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Towards Carbon-Neutral Cities: Urban Classification Based on Physical Environment and Carbon Emission Characteristics

Jiah Lee and Seunghyun Jung *

Department of Building Research, Korea Institute of Civil Engineering and Building Technology, Goyang-si 10223, Republic of Korea
* Correspondence: shjung@kict.re.kr; Tel.: +82-31-910-0377

Abstract: Cities are highly industrialized and populated areas and major sources of greenhouse gas emissions. For carbon neutrality, examining the correlation between urban characteristics and greenhouse gas emissions is necessary. This study aimed to analyze the characteristics of each city from a carbon neutrality perspective. As such, we conducted a carbon-neutral city analysis. First, the physical environmental variables of 250 municipal, county, and district local governments were collected and constructed and then reduced and purified through factor analysis. Second, the type was derived by performing cluster analysis on the reduced factor variables and carbon emissions by analysis unit. Finally, the characteristics of each type were analyzed, and the carbon-neutral city planning and applicable carbon-neutral technology fields were proposed according to the characteristics. After the categorization of carbon-neutral cities throughout Korea, six cluster types were derived; cities in each cluster had similar characteristics. This study suggests that solutions for carbon reduction should be applied by comprehensively considering the social, economic, and environmental characteristics of each city. It concludes that regional physical environmental indicators and energy consumption statistics can be used comprehensively to establish effective policies and apply technologies and techniques at the local government level.

Keywords: greenhouse gas emission; carbon neutrality; urban planning; carbon reduction; city analysis; energy consumption

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1. Introduction

The global warming caused by the use of fossil fuels has become a major concern for governments worldwide. The challenge of achieving carbon neutrality in cities has attracted significant attention from policymakers, scholars, and practitioners worldwide. The Carbon Neutral Cities Alliance (CNCA) published a framework for action in 2015, which outlines several key strategies for reducing greenhouse gas emissions in cities, including energy efficiency, renewable energy, sustainable transportation, and waste reduction [1]. The Korean government is no exception. The Korean government has taken several steps towards realizing a carbon-neutral society, including enacting the Framework Act on Carbon Neutrality and Green Growth and establishing a roadmap for carbon neutrality. The Korean government's efforts towards carbon neutrality align with the CNCA framework, underscoring the importance of urban policies and plans to reduce greenhouse gas emissions.

However, given that most economic activities generating greenhouse gas emissions occur in cities, it is necessary to prepare measures at the urban level [2]. In particular, as of 2022 in Korea, the urbanization rate—that is, the ratio of the resident population in the urban planning zone to the total population—amounts to 81.4%, which is very high compared to the global urbanization rate of 57.0% [3].

In order to apply policies and technologies to reduce greenhouse gas emissions, it is essential to identify the characteristics of each city first. This is because each city has unique physical and non-physical characteristics, such as size, function, spatial structure, and industrial composition, which affect the type of emissions or absorption [4–11]. Solutions for carbon reduction should be applied by comprehensively considering the social, economic, and environmental characteristics of each city. Therefore, this study aimed to analyze the characteristics of each city in Korea from the perspective of carbon neutrality as a pre-stage of urban planning for carbon neutrality.

In particular, the study comprehensively considered various characteristics of the city. The study intended to include low-carbon emission potential by adding renewable energy source values, as well as characteristics of the city's physical environment, such as regional size, economic industry, land uses, and transportation services. By categorizing all cities in Korea based on their characteristics, this study provides direction for the establishment of urban policies to reduce carbon emissions comprehensively. Ultimately, this study contributes to the broader literature on carbon-neutral cities and provides insights for policymakers, scholars, and practitioners working towards achieving carbon neutrality in cities.

2. Review of Theory and Previous Research

2.1. Carbon Neutrality and Carbon-Neutral City

2.1.1. Concept of Carbon Neutrality

The United Nations defines carbon neutrality as a state in which net emissions offset the amount of greenhouse gas absorbed from that emitted or leaked into the atmosphere and become zero (United Nations, UN) [12]. Carbon neutrality does not impose unconditional carbon emission obligations; however, it refers to a comprehensive concept that defines responsible activities by balancing a measured amount of carbon released with an equivalent amount sequestered or offset. In general, the realization of carbon neutrality is divided into two strategies: reducing carbon emissions and increasing carbon absorption.

Policies have been enforced to increase the effect of carbon neutrality by reducing carbon emissions and increasing absorption sources, as well as actively utilizing carbon-neutrality-related plans and technologies.

2.1.2. The Emergence of Carbon-Neutral Cities and Paradigm Changes

The theories on carbon neutrality emerged from the development of "the countryside city" [13], in the early 20th century, to "the ecological city" that emerged in the mid-1970s. Low-carbon, zero-carbon, and carbon-neutral cities appeared to cope with climate change in the 2000s (Table 1). Recently, in response to the demand for carbon neutrality, a project aiming to build a carbon-neutral city with various similar concepts has been actively promoted worldwide.

While a carbon-neutral city can be defined in various ways, it is conceptualized as one with minimal carbon emissions and corresponding measures against carbon inevitably emitted from the economy, society, and leisure activities, resulting in a "zero" carbon net emission [14]. Broadly, carbon-neutral cities comprise eco-friendly and sustainable green cities aiming for carbon neutrality, cities with energy self-sufficiency, cities that absorb enough carbon because of abundant green infrastructure, and cities that use less fossil energy owing to easy walking and the development of public transportation.

In Korea, the legal definition of a carbon-neutral city (Framework Act on Carbon Neutrality and Green Growth) is a city that spatially implements carbon neutrality by actively utilizing plans and technologies related to carbon neutrality. Therefore, considering various urban emission and absorption factors, such as changes in population and industrial structure, urban decline, extinction, and the new development of transportation and IT technology, the urban concept can be expanded to realize carbon neutrality through space and infrastructure. Another characteristic of carbon-neutral cities is that they intend to mitigate climate change by setting a quantitative target of achieving a carbon-neutral state in their spatial unit.

In urban space, various fields such as energy, buildings, transportation, agriculture, and livestock, as well as absorption sources, are mutually influenced; therefore, an integrated approach is needed to view them as a system [15,16]. The advantage of this urban-centered integrated approach is that it can supplement the limitations of one field in another.

Table 1. Urban paradigms and characteristics related to carbon neutrality.

Urban Paradigm	Key Characteristics	Relationship with Carbon Neutrality
Sanitary reform (1840s)	• Removal of dirt and eradication of diseases, especially cholera • Elimination and disposal of sewage and waste, providing clean water	Importance of physical infrastructure
Garden city (1890s)	• New Town Movement in Low-Density, Car-Based Suburbs in the UK with an emphasis on the importance of nature in urban planning • Cities and villages are adjacent to green areas such as gardens, agriculture, etc.	Urban shape change through planning paradigm
Eco city (1990s)	• Integrated city planning and management leveraging the benefits of ecosystem • Urban planning and design in balance with nature	Reflection on the need to meet global and regional ecological needs
Sustainable city (1990s)	• Reducing resource consumption in cities, reducing dependence on cars, and pursuing economic and social sustainability based on ecology	Urban models enabling global and national sustainability models
Green city (2000s)	• Concepts including carbon reduction, sustainability, etc., in existing sustainable cities (eco-friendly cities) • Conservation of ecosystems, eco-friendly cities, cities that minimize carbon emissions, and the pursuit of sustainable development	Starting from qualitative concepts of being eco-friendly and sustainable to quantitative concepts such as carbon
Smart city (2000s)	• Digital-connected cities that measure, manage, and improve the quality of life and the efficiency of urban activities using information and communication technology	Reduction of energy use through smart systems and integration of local solar and wind systems into cities
Low-carbon city (2000s)	• Separating urban economies and activities from fossil fuel use and emphasizing energy efficiency, renewable energy, and green transportation	The main focus on carbon to be addressed
Carbon-neutral city (2020s)	• Reducing all fossil fuel use in larger categories beyond low-carbon cities and creating urban and regional landscapes with carbon sequestration and cyclical economic strategies • Similar concepts include net-zero-carbon city, zero-carbon city, and zero-emission city	Quantitative target setting for carbon neutrality

Reference: [16] Recertifying and modifying.

Cities around the world are increasingly turning to urban planning to achieve carbon neutrality, and a number of projects are underway to support this goal. The CNCA is a global urban cooperative that supports the development of methodologies, planning, standardization, and governance tools for measuring and improving carbon neutrality in cities [17]. Major eco-friendly cities in Europe, such as Copenhagen and Helsinki, as well as cities with high urbanization rates, such as New York in the United States and London in the United Kingdom, are participating. The Zero Cities Project, launched by the Urban Sustainability Directors Network (USDN) in 2017, is another example of an effort to develop carbon-free building sectors [18].

Meanwhile, the European Union has selected 100 cities to achieve climate neutrality by 2030, and launched the "100 Climate-Neutral Cities by 2030" campaign to support less capable cities. The EU is providing financial support and activity guidelines for cities to prepare and operate visions and roadmaps according to their size and capabilities [19]. In addition, the EU has several other initiatives to promote carbon-neutral urban planning: the initiative named the Covenant of Mayors for Climate and Energy, Smart Cities and Communities, the European Green Capital Award, and the EU's largest program, named Horizon 2020 [20–23].

One additional project worth noting is the C40 Cities Climate Leadership Group, a network of the world's megacities committed to addressing climate change [24]. C40 connects cities with the expertise and resources that they need to take bold climate action, and provides a platform for peer-to-peer sharing and collaborative problem solving. The group has more than 90 member cities worldwide, including Tokyo, Paris, and Los Angeles, and works to implement policies and projects to reduce greenhouse gas emissions and improve air quality.

Overall, these and other urban planning projects are critical in the fight against climate change, as cities are responsible for a significant share of the global carbon emissions. By implementing strategies for achieving carbon neutrality, cities can help to reduce their environmental impact and create more sustainable, livable communities for future generations.

2.2. The Relationship between Carbon Neutrality and the Urban Spatial Structure

Cities are highly industrialized and populated areas that are significant sources of greenhouse gas (GHG) emissions. Reducing GHG emissions is essential for mitigating climate change and achieving carbon neutrality. As such, understanding the correlation between urban characteristics and GHG emissions is crucial for developing effective policies and strategies to reduce emissions in urban areas.

To establish a carbon-neutral city, cities should be categorized based on the discussions regarding the components, functions, and structures of carbon-neutral cities. To analyze and understand cities correctly, attempts have been previously made to classify them according to such criteria as size, function, structure, shape, and location [25–28]. Analyzing and understanding cities in this manner is crucial as it enables the identification of appropriate carbon-neutrality-related projects and technologies based on the unique components and functions of each city. Thus, sustainable standards for zero-energy cities have been raised, and the development of simplified methodological evaluation tools has been required [29,30].

Studies have been conducted in earnest to understand the characteristics of energy consumption by country and city since the 1980s, when urbanization intensified. Early studies were conducted to analyze the energy demands of cities. Owens (1984a, 1984b) compared and analyzed urban change and energy demands (emissions) at the time of rapid urbanization [31,32]. As cities become more complex and diverse, he proved that not only simple land use patterns but also population movement between regions and the resulting increase in employment and economic power had an impact on the energy demand.

Urban form and density are important factors that play a role in GHG emissions. Compact, mixed-use urban areas with good public transportation systems can reduce emissions by encouraging active transportation and reducing car dependency [4,33,34]. Studies have also found that increasing the population density in urban areas can reduce emissions by promoting the efficient use of resources and encouraging sustainable transportation modes [35,36]. Newman and Kenworthy (1989; 2006) used regression analysis to examine the impact of the urban form on emissions in cities in Australia, Canada, and the United States [37,38]. The study found that cities with higher levels of density and mixed land use had lower levels of emissions. Studies by Heinonen and Junnila (2011) also compared and analyzed carbon consumption in the suburbs to the dense metropolitan center [7], deriving urban density as a major factor affecting greenhouse gas emissions. Liu et al. (2017) also explored the impact of the population density, land use mix, and public transportation accessibility on carbon emissions in Chinese cities [39]. The study found that cities with higher levels of population density and land use mix had lower levels of emissions.

One of the most active scholars, Frank (2000), analyzed how land use and vehicle traffic characteristics relate to automobile exhaust, a major factor in carbon emissions in Seattle [4]. As a result, he proved that population density and employment density, which are the main measurements of land use variables, have positive (+) relationships with exhaust gas. More specifically, his 2006 study demonstrated the influence of factors such as the residential density, number of intersections, and commercial areas on land characteristics [5]. Xia et al. (2018) proved that changing land use characteristics from agriculture to industry negatively affect carbon neutrality [9]. This is consistent with the findings of Gao et al. (2019) that urban green spaces such as parks and gardens can improve the air quality and reduce emissions by isolating carbon dioxide [40].

Transportation is also a key factor that influences GHG emissions in urban areas. Studies have consistently shown that cities with high levels of car dependency have higher levels of GHG emissions compared to cities with well-developed public transportation systems [41,42]. Mavroeidi et al. (2013) examined the impact of transportation mode choice on emissions in European cities [43]. The study found that cities with higher levels of public transportation use and cycling had lower levels of emissions. In a study by Dou et al. (2016), access to transportation facilities was noted as a key strategy for low-carbon urban planning [9]. Another study by Zhou et al. (2017) used regression analysis to explore the relationship between the transportation mode share, population density, and carbon emissions in Chinese cities [44]. The study found that cities with higher levels of public transportation use and population density had lower levels of carbon emissions. Liu et al. (2022) analyzed the relationship between carbon emissions and comprehensive urban environmental variables such as urban density, transportation network, industrial structure, and location [11].

Studies discussing greenhouse gas reduction based on the shape and use of buildings in cities have also emerged [32,33]. Buildings account for a significant portion of GHG emissions in urban areas, and energy-efficient buildings have been identified as an effective means to reduce emissions [45–48]. Studies have found that improvements in building design and materials, such as insulation, lighting, and ventilation systems, can significantly reduce energy consumption and emissions [49,50]. Building codes and standards that mandate energy efficiency measures have also been shown to be effective in reducing GHG emissions in urban areas [51]. The studies by Du et al. (2018) and Wang et al. (2020) used regression analysis to explore the impact of building energy efficiency on carbon emissions in Chinese cities and the United States [52,53]. The studies found that cities with more energy-efficient buildings had lower levels of emissions.

These previous research works suggest that transportation, building energy consumption, and urban form and density are important factors to consider when attempting to reduce GHG emissions in urban areas. Policies and strategies that promote sustainable transportation modes, energy-efficient buildings, and compact, mixed-use urban areas can effectively reduce emissions. In summary, the physical environment of cities plays a crucial role in carbon emissions, and urban design and planning are essential to achieving carbon neutrality. However, more research is needed to identify the most effective strategies and tools for carbon-neutral urban development. To support urban planning for carbon neutrality, this study categorizes cities based on their unique characteristics and greenhouse gas emissions. The results contribute to the development of targeted policy alternatives for achieving carbon-neutral cities.

3. Methodology

Previous studies on energy consumption analysis have been conducted mainly in a single city or a few specific cities, and there is a limit when viewing the various environments of the city comprehensively by analyzing some variables such as transportation and land use. Therefore, to reflect the characteristics of each city in the carbon-neutral city plan, cities should be categorized using variables that are more specific. As such, this study conducts a carbon-neutral city analysis. Consequently, regional physical environmental indicators and energy consumption statistics can be used comprehensively to establish effective policies and apply technologies and techniques at the local government level.

3.1. Cities to Be Analyzed

The spatial scope of the analysis included all 250 local governments in Korea.

The temporal range was set to 2019, when the statistics on carbon emissions and regional characteristic indicators obtained simultaneously in all regions analyzed were established.

For 2019's carbon emissions, the 2019 energy supply and demand statistics issued by the KESIS National Energy Statistics Comprehensive Information System were used as shown in Figure 1, and for regional characteristic indicators, the 2019 statistics of local governments were used [34]. KESIS's energy supply and demand statistics for cities, counties, and districts are used for preparing annual energy statistics and providing energy statistics necessary for regional energy planning and energy supply prospects considering regional characteristics. The main contents include measurements of final energy consumption by city, county, and district, and energy consumption by sector, such as industry, transportation, home, commerce, and public.

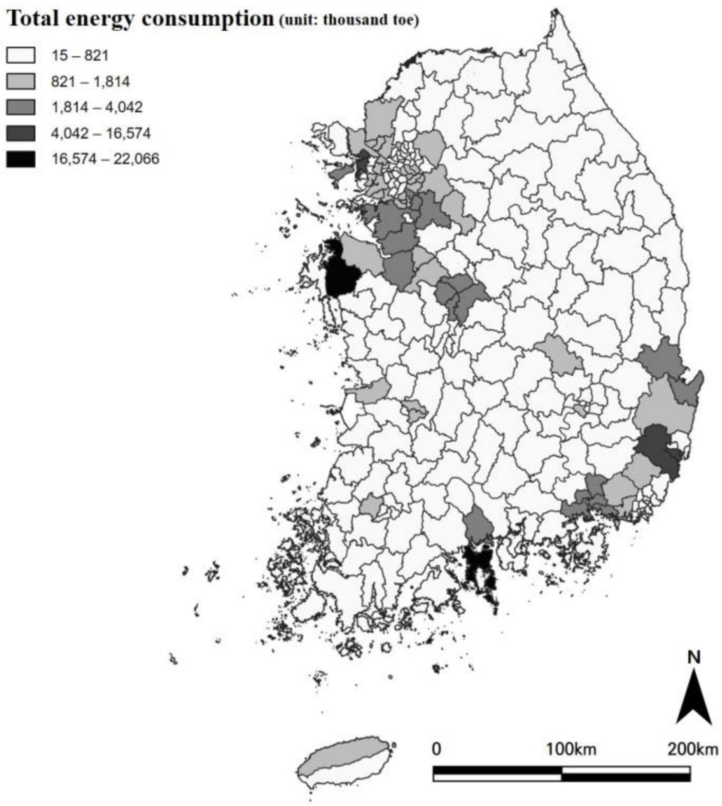

Figure 1. Total energy consumption of local governments nationwide in 2019.

The analysis procedure for the categorization of carbon-neutral cities was as follows. First, after collecting and constructing the physical environmental variables of 250 municipal, county, and district local governments, the analysis variables were reduced and purified through factor analysis.

Second, the type was derived by performing cluster analysis on the reduced factor variables and carbon emissions by analysis unit. Finally, the characteristics of each type were analyzed, and the carbon-neutral city planning and applicable carbon-neutral technology fields were proposed according to the characteristics.

3.2. Variable Construction and Measurement Units

Table 2 describes the analysis variables and measurement methods. First, through a review of the literature on energy production and consumption, variables such as regional size characteristics, economic industry characteristics (economic industry and land use), transportation service characteristics, and production by renewable energy source were derived as urban physical environment variables.

Table 2. Analysis variables and measurement methods.

Statistics Data			Unit (Measurement Time: 2019)	Spatial Scope
Regional Size Characteristics		Population density (per/ha)	Resident registration population/area (ha)	Cities, counties, and districts
		Urban area ratio	Urban area/total area	
		Residential area per person (per/m^2)	Residential area/resident registration population	
Economy Industry Characteristic	Economy Industry	Number of businesses (unit)	-	
		Number of businesses per 1000 people	Number of businesses/resident registration population × 1000	
		Number of manufacturers (unit)	-	
		Financial independence (%)	-	
	Special-Purpose Area	Land use_residential ratio	Residential area/total area	
		Land use_commercial ratio	Commercial area/total area	
		Land use_industrial ratio	Industrial area/total area	
		Land use_green area ratio	Green area/total area	
Traffic Service		Road ratio	Road area/total area	
		Paved road	Paved road (m)	
		Number of cars registered per person (unit)	Number of cars registered/residents registered	
Production Volume by Renewable Energy Sources		Solar power	toe	Cities, provinces
		Photovoltaics	MWh	
		Wind power	MWh	
		Hydropower	MWh	
		Marine power	MWh	
		Geothermal power	toe	
		Hydrothermal energy	toe	
		Fuel cell	MWh	
Energy Consumption Characteristics		Total energy consumption	thousand toe	Cities, counties, and districts
	Industry	Industrial energy consumption		
	Transportation	Transportation sector energy consumption		
	Household	Household energy consumption		
	Commercial Sector	Commercial sector energy consumption		
	Public Sector	Public sector energy consumption		

Population density represents the city size [3,5,7,31–39], and the density is usually measured by dividing the resident registration population by area. In this study, the ratio of urban areas and that of the residential area per capita were added as variables to consider the sizes of urban and non-urban areas, respectively, in the region.

Next, the characteristics of the economic industry were identified through the number of businesses and manufacturers in the region. In addition, the number of businesses per 1000 people was surveyed to determine the degree to which businesses accommodate the population in the region.

Finally, through the fiscal independence measured every year, regional economic and industrial competitiveness was included in the variables. Land use distribution is also used to determine regional economic and industrial characteristics [5,6,10,31,32,40,47,48,51–53]. Therefore, in this study, the ratios of residential, commercial, industrial, and green areas were included as variables and added only to urban areas.

Transportation is the most important and fundamental factor in discussing the characteristics of energy consumption in the region [9,11,41–44]. This study attempted to utilize fixed traffic-related variables (road area ratio, pavement size, and the number of cars registered per person), rather than reflect the characteristics of fluid traffic, because data are collected every year.

Finally, the output of each renewable energy source held by the region was included as a variable. It reflects the concept of carbon neutrality, whereby the sum of carbon emissions and absorption should be zero, in addition to existing carbon emission-related studies that consider only energy consumption and emission sources. Production by renewable energy sources, which is measured and provided as data in Korea, includes solar power, photovoltaics, wind power, hydropower, ocean, geothermal power, and fuel cells. However, although this is limited, the measurement variable is measured at the city and province level, and it was distributed as an average value and used while considering that energy production facilities in Korea are few.

In the case of energy consumption characteristics, energy consumption in cities, counties, and districts was included in the variables by utilizing the regional energy statistics yearbook provided by the KESIS National Energy Statistics Comprehensive Information System [54]. Specifically, total energy consumption by region and consumption by industry, transportation, home, commerce, and public sector were used separately.

4. Results of Categorization Analysis

4.1. Analysis Variable Basic Statistics

Table 3 shows the basic statistics for 28 analysis variables. Overall, the standard deviation of the measurement variable between samples is extreme, and the gap between the maximum and minimum values is wide. This means that the characteristics of cities between regions are diverse, proving that specialized policies and technologies through urban typification are necessary to implement effective carbon-neutral city policies.

Table 3. Analysis variable basic statistics.

Statistics Data		Average	Max	Min	Stv
Regional Size Characteristics	Population density (per/ha)	38.12	263.23	0.19	58.87
	Urban area ratio	0.46	1.00	0.00	0.41
	Residential area per person (per/m^2)	30.92	40.90	23.40	3.41

Table 3. *Cont.*

Statistics Data			Average	Max	Min	Stv
Economy Industry Characteristics	Economy Industry	Number of businesses (unit)	21,369.64	86,643.00	1308.00	19,409.01
		Number of businesses per 1000 people	88.89	476.60	49.90	38.75
		Number of manufacturers (unit)	334.26	4260.00	2.00	492.88
		Financial independence (%)	21.73	68.90	4.00	13.61
	Special-Purpose Area	Land use_residential ratio	21.63	91.50	0.12	15.74
		Land use_commercial ratio	3.06	44.24	0.00	4.88
		Land use_industrial ratio	6.77	51.38	0.00	8.41
		Land use_green area ratio	65.03	92.84	0.00	20.53
Traffic Service		Road ratio	0.05	0.74	0.00	0.08
		Paved road	502,674.04	2,045,533.00	55,276.00	335,497.26
		Number of cars registered per person (unit)	0.51	2.45	0.11	0.22
Production Volume by Renewable Energy Sources		Solar power	2183.77	4023.00	122.00	1241.18
		Photovoltaics	1,114,623.37	2,768,303.00	69,194.00	816,313.91
		Wind power	184,342.43	774,049.00	2.00	286,381.55
		Hydropower	251,147.73	708,305.00	101.00	250,306.44
		Marine power	452,760.97	474,321.00	0.25	98,800.49
		Geothermal power	19,306.90	48,650.00	1771.00	14,078.94
		Hydrothermal energy	2212.53	11,954.00	8.00	3741.24
		Fuel cell	230,104.90	793,295.00	50.00	28,7512.71
Energy Consumption Characteristics		Total energy consumption	965.79	22,066.00	15.00	2367.23
	Industry	Industrial energy consumption	497.68	21,230.00	1.00	2224.91
	Transportation	Transportation sector energy consumption	222.82	2313.00	4.00	277.44
	Household	Household energy consumption	121.29	509.00	3.00	124.29
	Commercial Sector	Commercial sector energy consumption	94.66	534.00	4.00	99.32
	Public Sector	Public sector energy consumption	29.41	419.00	1.00	41.59

4.2. Refining and Reducing Analysis Variables

Based on the interrelationships between the variables related to regional characteristics, variables were reduced through exploratory factor analysis. First, the measured values of all variables were standardized and used. In the first attempt at factor analysis, 22 variables, excluding energy consumption by region, were used to perform Verimax principal component analysis. In the process, the commonality of the land use–industrial ratio variable and the number of automobile registrations per person was 0.3 or less, and the two variables were deleted.

In the next attempt, the remaining 20 variables were input and re-analyzed. Consequently, five factors with an intrinsic value of 1 or more were extracted; they have a 100% cumulative explanatory power for the whole, and the load on each factor is shown in Table 4.

Table 4. Factors extracted by factor analysis and the load on factors.

Names of Factors	Names of Variables	Factor Rotation 1	Factor Rotation 2	Factor Rotation 3	Factor Rotation 4	Factor Rotation 5
Space Size and Land Use Characteristics	Population density	**0.88**	0.01	0.33	0.02	0.01
	Residential area per person	**0.81**	0.19	0.12	0.04	0.35
	Land use_green area ratio	**0.81**	0.02	0.24	0.08	0.09
	Road ratio	**0.65**	0.28	0.08	0.28	0.04
	Land use_residential ratio	**0.58**	0.23	0.38	0.22	0.19
	Urban area ratio	**0.55**	0.14	0.63	0.16	0.07
Economy Industry Characteristics 1	Number of businesses (unit)	0.28	0.27	0.27	**0.79**	0.02
	Paved road (m)	0.25	0.18	0.16	**0.77**	0.09
	Financial independence (%)	0.22	0.52	0.30	**0.60**	0.07
	Number of manufacturers (unit)	0.06	0.33	0.08	**0.70**	0.05
Economy Industry Characteristics 2	Land use_commercial area ratio	0.32	0.01	0.13	0.04	**0.84**
	Number of businesses per 1000 people (unit)	0.04	0.11	0.03	0.03	**0.91**
Region Renewable Energy Production 1	Hydropower	0.44	**0.63**	0.08	0.12	0.09
	Fuel cell	0.26	**0.87**	0.18	0.07	0.11
	Geo-power	0.07	**0.95**	0.11	0.13	0.09
	Marine power	0.03	**0.95**	0.12	0.15	0.09
Region Renewable Energy Production 2	Solar power	0.36	0.26	**0.72**	0.09	0.02
	Photovoltaics	0.27	0.07	**0.84**	0.06	0.13
	Wind power	0.25	0.16	**0.66**	0.11	0.11
	Hydrothermal power	0.04	0.17	**0.76**	0.07	0.18
SS loadings		4.65	3.80	3.27	2.33	1.94
Proportion Explained		0.29	0.24	0.20	0.15	0.12
Cumulative Proportion		0.29	0.53	0.73	0.88	1.00

The first factor comprises variables related to space size and land use characteristics. The characteristics of space size correspond to the population density and residential area per person. The characteristics related to land use correspond to the ratio of urban areas, the ratio of housing and green areas for land use, and the ratio of roads. The second factors are related to the economic industry characteristics and comprise the variables related to absolute figures related to the industry, such as the number of businesses, the number of manufacturers, and the length of paved roads. The third factor comprises variables related to the relative figures related to the ratio of land use commercial areas and the distribution ratio of industries by the number of businesses per 1000 people. The fourth and fifth factors are largely classified into two factors for each type of renewable energy. Solar power, photovoltaics, wind power, and hydrothermal power are divided into relatively generalized renewable energy groups and other groups of hydropower, fuel cell, geo-power, and marine energy.

The above five factors were standardized, converted, and used as regional characteristic variables for urbanization.

4.3. Analysis of Typification of Carbon-Neutral Cities

After standardizing the five regional characteristic variables and the energy consumption characteristic variables of cities and counties derived through factor analysis, cities were categorized by cluster analysis. After adjusting and analyzing the number of clusters, six clusters were found to be the most appropriate within the significance level of 0.01. However, very few cases included in two clusters, Clusters 5 and 6, were derived from three regions and one region. These can be interpreted as representing clusters with minimal cases.

Table 5 shows the regional classification values for each of the six cluster types according to the cluster analysis results. Cluster 1 has 70 cases, including most areas in metropolitan cities. Cluster 2 includes most of the local small and medium-sized cities; therefore, it is the largest case. Cluster 3 includes most of Gyeonggi-do, the metropolitan area. Cluster 4 includes fewer cases among local small and medium-sized cities, similar to Cluster 2. Clusters 5 and 6 have fewer cases and cover three areas, Jung-gu in Seoul, Jung-gu in Busan, and Jung-gu in Daegu, and the latter includes one area in Hwaseong.

Table 5. Types of carbon-neutral cities by region.

Regional Classification *	Cluster Classification					
	Cluster 1 (N = 70)	Cluster 2 (N = 109)	Cluster 3 (N = 41)	Cluster 4 (N = 26)	Cluster 5 (N = 3)	Cluster 6 (N = 1)
Seoul	24	-	-	-	1	-
Busan	15	-	-	-	1	-
Daegu	7	-	-	-	1	-
Incheon	8	2	-	-	-	-
Gwangju	5	-	-	-	-	-
Daejeon	5	-	-	-	-	-
Ulsan	5	-	-	-	-	-
Sejong	1	-	-	-	-	-
Gyeonggi-do	-	-	41	-	-	1 (Hwaseong-si)
Gangwon-do	-	16	-	2	-	-
Chungbuk	-	9	-	5	-	-
Chungnam	-	13	-	3	-	-
Jeonbuk	-	13	-	2	-	-
Jeonnam	-	22	-	-	-	-
Gyeongbuk	-	19	-	5	-	-
Gyeongnam	-	14	-	8	-	-
Jeju	-	1	-	1	-	-

* Representative target site (partial). Cluster 1: (Seoul) Jongno-gu, Yongsan-gu, Seongdong-gu, (Busan) Yeongdo-gu, Suyeong-gu, Gijang-gun, (Daegu) Dong-gu, Seo-gu, (Incheon) Yeonsu-gu, Bupyeong-gu, (Gwangju) Seo-gu, Buk-gu, (Daejeon) Yuseong-gu, Daedeok-gu, Jung-gu, Nam-gu, Ulju-gun, (Sejong) Sejong-si, etc. Cluster 2: (Incheon) Ganghwa-gun, Ongjin-gun, (Gangwon) Gangneung-si, Donghae-si, Hoengseong-gun, (Chungbuk) Jecheon-si, Jeungpyeong-gun, Jincheon-gun, (Chungnam) Boryeong-si, Seosan-si, Dangjin-si, (Jeonbuk) Gunsan-si, Namwon-si, Buan-gun, (Jeonnam) Mokpo-si, Yeosu-si, Gwangyang-si, (Gyeongbuk) Gimcheon-si, Goryeong-gun, Uljin-gun, (Gyeongnam) Jinju-si, Tongyeong-si, and Hamyang-gun, (Jeju), Seogwipo-si, etc. Cluster 3: (Gyeonggi-do) Suwon Gwonseon-gu, Seongnam Bundang-gu, Uijeongbu-si, Anyang Dongan-gu, Bucheon-si, etc. Cluster 4: (Gangwon-do) Chuncheon-si, Wonju-si, (Chungbuk) Cheongju Sangdang-gu, Chungju-si, (Chungnam) Cheonan Dongnam-gu, Asan-si, (Jeonbuk) Jeonju Wansan-gu, (Gyeongbuk) Pohangnam-gu, Gyeongju-si, Gumi-si, (Gyeongnam) Changwon Uijang-gu, Changwon Jinhae-gu, Sacheon-si, Geoje-si, (Jeju) Jeju-si, etc. Cluster 5: (Seoul) Jung-gu, (Busan) Jung-gu, (Daegu) Jung-gu. Cluster 6: (Gyeonggi-do) Hwaseong City.

4.4. Characteristics of Carbon-Neutral Cities by Type

The average values of all statistical data used in the analysis were compared to confirm the characteristics of the Si, Gun, and Gu regions by six clusters derived from the cluster analysis (Table 6). The characteristics of each cluster type were compared with the average value of each variable, and the name of the type was given accordingly (Figure 2).

- Cluster 1 has the following regional characteristics and energy consumption characteristics. It has a high population density in terms of space size and land use, with the highest proportion of residential areas and the lowest proportion of green areas. Conversely, the residential area per capita is relatively low because the population density is very high and the proportion of roads is 0.08, which is high. The economic industry is characterized by areas where manufacturing industries are less distributed and the proportion of paved roads is relatively low. The proportion of commercial areas is high; however, among the six clusters, the number of businesses per 1000 people and financial independence are among the upper–middle ranks. Renewable energy is not produced adjacent to the sea; therefore, there are no marine energy production facilities. The area is considered to have insufficient capacity to produce new and renewable energy as the energy produced by hydropower, geo-power, solar power, photovoltaics, wind power, and hydrothermal power is the lowest. Total energy consumption was found to be in the mid-range—that is, the early 1000 toe range. Consumption was high in the order of industry, transportation, household, commercial, and public sectors, and consumption was found to be moderate compared to other clusters. Based on these characteristics, Type 1 of the carbon-neutral city can be named as a dense residential center type (energy-small and medium-sized cost).
- Cluster 2 has the lowest population density, with a very small urban area ratio of 0.09, and green areas account for the majority. Despite the low ratio of the residential area, the per capita residential area is high because of the small population density. The proportion of roads is 0.01, which is low. The manufacturing industry is the least distributed, and the number of businesses, the ratio of commercial areas to land use, and financial independence are very low; therefore, it appears to be an area with no economic activity. Conversely, the production of new and renewable energy generated by solar power, photovoltaics, wind power, and hydrothermal power is significantly higher than that of other clusters. This may be because solar and wind power generation equipment is furnished while considering small-sized local cities' characteristics of spatial structure and climate. Energy consumption characteristics are the lowest at 600,000 toe, most of which is occupied by the industrial sector. This reflects the characteristics of local cities with a small population as, compared to other regions, the energy consumption in daily activities such as home, transportation, commerce, and the public is insignificant. Based on these characteristics, Type 2 carbon-neutral cities can be named low-density local small cities (low energy consumption).
- Cluster 3 has the following regional characteristics and energy consumption characteristics. The population density is in the middle-class area, comprising a high ratio of urban areas and residential areas, and the green area ratio is the highest. The proportion of roads is 0.08, which is high. In this area, a large number of manufacturers are distributed, and the number of businesses, paved road areas, and financial independence are all high. These regions have high population density and an active economy. Most areas near the metropolitan area have very high hydro-energy production related to new and renewable energy. The production of fuel cells, geo-power, and marine energy is also the highest. Conversely, the energy production of photovoltaics and wind power is low. The total energy consumption is moderate at around 1,000,000 toe. By sector, unlike other clusters, energy consumption in the transportation sector is the highest, followed by home, industry, commerce, and public. Based on these characteristics, Type 3 of the carbon-neutral city can be named the metropolitan area type (energy-small and medium-sized cost).

- Cluster 4 has a low population density, urban area ratio, and residential area ratio, and a low road ratio of 0.03. Conversely, the per capita housing area and green area ratio are high. Manufacturers are most distributed here, and the number of businesses and paved roads is the highest. While the proportion of commercial areas is relatively small, the degree of financial independence and the number of businesses per 1000 are high; therefore, it seems that the manufacturing-oriented industry is outstandingly active. The production of new and renewable hydropower, solar power, photovoltaics, wind power, and hydrothermal power energy is very high, indicating that many energy production facilities are located in the region. The total energy consumption is the highest at 1,800,000 toe. Considering that industries and transportation sectors account for the highest consumption, the area can be considered a transportation hub with substantial traffic and a manufacturing center with active industrial activities. In addition, energy consumption is high in the order of home, commerce, and public. Based on these characteristics, Type 4 of the carbon-neutral city can be viewed as a low-density manufacturing industry terrain (energy high cost).
- Cluster 5 is an overcrowded urban area with a very high proportion of population density, urban area ratio, and residential area for land use; the smallest proportion of green areas; and the highest proportion of roads. It has the lowest distribution of manufacturers, and the smallest proportion of paved roads. Conversely, as the proportion of commercial areas and the number of businesses per 1000 people is the highest, this area has active commercial activities. The production of new and renewable energy is the lowest among all types; accordingly, the production capacity of new and renewable energy is insufficient. Total energy consumption is the lowest at approximately 500,000 toe. By sector, consumption is high in the order of transportation, home, commerce, industry, and public, and consumption is lower than most types except for the commercial sector. Based on these characteristics, Type 5 of carbon-neutral cities is the urban type (low energy consumption).
- Regarding the last type, Cluster 6 has the highest population density. The green area ratio is high, while the residential area ratio is low. Conversely, the ratio of roads is 0.74, which is very high compared to other types. In particular, the manufacturing industry is at least 6 to 42 times higher than in other types. The number of businesses, paved roads, and financial independence is also the highest, and it can be considered a manufacturing-oriented industrial dense area. Compared to other types, the production of hydropower, fuel cells, geo-power, marine power, solar power, and photovoltaics is very high. On the other hand, wind and hydrothermal energy production is low, which seems to be due to the absence of related energy production facilities. Total energy consumption is the highest at 3,314,000 toe. Most energy is consumed in the industrial and transportation sectors, which seems to result from the regional characteristics of manufacturing-specialized areas. In addition, energy consumption is relatively high in the home, commercial, and public sectors. Based on these characteristics, Type 6 of the carbon-neutral city can be called the manufacturing industry specialization type (maximum energy consumption).

Table 6. Cluster analysis results summary and the average values of variables by type of carbon-neutral city.

Variables		Cluster Classification 1 (N = 70)	2 (N = 109)	3 (N = 41)	4 (N = 26)	5 (N = 3)	6 (N = 1)	F-Value (*p*-Value)
Space Size and Land Use Characteristics	Population density (per/ha)	100.07	1.90	37.35	9.68	139.69	151.03	6.175 ($p < 0.001$)
	Urban area ratio	0.92	0.09	0.69	0.37	0.93	0.40	
	Green area ratio	49.59	71.98	74.26	70.11	37.18	75.70	
	Residential area per person (per/m^2)	28.38	33.40	28.74	31.09	27.55	29.30	
	Land use_residential ratio	35.19	14.90	19.79	14.01	44.53	16.66	
	Road ratio	0.08	0.01	0.08	0.03	0.12	0.74	
Economy Industry Characteristics 1	Number of businesses (unit)	25,361.90	6732.57	38,148.12	42,547.35	26,724.71	66,767.00	85.117 ($p < 0.001$)
	Paved road (m)	339,321.64	462,457.59	489,513.98	1,172,214.31	281,173.71	662,864.00	
	Financial independence (%)	23.75	11.79	38.53	28.14	25.28	68.90	
	Number of manufacturers (unit)	287.11	108.60	687.63	726.15	199.32	4260.00	
Economy Industry Characteristics 2	Land use_commercial Ratio	3.87	1.99	2.42	1.89	6.75	1.90	92.677 ($p < 0.001$)
	Number of businesses per 1000 people	84.26	91.51	72.04	85.12	103.25	81.90	
Region Renewable Energy Production 1	Hydropower	6272.94	278,309.36	566,631.00	306,274.04	1157.05	566,631.00	42.346 ($p < 0.001$)
	Fuel cell	218,488.76	68,104.99	793,295.00	21,412.40	262,097.71	793,295.00	
	Geo-power	8441.76	16,331.39	48,650.00	14,908.00	10,086.80	48,650.00	
	Marine power	-	0.25	474,321.00	0.25	262,097.71	793,295.00	
Region Renewable Energy Production 2	Solar power	710.74	2808.93	2696.00	2858.54	757.05	2696.00	7.541 ($p < 0.001$)
	Photovoltaics	173,962.51	1,715,357.38	1,071,664.00	1,305,998.15	196,942.02	1,071,664.00	
	Wind power	5418.84	356,132.54	4834.00	250,205.08	245.49	4834.00	
	Hydrothermal power	60.22	3693.90	8.00	2029.05	23.00	8.00	
Energy Consumption Characteristics *	Total energy consumption	1017.90	686.60	1077.61	1807.00	500.07	3314.00	-
	Industrial energy Consumption	501.20	519.39	217.15	841.00	63.54	1817.00	-
	Transportation sector energy consumption	245.00	90.92	374.61	473.42	157.51	781.00	-
	Household energy consumption	137.27	35.39	244.07	246.12	136.80	335.00	-
	Commercial sector energy consumption	106.19	29.39	189.17	174.50	113.17	342.00	-
	Public sector energy consumption	28.21	11.68	52.41	72.12	28.90	39.00	-

* These variables are not used for cluster analysis.

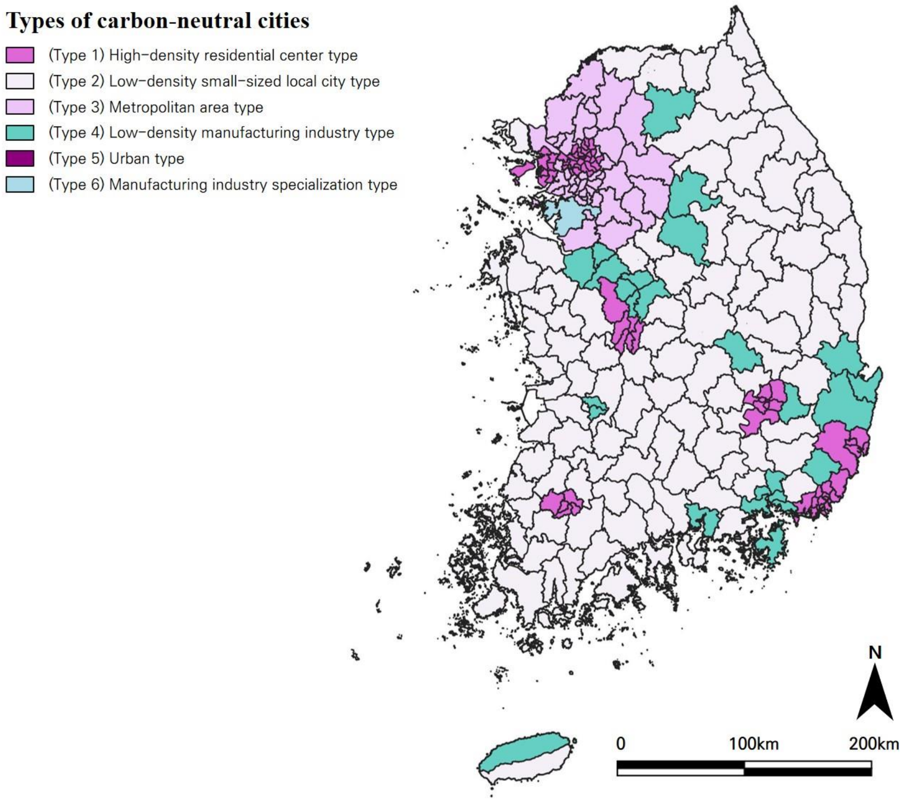

Figure 2. Types of carbon-neutral cities.

5. Discussion and Conclusions

After the categorization of carbon-neutral cities throughout Korea, six cluster types were derived. Cities in each cluster have similar characteristics, and there are many homogeneous factors in greenhouse gas emissions. These results are consistent with the arguments of previous studies that various characteristics of cities and energy consumption characteristics are closely related [4–11,37,38].

In other words, the results suggest that the classification of cluster types by city should be preceded by planning and managing carbon-neutral cities and that policies and technologies related to carbon neutrality need to be applied differently according to the characteristics of the cluster type.

The analysis identified five key planning elements that are central to carbon-neutral urban planning in Korea: transportation (mobility), buildings, energy, absorption sources, and industries. Each planning element has specific characteristics that are related to the physical and non-physical features of a city. The technology in the mobility/transportation sector can be applied mainly to urban areas with high traffic demands and high efficiency due to mobility conversion [9,43,44]. Buildings are easy to apply when constructing and renovating buildings for an entire area [45–48]. Energy can be utilized for information on areas suitable for new and renewable energy production. For example, an energy absorption source can be applied to improve the absorption performance of park areas in established cities. Industry can be applied to the type of industrial manufacturing-centered city with technology dissemination. Accordingly, we propose the following recommendations for each cluster type.

For Type 1 (high-density residential center type), the direction of expanding low-carbon means of transportation in cities through mobility conversion should be considered first, considering the characteristics of regions with high urban activities. Type 2 (low-density local small-town type) is an area where public transportation is not developed compared to large cities, and policies are needed to improve transportation to meet carbon neutrality through its expansion. Conversely, as Type 3 (metropolitan area type) has the characteristics of a bed town outside of Seoul, it is important to establish a policy to convert the means of commuting to the city center from passenger cars to public transportation. As Type 4 (low-density manufacturing industry terrain) and Type 6 (manufacturing industry specialization type) have high energy demands in the industry, the application of renewable energy production technology should be actively considered. Additionally, direct carbon absorption facilities such as Carbon Capture, Utilization, and Storage (CCUS) should be introduced. Type 5 (urban type) is a traditional urban area in Korea; therefore, it will not be easy to secure absorption sources in the city because of the characteristics already developed. Instead, an integrated system such as a Building Energy Management System (BEMS) can be introduced for the energy management of existing commercial buildings. The carbon-neutral performance of the cluster can be improved by increasing the ratio of new and renewable energy when renovating buildings.

In sum, this study demonstrates that key regional characteristic indicators can be derived according to the classification of carbon-neutral cities, and related policies can be promoted around them. Our findings have important implications for policymakers and practitioners involved in carbon-neutral urban planning, highlighting the need to apply policies and technologies differently based on the characteristics of each cluster type. By adopting an efficient approach to carbon neutrality planning, cities in Korea can achieve sustainable and effective reductions in greenhouse gas emissions. This study identified the major variables that affect greenhouse gas emissions by city type, but did not analyze the factors in detail or consider the weight of each variable. In future studies, we plan to identify the key factors that have a significant impact on greenhouse gas emissions by region type. We will also develop mitigation policies and guidelines for applying relevant technologies in consideration of these factors. Additionally, we aim to classify other cities and establish international standards for carbon-neutral cities, based on a comparison with the Korean case.

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