application of the Ghosh model for city-scale supply-side carbon accounting is provided in Chen et al. (2017).

The direct emissions from household consumption should be included for the complete city-scale carbon accounting. It ranges from 0.49 tCO_2e/cap - 1.21 tCO_2e /cap for cities of the

BTH region (Cai et al., 2018). However, this study focuses on the supply-side emissions accounting and mitigation analysis for the industry, thus excluding the direct emissions of households in the final results.

2.2 The criteria of the four types of cities

To analyze the change of economic structure and mitigation policy under the framework of the *BTH-Strategy*, the 14 cities in the region can be further classified into four groups according to the sectoral percentages of value added as shown in Figure 2 overleaf. The four types of cities contain 'service-oriented' cities (Beijing and Qinhuangdao), cities in the 'transition' towards becoming service-oriented (Tianjin, Shijiazhuang, Zhangjiakou and Langfang), 'resource-oriented' cities (Handan, Chengde, Xingtai and Tangshan) and 'manufacturing-oriented' cities (Cangzhou, Dezhou, Baoding and Hengshui). The resource-oriented cities are essentially a type of manufacturing-oriented city, which is consistent with the official classification for resource-oriented (SCC, 2013).

2.3 Construction of two indicators - labour - capital ratio and carbon efficiency

Labour to capital ratio is the amount of labour employed in relation to capital input, indicating a measure of the degree of labour intensity of an industry. Both 'labour' and 'capital', measured in monetary units, are the main components of primary input (the value added). The 'labour uses' compensation of employees (labour income) and the 'capital' equals the depreciation of fixed assets plus gross operating (capital income).

Carbon efficiency in this study is defined as income-based emissions per unit of value added. It is an intensity indicator to present that one unit of primary input is supplied to the economic system that is how much emissions will be emitted in the downstream production process and its distribution in the supply-chain.

2.4 Data

The data used in this study include multi-regional input-output (MRIO) table for cities, sectoral carbon emissions for the cities, and the social and economic indicators such as labour, capital, population, and GDP.

The MRIO table for cities is generated from Chinese subnational multi-regional input-output database named the Chinese industrial ecology laboratory (IELab) (Wang, 2017; Wang et al., 2017). The MRIO table for cities from Chinese IELab follows the standard 'supply and use' framework developed by Eurostat (Eurostat, 2008) and the United Nations (United Nations, 2018), and is valued at the basic price in units of 10k CNY. The MRIO table developed in this study is a 42-region MRIO table consisting of 14 cities of the BTH region and the rest of the 28 provinces in China (Table S1), and each region which has 42 sectors (Table S2). We chose the year 2013 as the reference point since the *Beijing-Tian-Hebei Coordinated Development Strategy* was developed in the same year (Xinhuanet, 2014).

Sectoral carbon emissions for the 14 cities of the BTH region are calculated by energy consumption and emission factors with the unit of $MtCO_2e$. Sectoral energy consumption for cities are collected both from the city and provincial statistical yearbooks (NBS, 2014a, 2014b) as well as from energy balance sheets from the *2014 China Energy Statistical Yearbook* (NBS, 2014c). Both energy consumption and energy balance sheets were combined and adjusted to match the MRIO table following the methods from Peters et al. (2006). In order to calculate the differences between the data of city-level and provincial-level, we followed Shan et al.'s (2016) approach to process the data. The emission factors by sector and energy type come from Liu et al. (2012) and Liu et al. (2015).

The labour and capital use variables are calculated based on the compensation of employees and depreciation of fixed assets plus gross operating costs. Sectoral labour and capital of some cities (Beijing, Shijiazhuang, Tangshan, Qinhuangdao, Xingtai, Chengde, Cangzhou, Hengshui, and Dezhou) are taken from their Statistical Yearbooks (NBS, 2014a). The rest of the cities only have aggregated labour and capital in their Statistical Yearbooks and they also do not include sectoral information. We used the sectoral proportions of city value-added block (primary inputs) from the MRIO table to disaggregate compensation of employees and depreciation of fixed assets plus gross operating into sectors. Both Population and GDP at 2013 prices for each city comes from the Statistical Yearbooks published by the local statistical departments and institutes (NBS, 2014b, 2014d, 2014e, 2014f, 2014g). The Population figures for 2013 are based on the arithmetic average of the population at both 2012 and 2013 year-end respectively.

3. Results

In this section, we accounted for the total and sectoral income-based emissions of 14 cities of the BTH region. The ratios of both labour to capital and emissions to value added were also calculated to analyze the industry relocation under the framework of current policies.

3.1 Income-based emissions and relationships between emissions and cities' GDP

The BTH region is located in the north of China (Figure 3). Beijing (122.07 MtCO2e), Tangshan (101.47 MtCO2e), Tianjin (99.46 MtCO2e) and Shijiazhuang (85.45 MtCO2e) rank as the top four cities for carbon emissions from the supply-side perspective, followed by Handan (60.42 MtCO2e), Cangzhou (46.23 MtCO2e) and Baoding (37.73 MtCO2e). Beijing and Tianjin are metropolises with large populations and highly concentrated industries, which leads to greater levels of energy consumption and energy-related carbon emissions (NBS, 2014a). Tangshan relies on heavy industries that produce steel, energy and chemical products (NBS, 2014h). Shijiazhuang, the capital city of Hebei province, mainly produces pharmaceutical and textile products (NBS, 2014i). Handan is a city rich in coal and iron ore and also relies on the steel industry (NBS, 2014j). These high carbon-intensive industries mean that each of these cities produces large emissions.

Figure 4 overleaf illustrates a positive correlation between supply-side emissions per capita and value added per capita for developing cities. Cities of the BTH region with higher GDP per capita tend to have higher income-based emissions per capita, whilst wealthy cities do not necessarily follow the same rule. Beijing and Tianjin with 94.6k CNY/cap and 100.1k CNY/cap, respectively, are the two wealthiest cities in the BTH region, whilst they have relatively lower income-based emissions per capita. This is because the top two highest carbon efficiencies of the two cities indicated by bubble size with 0.62 tCO_2e/GDP (Beijing) and 0.69 tCO_2e/GDP (Tianjin). The carbon efficiency in this study is defined as income-based emissions per unit of GDP. Although Beijing and Tianjin are the wealthiest cities they have also been able to reduce their carbon emissions

The other cities of the BTH region that are plotted in Figure 4 below the dotted line have only slightly higher carbon efficiencies than the average, however, these are double Beijing and Tianjin. These cities include Hengshui (1.26 tCO2e/GDP), Langfang (1.25 tCO2e/GDP) and Dezhou (1.02 tCO2e/GDP). The 12 other cities plotted around the dotted line indicate that their carbon efficiencies of their production system each of these are similar, however, they are not as efficient as Beijing and Tianjin.

3.2 Sectoral analysis of income-based emissions in BTH agglomeration

Income-based emissions of the four types of cities show a significant difference. Beijing as a service-oriented city is prosperous due to its services (tertiary) based industries such as financial, technical and wholesale services. The service sectors together contribute 53.8% of the total emissions (see Figure 5 overleaf). The top five service sectors for carbon emissions are: Production and Supply of Electric Power and Heat (25) (22.2%), Traffic, Transport, Storage and Post (30) (12.2%), Financial Intermediation (33) (11.1%), Wholesale and Retail Trades (29) (6.2%), Scientific Research and Technical Services (36) (5.3%). Beijing is a major transport hub, especially for rail, as well as a major finance centra with many of China's financial organisation's headquarters based in the city (NBS, 2014e). The wholesale sector in Beijing is also very large with several hypermarkets such as the Beijing Zoo Wholesale Market and the Dahongmen Clothing Wholesale Market based in the city. Additionally, Beijing is an important higher education centre with more than 100 colleges, universities and research institutions based here as well (BMBS and SONBS, 2018). Each of these sectors are large carbon emitters so they are important targets for the BTH-Strategy, which seeks to transfer these to other cities in the region (Government of Beijing, 2018c) decreasing the city's overall emissions.

In contrast, Qinhuangdao shows a different emission pattern at the sectoral level. The lower carbon intensity of tertiary industry leads to smaller emissions in the service sectors (see Figure 5 overleaf). The largest emission sector is Production and Supply of Electric and Heat Power (25) with 24.7% of total emissions, followed by Smelting and Rolling of Metals (14) accounting for 23.2%, Manufacture of Nonmetallic Mineral Products (13) at 6.2% and Mining and Washing of Coal (2) at 5.2%. As Qinhuangdao is rich in mineral resources, the mining and related processing manufacturing sectors are key industries and therefore important economic drivers. These sectors always consume a large amount of energy and thus lead to relatively high levels of emissions.

Tianjin is currently in the transition phase to eventually becoming a service-oriented city. Its emissions pattern is similar to Beijing. However, its service sector industries have fewer emissions in comparison. Only three service sectors rank in the top ten sectors for emissions in Tianjin. These sectors include Traffic, Transport, Storage and Post (30), which is due to high levels of activity in its port and logistics. This is because Tianjin is the largest comprehensive port city in the northern China (Chinadaily, 2013). Tianjin's Wholesale and Retail Trades (29) also heavily rely on logistics, accounting for 2.2% of its total emissions. Financial Intermediation (33) makes up 4.5% of total emissions. This is likely to increase as Tianjin seeks to ramp up its financial innovation operations becoming a demonstration (pilot) area for northern China's first free trade zone (CPFTZA, 2017). Tianjin is one of four direct-controlled municipalities by China's central government and the financial center of northern China. Therefore, in the future it is likely to develop more diversified services becoming a fully-fledged service-oriented city (TDRC, 2018).

Other cities in transition towards becoming service-oriented have similar emission patterns. For example, both Shijiazhuang and Langfang have thriving manufacturing sectors that create large amounts of emissions. Smelting and Rolling of Metals (14) for both cities is the single highest emitter, accounting for 20.4% and 22.1% of the total emissions respectively. Similarly, the Chemical Industry (12) and Processing of Petroleum, Coking & Processing of Nuclear Fuel (11) are also two significant emitters for both cities. For the transitional city of Zhangjiakou, Production and Supply of Electric and Heat Power (25) is the single highest emitter, accounting for 40.7% of its total emissions, followed by Mining and Washing of Coal (2) with accounts for 16.3% of its total emissions.

A common feature of the resource-oriented cities (Tangshan, Handan, Xingtai and Chengde) is that a large amount of their emissions is generated in the mining sectors including Mining and

Washing of Coal (2), Extraction of Petroleum and Natural Gas (3) and Mining of Metal Ores (4). In combination these sectors contribute 30.2 - 43.6% of the total emissions for each of these cities. Mining and Washing of Coal (2) in Tangshan, Handan, Xingtai and Chengde contribute 21.1%, 32.9%, 25.5% and 18.5% of total emissions, respectively, followed by the Extraction of Petroleum and Natural Gas (3) and Mining of Metal Ores (4).

The manufacturing-oriented cities need to pay attention to the emissions of the manufacturing sectors, including Chemical Industry (12), Manufacture of Nonmetallic Mineral Products (13) and the Smelting and Rolling of Metals (14). The reason for this is these sectors are responsible for emitting between 17.7% to 30.4%, which is larger than any of the other sectors. The Smelting and Rolling of Metals (14) in the cities of Baoding and Hengshui account for 21.7% and 16.4% of total emissions, respectively. The Processing of Petroleum, Coking & Processing of Nuclear Fuel (11) are responsible for the highest levels of emissions in Cangzhou, contributing a total of 28.0%, while its Smelting and Rolling of Metals (14) is 11.5%. In Dezhou the Chemical Industry (12) is responsible for 13.7% of total emissions.

More attention needs to be paid to the Electric and Heat Power (25) industry because it accounts for between 9.8 - 28.4% of total emissions in the 14 cities that make up the BTH region. Generation of the BTH region's electricity relies mainly on thermal power, which makes up 95% of Beijing's energy needs, 90% of Tianjin and 65% of Hebei (Liu and Deng, 2017). These plants rely mainly on the burning of coal to generate electricity for these cities (Tang et al., 2018). The BTH region is in the process transitioning many of its electric power plants from 'coal to gas' in order to reduce emissions, but it contributed very little to the carbon reduction as BTH region still relies on the coal-fired power plants (Jiang et al., 2017). The main reason for this is that Hebei is one of thirteen coal bases for China (MNRC, 2016), which is the main source of electric and heat power for the BTH region (Tan-Soo et al., 2018).

3.3 Labor to capital ratio and carbon efficiency at sectoral level

Figure 6 shows that high labour to capital ratio can co-exist with low carbon efficiency. It indicates that labour-intensive industries are typically carbon efficient. This is especially significant when comparing labour-capital ratio with carbon efficiency in the agriculture sector. Most of the service industries in the 14 cities are also labour-intensive but carbon efficient, while this is opposite for the manufacturing and electricity sectors.

The labour-capital ratio and carbon efficiency combined can offer a potential solution for mitigating Beijing's 'big city disease' especially for a concentrated population by transferring the labour-intensive sectors under the BTH-Strategy. Some of the service sectors of Beijing are labour-intensive, therefore they should be the main focus for alleviating population problems (in Figure 6, left part). These sectors include Hotels and Catering Services (31), Health and Social Work (40), Services to Households and Other Services (38) with 14.0, 10.5, 9.4 for the ratio of labour to capital. However, these service sectors have relatively small scales of labour and capital. In contrast, Leasing and Business Services (35), Information Transmission, Software and Information Transmission Services (32), Scientific Research and Technical Services (36) do not have a high ranking in terms of labour to capital ratio but their scales of labour are the top three ranking should also be highlighted.

The other neighboring cities need to pay attention to the carbon efficiency of the mining and manufacturing sectors if they are to better mitigate their carbon output (Figure 6, Right). The carbon efficiency of Mining and Washing of Coal (2) with 8 - 20 tCO_2e/CNY should be highlighted for resource-oriented cities. The Electricity and Heating sector is less carbon efficient than the other sectors ranging from 5 - 27 tCO_2e/CNY, which is a common problem for all cities due to their reliance on coal-fired electricity generation. The Manufacturing Sectors (11)-(14) also need to be highlighting as they have relatively lower carbon efficiencies when to other manufacturing sectors in BTH. In addition, Dezhou's mining sectors are conspicuous due to their high carbon emissions per GDP when compared to the other cities in the BTH. This is because the GDP of this sector is relatively small and ranks at the bottom among all of the sectors in Dezhou. This is also given that mining is not the key sector of Dezhou in terms of value added.

4. Discussions

The continued phasing out of non-capital functions based in Beijing and limiting its population growth is the core mission of BTH-Strategy, while carbon reductions are another important goal that must be undertaken in China if the 13th Five-Year Greenhouse Gas (GHG) Control Work Plan is to achieve its goals. The practical way to accomplish these missions in the short-term is for Beijing to transfer a part of its service sectors including Wholesale and Retail

Trades (29), Information Transmission, Software and Information Transmission Services (32), Leasing and Business Services (35), Scientific Research and Technical Services (36) to other cities of BTH region. The results from our analysis indicate they not only contribute to high levels of carbon emission, but they are also labour-intensive. The transfer of Wholesale and Retail Trades (29) from Beijing to other cities has also had the added benefit of leading to a decrease in the population of Beijing as of 2017 when compared with the population figures of 2016 (BMBS and SONBS, 2018).

Tianjin plays a supporting role in the BTH-Strategy as it has been the recipient of Beijing’s manufacturing sector/industries (SCC, 2015). The relocation of these sectors will inevitably increase Tianjin’s carbon emissions, thus posing a new mitigation challenge for this city. The industrial integration and optimization of the BTH-Strategy will play an important role in developing more sustainable manufacturing sectors. Moreover, several of the service sectors located in Tianjin are also carbon-intensive and therefore worth highlighting, including Wholesale and Retail Trades (29) and Financial Intermediation (33).

Amongst the resource-oriented cities, Tangshan, which is categorized as a ‘regenerative city’ (SCC, 2013) has shifted away from its reliance on resource intensive industries (Li and Tang, 2017) and yet its GDP per capita ranks third after Beijing and Tianjin. The boost to the economy in other sectors also draws the attention to carbon mitigation efforts, especially for the mining related industries including Mining and Washing of Coal (2), Extraction of Petroleum and Natural Gas (3), Smelting and Rolling of Metals (14) and Traffic, Transport, Storage and Post

(30). These sectors are responsible for high levels of emissions. Although Tangshan does not rely on resources such as coal and steel, the mining related sectors still play an important role in its economy, because Tangshan is the main energy reserve base of northern China.

The other resource-oriented cities including Handan, Chengde and Xingtai are defined as 'grown-up cities' as they are at the stage of stable development and rely much on the resource-oriented economy (SCC, 2013). On one hand these three cities are shouldering the responsibility for ensuring the energy security of the nation. On the other, they are facing the challenge of GHG mitigation in the mining sectors and are therefore searching for new ways to support their economic growth in order to replace the mining sectors in the near future. The transfer of the labour-intensive sectors from Beijing to these cities could be a solution for their economic development, since the poverty alleviation and increasing employment in the new sectors are priorities for each.

All of the cities in the BTH need to pay close attention to the electricity and heating sectors. Coal fired power is the main energy type for electricity and heating generation in China (Tang et al., 2018). The share of coal in China's total power generation was approximately two thirds as of 2016 (IEA, 2017). A large number of wind and solar power plants now lay idle because of both a decrease in power demand and oversupply of electricity (Wei et al., 2017). This urges the government to cut the overcapacity of the electricity supply system rather than developing the new renewable energy plants at this stage, which should be considered to be an important element of the BTH strategy.

5. Conclusions

By conducting a supply-side emission accounting and analysis for the 14 cities of the BTH region, this study has sought to make a number of contributions to the literature and to recommend a set of policy implications that flow from these. The income-based carbon emissions of the 14 cities were found to be positively correlated with value added - the supply-side input, but subjected to carbon efficiency. Beijing and Tianjin are more carbon efficient, thus the increase of value added in these two cities can generate less income-based emissions than the other 12 cities in BTH region. This implies that there is a big gap at sectoral level in terms of carbon efficiency in production systems between these two cities (Beijing and Tianjin) and the other 12 cities in the BTH region. In addition, both Beijing and Tianjin are at a more developed stage in that both cities are more advanced in the implementing and following of environmental regulations, while the other cities are less developed in this respect. Therefore, Beijing and Tianjin are more carbon efficient when compared to the other cities in the BTH region.

The heatmap was first developed to display the patterns of income-based carbon emissions of the 14 cities, which were categorised into four types according to their characteristics, and 42 industry sectors. The highlighted area of Figure 6 is designed to identify the carbon-intensive sectors of the 14 cities. In general, the services of Beijing, several mining sectors of resource-oriented cities and the production of electricity in all of the cities are the most carbon-intensive sectors and should therefore be the main focus for policymakers.

Integrating labor-capital ratio with carbon efficiency for identifying the labour-intensive sectors and carbon efficient sectors from the income-based perspective is an innovative way to analyse mitigation in urbanised areas. This study indicates that the labour-intensive sectors are typically carbon-efficient. The combination of the three indicators for supply-side carbon emissions, carbon efficiency and labour-capital ratio helps identify the key sectors where trade-offs in the policy framework can be made.

This study complements previous research focused on consumption-based accounting from the demand-side perspective. Consumption-based studies are usually directed to mitigation policies related to changes in consumer behavior. However, there are some problems with taking a consumption-based approach. For example, economic policies designed to change consumer's behavior, such as a carbon tax on household electricity consumption, would need to be proceeded by a long-term and expensive public education program. Secondly, this approach poses a risk for politicians who would be concerned that such policies would be received in a negative way such that voters would feel that they are been forced to pay for emissions made by others. In contrast, supply-side emission reductions linked to the industrial value added are more targeted and practical. The Ghosh model that was employed in this study provides a criterion for the trade-off between economic development and mitigation. The balance among labour transfer, carbon mitigation and economic growth provides an evidential basis that can support the BTH-Strategy and for carbon mitigation in China more broadly. For example, the transfer of Wholesale and Retail Trades from Beijing to resource-oriented cities not only has the potential to assist in the mitigation efforts in big cities like Beijing, but also benefit the resource-oriented cities by providing new opportunities for employment, economic growth and poverty reduction.

While acknowledging insights and contributions, this study is not without limitations. The input-output model is still subjected to the classic limitations that are explained in literature. The emissions enabled by primary input from the rest of world has not been included since this research is only focused on domestic policies for industries, but it should be considered in future studies. This study only provided the carbon accounting results of sectors in the 14 cities, while the pollution haven effects should be further modelled when considering the relocation of industries (Wang et al., 2019).

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Figure
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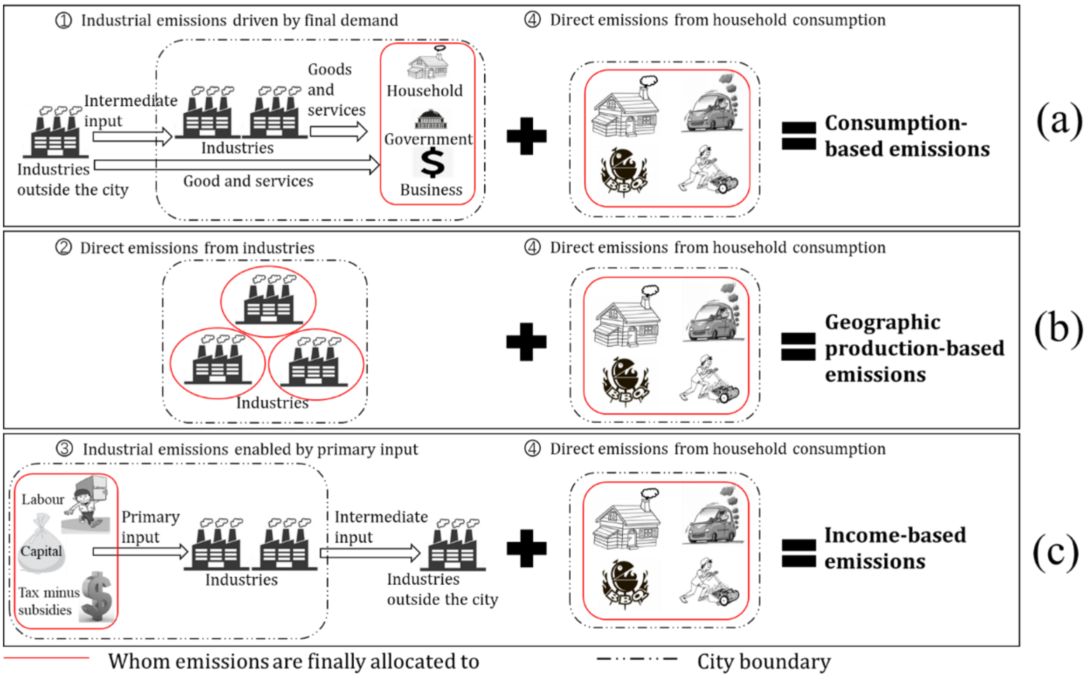

Figure 1. The three city-scale carbon accounting methods: (a) Consumption-based emissions, (b) Geographic production-based emissions and (c) Income-based emissions.

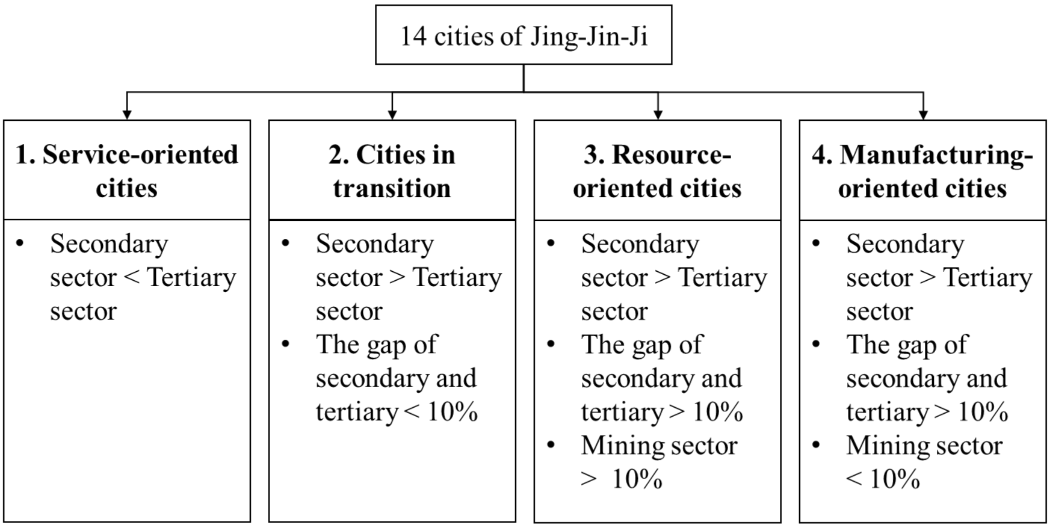

Figure 2. The criteria for the classification of four types of cities (all indicators are measured in percentage of Value added).

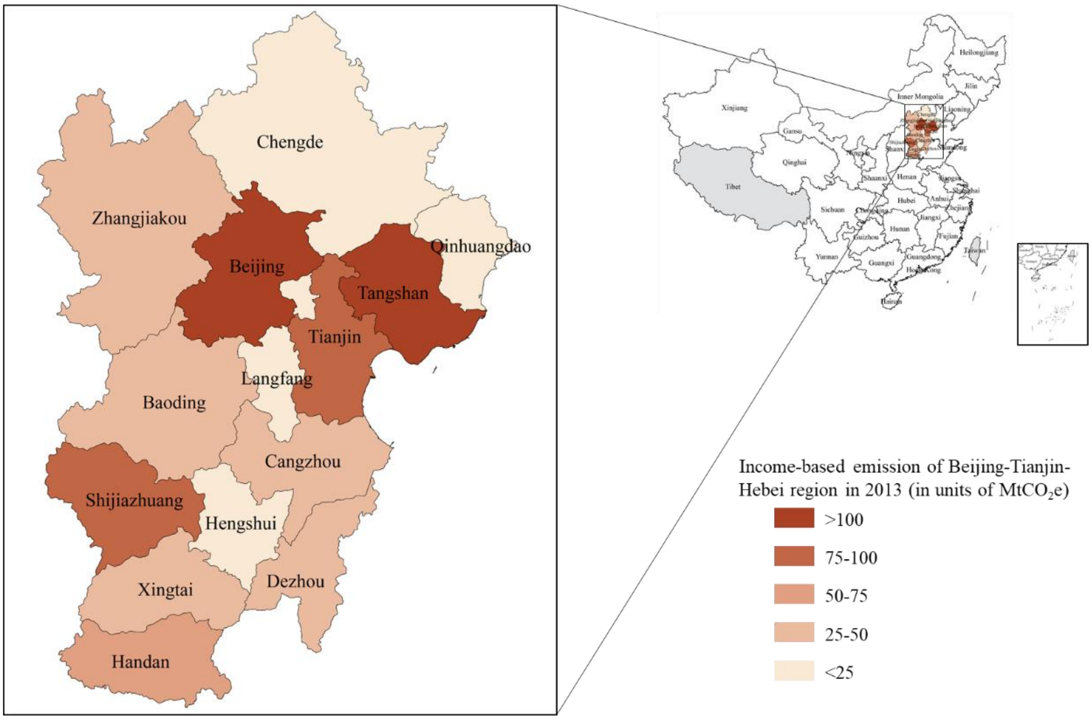

Figure 3. The heatmap of income-based emissions of the 14 cities of the BTH region. The colors yellow to red indicate the total income-based emissions of each city from low to high.

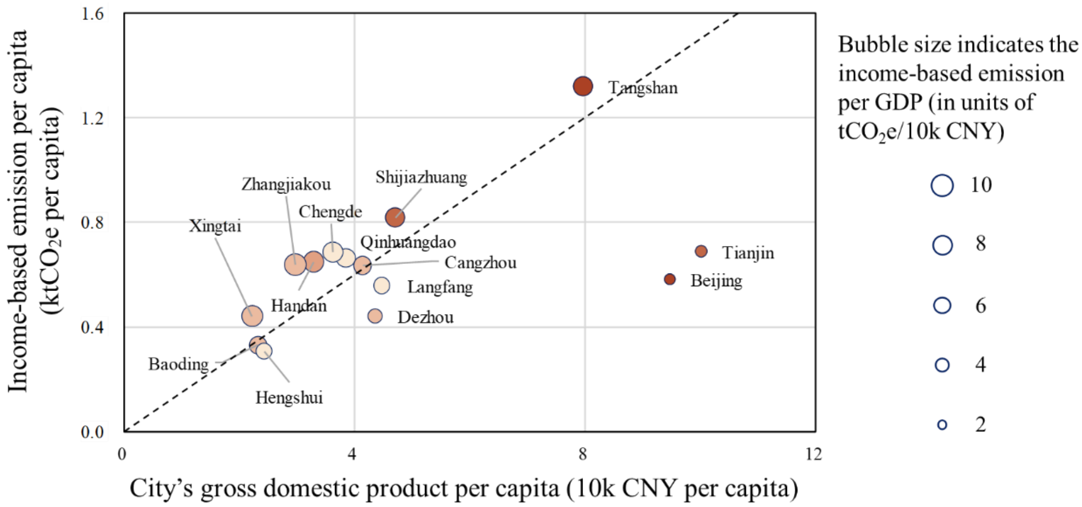

Figure 4. The relationship between GDP per capita, income-based emissions per capita and carbon efficiencies of the 14 cities in the BTH region. The bubbles represent carbon efficiency (i.e. income-based emissions per unit of GDP) with the colouring/shading based on the same scale as Figure 2. The dotted line indicates the average carbon efficiency of the14 cities.

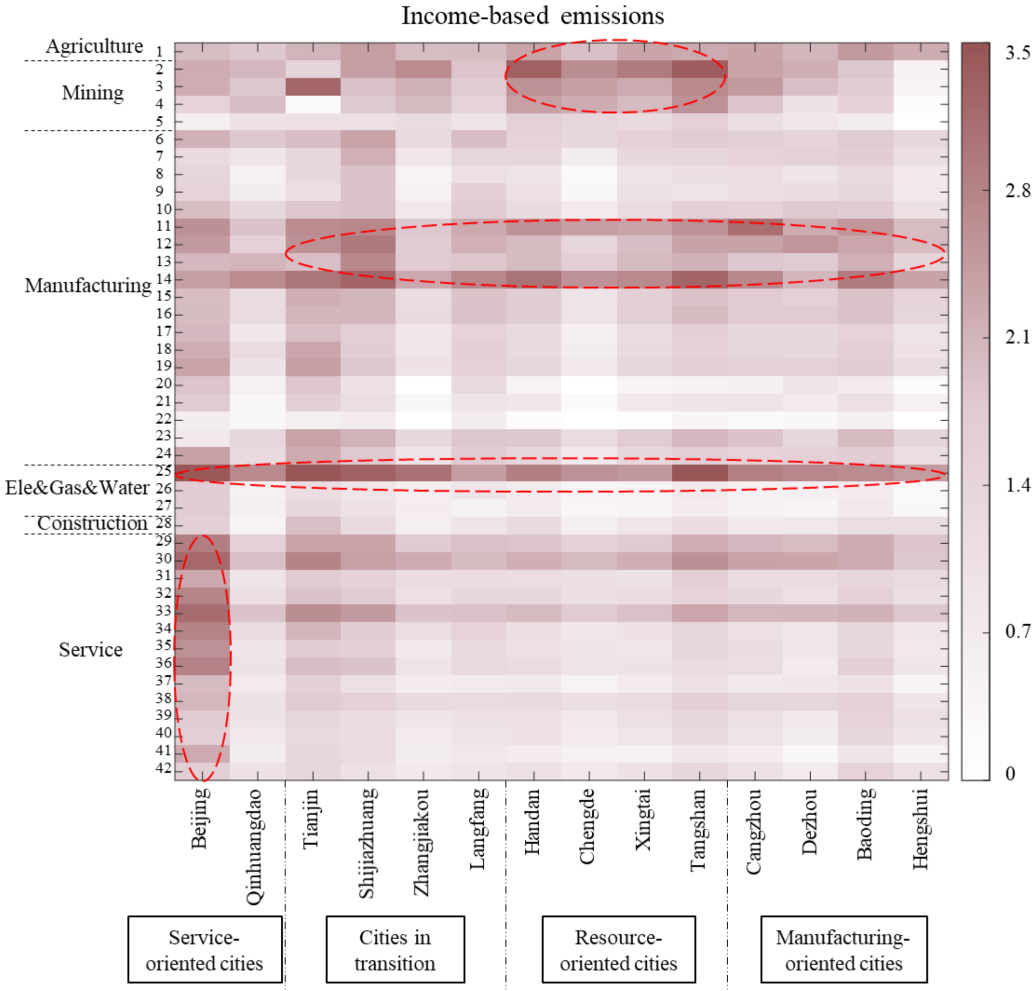

Figure 5. The heatmap of income-based emissions of the 14 BTH cities by sector in 2013. The horizontal axis represents the 14 cities of the BTH region being classified into the four types defined earlier in this paper. The vertical axis shows 42 sectors grouped into six main categories including: (1) Agriculture, 1; (2) Mining, 2-5; (3) Manufacturing, 6-24; (4) Ele&Gas&Water (Production and Supply of Electricity, Steam, Gas and Water), 25-27; (5) Construction, 28; (6) Service, 29-42. Detailed names of each of the 1-42 sectors are outlined in Table S2. Each cell represents one-sector emissions of each city, expressed in units of $MtCO_2e$, colour-coded on a logarithmic scale. The black circles highlight the sectors with significant emissions.

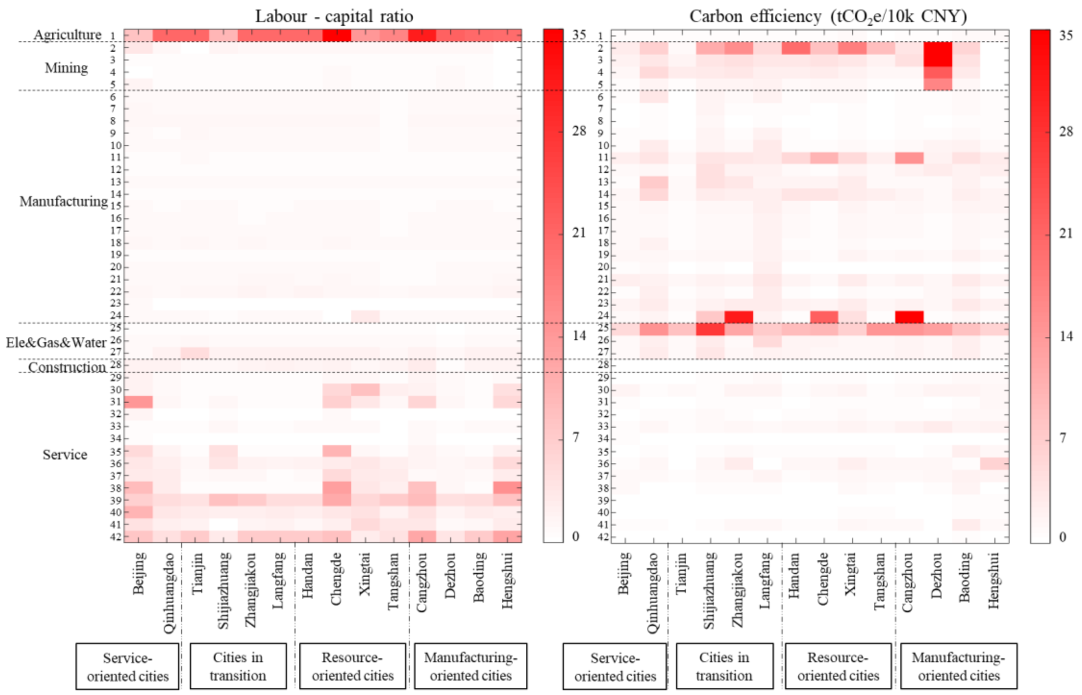

Figure 6. The heatmap of labour to capital ratio (*Left*) and carbon efficiency (*Right*) of 14 cities of BTH region by sector for the year 2013.