CLUSTER ANALYSIS OF CARBON EMISSION PEAKING TRENDS IN CHINA

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ABSTRACT

China proposed a 2060 carbon neutrality target in 2020 and proposed to accelerate the implementation of the 2030 national carbon peaking mandate. Considering the important mission and great potential of cities in national carbon reduction efforts, as well as the significant differences in their carbon emissions in terms of total volume, structure and trends, an in-depth understanding of the typological characteristics of China's urban carbon peaking trends is important for local governments to design and carry out differentiated peaking actions. In this paper, the static and dynamic factors influencing urban peak carbon trends are considered, and the K-means clustering algorithm is used to classify and analyze the peak trends of 286 sample cities in China. The results show that Chinese cities can be classified into five categories. Finally, the paper makes practical suggestions on the design of targets and action priorities for urban carbon peaking for different types of cities.

BIOGRAPHICAL SKETCH

Tianyi Nie is currently in his 3rd year of study in the Regional Science Program at Cornell University. In May 2023, he will graduate with a Master of Science degree, with a focus in city carbon emissions. In the past years, Mr. Nie had an interdisciplinary background, including geographic information system, economics and computer science. He established a 3D model based on digital elevation model to simulate the water supply and consumption of Mount Lu area. Also, he used convolutional neural network to recognized the ship target in Landsat remote sensing images. In big data area, he analyzed human mobility patterns by extracting and visualizing individual trajectories and comparing the similarity among Space-Time Prisms from millions of floating cars' data. These experiences provider him with valuable experience and insight into GIS, big data mining and machine-learning algorithms.

Outside of academics, Tianyi is also involved in university activities. He worked as a volunteer for 2 years, including telling movie story to blind people, taking care of lonely old man and disabled people, going to the countryside to give some educational lecture etc. He also took part in the Go club for 1 year and attend the game actively.

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First and foremost, I would like to express my deep and sincere gratitude to my committee member, Professor John Carruthers and Professor Nicholas Klein, for teaching me basic concept of regional science and providing invaluable guidance throughout my master thesis. Their patience, vision and sincerity have deeply inspired me. He has taught me the methodology to carry out the research and to present the research works as clearly as possible. It was a great privilege and honor to work and study under their guidance.

I am extremely grateful to my parents for their love, caring and sacrifices for educating and preparing me for my future. I am also very much thankful to my wife her love, understanding and continuing support to complete this research work.

It would have been the hardest year in my life. I suffered the most severe trouble that I would remember forever. Luckily, my parents, wife, committee member and friends stayed with me and helped me to fight against the trouble. Finally, I would give my thanks to all the people who have supported me to get over the trouble and complete the research work.

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PREFACE

In China’s statement at the General Debate of the 75th Session of the United Nations General Assembly, President Xi announced that China will scale up its Intended Nationally Determined Contributions by adopting more vigorous policies, measures and aims to have CO_2 emissions peak before 2030 and achieve carbon neutrality before 2060. Thus, accelerating the implementation of the National Carbon Peaking Action Plan has become a key task to promote high-quality economic development under the leadership of China's carbon neutrality target. Cities are the main source of energy consumption and greenhouse gas emissions in China, contributing to 85% of the country's direct carbon emissions. At the same time, cities are also the center of action for the implementation of various policies on energy efficiency, energy transition and environmental protection. Therefore, there is an urgent need for governments to accelerate the development of carbon peaking programs and carry out peaking actions to help China achieve its carbon peaking and carbon neutral goals.

Now, there exist significant difference in Chinese cities’ carbon emission due to the population, industrial structure and resource storage etc., which leads to the difference in major emission source, including energy production emission, industrial emission or service industry emission. There is huge difference in the speed, intensity and quality of reaching carbon emission peak in Chinese cites.

Considering the significant differences in the characteristics of urban carbon emissions in China, the design and implementation of urban carbon peaking initiatives should be carried out differently. This paper uses 286 cities in China as a sample, takes into account various static and dynamic factors affecting urban emission trends, and uses cluster analysis to classify and analyze urban carbon peaking trends. Through in-depth analysis of the characteristics of urban peaking trends in China, this paper provides a reference basis for local governments to design peaking routes and define peaking targets and key tasks according to local conditions.

CHAPTER 1

Literature review

As is shown in the past, urban carbon emissions are influenced by multi-dimensional factors. The important features concentrate on economy, technology, geography and policies, which not only make difference inside the city, but also have potential effects to upstream and downstream city emission. Among all factors, most research has focused on economy in previous articles. For example, the relationship between the level of economic development and carbon emission abides by Kuznets curve theory, similar to the level of urbanization, which is shown like an inverted U-curve.[1-2] Population and city carbon emission follows certain superlinear or sublinear relationship, which reflects to different urban form.[3-5] Also, compact city theory indicated that increasing population density will influence the city carbon emission by decreasing per capita living space, changing means of transportation and increasing the efficiency of energy utilization.[4,6] In terms of technical level, according to the former research, energy intensity, scientific research funding and foreign direct investment (FDI) has impact on city carbon emission by making difference in technical innovation and industrial clustering.[7-9] For geographical factor, the location, climate, transportation and land use will influence city carbon emission in a broad way. According to Zhang's research, citizens' energy consumption and choice of transportation will be influenced by the average amount of rainfall and average temperature, which finally influence city carbon emission.[10-12] Liu et al. point out that the emission efficiency in compact city is higher thus result in lower carbon emission level.[13] For policies, the low-carbon city pilot scheme increased the efficiency of carbon emission incredibly by optimizing the industrial structure, increasing energy efficiency etc.[14] According to Zheng's research, China's most carbon emissions are attributed to urban economic activities and can be decomposed into scale, composition and technique effects. Scale effects lead to increasing in carbon emissions and techniques decrease carbon emissions. The composition effects leads to increasing CO2 emissions in the third-tier cities, while it reduces CO2 emissions in the first and second-tier cities.

Based on the factors mentioned above, researches have been conducted on city classification and distinguished different emission reduction strategy by different urban characteristics. Two major methodologies on this problem are based on single factor and based on combined factors. For example, Auffhammer et al. divided 287 Chinese cities into 3 tiers and decomposed the industrial carbon emission to scale effect, structure effect and technology effect. He also studied the difference in contribution of reduction on carbon emission among 3 tiers cities.[15] Ramaswami divided 285 Chinese cities into industrial cities, business cities and mixed economy cities, based on which he analyzed the ratio among population, GDP and energy consumption in different cities.[16] Shan et al. divided 182 Chinese cities into 5 groups by the industrial production ratio of energy production, heavy industry, light industry and high-tech industry. The research named 5 groups as energy production cities, heavy manufacturing cities, light manufacturing cities, high-tech cities and service-based cities. For each of them, Shan et al. made specific suggestions on emission reduction according to the different features.[17] As a whole, the previous researches focused more on one single factor related to the city carbon emission and tended to ignore other factors that also made difference in this problem.

The previous research mainly adopted machine learning methods, like clustering analysis and classification tree, to study combined factors that influence the city classification. For example, Saldivar-Sali sampled and classified 155 cities from world according to climate, GDP, population and population density into 15 groups of energy consumption based on classification tree model and analyzed the resource consumption in different groups.[18] Hu et al. divided the energy consumption structure of 144 countries and district into 4 different type using K-means clustering algorithm and evolutionary trees model.[19] Yet, recent researches mostly focused on global level, and only few researches have been conducted on Chinese cities. Furthermore, classification for Chinese cities based on carbon peak view has not been studied much as well.

CHAPTER 2

Methodology

2.1 Indicators selection and data source

In view of the availability and consistency of data, we exclude Hongkong, Macau, Taiwan and autonomous prefectures. After data preprocessing, the final dataset consists of 286 Chinese cities, which take up 84% of Chinese national prefectural-level divisions.

The construction of evaluating indicator system should satisfy the scientific, systematic, comparable, and eligible characters. All related factors that influence the carbon emission and trend of peaking should be included in the system. Based on the past researches, secondary industry predominates the source of carbon emission and economy, population, urbanization and the resource intensity play important roles in regional carbon emission as well. Thus, we select population, level of economic development, industrial structure, energy consumption intensity and level of urbanization as the static indicators that affect the carbon emission. The details of indicators selections in each aspect are listed below.

a. **Population.** More population leads to the increase of energy demand, then increasing carbon emission caused by energy consumption. We select the population at the end of the year to represent the population scale of a city.

b. **Economy.** Development of economy requires the investment and consumption of energy. With the change of economic development level, the carbon emission level will go up at first and then fall after the turning point according to Environmental Kuznets Curve. We select GDP per capita to represent the level of economic development of a city.

c. **Energy consumption intensity.** Higher energy consumption intensity contributes to more carbon emission. In view of the lack of related energy consumption data, we select the annual electricity consumption over GDP to represent the energy consumption intensity.

d. **Industrial structure.** The burning of fossil resource by the second industry, especially high energy consumption industry, is an important source of city carbon emission. We select the secondary industry as percentage to GDP to represent the industrial structure of a city.

e. **Urbanization.** In the process of urbanization, the city expansion will promote the infrastructure development (e.g., house and transportation) and influence the carbon source and sink level, which impact the carbon emission eventually.

The main source of above-mentioned social and economic data is China City Statistical Yearbook in 2020 (Table 1).

Table 1. Clustering Indicators Selection

Category	Indicator	Data	Year
Static Indicators	Population	Annual average population	2020
	Economy	GDP per capita	2020
	Industrial Structure	Second industry as percentage to GDP	2020

	Energy Consumption	Annual electricity consumption/GDP	2020
	Urbanization	Constructed area as percentage to urban area	2020
	Carbon Emission	Carbon emission per capita	2020
Dynamic Indicators	Population Growth	Percentage of population growth	2019-2020
	GDP Growth	Percentage of GDP growth	2019-2020

2.2 K-means clustering

Clustering is a technical method for data mining and is widely used in regional classification. Cluster analysis is the process of obtaining the optimal division based on the similarity or distance of given sample features in an unsupervised state, which ultimately results in the maximum similarity of samples within a group and high heterogeneity of samples between groups. Currently, there are many different branches of cluster analysis algorithms, including hierarchical clustering, fuzzy clustering, systematic clustering and K-means clustering. In this paper, we choose the most commonly used K-means clustering algorithm to cluster the carbon peak trends of cities. The algorithm iteratively divides the samples into K classes such that each sample is closest to the center or mean of the class to which it belongs, thus obtaining K hierarchical classes.

First, in order to eliminate the influence of different metrics, all clustering metrics are standardized to form the sample set $X = \{x_1, x_2, \cdots x_n\}$ .Secondly, K sample points are randomly selected as the initial clustering centers, and then the distance from each sample to the class center is calculated and each sample is assigned to the nearest central class, which constitutes the initial clustering result. Again, the mean value of the samples in each class is calculated as the new class center, and the above steps are repeated until convergence. It should be noted that this paper uses the Euclidean distance squared to express the distance or similarity between samples, see equation (1).

$$d\left(x_i, x_j\right) = \sum_{k=1}^{m}(x_{ki} - x_{kj})^2 = \sum_{k=1}^{m}\left\|x_{ki} - x_{kj}\right\|^2 \quad (1)$$

CHAPTER 3

The features of carbon peaking trends

According to the Silhouette score, inertia and Calinski Harabasz score, the recommended number of clusters is 5. After the K-means clustering, the peaking trends of Chinese cities can be classified as 5 categories approximately (Table 2). The first type of cities can be summarized as “Potential Low-carbon City”, including 115 cities, which mainly distributes in middle-west of China. The second category can be summarized as “Model Low-Carbon City”, including 28 prefectural-level cities mainly composited by 4 municipalities and capitals of coastal provinces. The third category is summarized as "Population Loss City", including 62 prefecture-level cities, mainly located in the northeast of China, Guangxi and Gansu provinces. The fourth category is called “Resource Dependent City”, including 7 cities. The fifth category can be summarized as “Traditional Industrial City”, which includes 74 cities and distribute mainly in Hebei, Shanxi, Anhui and Henan.

Table 2. Results of K-means Clustering of Carbon Peaking Trends

Category	Count	Share of Carbon Emission	Share of Low Carbon Pilot City
Potential Low-carbon City	115	31.5%	38.4%
Model Low-Carbon City	28	18.9%	24.7%

Population Loss City	62	15.3%	16.4%
Resource Dependent City	7	3.1%	1.4%
Traditional Industrial City	74	31.3%	19.2%

From the view of overall characteristics potential low-carbon cities and traditional industrial cities have the highest share of total carbon emission in the country, which are 31.5% and 31.3% separately. These two categories of cities are the main point when China tries to implement the Carbon Peaking policy before 2030. Potential low-carbon cities and model low-carbon cities have the highest share of total low-carbon pilot cities, which takes 38.4% and 24.7% separately.

In order to figure out the features of different clusters of cities, we select 6 indicators (Annual average population, GDP per capita, second industry as percentage to GDP, energy consumption, urbanization, carbon emission per capita) to analyze 5 categories of cities. The following part will discuss the features and carbon peaking suggestion for each cluster specifically.

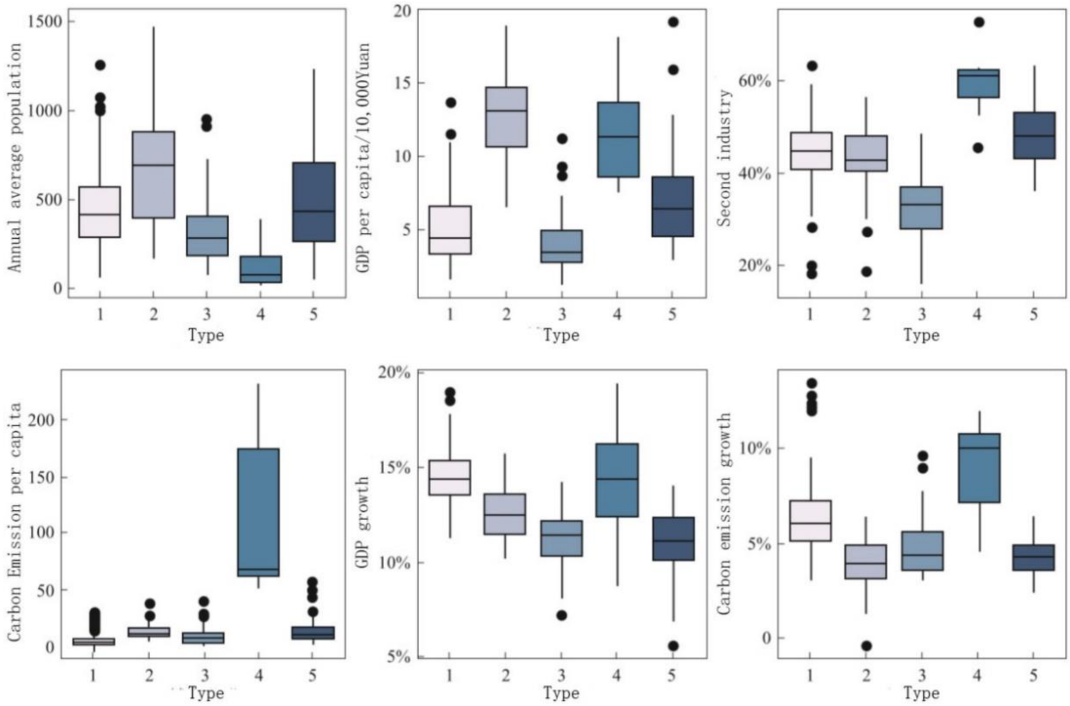

Figure 1. Features of Different Categories of Cities

Table 3. Indicator Range in Different Categories of Cities

Indicator/Category	Potential Low-carbon City	Model Low-Carbon City	Population Loss City	Resource Dependent City	Traditional Industrial City
Annual population /10,000	455.62 (61~1259)	829.64 (177~3404)	319.56 (78~952)	129.86 (21~384)	501.86 (45~1238)
GDP per capita /10,000 Yuan	5.14 (1.6~13.69)	12.8 (6.59~18.96)	3.98 (1.27~11.25)	11.65 (7.54~18.15)	6.98 (2.92~19.19)
Second Industrial Percentage	44.37% (18.27%~63.31%)	42.1% (18.63%~56.5%)	32.49% (15.75%~48.68%)	59.6% (45.61%~72.9%)	48.28% (36.01%~63.31%)
Carbon Emission per capita/t	6.23 (0.97~30.14)	14.16 (4.39~37.92)	9.9 (1.09~40.06)	117.7 (51.8~232.26)	13.63 (1.75~57.8)
Population Growth	0.73% (-2.23%~10.26%)	1.54% (0.51%~7.32%)	0.14% (-0.96%~1.65%)	1.14% (0.19%~2.56%)	0.76% (-0.55%~6.16%)

GDP Growth	14.63% (11.30%~18.96%)	12.7% (10.16%~15.71%)	11.22% (7.21%~14.27%)	14.28% (8.65%~19.49%)	11.08% (5.57%~14.14%)
Carbon Emission Growth	6.28% (3.02%~13.46%)	3.79% (-0.46%~6.37%)	4.8% (2.98%~9.62%)	8.88% (4.5%~11.95%)	4.21% (2.29%~6.41)

3.1 Potential Low-carbon City

The first category of city can be summarized as "potential low-carbon city" (e.g., Guiyang, Kunming, Changsha etc.). According to the Figure and Table 3, it is shown that such type of city has a large population and downstream level GDP per capita with an average of 514,000 Yuan. The second industry to percentage of GDP is about 44.37%, which is a good industry structure. Also, the population growth rate, GDP growth rate are leading in China and carbon emission ranked lowest in total 5 categories. With a rapid economic growth, the carbon emission still remains in a low level. It fully reflects its development model of economic growth driven by low-carbon industries. Guiyang, for example, with its unique natural geographical advantages, has been building an ecological civilization around the big data industry and has ranked first in economic growth in China's provincial capitals (autonomous regions' capitals) for six consecutive years since 2012, and is one of the representative cities of potential low-carbon cities.

Since the economic development of these cities is still in the accelerating stage, carbon emission is still increasing and the two have not yet shown signs of decoupling, it is expected that the carbon emission of these cities will continue to rise during “the 14th Five-Year Plan” period and gradually reach the peak in 2026-2029. It is recommended that the carbon peak target for these cities be set during 2026-2029. In addition, since these cities are at the early stage of industrialization and urbanization, they should avoid the traditional industrialization path of "polluting first and treating later" and focus on the layout of a low-carbon industrial system when planning and implementing their peaking policy. Specific measures include: (1) Introduce innovative low-carbon industrial technologies, establish market-oriented low-carbon mechanisms and encourage the development of strategic new industries; (2) Focus on low-carbon urban planning and the application of energy-saving building renovation technologies in urban construction.

3.2 Model Low-carbon City

The second group of cities is summarized as "Model Low-carbon City", represented by Beijing, Shanghai, Tianjin, Guangzhou, Shenzhen, Nanjing, and Hangzhou. According to Figure and Table 3, cities in this category have the largest population and the economic development level is significantly higher than the national average (the average GDP per capita is 128,000 Yuan). The share of secondary industry is about 42.1%, and the industrial structure is dominated by the service industry. Due to their leading position in terms of administrative level, human resources, science and technology, and management policies, these cities are the key cities with net population inflow, with an average annual population growth rate of 1.54% and a large and steadily growing economy. Compared with cities except the fourth category, they have the lowest carbon emissions growth in China, with an average annual growth rate of 3.79%, although their current per capita carbon emissions are still relatively high.

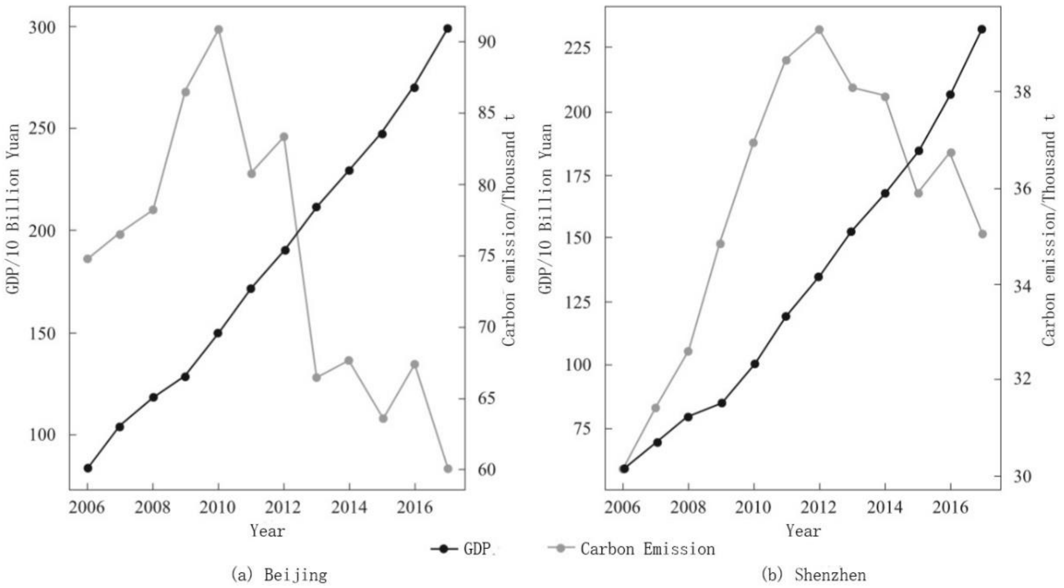

Figure 2. GDP and carbon emission change in two cities

Since "the 11th Five-Year Plan", the economic development of these cities has been decoupled from carbon emissions (e.g., Beijing and Shenzhen in Figure 2) or is in the process of decoupling. It is expected that the carbon emissions of these cities will continue to decline during "the 14th Five-Year Plan" period and reach the peak of carbon emissions by the beginning of "the 14th Five-Year Plan". It is recommended that the peaking target for this category of cities be set for 2020-2022. Since the energy supply of this category of cities mainly relies on foreign transfers, the low-carbon transformation of industrial structure has been basically completed, and the task of carbon emission reduction on the consumption side is more challenging, when implementing the peaking plan, governments should vigorously lead the low-carbon transformation on the consumption side, and take the lead in exploring the path of deep decarbonization with the goal of carbon neutrality. They should also actively build a new peak demonstration area to provide a model for other cities to achieve peak emissions. Specific measures include: (1) Promote low-carbon consumption lifestyles in architecture and transportation; (2) Accelerate the exploration of market-oriented low-carbon mechanisms, including carbon emissions trading and carbon finance, etc.

3.3 Population Loss City

The third category of cities is the "Population Loss City", represented by Fushun, Hohhot, and Tianshui. According to Figure 1 and Table 3, the most distinctive feature of this group of cities is their small population and slowest population growth (0.14% per year on average). Most of the cities have experienced continuous urban shrinkage over the past decade or so, and have experienced serious population loss. The current industrial structure of cities is in the late industrialization stage (32.49% of secondary industry on average) due to the lagging transformation or decline of traditional industries. In addition, the economic development of these cities is relatively backward, and with the loss of employment, the economic growth is significantly lower than that of other types of cities, showing a trend of slowdown or contraction. Compared with other types of cities, the per capita carbon emissions of these cities are relatively low and the growth of carbon emissions is also slow.

At present, the economy and carbon emission of these cities still show a slow growth trend, so it is expected that the carbon emission of these cities will continue to rise slowly at the beginning of “the 14th Five-Year Plan”, and then peak at the end of “the 14th Five-Year Plan”. It is recommended that the peak target for these cities be set at 2023-2025. Due to the structural crisis contraction, shrinkage of less developed cities and shrinkage of remote border cities, there are difficulties in industrial transformation and upgrading, serious employment loss and sluggish economic growth. These cities should focus on coordinating low-carbon development with economic growth and employment when planning and implementing the peak. Specific measures include: (1) Plan low-carbon development from the perspective of optimizing the spatial layout of the city and revitalize the stock of assets and facilities; (2) Find focused industries, eliminate backward production capacity and improve resource utilization efficiency.

3.4 Resource Dependent City

The fourth category of cities is "Resource Dependent City", including Erdos, Wuhai, Karamay, Yulin, Shizuishan, Yinchuan and Jiayuguan. Among them, Erdos, Wuhai, Yulin and Shizuishan are typical coal industrial bases in China, with coal industry as the leading industry. The city of Karamay is an important oil city in China, and is an important city for energy supply to the outside. According to Figure 1 and Table 3, the most distinctive feature of these cities is that they have the smallest population size but a more developed economy (GDP per capita of 116,500 Yuan). The current industrial structure of these cities is dominated by the secondary industry, accounting for 59.6% of the total, and the economic development has maintained a stable growth. Due to the long-term high energy consumption development model, the per capita carbon emissions of these cities are much higher than the national average (117.7 tons per capita), and the growth of carbon emissions has always been fast.

Since the current economic development and carbon emissions of these cities are still showing a slow growth trend, and the two have not yet shown signs of decoupling, it is expected that carbon emissions of these cities will continue to rise during “the 14th Five-Year Plan”, and then reach the peak of carbon emissions during “the 15th Five-Year Plan”. It is recommended that the peaking target for these cities be set at 2026-2029. Due to the long-term dependence on resource extraction and processing industries with high energy consumption and low output value, the situation of low-carbon transformation of energy supply is severe, and some cities (such as Shizuishan and Wuhai, which have been listed as resource depleted cities in China) have seen their leading industries shrink, so these cities should focus on improving the efficiency of resource use and building a diversified industrial system when planning and implementing the carbon emission peaking policy. Specific measures include: (1) Guide the scaling and intensive development of resources and improve the level of resource conservation and comprehensive utilization; (2) Renovate and upgrading traditional resource-based industries, develop green mining, cultivate successive alternative industries and accelerate the development of modern service industries.

3.5 Traditional Industrial City

The fifth group of cities is summarized as "Traditional Industrial City", represented by Xingtai, Handan, Baoding, Baotou, Lianyungang, Wenzhou, and Daqing etc. This category includes most of the heavy industrial cities in Hebei Province and northeast of China, which focus on steel and chemical industries, and some light industrial cities in the Yangtze River Delta, which focus on textile, garment and electronics industries. According to Figure and Table 3, the distinctive feature of these cities is their large population size, and their current economic development is in the middle and upper reaches of the country. The heavy industrial structure (48.28%) and the dependence of economic development on traditional industries directly lead to the relatively high per capita carbon emissions of these cities. The economic development of these cities is still on the rise, and although the industrial structure adjustment has to a certain extent restricted the high economic growth, the initial carbon emission reduction effect has been achieved, and the growth of carbon emission is relatively slow. Given that these cities have not yet shown signs of decoupling between carbon emissions and economic growth, and that there is still much room for adjustment and transformation of industrial structure, it is expected that their carbon emissions will still maintain an upward trend during “the 14th Five-Year Plan” and “the 15th Five-Year Plan”. It is suggested that the target for these cities to reach the peak is set at 2030. Since these cities are in the late stage of industrialization and the industrial structure has been basically formed, they should actively use low-carbon technology to transform and upgrade traditional industries and eliminate backward production capacity when planning and implementing the peaking plan. Specifically, we should: (1) Make effective use of low-carbon industrial technology and recycling technology; (2) Guide the transformation of industrial structure to low-carbon strategic emerging industries, such as high-end equipment manufacturing, new materials and modern service industry.

CHAPTER 4

Conclusion

Cities are the key to achieving China's carbon peaking and carbon neutral goals. Due to the socio-economic, technological, physical and cultural dimensions, there is a wide gap in the total amount, structure and progress of carbon emissions in different cities in China. In this context, the design and implementation of urban carbon peaking initiatives need to be differentiated. An important prerequisite for this task is an in-depth understanding of the typological characteristics of carbon emission peaking trends in Chinese cities. This paper uses cluster analysis to classify and analyze the carbon peaking trends of 286 sample cities in China, and provides scientific suggestions for the design of peaking targets and action priorities for different types of cities.

In terms of the trend of carbon peak attainment, Chinese cities can be classified into five types: potential low-carbon cities, model low-carbon cities, population loss cities, resource dependent cities, and traditional industrial cities. For cities with rapid economic growth and industrial structures that are not yet dependent on the heavy industry path, they should plan to establish a low-carbon industrial system and develop an innovative green economy; for cities with effective supply-side reforms and leading progress in the low-carbon transformation of industrial structures, they should accelerate the exploration of carbon-neutral paths, build new peak demonstration zones, and lead the low-carbon transformation of the consumption side. For cities with population loss and economic downward pressure, they should coordinate the relationship between low-carbon development and economic growth and employment; for cities that are resource-dependent and face certain growth difficulties, they should improve the efficiency of resource use and build a diversified industrial system; for cities that rely on traditional industries and are in the transition period of industrial structure, they should actively use low-carbon technologies to transform and upgrade traditional industries and For cities that rely on traditional industries and are in the process of industrial restructuring, they should actively use low-carbon technologies to transform and upgrade traditional industries and accelerate the elimination of backward production capacity.

REFERENCE

[1] WANG H K, LU X, DENG Y, et al. China's CO2 peak before 2030 implied from characteristics and growth of cities[J]. Nature sustainability, 2019, 2(8): 748-754.

[2] XU Q, DONG Y X, YANG R. Urbanization impact on carbon emissions in the Pearl River Delta region: Kuznets curve relationships[J]. Journal of cleaner production, 2018, 180: 514523.

[3] FRAGKIAS M, LOBO J, STRUMSKY D, et al. Does size matter? Scaling of CO2 emissions and U.S. urban areas[J]. PLoS one, 2013, 8(6): e64727.

[4] RIBEIRO H V, RYBSKI D, KROPP J P. Effects of changing population or density on urban carbon dioxide emissions[J]. Nature communications, 2019, 10(1): 3204.

[5] ZHANG C G, TAN Z. The relationships between population factors and China's carbon emissions: Does population aging matter?[J]. Renewable and sustainable energy reviews, 2016, 65: 1018-1025.

[6] WABG M S, MADDEN M, LIU X J. Exploring the relationship between urban forms and CO2 emissions in 104 Chinese Cities[J]. Journal of urban planning and development, 2017, 143(4): 04017014.

[7] KENNEDY C, STEINBERGER J, GASSON B, et al. Greenhouse gas emissions from global cities[J]. Environmental science & technology, 2009, 43(19): 7297-7302. [8] RAMASWAMI A, TONG K K, FANG A, et al. Urban cross-sector actions for carbon mitigation with local health co-benefits in China[J]. Nature climate change, 2017, 7(10): 736-742.

[9] ZHENG H T, HU J, WANG S S, et al. Examining the influencing factors of CO2 emissions at city level via panel quantile regression: evidence from 102 Chinese cities[J]. Applied economics, 2019, 51(35): 3906-3919.

[10] SONG W Z, ZHANG X L, AN K X, et al. Quantifying the spillover elasticities of urban built environment configurations on the adjacent traffic CO2 emissions in mainland China[J]. Applied energy, 2021, 283: 116271.

[11] CREUTZIG F, BAIOCCHI G, BIERKANDT R, et al. Global typology of urban energy use and potentials for an urbanization mitigation wedge[J]. Proceedings of the national academy of sciences of the United States of America, 2015, 112(20): 6283-6288.

[12] BAIOCCHI G, CREUTZIG F, MINX J, et al. A spatial typology of human settlements and their CO2 emissions in England[J]. Global environmental change, 2015, 34: 13-21.

[13] LIU X J, WANG M S, QIANG W, et al. Urban form, shrinking cities, and residential carbon emissions: evidence from Chinese city-regions[J]. Applied energy, 2020, 261: 114409.

[14] FU Y, HE C Y, LUO L. Does the low-carbon city policy make a difference? Empirical evidence of the pilot scheme in China with DEA and PSM-DID[J]. Ecological indicators, 2021, 122: 107238.

[15] AUFFHAMMER M, SUN W Z, WU J F, et al. The decomposition and dynamics of industrial carbon dioxide emissions for 287 Chinese cities in 1998-2009[J]. Journal of economic surveys, 2016, 30(3): 460-481.

[16] RAMASWAMI A, JIANG D Q, TONG K K, et al. Impact of the economic structure of cities on urban scaling factors: implications for urban material and energy flows in China[J]. Journal of industrial ecology, 2018, 22(2): 392-405.

[17] SHAN Y L, FANG S, CAI B F, et al. Chinese cities exhibit varying degrees of decoupling of economic growth and CO2 emissions between 2005 and 2015[J]. One earth, 2021, 4(1): 124-134.

[18] SALDIVAR-SALI A N D. A Global Typology of Cities: Classification Tree Analysis of Urban Resource Consumption[D]. Cambridge: Massachusetts Institute of Technology, 2010.

[19] HU Y, PENG L, LI X, et al. A novel evolution tree for analyzing the global energy consumption structure[J]. Energy, 2018, 147: 1177-1187.