University of Groningen

CO2 emission patterns in shrinking and growing cities

Xiao, Huijuan; Duan, Zhiyuan; Zhou, Ya; Zhang, Ning; Shan, Yuli; Lin, Xiyan; Liu, Guosheng

Published in:
Applied Energy

DOI:
10.1016/j.apenergy.2019.113384

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date:
2019

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):
Xiao, H., Duan, Z., Zhou, Y., Zhang, N., Shan, Y., Lin, X., & Liu, G. (2019). CO2 emission patterns in shrinking and growing cities: A case study of Northeast China and the Yangtze River Delta. *Applied Energy*, *251*, [113384]. https://doi.org/10.1016/j.apenergy.2019.113384

Copyright
Other than for strictly personal use, it is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license (like Creative Commons).

The publication may also be distributed here under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license. More information can be found on the University of Groningen website: https://www.rug.nl/library/open-access/self-archiving-pure/taverne-amendment.

Take-down policy
If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Downloaded from the University of Groningen/UMCG research database (Pure): http://www.rug.nl/research/portal. For technical reasons the number of authors shown on this cover page is limited to 10 maximum.

Download date: 12-10-2022

Applied Energy 251 (2019) 113384

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

CO_2 emission patterns in shrinking and growing cities: A case study of Northeast China and the Yangtze River Delta

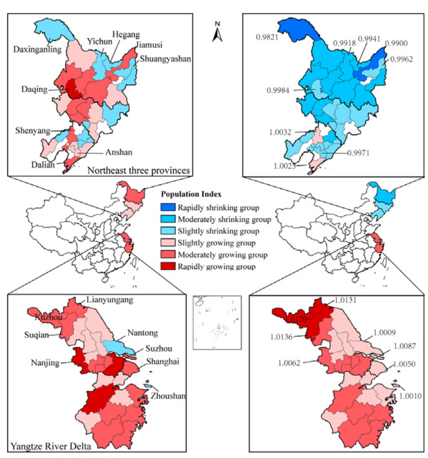
Huijuan Xiao[a], Zhiyuan Duan[b], Ya Zhou[c,d,*], Ning Zhang[a], Yuli Shan[e,*], Xiyan Lin[f], Guosheng Liu[d]

[a] Institute of Resource, Environment and Sustainable Development Research, College of Economics, Jinan University, Guangzhou, Guangdong 510632, China
[b] College of New Energy and Environment, Jilin University, Changchun, Jilin 130012, China
[c] Institute of Environmental and Ecological Engineering, Guangdong University of Technology, Guangzhou, Guangdong 510006, China
[d] School of Management, Guangdong University of Technology, Guangzhou, Guangdong 510520, China
[e] Energy and Sustainability Research Institute Groningen, University of Groningen, Groningen 9747 AG, Netherlands
[f] China Science and Technology Exchange Center, Beijing 100045, China

HIGHLIGHTS

- CO_2 emission inventories of shrinking and growing cities are compiled.
- Emission patterns of various shrinking and growing cities are investigated.
- CO_2 emission mitigation of shrinking cities occurred with the decline of secondary industry.
- Growing cities can achieve emissions mitigation with economic growth.
- Results are helpful for shrinking and growing cities' sustainable development.

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
CO_2 emissions
Shrinking city
Growing city
Population
Urbanization
China

ABSTRACT

The implementation of CO_2 emission mitigation policies in cities is the key to China achieving its national emission mitigation targets. China is experiencing rapid urbanization and facing huge inequality in regional development and then shrinking cities generate. This study, for the first time, discusses long-term CO_2 emission patterns of shrinking cities with comparisons of growing cities. 55 cities in Northeast China and the Yangtze River Delta are selected as cases. We first categorize these cities into three groups of shrinking cities and three groups of growing cities with a population index. Each group's emission patterns in terms of energy, employment and industry structures are then examined. We find that CO_2 emissions in the rapidly shrinking group presented a continuously increasing trend, while the other five groups reached their emission peaks in 2011–2013. For slightly and moderately shrinking groups, CO_2 emission mitigation was a positive sign but occurred with the decline of secondary industry, especially for resource-based or heavy manufacturing cities, such as Daqing and Anshan in Northeast China. In the case of three types of growing cities, cities were capable of mitigating CO_2

* Corresponding authors at: Institute of Environmental and Ecological Engineering, Guangdong University of Technology, Guangzhou, Guangdong 510006, China (Y. Zhou).
E-mail addresses: yazhou@gdut.edu.cn (Y. Zhou), y.shan@rug.nl (Y. Shan).

https://doi.org/10.1016/j.apenergy.2019.113384
Received 12 January 2019; Received in revised form 3 May 2019; Accepted 18 May 2019
Available online 01 June 2019
0306-2619/ © 2019 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/BY/4.0/).

emissions and maintaining economic growth. The slightly growing group was the optimal type among these six groups. Its CO_2 emissions experienced a decline with an annual rate of −1.47% during 2013–2015, while the economy still soared (increased by 7.27% annually). New economic growth points should be fostered to mitigate further shrinkage and achieve sustainable development for shrinking cities. The cities' categorization rules, research thinking, and results offered in this study could provide a reference for other cities or developing countries at similar industrialization/urbanization phases to abbreviate their path towards a low-carbon economy.

1. Introduction

China's urbanization and industrialization have grown rapidly in recent decades, which lead to a quick increase in the country's CO_2 emissions. Approximately 27.9% of global CO_2 emissions in 2017 come from China, which is more than come from the United States (15.2%) or total Europe (12.4%) [1]. China's national mitigation target, to decrease emission intensity by 60–65% (compared with the 2005 level) by 2030 [2], is expected to be allocated across prefecture-level cities [3–5]. The implementation of CO_2 emission mitigation policies in cities is the key to achieving the expected target and has attracted increasing attentions [6–8]. China is experiencing rapid urbanization and facing huge inequality in regional development. Population growth and shrinkage occur simultaneously in city development [9,10], and cities' growing and shrinking characteristics vary. A single mitigation action will not be suitable for all of Chinese cities [3,11]. Therefore, CO_2 emission mitigation policies should be adjusted according to the characteristics of different city types to reach its goal more effectively.

Demographic change is an important factor that affects carbon emissions [12–14]. Most studies focus on the CO_2 emissions of growing cities and note that population growth is one of the major driving forces [15–17]. Based on data from 93 countries from 1975 to 1996, Shi [18] found that global population growth is more than proportionally associated with an increase in CO_2 emissions. Poumanyvong and Kaneko [19] pointed out that 1% rise in population will increase CO_2 emissions by 1.12%, 1.23% and 1.75% in high, middle and low-income countries, respectively. As for China, Zhou and Liu [20] found that the elasticity of CO_2 emissions to population size was 0.46.

Urbanization has been a well-established trend in the 20th and 21st centuries. However, depopulation in some countries and numerous cities are becoming serious problems, known as shrinking cities. The concept of shrinking cities was first proposed by two German scholars, Häußermann and Siebel [21]. Turok and Mykhnenk [22] defined that shrinking cities are those with a rate of population change below their national average. Hoekveld [23] pointed out that city shrinkage means a decline of the total population in urban areas for at least 5 years. Besides, some scholars deemed that the generalized concept of city shrinkage goes beyond general population decline, which is a multi-dimensional process with multidimensional effects. Schilling and Logan [24] defined shrinking cities as some old industrial cities which suffer from significant and continuous population decrease by at least 25% over the past 40 years with rising levels of vacant and abandoned properties. Martinez-Fernandez et al. [25] considered city shrinkage as a city, part of a city, an entire metropolitan area or a town that suffers from population outflow, economic decline, increasing unemployment and social problems as symptoms of a structural crisis. The Shrinking Cities International Research Network (SCiRN), which was founded in 2004 for promoting global researches on shrinking cities, defined the shrinking city as a densely populated city with at least 10,000 residents that has suffered from population outflow in large parts for more than 2 years and is undergoing economic transformations with some symptoms of a structural crisis [26]. In this study, we follow the definition proposed by SCiRN, which has gained higher recognition worldwide and been adopted by many scholars [27–31]. We chose population as the variable to describe shrinking and growing cities and analyzed them under the framework of the 2008 financial crisis.

City shrinkage in developed countries is a more common phenomenon. For example, Schwedt and Dresden in eastern Germany [27,32], mining cities in Poland, Manchester and Leeds in the United Kingdom [33], the Osaka Metropolitan Area in Japan [34] and St. Louis in the United States [35] are struggling to retain human capital and shore up the economy. Recently, shrinking cities have raised Chinese scholars' concerns [31,36]. Long and Wu [31] also followed the definition proposed by SCiRN and identified 40 shrinking cities in China based on national population censuses in 2000 and 2010. Moreover, city shrinkage is first highlighted in the government document of Key Tasks in China's New-type Urbanization Construction in 2019 [37]. Policy-making about regeneration strategies [27,38,39] and spatial planning [40,41] for shrinking cities has attracted increasing attentions. CO_2 emissions mitigation policies for shrinking cities should also be emphasized and formulated to deal with the new challenge. However, CO_2 emissions analysis of shrinking cities is still poorly researched.

In order to fill this gap, in this study, we firstly propose a population index to measure population shrinkage and growth, and apply it for categorizing cities into three groups of shrinking cities and three groups of growing cities (see Methodology for categorization of shrinking and growing cities). We discuss the CO_2 emission patterns of the six groups based on their energy, employment and industry structures. The cities mentioned in this study refer to prefecture-level cities in China. The prefecture-level cities include both build-up city and rural area. Based on the latest administrative planning report, there are 334 prefecture-level cities in China. We select 55 cities from three provinces in Northeast China (Liaoning, Jilin, and Heilongjiang) and three provinces in the Yangtze River Delta (Shanghai, Jiangsu, and Zhejiang) as case cities in this study (see Methodology for case cities and data sources).

The contributions of this paper are threefold. First, we, for the first time, focus on the CO_2 emission patterns of shrinking cities with comparisons of growing cities. The reasons behinds the shrinkage and growth as well as their link with CO_2 emissions are discussed. Second, the city-level emission inventories are constructed using an internally consistent emission accounting framework. Our consistent, transparent and comparable emission inventories provide robust data support for China's emission mitigation. Third, the cities' categorization rules, research thinking and results offered in this study provide a reference to help other cities or even other developing countries at similar industrialization or urbanization phases to abbreviate their path towards a low-carbon economy.

2. Methodology

2.1. Case cities

Due to the broadness of the area under study and the imbalanced levels of socioeconomic development, different parts of China are currently experiencing various stages of CO_2 emissions and demographic change [42]. As the cradle of industrial development, Northeast China consists of three provinces, namely, Liaoning, Jilin and Heilongjiang. However, Northeast China was left behind after China's economic reform in 1978, and heavy industry declined. Due to the shrinking of its once-powerful industrial sector and the decline of its economy, this region is called the Rust Belt in China [43]. For example, the GDP growth rate of Fuxin, a coal city in Liaoning Province, was −6% in

2015 [44], while the national level figure was 6.9% [45]. To bring the economy of Northeast China back on track, the “Northeast Revitalization Plan” was implemented to promote the economic transformation of resource-based or heavy industry-based cities after 2003 [46]. In recent years, Northeast China has faced resource exhaustion [47] and problems from its unbalanced industry structure [48], and it has suffered from human capital flight [36] (see Fig. 1). Its total population decreased from 105.52 million in 2009 to 103.19 million in 2015 [45]. The Yangtze River Delta consists of Shanghai, Jiangsu and Zhejiang provinces. With its higher urbanization rate and industrialization level, the Yangtze River Delta is densely populated; since the reform and opening up, urbanization and industrialization have stimulated the mobility of people across regions [49]. The total population in this region experienced a significant increase, rising from 135.36 million in 2009 to 140.34 million in 2015 [45,50]. Thus, the Yangtze River Delta has become one of China’s three major urban agglomerations. In terms of CO_2 emissions, the Yangtze River Delta and Northeast China both contributed a considerate amount of CO_2, representing approximately 13.3% and 9.9% of China’s CO_2 emissions in 2015, respectively [51]. In this research, 25 Yangtze River Delta cities and 30 Northeast China cities were selected to conduct an empirical study on the emissions

Table 1
Categorization rules of city types.

Group	Population Index
Rapidly shrinking group (RSG)	[0,0.990)
Moderately shrinking group (MSG)	[0.990,0.995)
Slightly shrinking group (SSG)	[0.995,1.000)
Slightly growing group (SGG)	[1.000,1.005)
Moderately growing group (MGG)	[1.005, 1.010)
Rapidly growing group (RGG)	[1.010, + ∞)

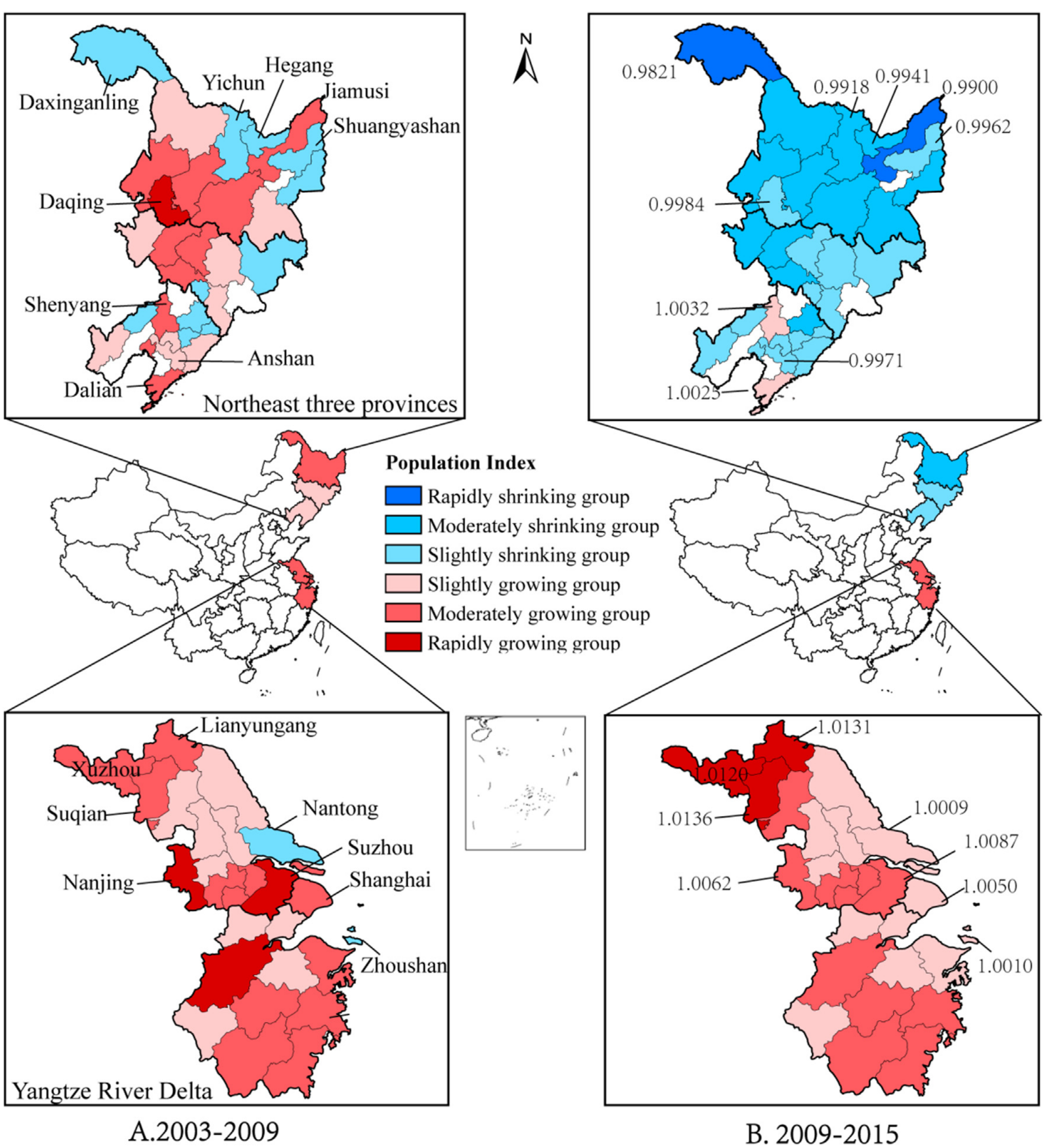


Fig. 1. Spatial distribution and population index of cities in Northeast China and the Yangtze River Delta for 2003–2009 (A) and 2009–2015 (B). We categorize 55 cities into the rapidly shrinking group (dark blue), moderately shrinking group (blue), slightly shrinking group (light blue), slightly growing group (light red), moderately growing group (red) and rapidly growing group (dark red). Qitaihe, Baishan, Jinzhou, Tiding, Yingkou, and Huludao in Northeast China (blank) are excluded due to the unavailability of energy data. The sub-picture in the middle indicates the South China Sea Islands.

patterns experienced under city growth and shrinkage. Because significant population change was detected around the 2008 financial crisis (see Fig. 1), the 55 cities were categorized into six categories based on their demographic change from 2009 to 2015 (see Table 1). The period of 2003–2008 is also taken into account for comparison.

2.2. CO_2 emission inventory construction

We estimated CO_2 emissions for 30 cities in Northeast China and 25 cities in the Yangtze River Delta from 2003 to 2015. The CO_2 emissions calculation method used in this study was discussed in our previous study [7] and only the significant details are shown here. The calculation of CO_2 follows the Intergovernmental Panel on Climate Change [52], and we scale down the provincial energy balance table to the city level based on GDP, industrial output and demographic data [7]. CO_2 emissions contain two components, namely, energy-related and process-related emissions.

Energy-related CO_2 emissions:

$$CE_{ij} = \sum_{i=1}^{17}\sum_{j=1}^{47} AD_{ij} \times NCV_i \times CC_i \times O_{ij} \tag{1}$$

In Eq. (1), CE_{ij} represents CO_2 emissions from 47 sectors and 17 fuel types [7]. AD_{ij} indicates the amount of fossil fuel consumption, NCV_i and CC_i are the net caloric value and carbon content per calorie of different fuel types, respectively. O_{ij} is the carbon oxidation ratio for different sectors and fuel types. Newly measured emission factors, which are now widely adopted in many studies [51,53–55], from Liu et al. [8] are used in this study.

Process-related CO_2 emissions:

$$CE_{\text{process}} = \sum_{t} AD_t \times EF_t \tag{2}$$

In Eq. (2), CE_{process} indicates CO_2 emissions from 9 main industrial processes [7], and t refers to industrial process t. AD_t indicates activity data, and EF_t is the emission factor, as per Liu et al. [11].

2.3. Categorization of shirking and growing cities

Some studies adopt the population change rate over a period [24,56] or absolute population change over a period [27,35] to measure demographic decline. However, these two indexes will obtain negative numbers which can't take logarithmic forms in econometric analysis [57]. Also, these indexes fail to provide better insights without calculating them as an annual term. To overcome these limitations, we propose a population index to measure city shrinkage and city growth, as follows:

$$\text{PI}_{(t_0,t_1)} = \sqrt[t_1-t_0]{\frac{P_{t_1}}{P_{t_0}}} \tag{3}$$

$\text{PI}_{(t_0,t_1)}$ represents the population index (PI) between year t_0 and year t_1, and this can be used to measure the population change for each region over a defined period. PI varies on the interval $[0, +\infty)$. PI > 1 (or < 1) corresponds to population expansion (or shrinkage). P_{t_0} and P_{t_1} are the mean population in years t_0 and t_1, respectively.

Comprehensively considering the studies about group divisions [27,34,58] and population characteristic of these 55 cities, the categorization rules can be obtained as follows:

According to the value of PI in Table 1, cities can be divided into six groups. For example, if the PI of a city equals to 1.004, the population is 1.004 times larger than it was in the previous year or the average annual growth rate (AAGR) of the population is 0.4%, and this city belongs to the slightly growing group.

2.4. Data

Due to the availability, registered population data are selected to describe shrinking and growing cities, which are collected from the China City Statistical Yearbooks between 2004 and 2016 [59]. The 47-sectoral fossil fuel consumption is collected based on the energy balance table and industrial sectoral energy consumption table from each city's statistical yearbook. Due to the limitations of data quality, most cities do not have energy balance tables, except Shanghai. We follow our previous study to scale down the corresponding provincial tables to obtain the city-level energy balance tables [7]. The data used for scaling (that are urban/rural population, GDP, gross value of industrial output) and employed persons are derived from cities' and their corresponding province's statistical yearbooks from 2004 to 2016. Outputs of industrial product, which are used for process-related CO_2 emissions calculation, are derived from each city's statistical yearbook. Value added of primary, secondary and service industries shown in Fig. 4 is converted into 2000 constant prices using the industry-level GDP index.

3. Shrinking and growing cities in Northeast China and the Yangtze River Delta

Fig. 1 shows the spatial distribution of cities in each group. Based on the value of PI (2009–2015) (see Table S3) and the categorization rules (see Table 1), 28 cities (e.g., Daxinganling, Anshan, Yichun, Hegang, Jiamusi and Daqing) shrank in 2009–2015, although only 12 cities were shrinking before the 2008 financial crisis. The PI of 2, 12 and 14 cities varies on the interval [0,0.990), [0.990,0.995) and [0.995,1.000), which indicates that they belong to the rapidly shrinking group (RSG), moderately shrinking group (MSG) and slightly shrinking group (SSG), respectively (see Fig. 1; Table S3). In contrast, 27 cities (e.g., Shenyang, Dalian, Xuzhou, Lianyungang and Suqian) grew from 2009 to 2015 (see Fig. 1; Table S3). The PI of 14, 10 and 3 cities varies on the interval [1.000,1.005), [1.005, 1.010) and $[1.010, +\infty)$, respectively, which indicates that they belong to the slightly growing group (SSG), moderately growing group (MGG) and rapidly growing group (RGG) (see Fig. 1; Table S3).

All of the cities in Northeast China belonged to shrinking groups, with the exception of Shenyang (PI_1:1.00320) and Dalian (PI_1:1.00248) (see Fig. 1; Table S3). Daxinganling (PI_1:0.98211) and Jiamusi (PI_1:0.98998), belonging to RSG, were the two cities experiencing the most severe shrinking, with a −1.789% and −1.002% AAGR of the population, respectively (see Fig. 1; Table S3). Meanwhile, Daqing, which has the largest oilfield in China, shifted from the RGG to the SSG due to the problem of resource exhaustion [60].

There are many reasons for the phenomenon of shrinking cities. First, the negative impact exerted by the 2008 financial crisis on the vulnerable and unbalanced industry structure of Northeast China forced these cities to adjust industry structures and address excess production capacity [61]. However, the industry adjustment was sluggish and new economic growth points have not been fostered. This economic depression led to a substantial number of employees losing jobs and leaving their home region for better employment and living conditions elsewhere. Second, Northeast China has relatively closed geographical position, bordered by North Korea to the east, Russia to the north and Mongolia to the west. This location holds back economic development, and more high-quality resources are allocated to developed regions. Lastly, well known as heavy industry-based and resource-based region, Northeast China has many internal problems, such as an unreasonable industrial structure, resource exhaustion and drawbacks of planned economy [47,48,62]. High-emitting, high energy-consuming and low value-added development path failed to meet the demands of the new era. It is notable that Dalian and Shenyang in Northeast China were the only two cities in that region growing over the 12-year period under study (see Fig. 1). This may result from the fact that Shenyang, a provincial capital of Liaoning Province, is an important advanced equipment manufacturing base and national historical city [63]. Meanwhile, Dalian's petrochemical industry, its pillar industry, contributed substantially to Dalian's economic and social development and attracted an increasing workforce [64].

In contrast, the population of cities in the Yangtze River Delta all increased between 2009 and 2015, especially for Xuzhou (PI_1:1.01201), Lianyungang (PI_1:1.01312) and Suqian (PI_1:1.01361) (see Fig. 1; Table S3). Although Xuzhou, Lianyungang and Suqian in Jiangsu Province were less developed, they experienced rapid economic growth, with 13.9%, 13.6% and 13.5% GDP growth rates in 2009. These growth rates were much higher than that of Suzhou (11.5%), which had the highest GDP per capita in Jiangsu Province in 2009 [65]. In another case, Zhoushan experienced a population decrease before 2009 (PI:0.99940), while it witnessed an increase between 2009 and 2015 (PI:1.00102) (see Fig. 1; Table S3). This change reflects a significant industry adjustment and upgrading towards marine economy because Zhoushan became one of the designated State-level New Areas in 2011 [66,67]. Growing cities concentrate resources, key infrastructure and intellectual assets, which act as magnets for population and skills.

4. Emission patterns and development pathways of shrinking and growing cities

The total CO_2 emissions of these six groups all reached their emissions peak or witnessed even a decreasing trend after 2011 or 2013, with the exception of the RSG (see Fig. 2). Specifically, the patterns of CO_2 emissions variation tendencies in SSG, MSG, RSG, SGG, MGG and RGG were "decrease after 2011", "peak in 2011", "increase after 2013", "peak in 2011", "peak in 2011" and "quick growth and then stability after 2013", respectively (see Fig. 2). The slower growth trajectories of CO_2 emissions in SSG, MSG, SGG, MGG and RGG were consistent with the result of a recent study that China's emissions might have peaked in 2013 [68]. However, the reasons for CO_2 emissions mitigation in these five types of cities differed significantly. In the following sections, we will analyze and compare the CO_2 emissions patterns of these six groups in more detail, examine the similarities and differences, and their corresponding determinants driving the patterns.

4.1. Slightly and moderately shrinking groups (SSG and MSG)

Because CO_2 emissions patterns and structures were similar in the SSG and MSG, we will analyze them together for better comparison. Even with the impact of the financial crisis in 2008, economic development was not negatively influenced in the shrinking groups (see Fig. 4(A; B)) given financial support from the Chinese government, such as the launch of a 4 trillion-yuan stimulus plan in 2008 [69]. In other words, after 2009, many cities in the SSG and MSG continued to develop traditional carbon-intensive industries such as the resource-related heavy manufacturing sectors and energy production sectors [62,70]. Therefore, the CO_2 emissions of SSG and MSG continued to increase rapidly until 2011. Specifically, the SSG and MSG saw an increase in carbon emissions generated from heavy manufacturing sectors, rising by 11.86% and 10.13% between 2009 and 2011, respectively (see Fig. 2(A; B)). For the energy production sectors, the SSG and MSG also experienced an upward trend of 12.10% and 24.03% over the same period, respectively (see Fig. 2(A; B)).

It is noteworthy that after 2011, CO_2 emissions started to decrease (SSG) or stabilize (MSG) (see Fig. 2(A; B)). However, the carbon intensity of these two shrinking groups started to experience a much slower decrease after 2013 (see Fig. 2(A; B)). To be precise, in SSG, carbon intensity experienced a significant decrease between 2003 and 2013, dropping by 6.63% annually, while dropping by 3.95% annually between 2013 and 2015. In MSG, carbon intensity decreased by 6.65% annually between 2003 and 2013, while it decreased by a mere 0.42% annually between 2013 and 2015 (see Fig. 2(A; B)). Previous research has illustrated that different emission intensities are the result of critical

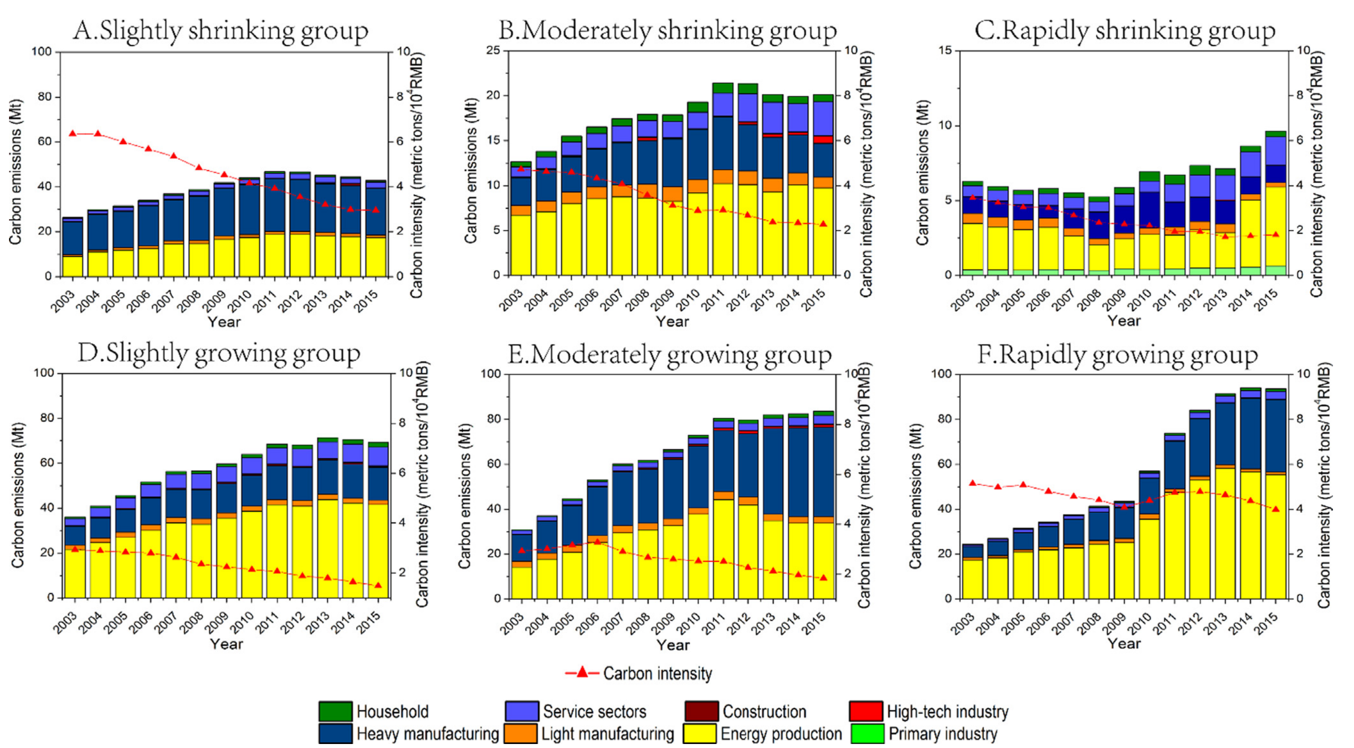


Fig. 2. Mean CO_2 emissions and carbon intensity of each city group. The bar chart is carbon emissions (mt) by socioeconomic sector. The red broken line indicates carbon intensity (metric tons/10^4RMB). In this study, 47 sectors are divided into eight main socioeconomic sectors, namely, primary industry, secondary industry (construction, high-tech industry, heavy manufacturing, light manufacturing and energy production sectors), tertiary industry and households (see Table S1). The results of the six groups are presented at an average instead of a cumulative level, meaning that we divide the results of each group by the number of cities in that group.

differences in technology [71,72]. This indicates that low-carbon technology may not the reason for CO_2 emissions mitigation after 2011. In terms of energy structure, in the SSG, the percentage of energy consumption derived from coal decreased by a mere 4.27% over the study period, while the same figure for the SGG, MGG and RGG declined by 6.05%, 8.43% and 8.48%, respectively (see Fig. 3). It is noteworthy that MSG even showed an increasing trend of 5.00% over the period under study (see Fig. 3). This indicates that the energy structure in the SSG and MSG did not improve significantly over the study period.

CO_2 emission mitigation was a positive sign in SSG and MSG but occurred with the decline of secondary industry. We argue that the decline of secondary industry may account for the mitigation of CO_2 emissions in SSG and MSG after 2011. Several years after the launch of a 4 trillion-yuan stimulus plan, traditional industrial enterprises reduced their production scale to address the overcapacity problem [62]. This was supported by the slowing economy and human capital flight around 2011, especially for secondary industry (see Fig. 4(A; B)). Specifically, in the SSG and MSG, value added in secondary industry experienced a decline after 2014, dropping from 93.24 billion RMB and 56.86 billion in 2014 to 89.70 billion RMB and 56.29 billion in 2015, respectively, while the figure for primary and service industry continued to reflect growth (see Fig. 4(A; B)). Additionally, from the perspective of employment structure, secondary industry suffered from remarkable human capital flight, which further hindered the development of secondary industry. Specifically, there was a significant decrease in workers in secondary industry in the SSG and MSG, dropping by 6.17% and 16.02% between 2011 and 2015, respectively (see Fig. 4(A; B)). All cities in SSG and MSG are located in Northeast China, an old industrial base in China that relies heavily on secondary industry, such as iron and steel, automobiles and manufacturing. Many studies have found that secondary industry is the main contributor to total CO_2 emissions because it has the largest number of energy-intensive sectors and a high level of industrial activity [73–75]. When these heavy manufacturing sectors shrink, it inevitably results in the decrease in CO_2 emissions. Therefore, declining secondary industry in the SSG and MSG can partly explain why total CO_2 emissions decreased after 2011. For example, Angang Steel Company Limited in Anshan of the SSG, one of the largest steel-making companies in China, had to phase out its backward and redundant industrial capacity to address a major deficit after 2015 [76]. Even worse, the resource exhaustion problem of many cities in these two shrinking groups, such as Liaoyuan, Tonghua, Yichun, Hegang and Shuangyashan [47], further hindered the improvement of energy structure and the development of secondary industry.

4.2. Rapidly shrinking group (RSG)

For the RSG, total CO_2 emissions were the lowest among the six groups, mainly because of its industry structure. Primary industry in the RSG contributed remarkably to economic development, accounting for 22.0% of GDP in 2015, followed by its contribution to the MSG (14.0%), the SSG (5.8%), the RGG (8.27%), the SGG (2.37%) and the MGG (2.98%) (see Fig. 4). For example, the pillar industry of Daxinganling is primary industry, accounting for 48.7% of total GDP in 2015, followed by service industry (41.8%) and secondary industry (9.5%) [77]. However, primary industry contributed a negligible amount of CO_2 emissions (see Fig. 2 (C)) because the farming, forestry, animal husbandry, fishery and water conservancy sectors consume a small amount of fossil fuels. Therefore, the RSG had the lowest amount of CO_2 emissions among the six groups. However, the RSG experienced a slight increase in CO_2 emissions after 2013 (see Fig. 2(C)). The increasing trend of carbon emissions after 2013 mainly resulted from the prosperous tertiary industry and energy production sectors. Specifically, the amount of CO_2 emissions produced by the energy production sectors and service industry increased by 124.79% and 17.28% during 2013–2015, respectively (see Fig. 2(C)).

In terms of carbon intensity, the RSG saw an increasing trend in recent years, rising from 1.72 metric tons/(10^4 RMB) in 2013 to 1.81 metric tons/(10^4 RMB) in 2015. The primary reason for the increase was that the slower growth of GDP (see Fig. 4(C)) occurred with the significant rise of CO_2 emissions after 2013 (see Fig. 2(C)). The increasing carbon intensity indicates that the RSG has deviated from low-carbon economy development. It is noteworthy that the RSG suffered from the earliest and most severe workforce loss compared with the other shrinking groups (see Fig. 4). Specifically, the primary, secondary and tertiary industries began to decline after 2005, 2007 and 2012 and lost 15.55%, 30.22% and 8.94% of the workforce, respectively (see Fig. 4(C)). For example, population in Daxinganling dropped by around 19.7% during 2005–2018, and the decreasing employees in primary industry was mainly attributed to the ban on deforestation for commercial purposes announced by the central government [78,79].

The severe labour outflow indicates a loss of skilled workers who could have promoted innovation and developed high value-added and low-carbon industries. To make things worse, energy consumption derived from coal witnessed an increase after 2009, rising from 71.44% in 2009 to 79.64% in 2015, and thus the RSG remained the highest among six groups for this metric after 2013 (see Fig. 3). This energy structure change indicated the failure to adjust the energy types from coal to clean energy.

The RSG is experiencing the most worrisome situation in terms of carbon mitigation. A high level of coal share in the energy mix, a remarkable outflow of intellectual assets and increasing carbon intensity make it more difficult to curb the increase in CO_2 emissions. More actions should be taken to promote industrial transformation and upgrading, retain the workforce, optimize the energy structure, and further reverse the worsening situation in the RSG.

4.3. Slightly and moderately growing groups (SGG and MGG)

The SGG and MGG had similar CO_2 emissions patterns, and we analyzed them together for better comparison. There was a slower growth rate in CO_2 emissions in the MSG and SSG after 2011 (see Fig. 2(D; E)). Looking at the information in more detail, secondary industry was the main contributor to CO_2 emissions, especially the energy

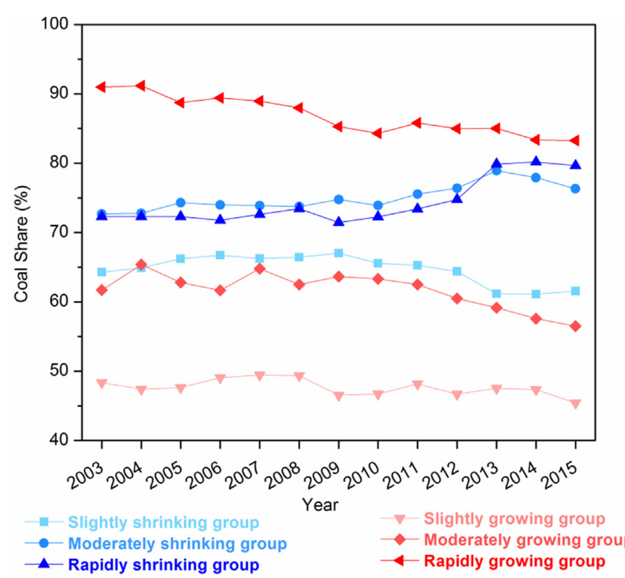


Fig. 3. Energy structure of each city group. We merge 17 energy types into three categories, including coal, oil and natural gas (see Table S2; Fig. S1), and use the ratio of coal to total energy consumption to measure energy structure. The results of the six groups are presented at an average instead of a cumulative level, meaning that we divide the results of each group by the number of cities in that group.

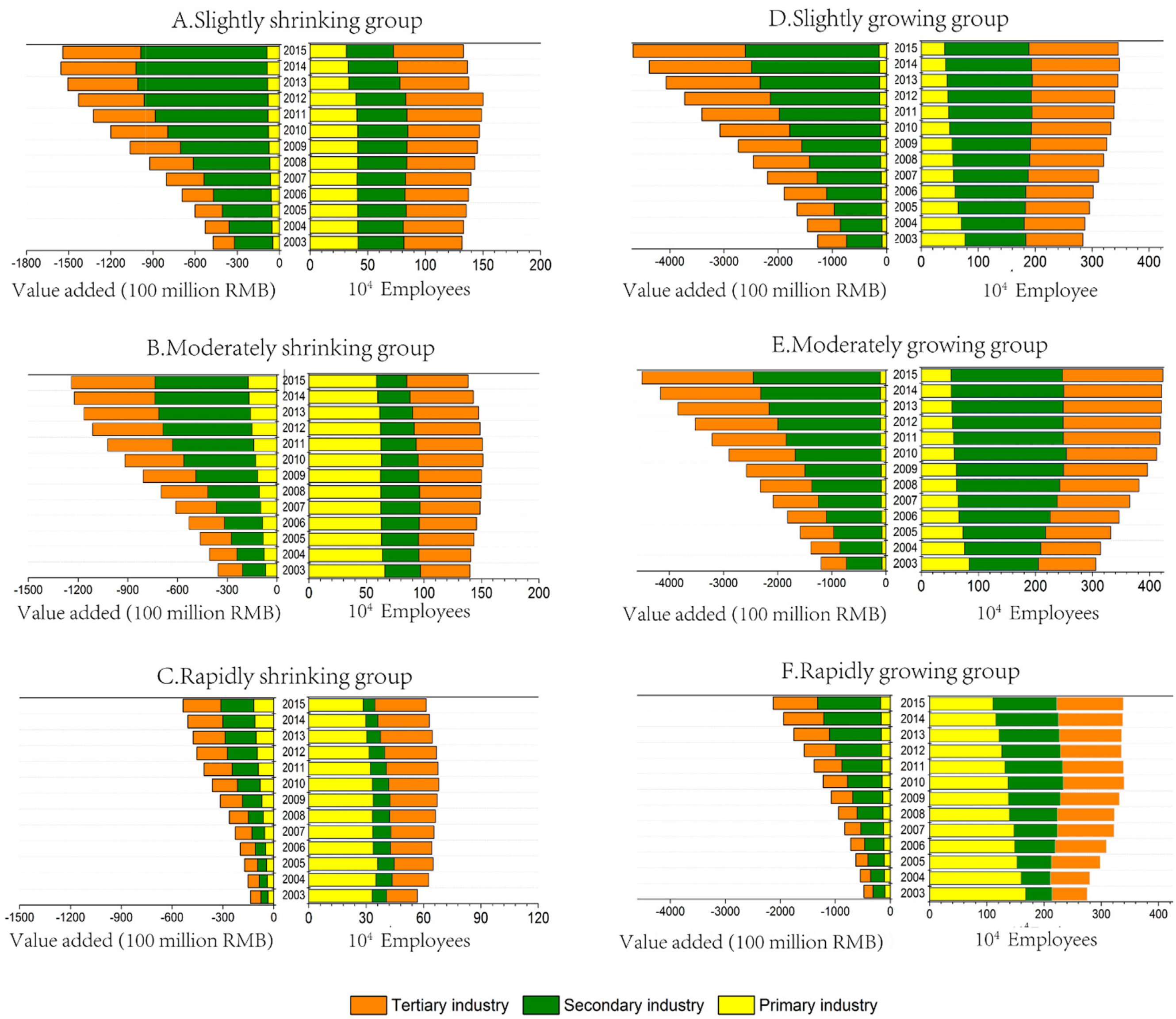


Fig. 4. Employment and industry structure of each city group. The employment structure (right) and industry structure (left) of each group are presented by using employees and value added of primary, secondary and tertiary industries. It should be noted that the coordinate axes of the rapidly shrinking group (C) are smaller than those of other groups for clear demonstration. The results of the six groups are presented at an average instead of a cumulative level, meaning that we divide the results of each group by the number of cities in that group.

production and heavy manufacturing sectors (see Fig. 2(D; E)). In the SGG, the energy production sectors contributed the most to CO_2 emissions at 59.43% in 2015, followed by the heavy manufacturing sectors (20.83%), service sectors (11.81%) and household sectors (3.10%) (see Fig. 2(D)). In comparison, the proportion of CO_2 derived from the heavy manufacturing sectors was the largest for the MSG, at 47.29% in 2015, followed by the energy production sectors, service sectors and light manufacturing sectors, which represented emissions proportions of 40.13%, 4.48%, and 3.47%, respectively (see Fig. 2(E)). In terms of carbon intensity, the SGG and MGG saw a steady decrease from 2.93 metric tons/(10^4RMB) and 2.92 metric tons/(10^4RMB) in 2003 to 1.49 metric tons/(10^4RMB) and 1.84 metric tons/(10^4RMB) in 2015, respectively (see Fig. 2 (D; E)). For energy structure, the share of energy consumption derived from coal in the SGG decreased from 48.33% in 2003 to 45.41% in 2015, which was the lowest among the six groups (see Fig. 3). It is noteworthy that the SSG was the only group that had a higher proportion of oil (47.62%) than of coal (45.41%) in total energy consumption in 2015 (see Fig. 3; Fig. S1), meaning that it had the best energy structure. Take Shanghai, a megacity in China, for example, the oil share in energy mix is the largest, accounting for 65.64% in 2015, followed by gas (19.28%) and coal (15.08%). For the MGG, the proportion of coal consumption declined from 61.69% in 2003 to 56.48% in 2015 (see Fig. 3). These results indicate that both the SGG and the MGG experienced energy structure optimization from 2003 to 2015.

With regard to industry structure, the SGG and MGG experienced a dramatic rise in value added in secondary industry of 278.22% and 256.24% from 2003 to 2015, respectively (see Fig. 4(D; E)). Meanwhile, value added in the service industry of the SGG and MGG increased by 289.96% and 338.63% over the period shown, respectively (see Fig. 4(D; E)). The service industry has been the main source of economic growth for these two groups, taking up 47.98% and 43.74% of total value added in 2015, respectively (see Fig. 4(D; E)). For example, the GDP shares of secondary and service industries in Shanghai shifted from 50.1%, 48.4% in 2003 to 31.8% and 67.8% in 2015, respectively [80], suggesting a transition from an energy-intensive economy to a service-based economy. For the employment structure, SSG and MSG saw a remarkable decrease in terms of the number of employees from primary industry, which dropped by 46.80% in SSG and 38.02% in

MGG over the 13-year period (see Fig. 4(D; E)). However, a significant increasing trend can be found in terms of workers in the secondary and service industries over the same period.

From the analysis above, it is clear that the SGG and MGG were capable of mitigating CO_2 emissions after 2011 while improving their economy. Several trends can account for this phenomenon. First, the departure of employees in the primary industry consistently accompanies the significant increase in employees in the secondary or service industries. These results indicated a positive employment and industry structure change in the shift towards high value-added sectors in growing groups. Second, carbon intensity decreased continuously, meaning that GDP grew faster than emissions and that these two groups moved towards low-carbon economies. Lastly, the SGG and MGG experienced a decreasing trend in terms of coal share in the energy mix. It is universally known that coal is a high-emission energy type compared with crude oil and natural gas because coal produces more CO_2 emissions when generating the same amount of heat [71]. In addition, the SGG was the optimal type among the six groups because it had decreasing CO_2 emissions, the lowest carbon intensity and optimal energy structure. Additionally, its CO_2 emissions experienced a decline of 1.47% annually, while the growth rate in economy still soared (increase by 7.27% annually).

4.4. Rapidly growing group (RGG)

Among the six groups, the clearest differences were observed in the CO_2 emissions trend in the RGG over time (see Fig. 2). We can divide the study period into three distinct periods for the RGG, namely, 2003–2009, 2009–2013 and 2013–2015. Before the 2008 financial crisis, the RGG observed a rapid growth trend in terms of CO_2 emissions, with an AAGR of 1.10% from 2003 to 2009 (see Fig. 2(F)). However, the AAGR of CO_2 emissions from 2009 to 2013 increased to 1.20% (see Fig. 2(F)), mainly because of the prosperous of secondary industry. Therefore, secondary industry inevitably produced a large amount of CO_2 emissions, especially in Xuzhou, an old industry base in Jiangsu Province. The GDP growth rate of Xuzhou was 13.2% in 2012, ranking first in Jiangsu Province, and secondary industry even saw a rapid increase in value added of 14.5% [81]. After 2013, the growth rate of carbon emissions slowed from 2013 to 2015 in the RGG, dropping to 1.01% (see Fig. 2(F)). For carbon intensity, there was a declining trend from 2003 to 2009, then the figure increased to 4.78 metric tons/(10^4RMB) in 2012 and finally decreased to 3.99 metric tons/(10^4RMB) in 2015 (see Fig. 2(F)). Interestingly, the RGG, which relied heavily on coal, also witnessed a continuous and significant decreasing trend in terms of the share of coal, from 90.98% in 2003 to 83.26% in 2015 (see Fig. 3). With regard to industry structure, there was a dramatic increase in terms of value added in primary, secondary and tertiary industries in the RGG over the period from 2003 to 2015, as they rose by 76.67%, 430.03% and 388.57%, respectively (see Fig. 4(F)). In terms of employment structure, the rise for the RGG was particularly noticeable between 2003 and 2015, during which time the number of employees in secondary industry increased by 141.67% and the figure for the service industry increased by 89.48%, while the figure for primary industry dropped 34.12% (see Fig. 4(F)).

Compared with the other two growing groups, the RGG experienced the most remarkable employment and industry structure transformation, especially for secondary industry (see Fig. 4). This change could be responsible for the rapid rise in CO_2 emissions from 2009 to 2013. However, after 2013, similar to the other growing groups, industrial transformation and upgrading, workforce aggregation, decreasing carbon intensity and energy structure optimization help to curb the increase in CO_2 emissions.

5. Conclusion

To help policy-makers to implement CO_2 emissions policies according to varied city types and promote sustainable development, this study analyzes long-term CO_2 emission patterns under the framework of shrinking and growing cities, and discusses the reasons driving the patterns. As the representatives of shrinking and growing cities, 55 cities from Northeast China and the Yangtze River Delta are selected as case cities. These cities are then categorized into six groups: three groups of shrinking cities and three groups of growing cities. Emission patterns in terms of energy, employment and industry structures are discussed by group. The empirical results are as follows.

First, for the slightly and moderately shrinking cities, CO_2 emission mitigation was a positive sign but occurred with the decline of economic activities in secondary industry, especially for resource-based or heavy manufacturing cities, such as Daqing and Anshan in Northeast China. The negative impact exerted by the 2008 financial crisis on the vulnerable and unbalanced industry structure of these cities forced them to address excess production capacity of secondary industry and adjust industry structure. However, the industry adjustment was sluggish and new economic growth points have not been fostered. Therefore, a substantial number of employees of secondary industry lost jobs and left their home region for better employment and living conditions elsewhere. When economic activities of secondary industry slowed down, it may result in the decrease in CO_2 emissions. For example, Daqing Oilfield Limited Company in Daqing, which has the largest oilfield in China, has been under pressure to transform and upgrade to better manage the resource exhaustion problem [60] and resource-related activities declined.

Second, CO_2 emissions in the rapidly shrinking group were the lowest among the six groups. It can be interpreted that primary industry in these cities contributed a lot to the economy, accounting for around 22.0% of GDP in 2015, while it contributed a negligible amount of CO_2 emissions. However, the rapidly shrinking group experienced a continuous increase in CO_2 emissions resulting from the industry transformation towards secondary and service industries.

Third, the slightly and moderately growing city types were capable of mitigating CO_2 emissions while maintaining rapid economic growth. The decrease in emissions was driven by a combination of industry structure adjustment, workforce aggregation, decreasing carbon intensity and energy structure optimization. The slightly growing group performed the best among the six groups because of its decreasing CO_2 emissions, lowest carbon intensity and optimal energy structure. For the slightly growing group, CO_2 emissions experienced a decline of 1.47% annually, while the economy still soared (increase by 7.27% annually). Take Shanghai, a slightly growing city, for example, oil represented the largest share (65.64%) in energy mix in 2015. Its GDP shares of secondary and service industries suggest a transition from an energy-intensive economy to a service-based economy and a large number of workers flood into Shanghai.

Last, CO_2 emissions of the rapidly growing group presented a rapid growth during 2010–2013, while the growth rate slowed down significantly after 2013. Such rapid growth can be attributed to the fact that this group experienced the most remarkable employment and industry structures transformation, especially for secondary industry. After 2013, similar to the other growing groups, industrial transformation and upgrading, workforce aggregation, decreasing carbon intensity and energy structure optimization help to curb the increase in CO_2 emissions.

Further progress in reducing carbon emissions effectively should depend on policies that differentiate according to city type. Some suggestions for policy-makers are as follows. First, if CO_2 emissions fall primarily as a result of the shrinkage of economic activity in secondary industry, as occurred in the USA during the global financial crisis, renewed economic growth could reverse the decrease [82,83]. Policy-makers should be alert to the possibility that such carbon mitigation would not continue if secondary industry redevelops. The primary mission of these shrinking cities is to mitigate CO_2 emissions under the premise of keeping the economy healthy and growing. Escaping from an institutional lock-in and path-dependence towards economic success based on heavy industries is a crucial step [84]. Moreover, urban rescaling would be an important issue to mitigate further shrinkage and promote sustainability.

Second, existing improvements through energy structure optimization and structural adjustment in these shrinking cities were far from sufficient and saw sluggish implementation. Optimizing energy mix and boosting recycling and renewable energies should be highlighted. Industry structure adjustment towards high value-added and low-emissions industries should be integrated in curbing emissions.

Last, to mitigate further shrinkage and curb the negative effects of human capital flight, governments should implement some population policies to tackle the new challenge. Some effective schemes should be carried out to retain skilled workers and to help employees with enhanced knowledge and skills to return to their hometown.

This study has some limitations. First, this paper only considers population as the variable to measure shrinking and growing cities. In future work, we will take into account multiple dimensions to measure city shrinkage, such as economic depression, employee outflow, and social problems. Second, some cities' CO_2 emission inventories, especially in those in Northeast China in individual years or cities, are missing due to a lack of energy consumption data, which leads to uncertainties in the results. Further research will be focused on data investigation to improve the data quality.

Acknowledgements

All the data and results can be download freely from China Emission Accounts and Datasets (CEADs) at www.ceads.net. This work was supported by the National Natural Science Foundation of China (71704029, 71822402, 91746112), the Humanities and Social Science Fund of Ministry of Education of China (16YJCZH162), and the Guangzhou City Philosophy and Social Sciences Planning Project of Guangand (2016GZQN25), Research Center on Low-carbon Economy for Guangzhou Region, and the New Pearl River Star Program of Guangzhou City (201610010035).

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2019.113384.

References

[1] British Petroleum. Statistical Review of World Energy; 2018 < https://www.bp.com/content/dam/bp/end/corporate/pdf/energy-economics/statistical-review/bp-stats-review-2018-full-report.pdf > .

[2] The State Council Information Office of the Peoples's Republic of China. Enhanced actions on climate change: China's intended nationally determined contributions; 2015 < http://www.scio.gov.cn/xwfbh/xwbfbh/wqfbh/33978/35364/xgzc35370/Document/1514539/1514539.htm > . [Chinese Document].

[3] Shan Y, Guan D, Hubacek K, Zheng B, Davis SJ, Jia L, et al. City-level climate change mitigation in China. Sci Adv 2018;4:eaaq0390.

[4] Zhou Y, Shan Y, Liu G, Guan D. Emissions and low-carbon development in Guangdong-Hong Kong-Macao Greater Bay Area cities and their surroundings. Appl Energy 2018;228:1683–92.

[5] Rosenzweig C, Solecki W, Hammer SA, Mehrotra S. Cities lead the way in climate–change action. Nature 2010;467:909–11.

[6] Wang S, Shi C, Fang C, Feng K. Examining the spatial variations of determinants of energy-related CO_2 emissions in China at the city level using Geographically Weighted Regression Model. Appl Energy 2019;235:95–105.

[7] Shan Y, Guan D, Liu J, Mi Z, Liu Z, Liu J, et al. Methodology and applications of city level CO_2 emission accounts in China. J Clean Prod 2017;161:1215–25.

[8] Wang S, Liu X, Zhou C, Hu J, Ou J. Examining the impacts of socioeconomic factors, urban form, and transportation networks on CO_2 emissions in China's megacities. Appl Energy 2017;185:189–200.

[9] Mykhnenko V, Turok I. East European cities — patterns of growth and decline, 1960–2005. Int Plan Stud 2008;13:311–42.

[10] Reis JP, Silva EA, Pinho P. Spatial metrics to study urban patterns in growing and shrinking cities. Urban Geogr 2016;37:246–71.

[11] Liu Z, Guan D, Wei W, Davis SJ, Ciais P, Bai J, et al. Reduced carbon emission estimates from fossil fuel combustion and cement production in China. Nature 2015;524:335–8.

[12] O'Neill BC, Liddle B, Jiang L, Smith KR, Pachauri S, Dalton M, et al. Demographic change and carbon dioxide emissions. Lancet 2012;380:157–64.

[13] Wang S, Fang C, Sun L, Su Y, Chen X, Zhou C, et al. Decarbonizing China's urban agglomerations. Ann Am Assoc Geogr 2019;109:266–85.

[14] Wang S, Zeng J, Huang Y, Shi C, Zhan P. The effects of urbanization on CO_2 emissions in the Pearl River Delta: a comprehensive assessment and panel data analysis. Appl Energy 2018;228:1693–706.

[15] Alam MdM, Murad MdW, Noman AHMd, Ozturk I. Relationships among carbon emissions, economic growth, energy consumption and population growth: Testing Environmental Kuznets Curve hypothesis for Brazil, China, India and Indonesia. Ecol Indic 2016;70:466–79.

[16] Asumadu-Sarkodie S, Owusu PA. Carbon dioxide emissions, GDP, energy use, and population growth: a multivariate and causality analysis for Ghana, 1971–2013. Environ Sci Pollut Res 2016;23:13508–20.

[17] Knapp T, Mookerjee R. Population growth and global CO_2 emissions: a secular perspective. Energy Policy 1996;24:31–7.

[18] Shi A. The impact of population pressure on global carbon dioxide emissions, 1975–1996: evidence from pooled cross-country data. Ecol Econ 2003;44:29–42.

[19] Poumanyvong P, Kaneko S. Does urbanization lead to less energy use and lower CO_2 emissions? A cross-country analysis. Ecol Econ 2010;70:434–44.

[20] Zhou Y, Liu Y. Does population have a larger impact on carbon dioxide emissions than income? Evidence from a cross-regional panel analysis in China. Appl Energy 2016;180:800–9.

[21] Häußermann H, Siebel W. Die Schrumpfende Stadt und die Stadtsoziologie. In: Friedrichs J, editor. Soziol. Stadtforsch., Wiesbaden: VS Verlag für Sozialwissenschaften; 1988, p. 78–94.

[22] Turok I, Mykhnenko V. The trajectories of European cities, 1960–2005. Cities 2007;24:165–82.

[23] Hoekveld JJ. Time-space relations and the differences between shrinking regions. Built Environ 2012;38:179–95.

[24] Schilling J, Logan J. Greening the rust belt: a green infrastructure model for right sizing America's shrinking cities. J Am Plann Assoc 2008;74:451–66.

[25] Martinez-Fernandez C, Audirac I, Fol S, Cunninghamsabot E. Shrinking cities: urban challenges of globalization. Int J Urban Reg Res 2012;36:213–25.

[26] Wiechmann T. Types of shrinking cities–Introductive Notes on a Global Issue. Pap. Present. L'International Symp. Coping City Shrinkage Demogr. Change-Lessons Globe' Dresd. Ger.; 2006.

[27] Wiechmann T, Pallagst KM. Urban shrinkage in Germany and the USA: a comparison of transformation patterns and local strategies. Int J Urban Reg Res 2012;36:261–80.

[28] Wiechmann T, Bontje M. Responding to tough times: policy and planning strategies in shrinking cities. Eur Plan Stud 2015;23:1–11.

[29] Hollander JB, Németh J. The bounds of smart decline: a foundational theory for planning shrinking cities. Hous Policy Debate 2011;21:349–67.

[30] Pallagst K. Shrinking cities: planning challenges from an international perspective. Cities Grow Smaller 2008;10:5–16.

[31] Long Y, Wu K. Shrinking cities in a rapidly urbanizing China. Environ Plan A 2016;48:220–2.

[32] Glock B, Haussermann H. New trends in urban development and public policy in eastern Germany: dealing with the vacant housing problem at the local level. Int J Urban Reg Res 2004;28:919–29.

[33] While A, Jonas AEG, Gibbs D. The environment and the entrepreneurial city: searching for the urban 'sustainability fix' in Manchester and Leeds. Int J Urban Reg Res 2004;28:549–69.

[34] From Buhnik S. Shrinking cities to Toshi no Shukushō: identifying patterns of urban shrinkage in the Osaka Metropolitan Area. Berkeley Plan J 2011;23.

[35] Beauregard RA. Urban population loss in historical perspective: United States, 1820–2000. Environ Plan Econ Space 2009;41:514–28.

[36] Long Y, Gao S, editors. Shrinking Cities in China: The Other Facet of Urbanization. Singapore: Springer Verlag; 2019.

[37] National Development and Reform Commission of China. Key tasks in China's new-type urbanization construction in 2019; 2019 < http://www.ndrc.gov.cn/zcfb/zcfbtz/201904/t20190408_932843.html > . [Chinese Document].

[38] Camarda D, Rotondo F, Selicato F. Strategies for dealing with urban shrinkage: issues and scenarios in Taranto. Eur Plan Stud 2015;23:126–46.

[39] Pallagst K, Al E. The future of shrinking cities: problems, patterns and strategies of urban transformation in a global context. Inst Urban Reg Dev Cent Glob Metrop Stud Shrinking Cities Int Res Netw Monogr Ser 2009.

[40] Sousa S, Pinho P. Planning for shrinkage: paradox or paradigm. Eur Plan Stud 2015;23:12–32.

[41] Bontje M. Dealing with deconcentration: population deconcentration and planning response in polynucleated urban regions in North-west Europe. Urban Stud 2014;38:769–85.

[42] Liu Q, Wang S, Zhang W, Li J, Kong Y. Examining the effects of income inequality on CO_2 emissions: Evidence from non-spatial and spatial perspectives. Appl Energy 2019;236:163–71.

[43] Campbell C. Swallows and settlers: the great migration from North China to Manchuria. J Asian Stud 2005;64:1004–5.

[44] National Bureau of Statistics of China. China City Statistical Yearbook. Beijing, China: China Statistics Press; 2016.

[45] National Bureau of Statistics of China. China Statistical Yearbook. Beijing, China: China Statistics Press; 2016.

[46] The Chinese Government. Notice of the General Office of the State Council on issuing the key points about revitalizing the old industrial bases in Northeast China in 2004; 2004 < http://www.gov.cn/zhengce/content/2008-03/28/content_2058.

htm > . [Chinese Document].
[47] The Chinese Government. The list of resource exhausted cities in China; 2011 < http://www.gov.cn/gzdt/2011-03/10/content_1821480.htm > . [Chinese Document].
[48] Xinhua. Industrial transformation in Northeast China is highlighted; 2016 < http://www.xinhuanet.com/politics/2016-03/03/c_128771160.htm > . [Chinese Document].
[49] He C, Chen T, Mao X, Zhou Y. Economic transition, urbanization and population redistribution in China. Habitat Int 2016;51:39–47.
[50] National Bureau of Statistics of China. China Statistical Yearbook. Beijing, China: China Statistics Press; 2010.
[51] Shan Y, Guan D, Zheng H, Ou J, Li Y, Meng J, et al. China CO_2 emission accounts 1997–2015. Sci Data 2018;5:170201.
[52] Intergovernmental Panel on Climate Change (IPCC). IPCC Guidelines for National Greenhouse Gas Inventories. Hayama (Japan): Institute for Global Environmental Strategies; 2006.
[53] Shan Y, Liu J, Liu Z, Xu X, Shao S, Wang P, et al. New provincial CO_2 emission inventories in China based on apparent energy consumption data and updated emission factors. Appl Energy 2016;184:742–50.
[54] Shan Y, Liu J, Liu Z, Shao S, Guan D. An emissions-socioeconomic inventory of Chinese cities. Sci Data 2019;6:190027.
[55] Li L, Shan Y, Lei Y, Wu S, Yu X, Lin X, et al. Decoupling of economic growth and emissions in China's cities: a case study of the Central Plains urban agglomeration. Appl Energy 2019;244:36–45.
[56] Bernt M, Haase A, Großmann K, Cocks M, Couch C, Cortese C, et al. How does(n't) Urban Shrinkage get onto the Agenda? Experiences from Leipzig, Liverpool, Genoa and Bytom. Int J Urban Reg Res 2014;38:1749–66.
[57] Zhang N, Yu K, Chen Z. How does urbanization affect carbon dioxide emissions? A cross-country panel data analysis. Energy Policy 2017;107:678–87.
[58] Oswalt P, Rieniets T, Schirmel H. Atlas of shrinking cities. Ostfildern: Hatje Cantz; 2006.
[59] National Bureau of Statistics of China. China City Statistical Yearbook. Beijing, China: China Statistics Press; 2004–2016.
[60] Xinhua. The resource exhaustion problem was worsening under the circumstance of low oil price and Daqing Oilfield Limited Company suffered from a great loss; 2016 < http://www.xinhuanet.com//fortune/2016-03/17/c_128806014.htm > . [Chinese Document].
[61] Xinhua. Viewpoints about Chinese economy from Xinhua Net: overcapacity problem has been a Malignant Tumor; 2015 < http://www.xinhuanet.com/2015-06/30/c_1115774759.htm > . [Chinese Document].
[62] Xinhua. What is the economic development path in Northeast China; 2017 < http://www.xinhuanet.com/finance/2017-09/12/c_129701996.htm > . [Chinese Document].
[63] Shenyang Municipal Bureau of Statistics. Brief introduction of economic performance of Shenyang from January to July; 2018 < http://www.sysinet.gov.cn/news.aspx?id=13664 > . [Chinese Document].
[64] Dalian municipal bureau of statistics. Reducing consumption and optimizing the development of Dalian's petrochemical industry; 2016 < http://www.stats.dl.gov.cn/index.php?m=content&c=index&a=show&catid=48&id=11229 > . [Chinese Document].
[65] Statistical Bureau of Jiangsu. Jiangsu statistical yearbook. Beijing, China: China Statistics Press; 2010.
[66] The Chinese Government. The State Council formally approved to establish Zhoushan Islands New District of Zhejiang province; 2011 < http://www.gov.cn/jrzg/2011-07/07/content_1901558.htm > . [Chinese Document].
[67] Zhoushan Statistical Information Net. Analysis of Zhoushan's economic development in 2016; 2017 < http://zsfgw.zhoushan.gov.cn/art/2017/2/8/art_1297631_7554982.html > . [Chinese Document].
[68] Guan D, Meng J, Reiner DM, Zhang N, Shan Y, Mi Z, et al. Structural decline in China's CO2 emissions through transitions in industry and energy systems. Nat Geosci 2018;11:551–5.
[69] The Chinese Government. Chinese economic stimulus package is "a smart move at a right time"; 2008 < http://www.gov.cn/ztzl/2008-11/15/content_1150131.htm > . [Chinese Document].
[70] World Wide Fund for Nature and Development Research Center of the State Council. Chinese economy stimulus plan's impact on climate change and energy; 2010 < http://www.wwfchina.org/content/press/publication/Stimuluspackagereport_CN.pdf > . [Chinese Document].
[71] Li L, Chen C, Xie S, Huang C, Cheng Z, Wang H, et al. Energy demand and carbon emissions under different development scenarios for Shanghai. China. Energy Policy 2010;38:4797–807.
[72] Liu Z, Geng Y, Lindner S, Guan D. Uncovering China's greenhouse gas emission from regional and sectoral perspectives. Energy 2012;45:1059–68.
[73] Cole MA, Elliott RJR, Shanshan WU. Industrial activity and the environment in China: an industry-level analysis. China Econ Rev 2008;19:393–408.
[74] Panayotou T. Demystifying the environmental Kuznets curve: turning a black box into a policy tool. Environ Dev Econ 2001;2:465–84.
[75] Fisher-Vanden K, Jefferson GH, Ma J, Xu J. Technology development and energy productivity in China. Energy Econ 2006;28:690–705.
[76] Xinhua. Angang steel company reduced scale for acceleration, but where should the redundant employees go; 2016 < http://www.xinhuanet.com//finance/2016-09/19/c_129287116.htm > . [Chinese Document].
[77] Statistical Bureau of Daxinganling. Daxinganling statistical yearbook. Beijing, China: China Statistics Press; 2016.
[78] Daxinganling Government. Analysis report on population in Daxinganling; 2019 < http://www.dxal.gov.cn/publicity_xsfzhggwykw/zdxx/2934 > . [Chinese Document].
[79] Daxinganling Government. Ban on deforestation for commercial purposes of key state-owned forest areas in Heilongjiang province; 2014 < http://www.dxal.gov.cn/xwdt/xayw/content_39206 > . [Chinese Document].
[80] Statistical Bureau of Shanghai. Shanghai statistical yearbook. Beijing, China: China Statistics Press; 2004. p. 2016.
[81] Xuzhou Statistical Information Net. Analysis of economic situation of Xuzhou in 2012; 2013 < http://tj.xz.gov.cn/TJJ/fxdy/20130207/006_5fb5c9fc-daab-4ee0-8f7a-a1d6f041e451.htm > . [Chinese Document].
[82] Jackson RB, Canadell JG, Le Quéré C, Andrew RM, Korsbakken JI, Peters GP, et al. Reaching peak emissions. Nat Clim Change 2015;6:7–10.
[83] Peters GP, Andrew RM, Canadell JG, Fuss S, Jackson RB, Korsbakken JI, et al. Key indicators to track current progress and future ambition of the Paris Agreement. Nat Clim Change 2017;7:118–22.
[84] Seto KC, Davis SJ, Mitchell RB, Stokes EC, Unruh G, Ürge-Vorsatz D. Carbon lock-in: types, causes, and policy implications. Annu Rev Environ Resour 2016;41:425–52.