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Cluster analysis of city-level carbon mitigation in South Korea

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[Abstract]

The phenomenon of climate change is deteriorating which increased heatwaves, typhoons and heavy snowfalls in recent years. Followed by the 25th United nations framework convention on climate change(COP25), the world countries have achieved a consensus on achieving carbon neutrality. City plays a crucial role in achieving carbon mitigation as well as economic development. Considering economic and environmental factors, we selected 63 cities in South Korea to analyze carbon emission situation by Elbow method and K-means clustering algorithm. The results reflected that cities in South Korea can be categorized into 6 clusters, which are technology-intensive cities, light-manufacturing intensive cities, central-innovation intensive cities, heavy-manufacturing intensive cities, service-intensive cities, rural and household-intensive cities. Specific suggestions are provided to improve city-level carbon mitigation development.

▸ **Key words**: climate change, CO_2 emission, carbon neutrality, K-means cluster, city-level

[요 약]

최근 지구온난화로 인한 폭염, 태풍, 폭설 등 기후변화를 급증하고 있다. 미국 뉴욕에서 개최된 제 25차 '기후변화 당사국총회(COP25)'에 따른 세계 각국은 '탄소중립' 달성하기 위한 협상을 진행했다. 도시는 경제발전뿐만 아니라 탄소중립 과정에서도 중요한 역할을 수행한다. 본 연구는 이산화탄소와 관계되는 경제요인 및 환경요인을 고려하여 엘보우 규칙 (Elbow method) 과 K-means 군집 알고리즘을 활용하여 한국 63개 도시의 탄소배출 현황을 분석하였다. 연구결과에 따른 한국 도시는 기술집약 도시, 경공업 도시, 미래 혁신도시, 중공업 도시, 서비스 집약도시 및 농촌, 가정생산집약도시로 구분될 수 있고 향후 시도별 탄소중립 목표를 실천하기 위해 구체적인 제안을 제시하였다.

▸ **주제어**: 기후변화, 이산화탄소배출, 탄소중립, K-means 군집분석, 시도별

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I. Introduction

Climate deterioration is changing the world, which increased heatwaves, typhoons and heavy snowfalls. Recognizing the urgency issue, policy makers need specific information on relationship with climate change and carbon emission. The UN climate change conference (COP25) presented the pathways to reduce global net emissions by approximately 45% from 2010 levels to 2030 and achieve net zero emissions around 2050. South Korea has finalized its policy road maps to achieve carbon neutrality by 2050, which focus on limiting the consumption of coal and liquefied natural gas (LNG) for power generation.

Urbanization plays a significant role in driving economic growth. It serves as a connection for industrialization, investment attraction and economic productivity while also contribute to large percentage of emissions. Effective urban planning and sustainable development practices are crucial for environmental challenges. Carbon-neutral cities, also referred to zero-carbon cities or climate-neutral cities, have become increasingly important in the global effort to achieve carbon mitigation. The goal of carbon-neutral city is to balance the amount of carbon dioxide (CO_2) emissions it produces with an equivalent amount of CO_2 removal or offsetting.

South Korea is actively engaged in the "Carbon Neutral Green City Project" to strengthen the capacity of local governments in addressing climate change. The project involves the joint efforts of the Ministry of Environment and the Ministry of Land, Infrastructure and Transport in order to monitor and regulate energy consumption and national CO_2 emissions at city level. In 2022, the Korea Ministry of Environment selected Suwon and Chungju as recipients of the "Carbon Neutral Green City Project", which aims to establish a system for implementing zero-carbon emissions and enhance energy efficiency. The project has been allocated a budget of 400 billion Korean Won, with 240 billion Won (60%) provided by the central government and an additional 160 billion Won (40%) contributed by the local governments.

Currently, the analysis related to carbon neutrality primarily focused on international trends and policy directions. Limited research was conducted at city level due to data accessibility. Compared with national and provincial CO_2 emissions, data supporting city-level emission inventories are also insufficient and often of lower quality. As a result, this study select 63 cities from 2016 to 2022 to explore the city-level carbon-mitigation situation in South Korea. By analyzing the specific characteristics and trends of CO_2 emission in different cities, the study aims to identify effective strategies and provide suggestions for sustainable and carbon-neutral development.

II. Literature Review

Previous research has indicated that carbon emissions are influenced by multiple factors, including economic level, population, technology, natural geography and policies, among which economic levels have been widely discussed. The Environmental Kuznets Curve (EKC) illustrated the relationship with economic level and environmental degradation and has been validated by numerous scholars across different contexts. Adebayo [9] conducted a re-examination of the relationship between gross capital formation, economic growth, urbanization, CO_2 emissions and energy use in South Korea by using time series analysis. The findings revealed that CO_2 emissions have the positive relationship with economic growth. In order to promote sustainable energy sources and improve environmental development, it is crucial to change energy mix in South Korea. Kim [4] conducted a study to examine the decoupling effect between greenhouse gas (GHG) emissions and economic development. The findings revealed that fossil fuel dependence is important for increasing short-term volatility and breaking the causal link between GHG emissions and GDP growth.

Other scholars analyzed different factors to explain carbon emissions. Zhang [7] conducted a study to explore the impact of population on carbon emissions by using STIRPAT model. The study reflected the impact of population aging on carbon emissions varied across different regions. Kennedy [3] conducted an analysis of 10 global cities and demonstrated how the metabolism and emissions of a city are strongly influenced by geophysical factors such as climate, resources and population. Zheng [6] indicated that GDP per capita positively influence carbon emissions, mainly due to the development of household consumption. Urbanization, on the other hand, had a decreasing positive effect on carbon emissions, which suggest that urbanization process may contribute to more efficient resource use. Fu [10] analyzed the effectiveness of policy interventions in reducing carbon emissions and the findings demonstrated that the implemented policies improved the overall carbon emission efficiency.

In contrast to traditional research approaches, some studies focus on conducting CO_2 emission analyses based on different urban characteristics. Auffhammer [8] conducted an analysis of city-level industrial carbon dioxide emissions growth from scale, composition and technique. The study revealed how cities exhibit behaviors diverse under the industrial carbon dioxide emissions. Ramaswami [2] selected new models and apply cross-sectoral strategies for CO_2 mitigation based on 637 Chinese cities. Shan [12] selected 294 Chinese cities and examined the extent to which economic growth has decoupled from emissions between 2005 and 2015.

Generally, existing literature on urban carbon emissions predominantly focused on examining the impact of single factors, often neglecting the comprehensive consideration of city-level characteristics. Recently some studies have employed tree algorithms, such as decision trees or classification and regression trees (CART), as well as clustering algorithms to analyze this issue. Saldivar-Sali [1] conducted a study focusing on 155 globally cities to establish a model that examines the relationship between climate, city GDP, population, population density and levels of resource consumption. Hu [11] categorized 144 countries and regions to analyze the evolution of global energy consumption structure by using an evolution tree model. Creutzig [5] analyzed 274 cities to demonstrates that economic activity, transport costs, geographic factors and urban form can explain 37% of urban direct energy use and 88% of urban transport energy use.

However, the existing literature primarily focused on CO_2 emission situations among global countries while paying limited attention on South Korea's city-level analysis. Additionally, most studies mainly explained carbon emission reasons from selected key sectors, like population or economic level. Thus, the contributions of this study are as follows.

First, this is the first study to analyze CO_2 emission in South Korea under city-level. A total of 63 cities were selected to examine their energy consumption structure and carbon emission situation. Second, this study employed cluster algorithms to provide valuable insights into the diverse characteristics and patterns of carbon emissions across different cities.

The content of this study is organized as follows: Section 3 provides a detailed description and analysis of the city-level carbon emissions situation in South Korea. Section 4 describes the variables, explains the data resources and principles of cluster algorithm. Elbow method was also applied to enhance the robustness of the findings. Section 5 analyzes city-level carbon emission characteristics under six clusters and provide some suggestions. Section 6 makes conclusions.

III. City-level carbon emission inventories in South Korea

CO_2 emissions in South Korea have more than doubled since 1990. When analyzing it by sectors from Figure 1, it is evident that 55% of carbon emission were generated from electricity and heat while 16% were originated from transport sector. More specifically, emissions from transport sector (including rail, land, water, and air transport) were primarily attributed from land transport activities. On the other hand, emissions from industrial processes, agriculture and waste accounted for 13%, 2.2% and 1.4% of total amount separately. Additionally, land-use change and forestry contributed -6% of carbon emissions.

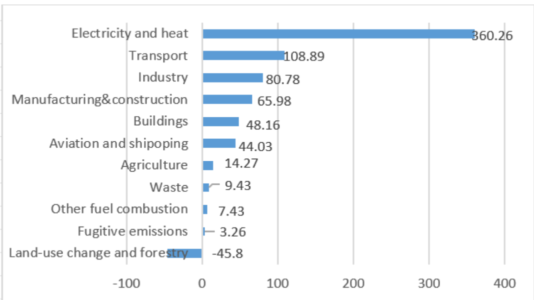

Fig. 1. Carbon emission by sectors in 2020
(unit: million tons)

The urbanization rate in South Korea covered more than 90% in 2022, which has led to a significant increase in urban population, causing depopulation in many rural areas. More than four-fifths of the population is classified as urban, with approximately half of the population residing in country's seven metropolitan cities. Th total 85 cities in South Korea can be categorized into one central metropolitan city(Seoul), six metropolitan cities (Busan, Daegu, Incheon, Gwangju, Daejeon, Ulsan), one special self-Governing city(Sejong) and municipal-level autonomous entities, which are organized under the jurisdiction of provinces and play important roles in regional development and governance.

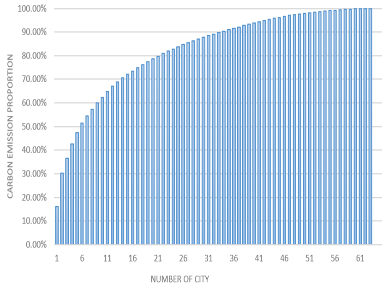

Fig. 2. Urban carbon emission ratio in 2020

The characteristics of carbon emissions among cities vary significantly due to urban development, population size and resource endowment. According to Figure 2, top 13% of cities in South Korea contribute 60% of the total carbon emission nationwide in 2020. The detailed distribution structure of city-level carbon emissions can be visualized in Figure 3.

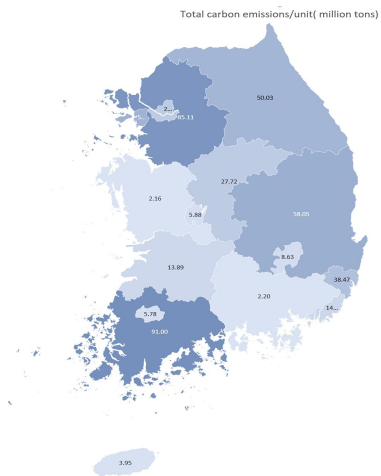

Fig. 3. City-level carbon emission distribution in 2020

IV. Methodology and data

1. K-means cluster algorithm

Clustering is a mechanism used to group data points based on their similarities. By applying a clustering algorithm, we can categorize data points into specific clusters or groups and the goal is to collect the same cluster exhibit within similar characteristics. One commonly used clustering algorithm is the K-means algorithm, which is an unsupervised learning method employed for statistical data analysis in various fields.

Before conducting the analysis, it is important to consider centroid-based algorithms, where each cluster is represented by a centroid. The primary objective of these algorithms is to minimize the total distance between data points and respective cluster centroids. The algorithm takes the unlabeled dataset as input, divides it into a predetermined number of clusters (k), and iteratively refines the clusters until an optimal solution is obtained. The k value, representing the number of clusters, needs to be predetermined for this algorithm.

For more in detail, here we are given a training set $x = [x_1, x_2, ... x_n]^T$ and define Euclidean norm as $|x| = \left[\sum_{i=1}^{n} x_i^2\right]^{1/2}$ The K-means algorithm can be analyzed by the following steps:

Step 1. Define the K number of clusters in which we will group the data.

Step 2. Initializing centroids is a crucial step. Since the exact center of the data points is initially unknown, random data points are typically selected and defined as the initial centroids for each cluster.

Step 3. After centroids are initialized, data X_n are grouped to their closest cluster C_k. The distance between a data point and a centroid is typically measured using the Euclidean distance metric in equation (1).

$$|x - z| = \left[\sum_{i=1}^{n} (x_i - z_i)^2\right]^{1/2} \tag{1}$$

Step 4. Re-initialize the centroids by calculating average of all data and the metrics are shown in equation (2). Step 3 and step 4 should be repeated until a stopping criterion is met.

$$Ci = \frac{1}{|\ni|} \Sigma x_i \tag{2}$$

Step 5. K-means clustering algorithm is highly dependent on the quality of the clusters it forms. Elbow method is a popular way and WCSS value (Within cluster sum of squares) is applied as well, which defines the total variations within a cluster. The formula of WCSS is expressed in equation.

$$WCSS = \Sigma_{P_{i \in cluster1}} distance(P_i C_1)^2 + \Sigma_{P_{i \in cluster2}} distance(P_i C_2)^2 + ... + \Sigma_{P_{i \in cluster n}} distance(P_i C_n)^2$$

(3)

where $\Sigma_{P_{i \in cluster1}} distance\ (P_i C_1)^2$ is the sum of the square of the distances between each data point and its centroid within a cluster 1 and the same for the other terms.

In the Elbow method, the cluster number (K) is varied from 1 to a predefined maximum value, typically up to 10. For each value, WCSS is calculated, which represents the sum of the squared distances between each data point and its centroid within a cluster.

The optimal number of clusters is typically determined at the elbow point. It represents the value of K where the additional improvement gained by adding more clusters is minimal compared to the complexity introduced. The elbow point signifies a balance between capturing meaningful patterns in the data and avoiding overfitting or excessive fragmentation.

2. Data resource

In this study, the term "city" refers to metropolitan cities and local governments, including units within administrative divisions. Due to data availability and limitations, certain municipal cities and counties were excluded. Based on statistics, our analysis focus on 63 Korean cities at the prefectural level. In 2020 the total GRDP (Gross Regional Domestic Product) of 63 cities amounted to 12,657.45 trillion won, accounting for 90% of the country. The collective population of 63 cities reached 44.54 million, representing 86% of the entire population. It is concluded that 63 cities are geographically distributed and economically developed in a way that reflects the overall characteristics of South Korea. The data related to economy and production were obtained from the Korean Statistical Information Service (KOSIS).

Meanwhile, the Greenhouse Gas Inventory and Research Center (GIR) first published South Korea's city-level CO_2 emission indicators at 2022, which covering the period from 2016 to 2020.

The main factors influencing carbon emission performance vary depending on the economy, energy consumption, transportation, infrastructure and technology. Considering the correlations and the complexity of indicator design, panel data is created and the representative factors are summarized in Table 1.

Table 1. Carbon emission indicators

Indicator	Definition	Data Source	Year
Population	Total population (unit: million)	KOSIS	2016-2020
Economic level	Gross regional domestic product (GRDP) (unit: trillion won)	KOSIS	2016-2020
Industrial structure	Manufacturing output (unit: trillion won)	KOSIS	2016-2020
Energy consumption	Electric consumption (unit:MWh)	KOSIS	2016-2020
Transportation /infrastructure	Total vehicle registrations	KOSIS	2016-2020
Co2 emission	Total Co2 emissions (unit:million tons)	GIR	2016-2020

Population. Rapid population growth often accompanies urbanization and the expansion of cities, which lead to an increasingly energy needs. Urban areas with larger populations tend to exhibit higher energy consumption, transportation demands, and infrastructure requirements. In this study, city annual population is selected as a variable to elucidate its population size and its implications for carbon emissions.

Economic level. Economic indicators are closely linked to both output and carbon emissions. According to EKC, environmental pressures tend to increase during the initial stages of income growth and industrialization but eventually decline after reaching a certain level of economic development. In this study, the city-level Gross Regional Domestic Product (GRDP) is chosen as an economic development indicator to evaluate the overall production of goods and services within a specific time period.

Industrial structure. As we known, certain industrial sectors, such as energy production, manufacturing and transportation are generally more carbon-intensive due to their heavy reliance on fossil fuels. In this study, city-level manufacturing output is chosen to analyze the impact on carbon emissions.

Energy consumption. Energy consumption, particularly in electricity generation, heating, and transportation, is directly associated with higher carbon emissions. Due to data limitations, this study uses annual electricity consumption as a proxy to represent the intensity of energy consumption at city level.

Transportation. The expansion of cities leads to the development of transportation and infrastructure construction. The combustion of fossil fuels in cars, trucks, ships, and airplanes, the fuel efficiency of the transportation system and the type of fuel used have a significant impact on the level of carbon emissions. In our study, annual amount of newly registered vehicles is chosen as a proxy to represent the transportation sector.

CO_2 emission. The CO_2 emission proxy represents a specific numerical measurement that quantifies the amount of carbon dioxide (CO_2) emissions attributed to a country, region or industry. The variable plays a critical role in assessing and monitoring environmental impacts, analyzing climate change trends and formulating policies and strategies for carbon management and mitigation. In our study, the emission amounts are examined to demonstrate the environmental issues in different cities.

V. City-level carbon mitigation clustering result

In this study, the initialization point in K-means clustering algorithm was determined by elbow method. The stability of the clustering results was

Table 2. K-means cluster analysis result

Cluster/Number	City Characteristics	Cities	City Ratio of total
Type 1/n=6	Technology-intensive cities	Daegu, Daejeon, Busan, Seongnam, Suwon, Yongin	9%
Type 2/n=7	Light-manf intensive cities	Gwangju Metropolitan City, Gumi, Ansan, Changwon, Cheonan, Cheongju, Pyeongtaek.	11%
Type 3/n=1	Central-innovation intensive city	Seoul	1.6%
Type 4/n=3	Heavy-manf intensive cities	Ulsan, Incheon, Hwaseong	4.7%
Type 5/n=16	Service intensive cities	Jeju Island, Geoje, Gyeongju, Goyang, Gunsan, Gimpo, Gimhae, Bucheon, Siheung, Anseong, Anyang, Yeosu, Icheon, Jeonju, Paju, Pohang	25%
Type 6/n=30	Rural/household intensive cities	Gangneung, Gyeongsan, Gyeongju, Gongju, Gwacheon, Gwangmyeong, Guri, Gunpo, Namyangju, Donghae, Mokpo, Mungyeong, Miryang, Sacheon, Sejong, Sokcho, Andong, Yeongju, Osan, Wonju, Uiwang, Iksan, Jecheon, Jinju, Chuncheon, Chungju, Tongyeong, Pocheon, Hanam.	47.6%

Table 3. The summary statistics for city-level analysis

Indicator	Technology-intensive cities	Light-manf intensive cities	Central-innovation intensive city	Heavy-manf intensive cities	Service intensive cities	Rural/household intensive cities
Population/unit: million	176.20 (91.76)	79.67 (33.81)	979.02 (10.42)	161.89 (98.84)	47.55 (23.62)	20.24 (12.63)
GRDP/trillion won	49.38 (19.91)	32.49 (5.41)	418.28 (22.27)	76.95 (7.91)	16.19 (4.74)	5.40 (2.60)
Manufacturing output/trillion won	20.08 (9.76)	43.02 (9.72)	30.25 (1.77)	123.02 (48.94)	11.83 (7.54)	3.43 (2.73)
Electricity consumption/MWH	10.97 (5.64)	9.52 (1.31)	46.39 (1.13)	25.13 (6.54)	4.92 (2.46)	1.53 (0.83)
Trasportation	252.03 (62.28)	167.11 (49.58)	281.2 (15.81)	197 (29.89)	110.93 (38.16)	115.21 (40.73)
Co2emission／million tons	8.29 (4.14)	5.90 (2.13)	22.62 (1.19)	38.78 (23)	4.44 (5.05)	2.05 (2.99)

notice: the number present the mean value of the variables, while the () below the number show the SD of the variables.

evaluated by randomly selecting 1000 initial points. The clustering process, along with the within-cluster sum of squares (WCSS), was calculated by Python 3.11.

Based on Elbow Method and Silhouette Coefficient, the city-level carbon emission situation in South Korea can be broadly classified into six clusters [Table 2].

When analyzing the mean values and standard deviations (SDs) of CO_2 emission intensity, additional findings can be made. Table 3 presents a summary of variables across the six city clusters. It reveals that the average CO_2 emission intensity is 8.29 million tons in technology-intensive cities, 5.90 million tons in light-manufacturing intensive cities, 22.62 million tons in central-innovation intensive city, 38.78 million tons in heavy-manufacturing intensive cities, 4.44 million tons in service intensive cities, and 2.05 million tons in rural/household intensive cities seperately.

Among six city groups, it is observed that the heavy manufacturing intensive cities have the highest CO_2 average emission intensity, while the rural/household intensive cities present the lowest. The z-test of mean values reveals that the average emission intensities of the service and light-manufacturing intensive cities are significantly lower than those of Seoul and heavy manufacturing intensive cities. Furthermore, the average emission intensity of technology intensive cities is also significantly low.

The variation in CO_2 emission intensity can be attributed to their economic structures. Figure 4 shows the city-level characteristics under six clusters and Figure 5 illustrates the decoupling effect between economic performance and emissions. According to Figure 4 and 5, we can analyze the results as follows.

Type 1. Technology-intensive cities

The technology-intensive cluster consisting of Daegu, Daejeon, Busan, Seongnam, Suwon, and Yongin in Gyeonggi-do represents a rapidly developing economy with a strong emphasis on technology and innovation. These cities, characterized by larger population sizes and higher economic growth rates, present a relatively higher proportion of carbon emissions but also demonstrate a decreasing annual growth rate. A strong decoupling effect between economic growth and CO_2 emissions since 2018 is reflected.

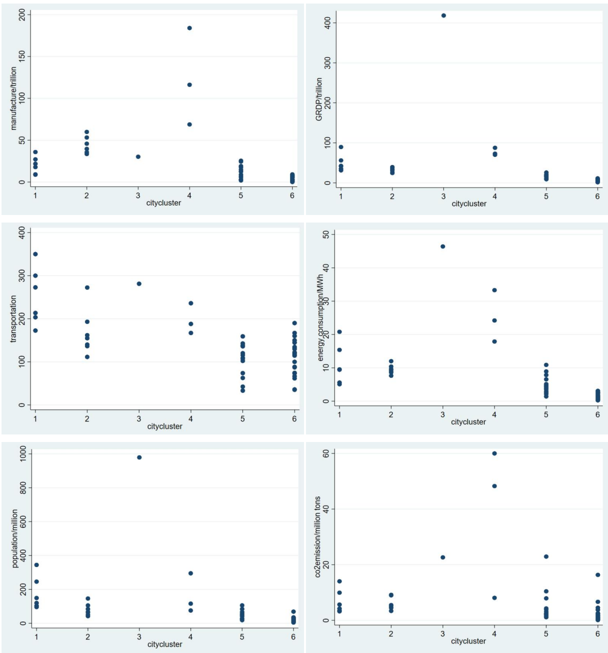

Fig. 4. Characteristics of city clusters

Type 2. Light-manufacturing intensive cities

Type 2 cities are characterized by a significant presence of both manufacturing and service industries, which is recognized as light-manufacturing intensive cluster. The primary industries focus on information and communication technology, semiconductor manufacturing, robotics engineering and renewable energy.

The results show that type 2 cities have a relatively larger proportion of industrial output and energy consumption while also tend to have a higher proportion of carbon emissions. However, the decoupling effect is fluctuating during past years. As a result, it is important to promote policies related to renewable energy transition and energy efficiency measures such as solar, wind and hydro power. Additionally, implementing energy efficiency measures across various sectors such as buildings and transportation should also be encouraged.

Type 3. Central-innovation intensive city

Seoul, as the capital city of South Korea, has a diverse and dynamic economic structure that includes finance, manufacturing, technology, retail and services. According to Figure 4, Seoul has the highest population and Gross Regional Domestic Product (GRDP) among six city clusters and its carbon emissions account for 6.3% of the total. In particular, the city's dense population and extensive transportation networks result in high levels of vehicle usage and associated emissions. Compared with the others, Seoul faces significant pressure from consumption side. The future efforts should be suggested on promoting low-carbon consumption lifestyles, particularly in buildings and transportation sectors. Furthermore, the exploration of market-driven low-carbon mechanisms, such as carbon emissions, trading and carbon finance should also be encouraged.

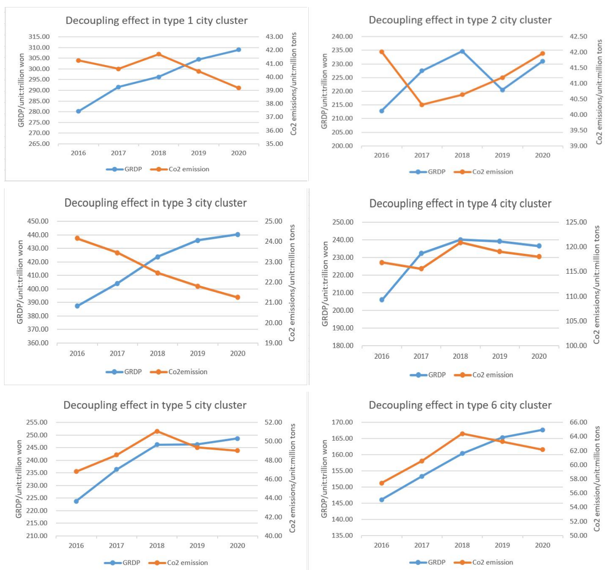

Fig. 5. Decoupling effect in six city clusters

Type 4. Heavy-manufacturing intensive cities

Type 4 cities, which are represented by Ulsan, Incheon and Hwaseong can be classified as heavy manufacturing cities with larger population size and relatively higher economic levels. The manufacturing industry plays a significant role, accounting for 48.28% of economic structure while also contribute to the highest carbon emission level. Figure 5 shows that the decoupling effect in type 4 is not significant and it is crucial to promote adjustments and transformations in industrial structure. Specific measures are provided which include (1)effective utilization of low-carbon industrial technology and recycling techniques. (2)guiding the industrial structure towards low-carbon strategic emerging industries, such as high-end manufacturing industries, new materials and service industries.

Type 5. Service-intensive cities

Type 5 city cluster represents the national average level in terms of population, industrial added value and energy consumption. The cities have a relatively lower proportion of industrial output, with service sector playing a prominent role. Consequently, carbon emissions in these cities are relatively lower and the decoupling effect was achieved after 2019. Take Jeju Island as an example, traditionally the island's unique natural beauty and cultural attractions make it famous for service industry. Recently, Jeju Island also strives towards promoting clean energy sources such as solar power and wind power as well as the development of renewable energy, EV, smart grids and microgrids.

Type 6. Rural and household intensive cities

Based on figure 4, type 6 cities are characterized by their small population size and lower economic performance, which exhibit an average annual growth rate of only 0.14%. Most cities have faced ongoing urban contraction over the past decades, resulting in significant population outflow issues. The primary industries in these cities focused on agricultural products and household industries, with a smaller proportion in the secondary industry. Due to structural crises, shrinkage of declining industries and the outflow of the working-age population, these cities have experienced relatively slower economic development as well as the lowest carbon emission level. As a result, it is crucial to prioritize the coordination between low-carbon development, economic growth, and employment by optimizing urban spatial development and maximizing the utilization of existing resources.

VI. Conclusions

This study applied cluster analysis to analyze the city-level carbon emission situation in South Korea by using panel data analysis from 2016 to 2020. The results show a strong correlation between carbon emissions and regional economic development. From the overall perspective, city-level carbon emission in South Korea can be divided into six clusters and there are some important policy implications to consider.

Firstly, it is necessary to regulate carbon mitigation policies based on the specific characteristics of each cluster. For heavy industry and resource-dependent cities, it is crucial to utilize low-carbon technologies, transform traditional industries and expedite the phasing out of outdated production capacities. For technology-intensive and light-manufacturing industry cities, it should focus on economic structural adjustments, enhance energy efficiency and increase the proportion of tertiary and high-end industries. For cities experiencing population outflow and economic downturn, efforts should be made to improve the utilization of local wind power, solar energy and other renewable energy sources.

Secondly, it is essential to promote public understanding and awareness of environmental protection and carbon-neutral development. Educational initiatives and lectures should be organized to encourage more individuals to consciously adopt a low-carbon lifestyle.

Additionally, due to data limitation, the study developed only 5-year panel data to analyze the city-level carbon mitigation situation. More research should be developed to disclose the dynamic changes of carbon emissions during different periods and make the comparative analysis in the future.

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