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Research paper

Regional-based strategies for municipality carbon mitigation: A case study of Chongqing in China

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ABSTRACT

Different CO_2 carbon mitigation strategies are required due to the uneven development of regions. In China, the western region is rich in natural resources, but its industrial technology is not as advanced as other regions. In addition, a few studies have attempted to explore the CO_2 carbon mitigation strategies for a municipality of this region. In terms of modeling, the current studies often focus on the low-carbon potentials at the country, province, city and sector levels, while the carbon flows and their integration in neighboring regions are not well studied. In this paper, to explore the impact of regional-difference factors on CO_2 reduction, we propose regional-based CO_2 mitigation for a municipality and use Chongqing as a case study. In our methodology, the hierarchical structure analysis is conducted to identify the primary contradictions of regional CO_2 emissions. Then, using system dynamics, CO_2 emission systems of major industries, including cement, power and transportation, are modeled. Through simulations of baseline and low-carbon scenarios, key influencing factors in each industry are analyzed. They are then generalized to identify the important aspects of CO_2 emission reduction for this region. Finally, the low-carbon development strategy covering three sub-pathways, i.e., the industrial system, energy structure and socio development is discussed to help the local government for policy-making.

1. Introduction

Over the past decades, climate change with rising greenhouse gases (GHG) has very serious impacts on growth and development, resulting in huge economic losses worldwide (Stern, 2006). Significantly, the CO_2 emissions consisted of 70% of GHG emissions and become a global issue for various countries (Lin and Xu, 2018b). In 2015, China produced one-third (29.5%) of the global CO_2 emissions (Boden et al., 2016). China proposed to reduce its CO_2 emissions per unit of GDP by 60%–65% by 2030 compared to the 2005 levels (Paris, 2016). As one of the countries with the largest CO_2 emissions (Dong et al., 2018), it is an especially challenging task for central and local governments.

Advanced information management and analytics technology provide feasible solutions to support objective analysis of CO_2 emissions. It can help governments to understand the problems and policy-making. China is currently on the road towards low-carbon development, relying on large-scale industries to utilize high-technologies and circular economy to reduce CO_2 emissions. In the current measure, the central government formulated relevant incentive policies for the carbon emission reduction of sectors. Industries of different sectors were then adopted suitable technology and strategy to control CO_2 emissions. However, since the huge differences in regional industrialization and urbanization processes and their imbalanced development, the existing top-down emission reduction measures can no longer better explore the potential of carbon emission reduction in various regions. Therefore, it is urgent to study regional differences in emission reduction and explore regional-based low-carbon development.

In China, the western region has a special geographical nature with a high proportion of mountainous areas. In this context, it involves mountain agriculture, industries with small factories scattered in various regions, transportation system which requires more bridges, tunnels and slope protection and cases of buildings constructed in mountain areas. In addition, while the western region is urbanizing rapidly, its pressure to control GHG is greater than other regions. Although Western China is rich in natural resources, its industrial technology is less advanced than other regions (Cheng et al., 2018). It probably leads to more CO_2 emissions. The increasing population in cities needs more facilities and resources for a variety of activities (Wu and Chen, 2021).

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It also affects industrial demand, production and transportation. Besides, western China receives less attention in CO_2 emission study than other regions of China (Chen et al., 2017).

In western China, Chongqing is a municipality with various non-connected cities and rural counties. It is a typical heavy industry city across the country (Tan et al., 2016). In 2012, Chongqing ranked the third-highest CO_2 emitter in China, with about 192Mt CO_2 emitted (Cai et al., 2018). Chongqing is industrializing and urbanizing rapidly. In this process, the total amount of carbon emissions keeps increasing. In this context, the CO_2 mitigation of Chongqing needs systematic analysis that involves local industries, people and collaboration with neighboring regions. However, the related research topics have not been well studied, especially for regions with mountainous areas.

In this paper, we attempt to explore the impact of regional-difference factors on CO_2 reduction for a municipality and use Chongqing as a case study to demonstrate our approach. In our methodology, we extend a systematic CO_2 mitigation analysis based on the system dynamic model from a regional perspective, by integrating regional advantages. A comprehensive and systematic carbon emission simulation model is proposed using system dynamics and leveraging regional differences and advantages of industrial development. From a conceptual level, it integrates regional low-carbon development, regionally balanced development, and regional optimized development. In a detailed level, it combines regional features, e.g., the characteristics of regional development, factors affecting overall demand within the region, the connections between supply and demand in the region, industry carbon emission processes, characteristics and technological development level parameters, and life carbon emission processes and characteristics.

In the case study, we use Chongqing as an example. To better simulate its CO_2 emissions, we apply scenario assumption and trend extrapolation to build up a research model that can leverage the imbalanced development and comparative advantages of different regions. Especially, we lower the assumptions on various constraints from the regional level and provide parameter settings that are in line with the actual regional conditions. Based on the simulation, the overall carbon emissions in Chongqing and the key domains to emission reduction are first analyzed. By studying the status quo and features of each industry, the research framework for carbon emissions reduction of the industry system is designed. Three typical industries, e.g., cement, power and transportation industries, are selected for further simulation analysis. For each industry, three major subsystems of demand, supply, and emission are established to study the correlation between various variables and carbon emissions. By using the historical data of Chongqing, scenario simulations are conducted to identify the key factors in CO_2 emissions and estimate the industry's total carbon emissions from 2000 to 2030. Based on the simulation results, a low-carbon development path for Chongqing's industries is proposed. It helps to explore the effective carbon control measures in the western region.

The rest of this paper is organized as follows. Section 2 is the related work in regional CO_2 emissions. In Section 3, the methodology for municipality carbon mitigation is proposed. Section 4 reports the simulations and prediction results, and Section 5 discusses policy implications.

2. Related works

In the studies of regional carbon emissions, most of the research focuses on the relationships between carbon emissions and economic development, the overall characteristics of carbon emissions, and their driving factors in a region. Some of the studies focus on factor analysis to estimate the low-carbon potential at the country, province, city and sector levels. They include top-down and bottom-up analysis using factor categories defined in the Intergovernmental Panel on Climate Change (IPCC, 2006) and BSI (2008), structural decomposition analyses (SDAs) to identify key factors, and index decomposition analyses (IDAs) to investigate sector-level factors. Based on data from 25 countries in Africa, Ehigiamusoe (2020) employs estimation techniques that are appropriate for integrated panels to examines the effects of diverse electricity sources (e.g. hydro, oil, natural gas, coal) and renewable electricity output on carbon emissions. He proposed that electricity consumption has a detrimental effect on carbon emissions, while renewable electricity output mitigates carbon emissions in African countries. Sun and Ren (2021) used the Shannon–Wiener index as a new indicator to study the impact of energy consumption structure on China's carbon emissions. They found that the improvement of urban development and trade structure will bring about an increase in carbon emissions, and the optimization of energy consumption structure will slow down the growth of carbon emissions. Zhou et al. (2018) studied the CO_2 emissions and low-carbon development in Guangdong–Hong Kong–Macao gradate bay area cities. They designed a sectoral approach of IPCC and analyzed 17 kinds of fossil fuel consumption and 7 industrial processes with the city boundary. Jing et al. (2018) focused on the CO_2 emissions of 41 cities across China. They categorized energy into oil-related, coal-related and gas-related types and then used a top-bottom method to estimate the energy-related CO_2 emissions. They found that coal-related energy emissions are quite different among cities. Wang et al. (2019) studied the carbon emissions efficiency of regional industrial sectors, including the provinces in the west, central and east of China. By considering industrial heterogeneity, they applied a metafrontier-Malmquist index analysis to estimate and decompose the efficiency and changes of carbon emissions. Feng et al. (2019) decomposed carbon emissions at the overall and sub-industrial level through the logarithmic mean score method (LMDI) method, and evaluated the decoupling status of Zhuhai, a coastal city in China, and the driving force of industrial carbon emissions. Cai et al. (2018) provided a systematic analysis of the local CO_2 mitigation strategy for 286 cities in China. They suggested that local features, e.g., climate conditions, urbanization, and public investment in R&D, should be considered as the main reasons lead to CO_2 emission increasing. Lin and Xu (2018a) investigated what factors mostly affect CO_2 emissions in China's agriculture sector of 30 provinces. They classified the CO_2 emissions into high, medium, and low emission levels. By adding economic variables as inputs, they used the quantile regression to study what causes CO_2 emissions at different emission levels.

Some studies selected Chongqing as a case study. Tan et al. (2016) calculated the CO_2 emissions at the sector-level and predicted the future CO_2 emissions using STIRPAT (stochastic impacts by regression on population, affluence, and technology) model. Tian et al. (2017) attempted to estimate the impact of socioeconomic transitions on CO_2 emissions. They developed a framework using the input–output (IO) model and SDA to analyze the effects from different sectors. Their findings show that most CO_2 emissions come from construction activities and heavy manufacturing. Hu et al. (2017) also investigated the factors behind changes at the sector level in GHG emissions in Chongqing using the SDA method. Although these studies to some extent have identified some important factors on CO2 emissions of Chongqing, some geographical features of this mountain city are not well studied, which directly or indirectly affect people's activities and thus affect carbon emissions. For example, in the process of urban construction, it is necessary to excavate mountains, build slopes and river bridges, and develop multi-layer road networks. In this context, more building materials such as cement are required compared with plain cities. Furthermore, in terms of traffic and travel, due to the special transportation network, it is necessary to go uphill and downhill and to move between road networks. The CO2 emissions of both public and private travel will increase compared with the plain cities. In this regard, different from the previous studies, we attempt to explore a regional-based carbon mitigation strategy based on the special geographical features of mountain cities.

Although certain results have been achieved in the research of regional CO_2 emissions, further studies are needed. Firstly, they often focus on sector-level of CO_2 emissions, e.g., industrial, agricultural and other sectors. However, regional CO_2 emission studies from a more specific industrial-level, e.g., cement, power and iron industries, still need to be further explored to understand their influencing factors, since it is not easy to acquire the domain data. Besides, they often analyzed the carbon flows within the region, while some relevant factors of neighboring regions are not well studied, e.g., regional production demand and energy supplies. Moreover, in these approaches, qualitative analysis is often used. If there is information about the industrial distribution of a region, main industries causing CO_2 emissions, and influencing factors in these industries, it is helpful for the government to make effective policies for specific problems. Therefore, a methodology from a systematic aspect is needed to better understand the influencing factors of regional CO_2 emissions. In this paper, the regional differences and comparative advantages of industry development are taken into account. The characteristics of regional development, factors affecting overall demand in the region, the relationship between production supply and demand in the region, the process of industrial carbon emissions, characteristics and technological development level parameters, and the process of domestic carbon emissions are considered. Factors such as carbon emission reduction and characteristics are incorporated into the research framework of regional carbon emission. In addition, to design the optimal carbon emission reduction path design, the key factors of carbon emission reduction are quantitatively identified by using the principle of system dynamics.

System dynamics (SD) is an effective simulation method for policy analysis and design. It applies to complex dynamic system modeling, e.g., social, economic and GHG emission systems. Through a systematic analysis, it can help to sort out the interdependency of behaviors and factors, mutual interaction, information feedback and their causal relations. By formulating different policy scenarios through parameter tuning, it is able to understand the dynamic evolution mechanism of the system (Yuan et al., 2008).

Some SD methods are designed to investigate the CO_2 emission of different industries. By analyzing energy consumption using an SD approach, Ansari and Seifi (2012) intended to figure out the corrective measures and policies for the steel industry. They integrated energy consumption, steel demand and production in a Framework. Blumberga et al. (2014) focused on the residential building sector. They studied the impact of efficiency policies on consumer's orientation. They included factors from the local subsidy scheme and accompanying policy in their SD model. Besides, Li et al. (2017) studied China's primary aluminum industry. They intended to estimate potential CO_2 emission trends. Five subsystems were built in their SD method, including primary and secondary aluminum production, economy, CO_2 emission intensity and policies. Some studies focus on the mega-city level emission projections and reduction assessments. Feng et al. (2013) studied the CO_2 emissions in Beijing and energy consumption using dynamic modeling. They showed that the major contributors came from the service and transport sectors. Du et al. (2018) used Shanghai as a case study to investigate the CO_2 emission in urban areas based on an integrated SD model. According to the National Economy and Social Development Plan, they identified 8 submodels, e.g., social-economic, electricity and transportation. Gu et al. (2019) also studied Shanghai focusing on the factors leading to CO_2 emission change. They combined the logarithmic mean Divisia index (LMDI) model and the SD model in the analysis. The CO_2 emission growth in Shanghai is positively related to certain factors, especially in terms of transportation model and GDP, e.g., urban travel structure, private car ownership and income level.

By considering the research gaps found in the studies of regional carbon emissions and the advantages of SD methods, we attempt to explore the CO_2 mitigation of a municipality from a regional perspective and extend a systematic CO_2 mitigation analysis based on a system dynamic model by combining regional-difference factors.

3. Methodology

CO_2 emissions of a municipality like Chongqing is a complex giant system, involving many resources, factors, sub-systems, etc. Instead of modeling the whole CO_2 emission process of the region, we focus on exploring the suitable regional-based strategy for municipality CO_2 mitigation. Based on the data of different sectors, our objectives are to help the government to identify the primary contradictions of regional CO_2 emissions, clarify their main processes of CO_2 emissions from a regional perspective, and build up the system dynamic models for these processes to understand the driving factors and better support policy decision-making.

This study contributes to related research from three aspects. It extends a systematic CO_2 mitigation analysis from a regional perspective. In the methodology, combining the hierarchical analysis and SD modeling provides a new platform to leverage both macro and micro analysis for CO_2 prediction under different scenarios. By the detailed analysis of CO_2 emissions from representative industries, it provides a better platform to understand the driving factors of CO_2 emissions and develop appropriate mitigation policies for the relevant industries. In addition, by using Chongqing, typical mountainous areas, as a case study, our research model using scenario assumptions and trend extrapolation can better integrate the information of imbalanced development and comparative advantages of different regions for CO_2 emissions analysis.

3.1. CO_2 *mitigation strategy for the municipality from a regional perspective*

From a regional perspective, we leverage the regional differences in the analysis and utilize system dynamics to quantitatively simulate the most influencing factors for CO_2 mitigation policy suggestions. The framework of our regional-based CO_2 mitigation is shown in Fig. 1. It includes five stages, i.e., overall analysis, hierarchical structure analysis, model development, scenario simulation and prediction, and policy implications. In the overall analysis, the system boundaries, and main contradictions and variables are analyzed. The hierarchical structure analysis using a top-down approach is to identify and select the main driving industries of CO_2 emissions in the region. Then in the model development process, the regional-based SD model is designed to determine the variables and their relationships of each selected industry from both internal and external regions. In the scenario simulation and prediction, the outputs of different variable inputs and adjustments are studied to identify the influences of primary factors. Based on the simulation analysis, the policy implications process is to recommend the optimal CO_2 mitigation strategy for the region.

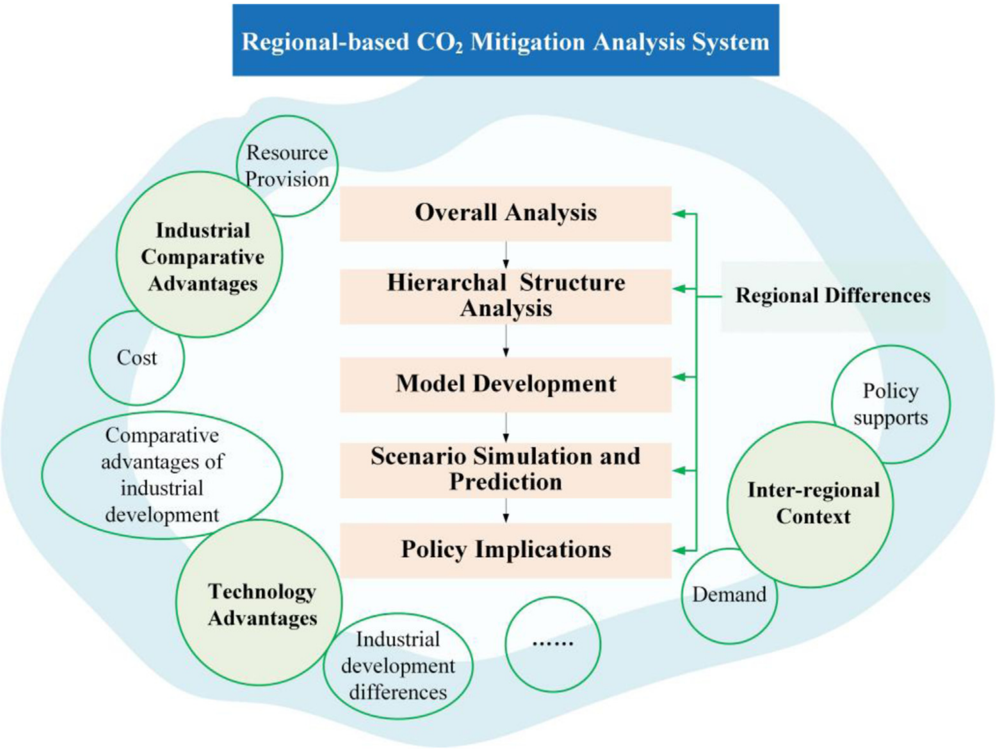

Fig. 1. Framework of the regional-based CO_2 mitigation.

In our methodology, we integrate the regional advantages, i.e., inter-regional context, technology advantages and industrial comparative advantages. Inter-regional context includes the general features of relevant regions, e.g., the government supports in industries, energy, transportation, the local or external population. In terms of technology advantages, the factors include cooperation with other organizations in R&D and production capacity, engineering, manufacturing, and waste and pollutant treatments. The industrial comparative advantages are analyzed by comparing factors between relevant regions. These factors include resources, costs and supplies of energy, material, and labor, the industrial specialization and scale, etc.

3.2. Overall analysis

We focus on the study of the CO_2 emission process caused by human activities. The GHG emissions by non-human activities are excluded, including emissions from wild animal activities and methane emissions in swampy areas. According to the IPCC, the CO_2 emissions of human activities can be categorized into five aspects, including agriculture, land-use change and forestry, industrial production processes, energy activities and waste treatment.

The key emission processes that are more sensitive to regional comparative advantage and affect the total regional carbon emissions are identified as sub-systems, such as the main CO_2 emission industries and departments. Then in each sub-system, the CO_2 emission flow path in the region is analyzed. It involves supplies, dynamic CO_2 emission processes and resources within and between regions. Different from most of the previous studies about the overall features of carbon emissions in the region, we attempt to seize the primary contradictions of regional CO_2 emissions through a top-down analysis and to explore the driving factors of CO_2 mitigation.

3.3. Hierarchical structure analysis

To seize the primary contradictions of regional CO_2 emissions in Chongqing, a top-down investigation is conducted to study the hierarchical structure of CO_2 emissions. The CO_2 emissions generated from human activities can be analyzed from two aspects, including the industry sector emissions and daily activity emissions. The regional differences between these two aspects should be also considered. Also, the availability of data and how to obtain the data constrain the variable categories we break down.

Given these considerations, the regional-based CO_2 emission system is divided into layers, as shown in Fig. 2. Firstly, it combines industry sector emissions and daily activity emissions. The industry sector emissions are further divided into CO_2 emissions from three main sectors, including the primary, secondary and tertiary sectors of the industry respectively. For each main sector, the CO_2 emissions can be breakdown into several categories. The daily activity emissions consist of CO_2 emissions from urban and rural resident activities.

Based on the hierarchical structure, Chongqing has its characteristics across sectors and living activities. Chongqing is one of the central cities in Western China. It is a group-type city integrating large cities, rural areas, mountainous areas and reservoir areas. Like most of the cities in China, Chongqing continues to develop rapidly towards industrialization and urbanization. Its proportion of industry keeps increasing and the consumption of its tertiary industry is accelerating. Besides, an increasing number of rural residents are relocating to urban areas, which leads to ever-growing carbon emissions in living.

In terms of energy structure, the main energy sources of Chongqing are natural gas, oil, and coal. As shown in Fig. 3, from 2005 to 2010, Chongqing's total CO_2 emissions and energy consumption continued to increase. In 2010, the CO_2 emissions from

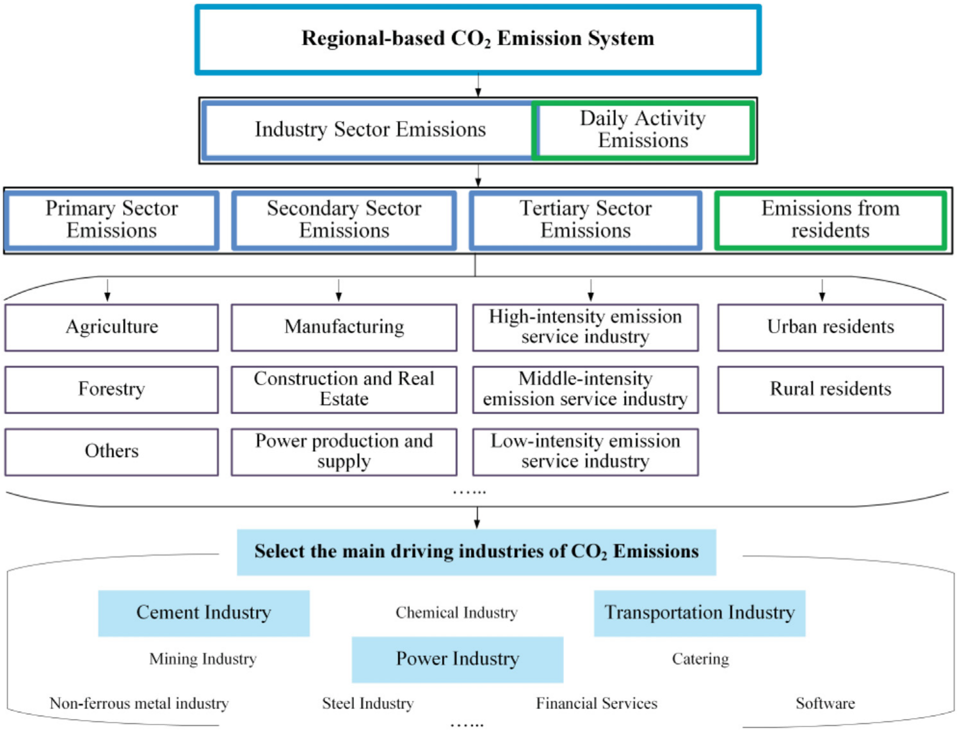

Fig. 2. Hierarchical structure for regional-based CO_2 emission system.

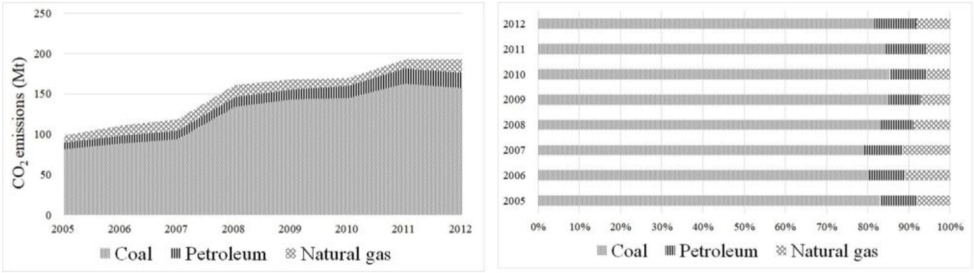

Fig. 3. Chongqing's CO_2 emissions by energy type.

fossil fuel combustion were 159 million tons (Mt) of CO_2, whose amount was about 1.89 times the volume in 2005. Especially, the CO_2 generated from direct coal combustion contributed about 70%. From 2005 to 2010, the total amount of CO_2 produced by coal combustion increased by 95%.

In terms of CO_2 emission structure, the CO_2 emissions from industries cover 60% of the total CO_2 carbon emissions of Chongqing. As shown in Fig. 4, from 2005 to 2010, only in the industrial sector, the CO_2 emissions generated from the combustion of fossil fuels consist of more than 70% of total emissions, which are the first contributor to CO_2 emissions. Their proportion rose from 71.4% to 73.2%. The second highest CO_2 emissions are from residents' daily activities, exceeding 11% of the total emissions.

The primary sector, involving the agriculture, forestry, animal husbandry and fishery industries, produces CO_2 emissions in the first two. Their proportion decreased from 5.2% in 2005 to 3.7% in 2010.

In addition, CO_2 emissions from transportation and residential activities have grown rapidly in Chongqing. From 2005 to 2010, the average annual CO_2 emissions of the transportation and storage industry raised by 10.24%. The average annual CO_2 emissions of residents, including both urban and rural areas, increased by over 6%, more than the city's average growth rate of CO_2 emissions during the same period.

In the short term, it is difficult for Chongqing to change its coal-based energy consumption structure. We can foresee that its industrial sector will still contribute most of the energy consumption and carbon emission. More efforts should be emphasized on industrial carbon reduction. However, the CO_2 emissions from industry sectors involve more than 40 industries of the national economic system. It is extremely complex to design a simulation model for a municipality-level system and the interactions between different industrial sectors. In this study, we attempt to combine the regional features and to better investigate the most main factors of CO_2 emissions in Chongqing while identifying the potential strategies from a broad regional perspective. To identify the typical industries for further analysis, the current economic development is considered. In Chongqing, rapid development involves a series of infrastructure constructions, e.g., high-speed railways among regions and city transportation. It increases needs in the cement industry. Moreover, various industries continue to upgrade and new facilities keep on building up. These, in turn, enlarge the energy demands while the electricity industry is the largest part involved. Moreover, because Chongqing locates in the mountain areas, transportations are more energy-consuming than the plain area. The population growth and the increasing living standards of residents also put pressure on the environment.

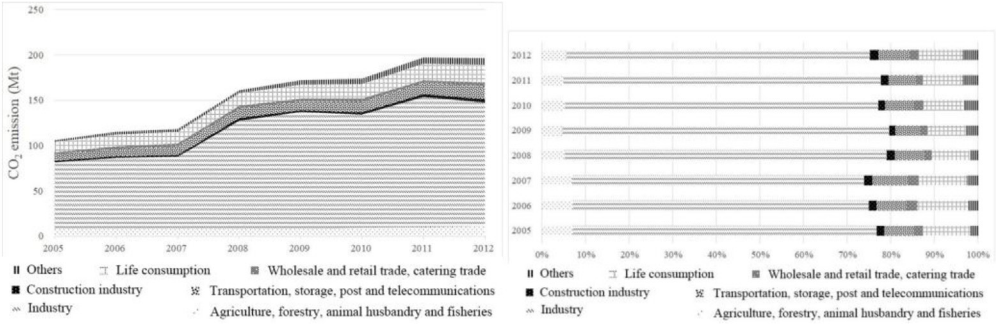

Fig. 4. Chongqing's CO$_2$ emissions by sector.

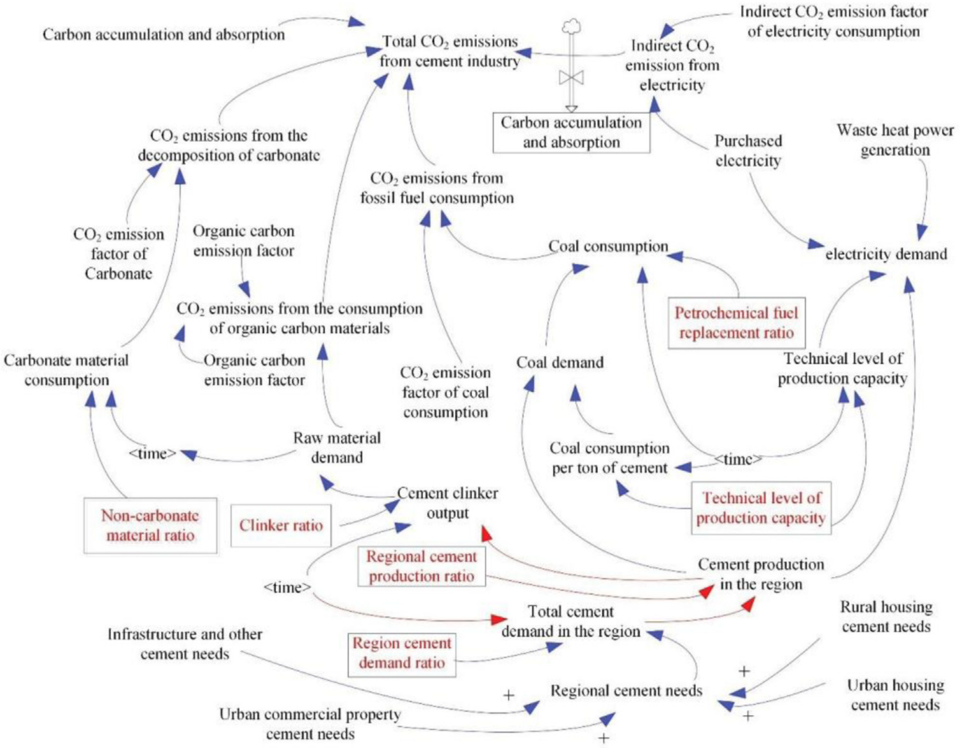

Fig. 5. Cement industry sub-system flow diagram.

To identify the typical industries for further analysis, the geographical nature and current economic development are considered. In Chongqing, rapid development involves a series of infrastructure constructions, e.g., high-speed railways among regions and city transportation. It increases needs in the cement industry. Moreover, various industries continue to upgrade and new facilities keep on building up. These, in turn, enlarge the energy demands while the electricity industry is the largest part involved. Moreover, because Chongqing locates in the mountain areas, transportations are more energy-consuming than the plain area. The population growth and the increasing living standards of residents also put pressure on the environment.

Based on these observations, three significate contributors to Chongqing's CO$_2$ emissions are identified, including cement, electricity and transportation industries. By leveraging the regional carbon modeling based on system dynamics, influencing factors of energy consumptions and carbon emissions are simulated and analyzed. Baseline and low-carbon scenes are designed to simulate the CO$_2$ emission changes from 2000 to 2030 under different parameter settings. By analyzing the CO$_2$ emission patterns in these major industries, we discuss the potential strategies for CO$_2$ reduction.

3.4. Model development for individual sub-system

In the model development, the CO$_2$ emission process of each selected industry is analyzed using our regional-based system dynamics model to determine the influencing variables and their relationships from the local and outside the region. The model is based on our recent study (Tang et al., 2020). Data related to Chongqing's population, industrial development, current government policies and regional development statistic are collected. The data sources include National Bureau of Statistics (2014, 2018), report of the 18th National Congress, Regional Statistical Yearbook, regional "Twelfth Five-Year" plans, Population Development Plan of Chongqing (2016–2030), Municipal People's Government Report (2017), relevant industrial research reports (Qianxun-consultation, 2017) and field investigations. Based on the data, the variables and equations of each system are formulated, as shown in Appendices A–F.

3.4.1. Cement industry sub-system

To simulate the CO$_2$ emissions from the cement industry, the regional-based system is broken down into three parts, i.e., cement demand, local cement supply and CO$_2$ emissions caused.

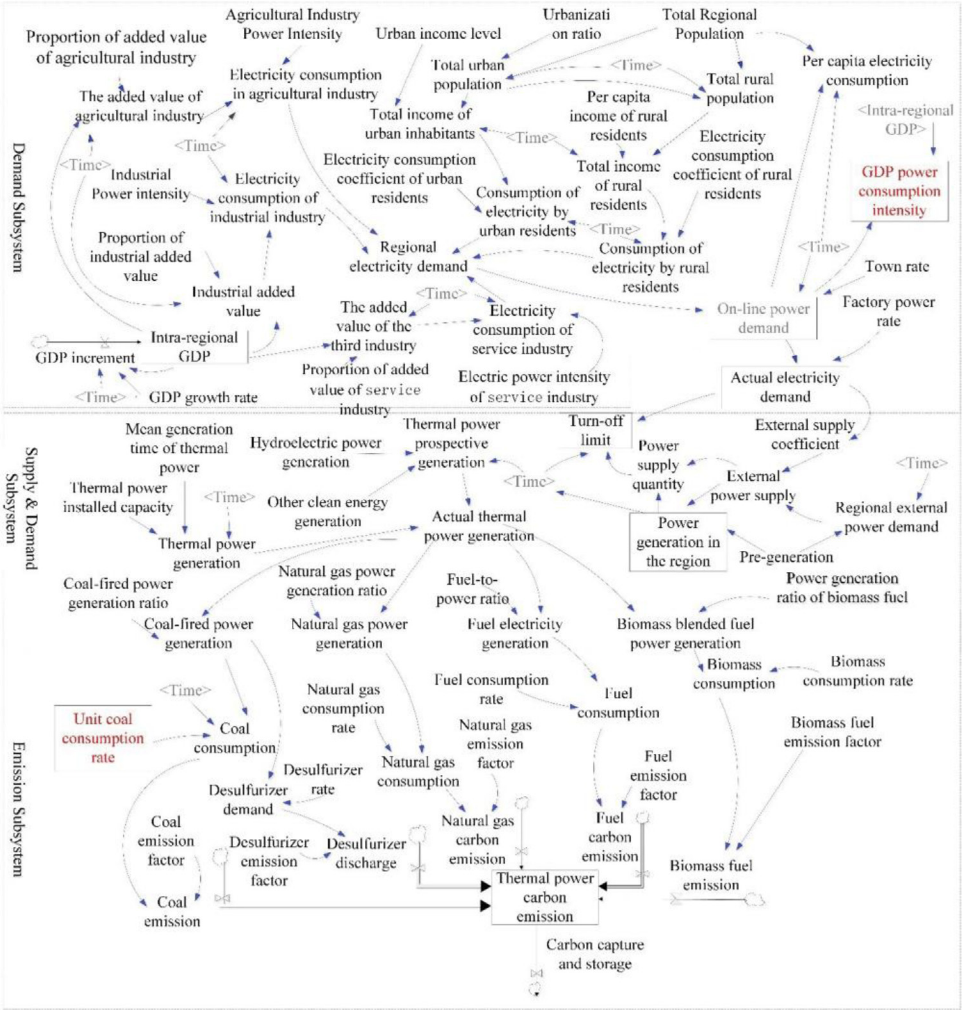

Fig. 6. Power industry sub-system flow diagram.

Starting from the regional perspective, the cement demand comes not only from the locals but also from the neighboring regions. By combining the regional distribution of the cement industry and its advantages among the neighboring regions, the production of the local cement industry is then identified. For the cement industry in Chongqing, the total CO_2 emissions largely result from the production process and energy consumption. Fig. 5 shows the variables and parameters involved.

3.4.2. *Power industry sub-system*

In Chongqing, the power industry mainly relies on thermal power generation. It is a challenging task to adjust the power supply structure. The largest energy consumptions are from industrial sectors. In addition, the power industry involves a number of small thermal power units. It is arduous to merge them in order to improve the efficiency of electricity production. In our simulation, we use three sub-modules to analyze the CO_2 emissions from the power industry, including the energy demand, power supply and CO_2 emission sub-modules. The system inputs and outputs as well as their interactions are then analyzed. The energy demands consist of power consumption from three major industries and rural and urban residents. The power supplies in the local region come from hydropower, thermal power, and other clean energy. When accessing the power balance in the supply–demand relationship, the purchase of electricity from neighbor regions should be included. Based on these considerations, the CO_2 emissions for the power industry are simulated. Fig. 6 shows the variables of Chongqing's power industry.

3.4.3. *Transportation industry sub-system*

Chongqing is a typical representative of mountainous cities. With economic development, its road network and facilities are being rapidly expanded and upgraded. However, because of its special geographical conditions, there are frequent cases of mountain roads, slopes and bridges with different numbers of lanes, main roads in weak shunting capacity and bus stops which often make the road become narrow and disturb smooth traffic flow. These give rise to weakening the road capacity and increase congestion. In addition, the light rail networks for mass transit that use green energy are not yet fully built up. Moreover, while Chongqing covers large rural areas, most of the economic activities are driven in the main urban areas which are only about 1% of Chongqing's area. The traffic of main urban areas thus reflects most of the mass transportation capacity and volume transportation capacity in Chongqing. Based on this analysis, we emphasize transportation activities in the main cities. The model is divided into a demand subsystem and an emission subsystem. The frequent modes of passenger transportation cover bus, rail transit, taxi and private vehicle. The variables of the transportation industry are identified as shown in Fig. 7.

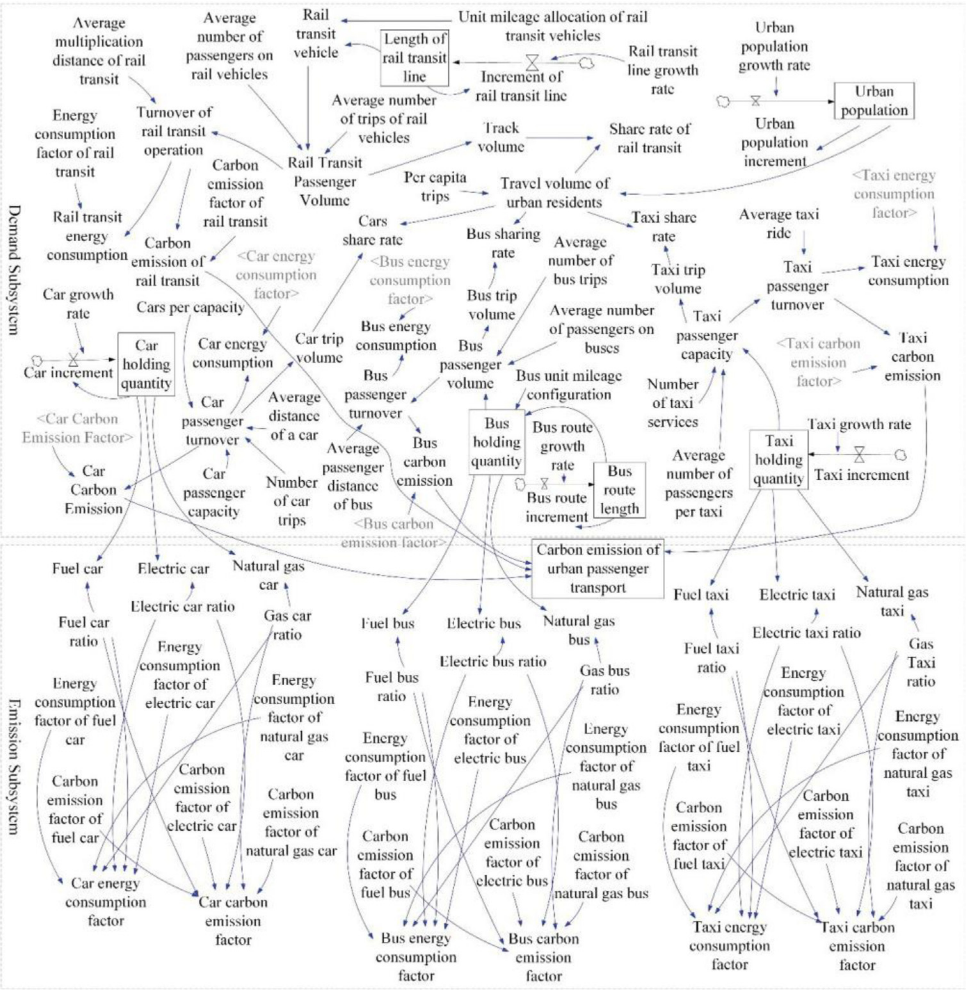

Fig. 7. Transportation industry sub-system flow diagram.

4. Simulations and predictions

The feasibility of the SD models for these three major industries was analyzed using validity tests and sensitivity analysis. The baseline and low-carbon scenarios are simulated based on the evolution and development of key factors in the industry's CO_2 emissions. The baseline scenario is to investigate how the current development of the industry would evolve without additional government policies. In the low-carbon scenario, the target is set to a 50% reduction in CO_2 emissions in 2020 compared to 2005.

4.1. CO_2 emission in cement industry

Compared with the baseline scenario, in the low-carbon scenario, it is considered that the industrial concentration and the overall efficiency of industrial production are improved. In addition, advanced power production capacity from an inter-regional perspective is integrated and utilized. Relevant parameter settings are shown in Appendix B.

Fig. 8 shows that the CO_2 emissions of the cement industry under both baseline and low-carbon scenarios have a similar trend. Their volumes climb up to the peak at around 2020, with around 57 Mt (million tons) in the baseline scenario and 50.67 Mt in the low-carbon scenarios respectively. However, if the low-carbon policies are taken, there will be about 6.23 Mt CO_2 emissions reduction in 2020. Continuous CO_2 mitigation will also be foreseen from 2020 to 2030.

When we investigate the key factors in terms of cement manufacturing as shown in Fig. 9, it indicates that carbonate decomposition caused nearly half of the CO_2 emissions in both scenarios. In this regard, the CO_2 emissions of the low-carbon scenario in cement production reach the top in 2020. If the low-carbon policies are adopted continually, in 2030, its amount will drop about 1/3 compared to that in the baseline scenario. The second contributor is fossil fuel consumption, which produces about 1/4 of the CO_2 emissions in both scenarios. It keeps increasing until 2020 and then turns downward.

Some relevant key parameters between these two scenarios are considered, as shown in Fig. 10. In terms of demand, the regional cement production ratio should increase to 0.1. It suggests importing some cement production from the neighboring regions. Concerning production capacity, the technical level should improve by about 0.1, combined with increasing the Non-carbonate material ratio and lowering the clinker ratio. In terms of energy supply, the ratio of petrochemical fuel replacement should be upgraded. As to the emission sub-system, the waste heat utilization and the CO_2 emission intensity should be raised to advanced standards.

4.2. CO_2 emission in the power industry

Concerning the power industry of Chongqing, there are limited data about oil-fired power generation, gas power generation and biomass power generation. Therefore, relevant data are set to 0

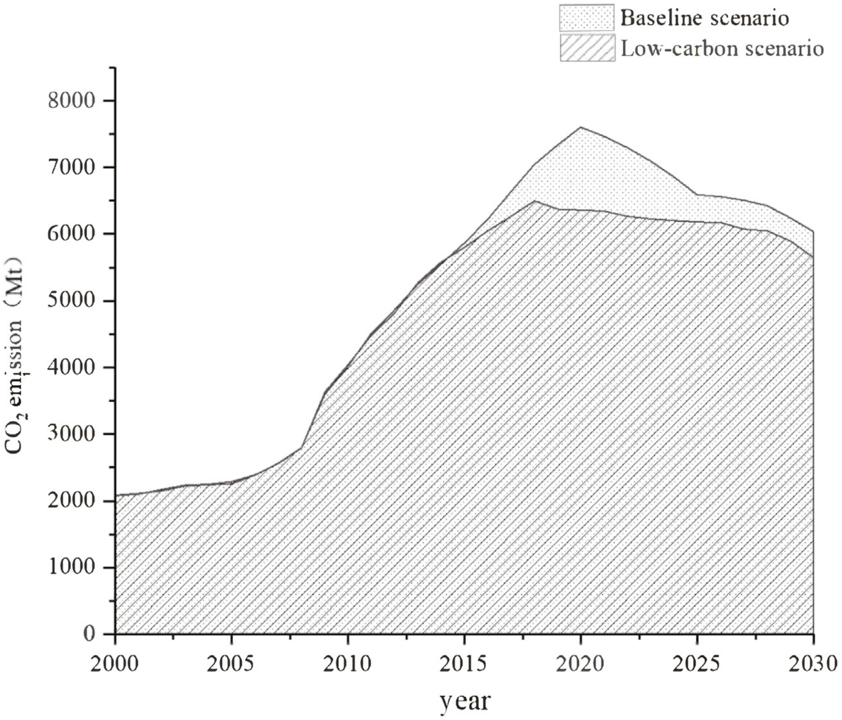

Fig. 8. The estimated CO_2 emissions in the cement industry of Chongqing.

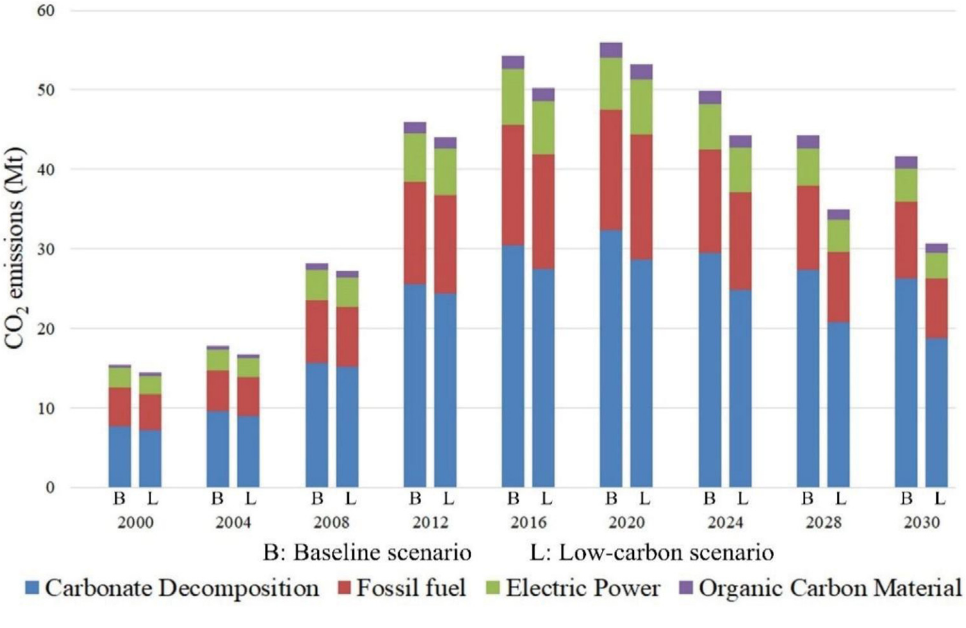

Fig. 9. Key factors affecting the CO_2 emissions of Chongqing's cement industry.

in the experiment and CO_2 emissions from these sources are not applicable in both scenarios.

In the low-carbon development scenario, several factors are considered, including the most stringent industrial capacity reduction and capacity expansion policies is considered, integrating advanced power production capacity, improving the industrial concentration from a regional perspective, increasing clean energy power generation, and reducing coal-fired power generation ratio. Relevant parameter settings are shown in Appendix C.

As shown in Fig. 11, in the baseline scenario, the simulation result shows that Chongqing's power industry keeps generating a high amount of CO_2 from the year 2000 to 2030. The CO_2 emissions caused by coal-fired power generation in electricity production also continue increasing during the same period.

Concerning the low-carbon development scenario, the CO_2 emission of the power industry in Chongqing also rises from 2000. However, it shows that, compared to the baseline scenario, its value grows slowly over the decade starting in 2020. The CO_2 emissions caused by coal-fired power generation also continue increasing. The volumes in the low-carbon scenario show a considerable reduction compared with the baseline scenario. Some key factors in Chongqing's power industry are shown in Fig. 12.

By comparing the parameter settings of these two scenarios, it is noticed that some key factors are important in reducing the CO_2

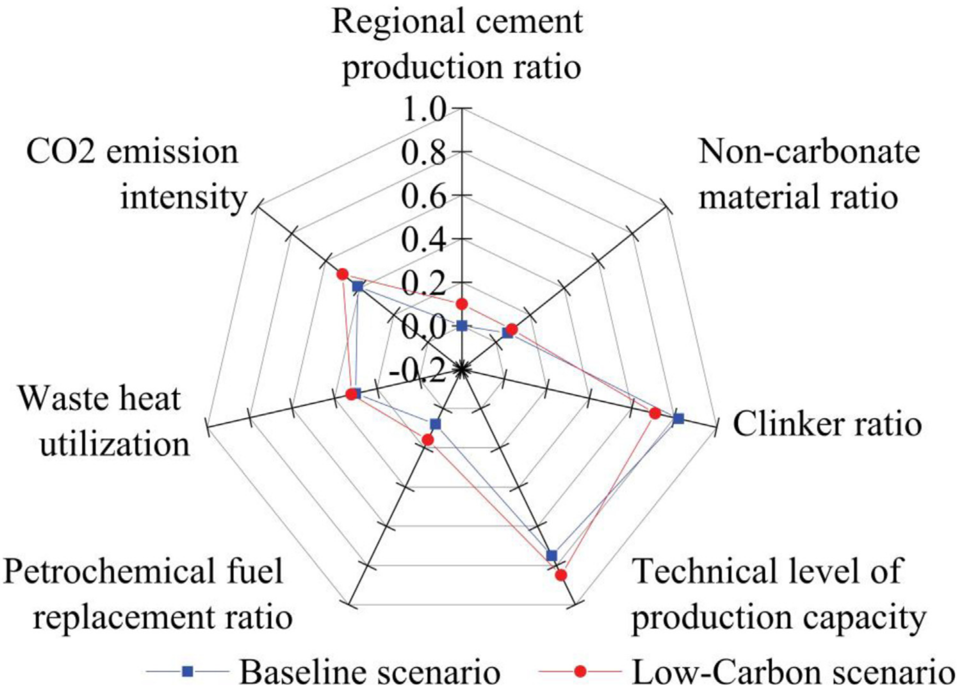

Fig. 10. Key parameter settings of the cement industry in 2020.

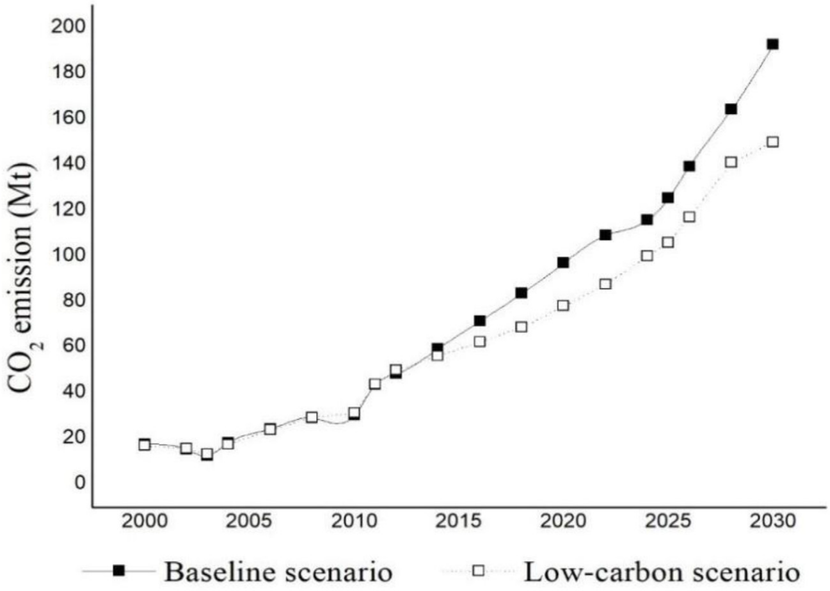

Fig. 11. The predicted CO_2 emissions of Chongqing's power industry.

emissions in Chongqing's power industry, as shown in Table B.1. In 2020, the thermal power generation ratio was reduced from 0.6820 of the baseline scenario to 0.5826 of the low-carbon scenario, and the line loss rate was reduced from 0.084 to 0.064. This requires the power industry to adopt the improvement in clean energy, biomass power generation, coal consumption rate and line loss rate and to meet the advanced European technical conditions. It is also possible to lower the power generation in the local region by increasing the supply from neighboring regions. In 2020, the extra-terrestrial supply coefficient in the low-carbon scenario should be increased from 0.5825 to 0.8825 compared with the baseline scenario.

4.3. CO_2 *emission in the transportation industry*

In the low-carbon development scenario, several factors are considered, including the advanced new energy vehicle technologies from a regional perspective, increasing the use of alternative fuels and travel activity such as private car usage, rail transit and bicycle trips. Relevant parameter settings are shown in Appendix D.

As to Chongqing's transportation industry, the estimated CO_2 emissions are shown in Figs. 13–14. The CO_2 emissions of both scenarios keep rising and the rising ranges become higher from 2008. Four important components are shown, i.e., CO_2 emissions

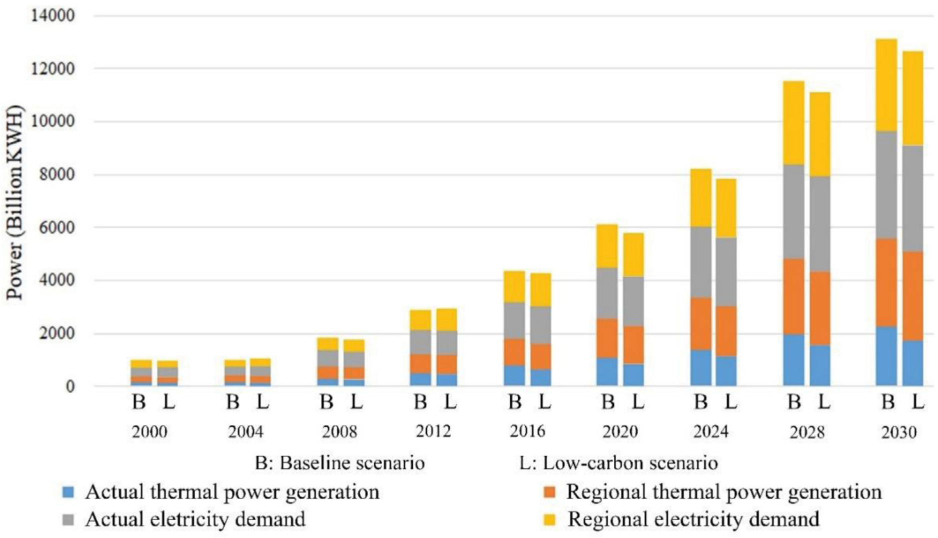

Fig. 12. Key factors affecting the CO_2 emissions of Chongqing's power industry.

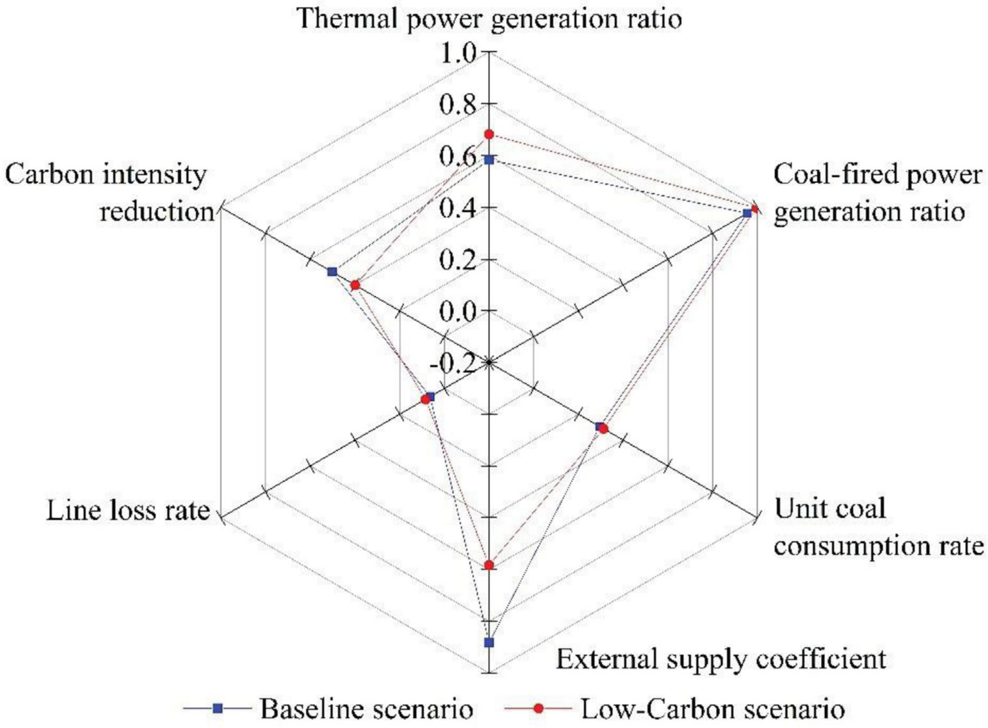

Fig. 13. Key parameter settings of the power industry in 2020.

from public buses, taxis, private cars and rail transit respectively. Their values demonstrate linear increasing trends, especially emissions from private cars.

However, some differences are shown regarding per time of travel in both scenarios, as shown in Fig. 14. In the baseline scenario, there is a rapid acceleration period from 2008 to 2014, while the incremental volume slows down to a steady level from 2015 to 2020. Its value then decreases slowly from 2020 and then the downward trend goes faster in 2026. In the low-carbon scenario, although the acceleration period is similar to the baseline scenario, the CO_2 emissions trend of per time of travel goes up gradually. Then its value goes down rapidly. Also, regarding per capita daily carbon emissions, the volumes grow up quickly since 2000 in both scenarios. However, the growth rate becomes slow after 2020 in the baseline scenario, while its volume of the low-carbon mode reaches a peak in 2014 and turns downward at 2025 after a slight change period.

Variable settings in these two scenarios lead to different CO_2 emission patterns. Fig. 15 shows that to performant low-carbon development, the ratio of each transportation mode should be adjusted. For example, in 2020, the public bus ratio on the roads should decrease from 26.99% of the baseline scenario to 25.99% of the low-carbon scenario. Correspondingly, the rail trip ratio should increase from 22% to 30%, and the car trip ratio should decrease from 8.83% to 6%.

When investigating different parameter settings between these two scenarios, we found several key factors that lead to different CO_2 emission patterns. Fig. 15 shows that to reduce the CO_2

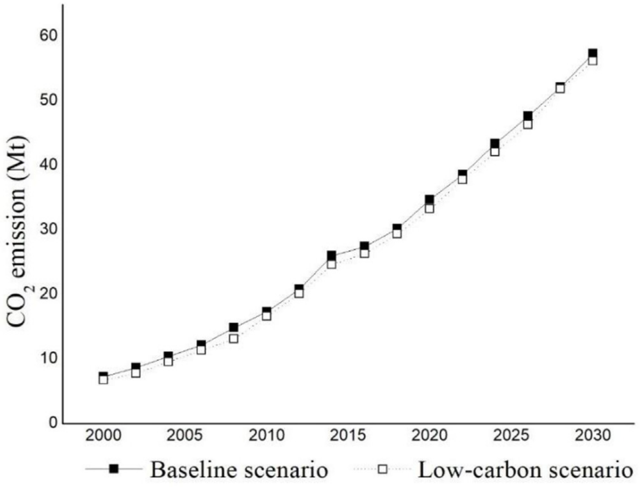

Fig. 14. The predicted trends of CO_2 emissions in Chongqing's transportation industry.

emissions from the baseline scenario to the low-carbon scenario, the ratio of public electric buses should be increased from 0 to 10% while reducing the ratio of public gas buses from 95% to 87%. In addition, the ratio of electric taxis should be raised to 8%, while the ratio of gas taxis should decrease from 98% to 90%. As regards private cars, it requires to increase the ratio of electric cars from 0 to 3%, and at the same time reduce the ratio of fuel cars from 98% to 95%.

Moreover, the average distance traveled is another key factor in controlling CO_2 emissions. Fig. 16 shows that to ease the CO_2 emissions problem to perform low-carbon development, the average distance traveled by public buses, taxis and private cars should reduce from 8.6 km to 8 km, from 8.3 km to 7.7 km and from 9 km to 8.4 km, respectively.

4.4. Summary

In summary, we further analyze the reasons behind the patterns of CO_2 emissions between these two scenarios in the cement, power and transportation industries of Chongqing.

Under the baseline scenario of the cement industry, one possible reason for the fall of CO_2 emission after 2020 is that the demand from urban infrastructure construction and urban per capita construction will reach its peak. In addition, according to city planning, the cement industry will likely shift from extensive development to capacity upgrades. This will also drop the demand for cement. The decline of demand will reduce energy consumption and thus reduce CO_2 emissions.

Regarding the power and transportation industries, we believe the industrial development reform and energy resources supported by the nearby region will reduce the CO_2 emission in these two industries. According to city planning, from 2020 to 2030, Chongqing's industry will gradually transform into a manufacturing service industry, and the recycling, low-carbon and intelligent operation of iron and steel, nonferrous metals, building materials, chemicals and other industries will lead to a significant drop in their emissions.

In addition, Chongqing's power supply is connected to the State Electricity Grid of the neighboring provinces, such as Sichuan Province, which is dedicated to providing clean power. If the proportion of clean electricity in Sichuan Province increases, it will lead to a decrease in the emission coefficient of the State Electricity Grid to which Sichuan and Chongqing belong, and thus the emission of the power industry will tend to reach a plateau at that time.

Although carbon emissions from the transportation industry will rise slightly, these small increases will be canceled out by lower emissions from sectors such as agriculture, industry, and construction.

5. Policy implications

Based on the detailed results of scenario analysis in Section 4, this section discusses the regional-based CO_2 mitigation strategies for Chongqing.

5.1. Suggestions for cement industry

The industrial structure of Chongqing's cement industry is unbalanced. Only a few proportions of cement factories can reach 4000 tons/day in production capacity. There are many cases of middle or small-size cement plants scattered in the region, low effective utilization in energy consumption and insufficient mechanism in resource integration and recycling.

Based on the comparisons between the two scenarios, several low-carbon development strategies should be established. Firstly, the industrial structure should be rearranged to enhance industrial integration and improve its competitiveness in the neighboring regions. Chongqing's cement industry should focus on building up leading enterprises, through re-organizing or merging separated firms or production processes, to reap production of scale and production efficiency.

Secondly, the adjustment of relevant factors in the low-carbon scenario provides an effective way to optimize the production process to balance the cement demand, energy utilization and CO_2 emissions. In this scenario, the share of raw material substitution and production capacity increased. Therefore, it is imperative to replace raw materials with better quality, use green energy, and improve industrial waste treatment. Regarding these aspects, the cement manufacturers should apply low-carbon technology applications to explore and produce green types of cement, such as ecological cement and concrete and composite cement. Also, the local government should encourage these reforms by stimulus policies, including funds, tax reductions and subsidies.

Thirdly, in the low-carbon scenario, the utilization of recycling waste and resources is also a significant part. Therefore, the government should encourage and make policies to support using resources more efficiently. Fourthly, how the carbon can be captured and stored is also a potential approach towards low-carbon production. Relevant policies should be strengthened in this regard.

5.2. Suggestions for power industry

The power industry also has similar problems as the cement industry, e.g., imbalance industrial structure, high energy consumption and insufficient mechanism in resource integration and recycling. According to the simulation results of the two scenarios, measures for the power industry towards low-carbon development include seven aspects as follows. The first important part is to improve the organizational structure of power companies. The government should encourage cultivating leading enterprises and merging small power companies with low efficiency to improve the industrial integration and competitiveness in the neighboring regions. Some promising policies regarding the power grid include upgrading the intelligence of the power grid and increasing the length of the UHV transmission line to strengthen the construction and transformation; reducing

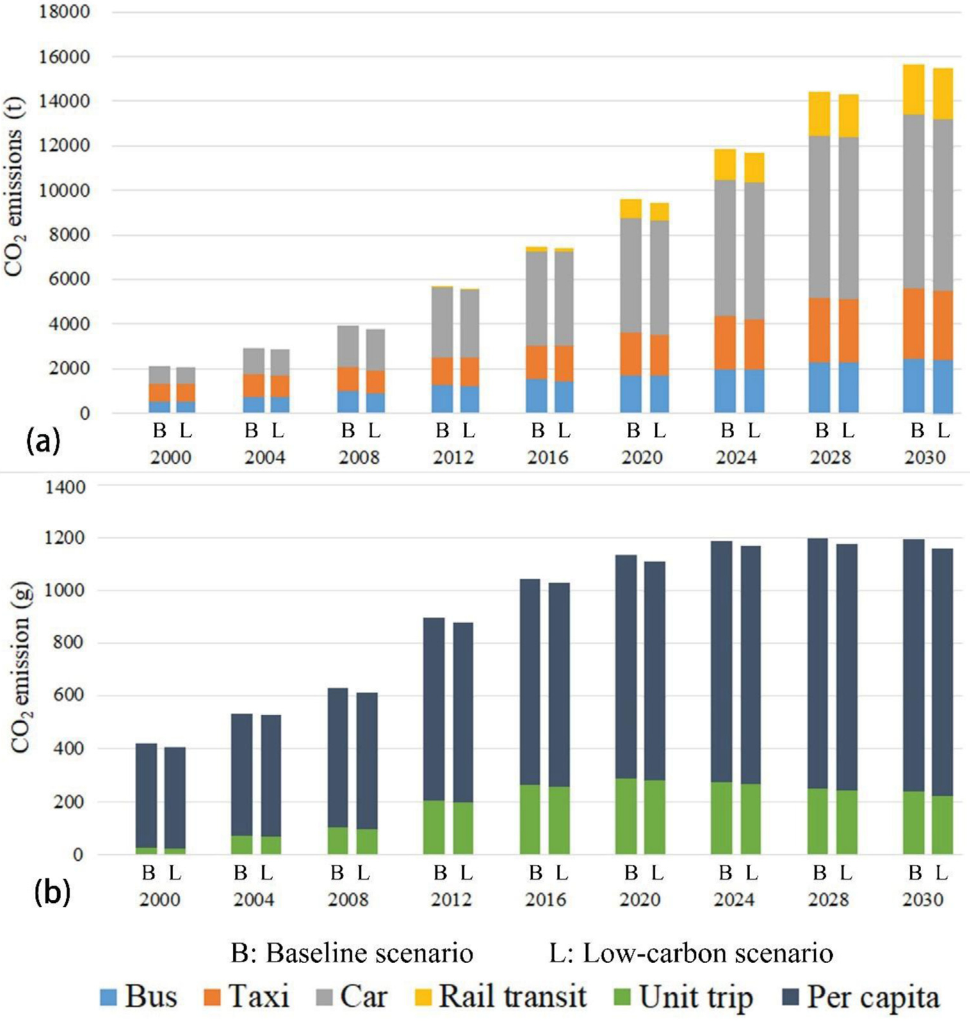

Fig. 15. Key factors affecting the CO_2 emissions of Chongqing's transportation industry.

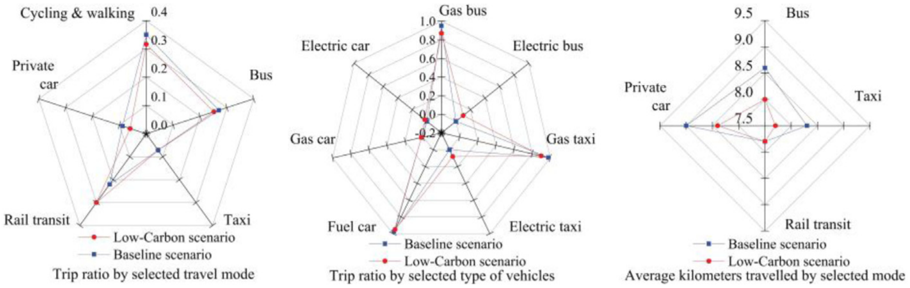

Fig. 16. Variables of Chongqing's transportation industry.

the repeated substation capacity, choosing the reasonable economic operation mode, improving the reactive power optimization to reduce the losses in power distribution and transmission, and upgrading the power utilization rate. On the one hand, the smart power grid can integrate different energy sources, e.g., solar power, and coal-generated power. On the other hand, it can be used as a green platform to allocate energy through large-scale power transmission to absorb clean energy and boost the power system to improve energy efficiency.

Secondly, to alleviate the tight supply of energy, foster new industries, and respond to global warming and reduce GHG emissions, the exploration of clean energy is a promising measure. Clean energy includes wind power, solar power, hydropower, nuclear power, geothermal power, etc. The government and local power industry should increase investment in the power generation of clean energy to gradually replace the thermal power generation and reduce fossil energy consumption.

Thirdly, it is also important to apply low-carbon technologies for coal-fired power generation, such as gas-fired power generation technology and high-capacity, high-parameter thermal power units with higher efficiency. The local power industry should use ultra-supercritical units to install thermal power units to improve the coal consumption efficiency and lower the line loss rate of coal-fired power generation units.

Fourthly, it is highly possible to reduce the power consumption of a unit product by increasing energy-saving investment and accelerating technological transformation and upgrading. Policies about comprehensive utilization of resources in the cogeneration, biomass power generation and waste-to-energy industries to improve the recycling mechanism of the industry should be emphasized and formulated.

Fifthly, on the demand side, it is also extremely important to conduct a green electricity price mechanism to manage the consumption of power energy in an effective economic way. Green electricity pricing refers to relevant electricity pricing policies that stimulate energy conservation, reduce pollution emissions from thermal power generation, and encourage renewable energy power development. It includes desulfurization electricity pricing, differential electricity pricing, peak and valley electricity pricing, and renewable energy pricing strategies. For example, using differential electricity prices can limit the use of electricity in high-energy-consuming industries and encourage enterprises to use alternative energy sources and accelerate the development of electric vehicles.

Sixthly, it is a good choice to develop natural gas power generation by combining the local resource advantages. Chongqing holds a large volume of natural gas reserves while low volumes of coal reserves. Besides, using natural gas can improve power generation efficiency and reduce the CO_2 emission rate than using coal. It also helps to reduce emissions of sulfur dioxide and nitrous oxide. Lastly, another alternative is to research, develop or commercialize carbon capture and sequestration.

5.3. Suggestions for transportation industry

The transportation problems in the main urban area in Chongqing include inappropriate industrial structure, high energy consumptions and insufficiency in resource integration, and recycling and reuse mechanism. Based on our study, several low-carbon development measures can be conducted for Chongqing's main urban traffic.

Firstly, it is important to develop and encourage public transportation, such as bus and rail transit, by implementing a bus-priority strategy and development of rail transit. However, since most of the roads in Chongqing are narrow, usually with two lanes, it should maintain or appropriately reduce the public bus ratio on the roads to improve the vehicle passing rate, rather than increasing the number of public buses. A potential policy is to set up bus lanes or their periods of operation, especially at peak hours, to reduce obstruction of traffic caused by various vehicles, e.g., taxi and private cars, competing for roads. Another promising policy is to encourage developing rail transit and build a track network as the main public transportation. The successful examples of rail transit in New York and Paris show that their rail transits can meet the demands of 60% and 83% passenger traffic respectively. It is recognized that rail transit is a green, energy-saving and efficient commuting mode with a lower road occupation rate and CO_2 emission rate. The development of rail transit helps to alleviate traffic clogging. By promoting the use of rail transit and its services, the frequency of private car use can be reduced, thereby optimizing the allocation of road resources, and reducing CO_2 emission and noise pollution.

Secondly, it is necessary to restrict the number of cars on the roads. In Chongqing, most of the municipal-level administrative agencies, social public service organizations, and financial institutions' headquarters are in the core area, while most of the residential areas are scattered in various districts. Cars are often used as the main transportation for business travel between these institutions and between local and neighboring regions. From our simulation, it is noticed that CO_2 emissions from cars cover about 40%–50% of the total CO_2 emissions in passenger traffic. A surge in the number of cars on the roads is causing increased congestion and noise pollution. Even worse, the exhaust emissions from cars cause serious urban air pollution as the mountainous landform of Chongqing with poor air dilution capacity.

Thirdly, low-pollution and low-energy transportation modes should be promoted. Policies should be made to support new energy development and improving fuel utilization efficiency in the transportation industry and advocate the use of new energy vehicles and the development of electric vehicles. Fourthly, it is also important to improve the traffic environment in a large city like Chongqing. Some feasible traffic control measures can be applied, such as reducing congestion, energy consumption, and CO_2 emissions, and reducing the number of transfers and the average distance traveled. Fifthly, optimized urban planning also affects green transportation, such as reducing trip ratio by vehicles and shortening average distances traveled. In the planning, it should increase road spaces and pavement for bicycles and pedestrians to constrain the use of high-emission vehicles and encourage residents to use these facilities.

5.4. Overall carbon mitigation strategy for chongqing

Based on the analysis of CO_2 emission influential factors and key parameters from three representative industries in Chongqing, we investigate their relevant important aspects and then come up with an overall carbon mitigation strategy, as shown in Fig. 17. The strategy includes three sub-pathways, i.e., industrial system low-carbon pathway, low-carbon energy structure development pathway, and socio low-carbon development pathway.

In the industrial system's low-carbon pathway, the most important part is to keep a consistent effort in enhancing low-carbon industrialization. It should first adjust and optimize the industrial structure of Chongqing's industries by developing other low-carbon industries, e.g., the service industry and culture industry. Secondly, in the current industry, it is necessary to eliminate backward production capacity and implement energy-saving technological transformation. Meanwhile, it is necessary to strictly control the capacity expansion and output growth of other high-energy-consuming industries. Thirdly, new modern service industries should add to the current industry system. The government should encourage the development of intelligent soft industries centered on big data, productive service industries and low-carbon industries such as leisure and tourism Industrial development, and optimization and promotion of the living service industry.

In terms of low-carbon energy development, the local government should adjust both industrial and energy structures, optimize the energy consumption structure of the industrial sector and structural adjustment of the energy industry. From the regional perspective, Chongqing can focus on the development and cross-region utilization of clean energy and accelerate the energy revolution by importing a large proportion of clean power from neighboring regions, such as Yunnan and Sichuan provinces. Sichuan and Yunnan province has rich potential for non-fossil energy resources such as hydropower and photovoltaics. Besides, to accelerate the low-carbon energy reform in residential daily energy consumption, it is possible to build up some small power grids that can be integrated and monitored using an internet-based platform and provide energy corresponding to the demand. Another approach to increase the efficiency of end-use energy is to improve electrification. Efforts should also be made to promote the clean production of thermal power enterprises, focusing on the advancement of advanced smart grid, advanced energy storage, and energy cascade comprehensive utilization technology research and development technologies, and vigorously promote the development of shale gas, wind energy, hydropower and other clean energy development.

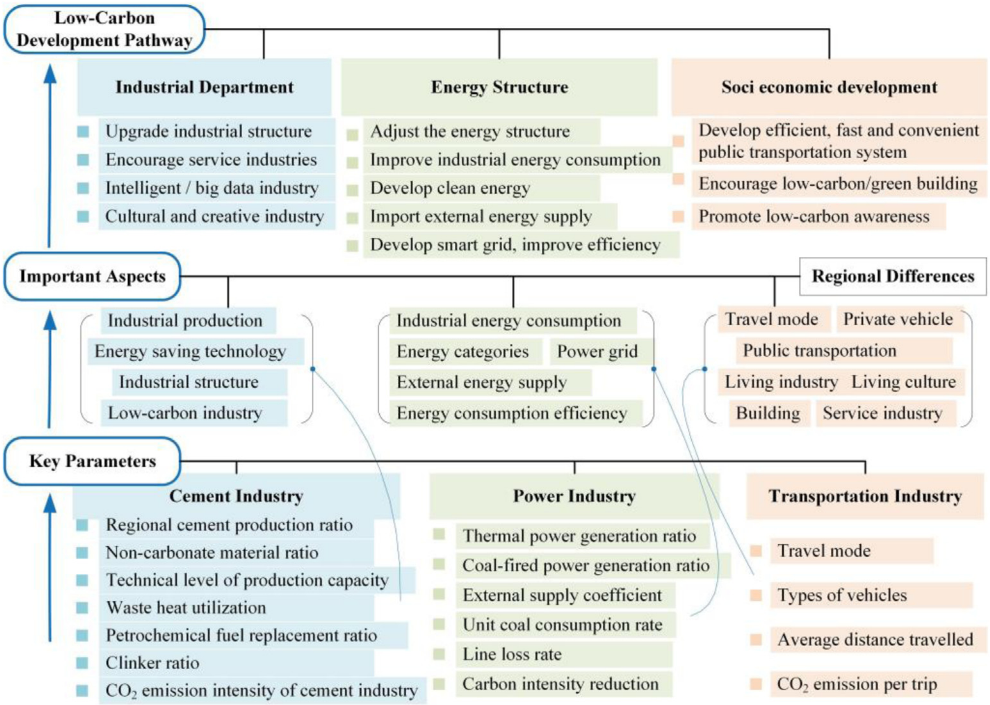

Fig. 17. The analysis of low-carbon development pathway for Chongqing.

From the green-oriented socio development perspective, the fundamental part is to establish a low-carbon transportation system with high-efficiency and low energy consumption industrial transportation system. The efficient, fast and convenient public transportation system can help to reduce the unit carbon emission using private transportation. Also, the transportation sector should strengthen transportation management and explore low-carbon operating strategies for vehicles. Moreover, it is important to encourage the operation of low-carbon buildings by controlling the excessive growth of per capita building area, widely building energy conservation, increasing the proportion of green buildings, reducing the consumption of unit building areas, and promoting technology for energy conservation. Lastly, we must raise the low-carbon awareness for the entire population by comprehensively strengthening low-carbon education, and cultivating low-carbon behaviors.

6. Conclusions

The rapid industrialization and urbanization of a region have caused a new set of challenges in finding the CO_2 emissions reduction measures. The government needs to track historical information of CO_2 emissions from industrial development and national statistic reports to assess the severity of problems and take proper measures. This paper provides a systematic model from a regional perspective to assist policy-making at municipality CO_2 mitigation and uses Chongqing as a case study. In the proposed regional-based framework, the hierarchical structure analysis helps to identify the main contributing industries of CO_2 emissions, including cement, power and transportation industries in the case. Then the model development using SD is conducted to analyze driving factors of CO_2 emissions from each industry. By comparing the results under different scenarios, it offers insights into making feasible measures to address specific problems of CO_2 emissions in the industry. Our framework can be used as a platform to estimate the effectiveness and dynamic consequences of input parameters and policy variables on the overall emissions of the system and to explore low-carbon and regional development.

Although the results are derived from an empirical study of Chongqing, our approach can be also applied to other regions or cities that have similar sector structures. Although the hierarchical structure analysis helps to identify the important industries in CO_2 emissions, in practice, more industrial sectors can be explored if relevant data are available. The data acquisition and uncertainties, especially data for small-size industries, are also issues. It is necessary to understand the system, its factors and interactions before adopting the model. In addition, some regional differences can be further explored. In our case study, the climate features of the western region are not included when analyzing the emission from buildings. This can be considered as a region difference as the emissions of buildings in mountain cities are higher than those in plain cities due to cold-winter and hot-summer climate features of the region.

CRediT authorship contribution statement

Min Tang: Conceptualization, Methodology, Software, Investigation, Formal analysis, Funding acquisition, Writing – original draft. **Zhaoqi Zhang:** Data curation, Investigation, Writing – original draft. **Ying Liu:** Visualization, Writing – original draft, Methodology. **Hongwu Zhang:** Visualization, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. The equations for the CO_2 emissions system of cement industry

Demand Subsystem

$$\begin{aligned}&\text{Regional cement needs} = \text{Urban housing cement needs}\\&\quad + \text{Urban commercial property cement needs}\\&\quad + \text{Rural housing cement needs}\\&\quad + \text{Infrastructure andother cement needs}\end{aligned} \tag{A.1}$$

Supply Subsystem

$$\begin{aligned}&\text{Regional cement needs} = \text{Total cement demand in the region} \,/\\&\quad \text{Region cement demand ratio (Time)}\end{aligned} \tag{A.2}$$

$$\begin{aligned}&\text{Total cement demand in the region}\\&\quad = \text{Cement production in the region} \,/\\&\quad \text{Regionalcement production ratio (Time)}\end{aligned} \tag{A.3}$$

CO_2 Emission Subsystem

$$\begin{aligned}&\text{Total } CO_2 \text{ emissions from cement industry} = CO_2 \text{ emissions from}\\&\quad \text{the consumption of organic carbon materials} + \text{Indirect } CO_2\\&\text{emission from electricity} + CO_2 \text{ emissions from the decomposition}\\&\text{of carbonate} + CO_2 \text{ emissions from fossil fuel consumption} -\\&\text{Carbon accumulation and absorption}\end{aligned} \tag{A.4}$$

$$\begin{aligned}&CO_2 \text{ emissions from the consumption of organic carbon materials}\\&\quad = \text{Organic carbon material} * \text{Organic carbon emission factor}\end{aligned} \tag{A.5}$$

$$\begin{aligned}&\text{Indirect } CO_2 \text{ emission from electricity} = \text{Purchased electricity} *\\&\text{Indirect } CO_2 \text{ emission factor of electricity consumption} \,/\, 1000\end{aligned} \tag{A.6}$$

$$\begin{aligned}&CO_2\text{emissions from the decomposition of carbonate} = \text{Carbonate}\\&\qquad \text{material consumption} * CO_2 \text{ emission factor of Carbonate}\end{aligned} \tag{A.7}$$

$$\begin{aligned}&\text{Carbonate material consumption} = \text{Raw material demand} -\\&\text{Raw material demand} * \text{Non} - \text{carbonate material ratio (Time)}\end{aligned} \tag{A.8}$$

$$\begin{aligned}&CO_2\text{emissions from fossil fuel consumption} = \text{Coal consumption} *\\&\qquad CO_2 \text{ emission factor of coal consumption} \,/\, 1000\end{aligned} \tag{A.9}$$

$$\begin{aligned}&\text{Cement clinker output} = \text{Cement production in the region} *\\&\quad \text{Clinker ratio (Time)}\end{aligned} \tag{A.10}$$

$$\begin{aligned}&\text{Coal consumption} = \text{Coal demand} - \text{Coal demand} *\\&\quad \text{Petrochemical fuel replacement ratio (Time)}\end{aligned} \tag{A.11}$$

$$\begin{aligned}&\text{Petrochemical fuel consumption ratio} = \text{Coal consumption} \,/\\&\quad \text{Coal demand}\end{aligned} \tag{A.12}$$

$$\begin{aligned}&\text{Coal consumption} = \text{Coal demand} * \text{Petrochemical fuel}\\&\quad \text{consumption ratio}\end{aligned} \tag{A.13}$$

$$\begin{aligned}&\text{Coal demand} = \text{Cement production in the region} *\\&\text{Coal consumption per ton of cement}\end{aligned} \tag{A.14}$$

$$\begin{aligned}&\text{Coal consumption per ton of cement} = 80.5 \,/\, \text{Technical level of}\\&\text{production capacity (Time)}\end{aligned} \tag{A.15}$$

$$\begin{aligned}&\text{Electricity demand} = \text{Purchased electricity} + \text{Waste heat}\\&\text{power generation}\end{aligned} \tag{A.16}$$

Appendix B. Parameter settings of 2020 for cement industry

See Table B.1.

Appendix C. The equations for the CO_2 emissions system of the power industry

Demand Subsystem

$$\begin{aligned}&\text{Total urban population} = \text{total regional population (Time)}\\&\quad * \text{urbanization ratio (Time)}\end{aligned} \tag{C.1}$$

$$\begin{aligned}&\text{Total rural population} = \text{total regional population (Time)}\\&\quad - \text{total urban population}\end{aligned} \tag{C.2}$$

$$\begin{aligned}&\text{Total income of urban inhabitants} = \text{total urban population}\\&\quad * \text{Urban income level (time)}/10000\end{aligned} \tag{C.3}$$

$$\begin{aligned}&\text{Total income of rural residents} = \text{total rural population}\\&\quad * \text{Per capita income of rural residents (time)}/10000\end{aligned} \tag{C.4}$$

$$\begin{aligned}&\text{Per capita electricity consumption} = \text{electricity demand for access}\\&\text{to the Internet}/\text{total regional population (Time)}\end{aligned} \tag{C.5}$$

$$\begin{aligned}&\text{Consumption of electricity by rural residents} = \text{total income of}\\&\text{rural residents} * \text{Consumption Coefficient of}\\&\text{electricity by rural residents (time)}/10000\end{aligned} \tag{C.6}$$

$$\begin{aligned}&\text{Consumption of electricity by urban residents} = \text{total income}\\&\text{of urban inhabitants} * \text{Consumption Coefficient of}\\&\text{electricity by urban residents (time)}/10000\end{aligned} \tag{C.7}$$

$$\begin{aligned}&\text{The added value of agricultural industry} = \text{GDP in the region}\\&\quad * \text{Proportion of added value of agricultural industry (Time)}/100\end{aligned} \tag{C.8}$$

$$\begin{aligned}&\text{Electricity consumption in agricultural industry} = \text{The added}\\&\text{value of agricultural industry} * \text{Agricultural Industry}\\&\text{Power Intensity (time)}/10000\end{aligned} \tag{C.9}$$

$$\begin{aligned}&\text{GDP power consumption intensity} = \text{grid demand}/\text{GDP}\\&\text{in the region}\end{aligned} \tag{C.10}$$

$$\begin{aligned}&\text{On} - \text{grid electricity demand} = \text{regional electricity demand} *\\&(1 + \text{line loss rate (Time)})\end{aligned} \tag{C.11}$$

$$\begin{aligned}&\text{Actual power demand} = \text{on} - \text{grid power demand} *\\&(1 + \text{auxiliary power consumption rate})\end{aligned} \tag{C.12}$$

Table B.1
Parameter settings of 2020 for cement industry.

Baseline scenario	Low-carbon scenario
Demand subsystem	
Regional cement needs = 7.61607 *e*+007 ton	Regional cement needs = 8.91881 *e*+007 ton
Urban commercial property cement needs = 7.207 *e*+006 ton	Urban commercial property cement needs = 9.009 *e*+006 ton
Urban housing cement needs = 8.008 *e*+006 ton	Urban housing cement needs = 1.001 *e*+007 ton
Rural housing cement needs = 8.322 *e*+008 ton	Rural housing cement needs = 1.04025 *e*+007 ton
Infrastructure and other cement needs = 4.78133 *e*+007 ton	Infrastructure and other cement needs = 5.97666 *e*+007 ton
Supply subsystem	
Total cement demand in the region = 7.61607 *e*+007 ton	Total cement demand in the region = 9.7215 *e*+007 ton
Cement production in the region = 7.31143 *e*+007 ton	Cement production in the region = 9.52707 *e*+007 ton
Cement production in the region ratio = 0.96	Cement production in the region ratio = 0.98
CO$_2$ **Emission subsystem**	
Organic carbon emission factor = 14	Organic carbon emission factor = 14
CO$_2$ emission factor of Carbonate = 0.527	CO$_2$ emission factor of Carbonate = 0.527
Carbonate material consumption = 6.698496 *e*+007 ton	Carbonate material consumption = 7.04764 *e*+007 ton
Non-carbonate material ratio = 0.068	Non-carbonate material ratio = 0.094
Organic carbon material = 1437449 ton	Organic carbon material = 155577 ton
Organic carbon material ratio = 0.002	Organic carbon material ratio = 0.002
Raw material demand = 7.187224 *e*+007 ton	Raw material demand = 7.77886 *e*+007 ton
Raw material demand ratio = 1.15	Raw material demand ratio = 1.15
Cement clinker output = 6.24976 *e*+007 ton	Cement clinker output = 6.76422 *e*+007 ton
Clinker ratio = 0.82	Clinker ratio = 0.71
Petrochemical fuel consumption = 7.526136 *e*+009 kg	Petrochemical fuel consumption = 7.57907 *e*+009 kg
Petrochemical fuel replacement ratio = 0.08	Petrochemical fuel replacement ratio = 0.16
Coal demand = 8.18056 *e*+09 kg	Coal demand = 9.0227 *e*+009 kg
Coal consumption per ton of cement = 107.33 kg	Coal consumption per ton of cement = 94.7059 kg
Technical level of production capacity = 0.75	Technical level of production capacity = 0.85
electricity demand = 8.43464 *e*+09 kwh	electricity demand = 9.30291 *e*+009 kwh
Waste heat power generation = 1.874928 *e*+09 kwh	Waste heat power generation = 2.16455 *e*+009 kwh
Purchased electricity = 6.559704 *e*+009 kwh	Purchased electricity = 7.13836 *e*+009 kwh

$$\textit{Regional electricity demand} = \textit{electricity consumption in agricultural industry} + \textit{electricity consumption of industrial industry} + \textit{electricity consumption of service industry} + \textit{consumption electricity of rural residents} + \textit{consumption electricity of urban residents} \tag{C.13}$$

$$\textit{Electricity consumption of industrial industry} = \textit{industrial added value} * \textit{Power Intensity of industrial Industry}\ (\textit{time})/10000 \tag{C.14}$$

$$\textit{Industrial added value} = \textit{GDP in the region} * \textit{Proportion of industrial added value}\ (\textit{Time})/100 \tag{C.15}$$

$$\textit{Electricity consumption of the third industry} = \textit{added value of the third industry} * \textit{Power Intensity of the Third Industry}\ (\textit{time})/10000 \tag{C.16}$$

$$\textit{Added value of service industry} = \textit{GDP in the region} * \textit{added value of service industry}\ (\textit{Time})/100 \tag{C.17}$$

$$\textit{GDP increment} = \textit{GDP in the region} * \textit{GDP growth ratio}\ (\textit{Time}) \tag{C.18}$$

Supply–Demand Subsystem

$$\textit{Actual power demand} = \textit{on} - \textit{grid power demand} * (1 + \textit{auxiliary power consumption rate}) \tag{C.19}$$

$$\textit{Closing limit} = \textit{IFTHENELSE}\ (\textit{actual power demand} > \textit{power supply},\ \textit{actual power demand} - \textit{power supply},\ 0) \tag{C.20}$$

$$\textit{Power supply} = \textit{power generation within the region} + \textit{power supply outside the region} \tag{C.21}$$

$$\textit{External power supply} = \textit{external power demand} * \textit{external supply coefficient} \tag{C.22}$$

$$\textit{Estimated thermal power generation} = \textit{power generation within the region} - \textit{hydropower generation}\ (\textit{Time}) - \textit{other clean energy generation}\ (\textit{Time}) \tag{C.23}$$

$$\textit{Regional External Power Demand} = \textit{Actual Power Demand} - \textit{Expected Power Generation}\ (\textit{Time}) \tag{C.24}$$

$$\textit{Power generation in the region} = \textit{power demand purchased from outside the region} - \textit{power supply from outside the region} + \textit{pre-generation}\ (\textit{Time}) \tag{C.25}$$

$$\textit{Actual Thermal Power Generation} = \textit{IFTHENELSE}\ (\textit{Thermal Power Potential Generation} > \textit{Thermal Power Pre} - \textit{Generation},\ \textit{Thermal Power Pre} - \textit{Generation},\ \textit{Thermal Power Potential Generation}) \tag{C.26}$$

$$\textit{Thermal power generation capacity} = \textit{thermal power installed capacity}\ (\textit{time}) * \textit{Average thermal power generation time}/10000 \tag{C.27}$$

$$\text{Coal-fired power generation} = \text{actual thermal power generation} * \text{coal-fired power generation ratio} \tag{C.28}$$

$$\text{Natural gas power generation} = \text{actual thermal power generation} * \text{natural gas power generation ratio} \tag{C.29}$$

$$\text{Fuel power generation} = \text{actual thermal power generation} * \text{fuel power generation ratio} \tag{C.30}$$

$$\text{Biomass mixed fuel power generation} = \text{actual thermal power generation} * \text{biomass mixed fuel power} \tag{C.31}$$

CO_2 Emission Subsystem

$$\text{Coal-fired power generation} = \text{actual thermal power generation} * \text{coal-fired power generation ratio} \tag{C.32}$$

$$\text{Coal consumption} = \text{coal-fired power generation} * \text{unit coal consumption rate}\ (\text{Time}) * 10 \tag{C.33}$$

$$\text{Desulfurizer demand} = \text{coal-fired power generation} + \text{desulfurizer consumption rate} \tag{C.34}$$

$$\text{Coal emissions} = \text{coal consumption} * \text{coal emission factor} \tag{C.35}$$

$$\text{Desulfurizer carbon emissions} = \text{desulfurizer demand} + \text{desulfurizer emission factor} \tag{C.36}$$

$$\text{Natural gas power generation} = \text{actual thermal power generation} * \text{natural gas power generation ratio} \tag{C.37}$$

$$\text{Natural gas consumption} = \text{natural gas power generation} + \text{natural gas consumption rate} \tag{C.38}$$

$$\text{Natural Gas Carbon Emission} = \text{natural gas consumption} * \text{Natural Gas Emission Factor} * 10000 \tag{C.39}$$

$$\text{Biomass mixed fuel power generation} = \text{actual thermal power generation} * \text{biomass mixed fuel power generation ratio} \tag{C.40}$$

$$\text{Biomass consumption} = \text{power generation of biomass mixed fuel} * \text{biomass consumption rate} \tag{C.41}$$

$$\text{Biomass combustion emissions} = \text{biomass consumption} * \text{biomass fuel emission factor} \tag{C.42}$$

$$\text{Total carbon emissions from thermal power} = \text{coal emissions} + \text{natural gas emissions} + \text{fuel oil emissions} + \text{biomass combustion emissions} + \text{desulfurizer emissions} - \text{CCS} \tag{C.43}$$

$$\text{Fuel carbon emissions} = \text{fuel consumption} * \text{fuel emission factor} * 1.4286 \tag{C.44}$$

$$\text{Fuel consumption} = \text{fuel power generation} * \text{fuel consumption rate} \tag{C.45}$$

$$\text{Fuel power generation} = \text{actual thermal power generation} * \text{fuel power generation ratio} \tag{C.46}$$

Appendix D. Parameter settings of 2020 for power industry

See Tables D.1–D.3.

Appendix E. The equations for the CO_2 emissions system of the transportation industry

Demand Subsystem

$$\text{Rail Transit Increment} = \text{Rail Transit Line Length} * \text{Rail Transit Line Growth Rate} \tag{E.1}$$

$$\text{Rail transit vehicles} = \text{rail transit unit mileage allocation vehicles} * \text{rail transit line length} \tag{E.2}$$

$$\text{Population increase} = \text{urban population} * \text{urban population growth rate} \tag{E.3}$$

$$\text{Rail transit passenger volume} = \text{rail transit vehicles} * \text{average trip number of rail vehicles} * \text{average passenger number of rail vehicles} \tag{E.4}$$

$$\text{Rail transit energy consumption} = \text{rail transit energy consumption factor} * \text{rail transit operation turnover}/100 \tag{E.5}$$

$$\text{Rail transit turnover} = \text{rail transit passenger volume} * \text{rail transit average ride distance} \tag{E.6}$$

$$\text{Rail transit carbon emission} = \text{rail transit carbon emission factor} * \text{rail transit operation turnover}/100 \tag{E.7}$$

$$\text{Rail transit energy consumption} = \text{rail transit energy consumption factor} * \text{rail transit operation turnover}/100 \tag{E.8}$$

$$\text{Rail transit sharing rate} = \text{rail transit volume}/\text{urban residents volume} \tag{E.9}$$

$$\text{Travel volume of urban residents} = \text{urban population} * \text{number of trips per capita} \tag{E.10}$$

Table D.1
Parameter settings of 2020 for power industry: Demand subsystem.

Baseline scenario	Low-carbon scenario
Total regional population = 32.5 million	Total regional population = 32.5 million
Total rural population = 9.75 million	Total rural population = 9.75 million
Per capita income of rural residents = 9669 yuan	Per capita income of rural residents = 9669 yuan
Total income of rural residents = 94 billion 268 million yuan	Total income of rural residents = 94 billion 268 million yuan
Electricity consumption coefficient of rural residents = 835.1 kwh/10000 yuan	Electricity consumption coefficient of rural residents = 835.1 kwh/10000 yuan
Consumption of electricity by rural residents = 7,871.97 million Kwh	Consumption of electricity by rural residents = 7,871.97 million Kwh
GDP in the region = 2756 billion yuan	GDP in the region = 2756 billion yuan
GDP growth ratio = 7%	GDP growth ratio = 7%
Proportion of added value of agricultural industry = 7.19%	Proportion of added value of agricultural industry = 7.19%
The power intensity of the agricultural industry = 15.15 kwh/10000 yuan	Agricultural industry power intensity = 15.15 kwh/10000 yuan
The proportion of added value of the industrial industry = 54.54%	The proportion of industrial added value = 54.54%
The power intensity of the industrial industry = 746.8 kwh/10000 yuan	Power intensity of industrial industry = 746.8 kwh/10000 yuan
The proportion of added value of the service industry = 38.3%	The proportion of added value of the service industry = 38.3%
Power intensity of the service industry = 250.4 kwh/10000 yuan	Power intensity of service industry = 250.4 kwh/10000 yuan
Line loss rate = 7.8%	Line loss rate = 7.8%
On-grid demand = 178.145 billion Kwh	On-grid demand = 178.145 billion Kwh
Electricity consumption per capita = 5481.39 Kwh	Electricity consumption per capita = 5481.39 Kwh
Urbanization ratio = 70%	Urbanization ratio = 70%
Total urban population = 22.75 million	Total urban population = 22.75 million
Per capita income of urban residents = 2468e + 004 yuan	Per capita income of urban residents = 2652e + 004 yuan
Total income of urban inhabitants = 603.312 billion yuan	Total income of urban inhabitants = 603.312 billion yuan
Electricity consumption coefficient of urban residents = 30408 kwh/10000 yuan	Electricity consumption coefficient of urban residents = 304.8 kwh/10000 yuan
Consumption of electricity by urban residents = 18,388.9 million Kwh	Consumption of electricity by urban residents = 18,388.9 million Kwh
GDP increment = 192 billion 920 million yuan	GDP increment = 192 billion 920 million yuan
Regional Electricity Demand = 165.255 Billion Kwh	Regional Electricity Demand = 165.255 Billion Kwh
The added value of the agricultural industry = 198 billion 156 million yuan	Added value of Agricultural industry = 198 billion 156 million yuan
Agricultural sector electricity consumption = 300.02 million Kwh	Electricity consumption in the agricultural sector = 300.02 million Kwh
Industrial added value = 1503.12 billion yuan	Industrial added value = 1503.12 billion yuan
Electricity consumption in the industrial sector = 112,259 million Kwh	Electricity consumption in the industrial sector = 12,259 million Kwh
The added value of the service industry = 1055.55 billion yuan	Added value of service industry = 1055.55 billion yuan
Electricity consumption in the service sector = 26,435.1 million Kwh	Electricity consumption in the service sector = 26,435.1 million Kwh
Auxiliary power consumption rate = 7.01%	Auxiliary rate = 6.21%
Actual electricity demand = 190,633 million kwh	Actual electricity demand = 189,208 million Kwh
GDP power consumption intensity = 0.0646391 kwh/10000 yuan	GDP power consumption intensity = 0.0646391 kwh/10000 yuan

Table D.2
Parameter settings of 2020 for power industry: Supply–demand subsystem.

Baseline scenario	Low-carbon scenario
Actual electricity demand = 190,633 million kwh	Threshold = 0 billion Kwh
Extraterritorial supply coefficient = 0.6825	Electricity supply = 189,208 million Kwh
External power supply = 44,998.7 million Kwh	Electricity purchased from outside the region = 64,507.1 million Kwh
Hydropower generation = 37.06 billion kwh	Actual electricity demand = 189,208 million Kwh
Thermal power generation capacity = 107.688 billion kwh	Extraterritorial supply coefficient = 0.8825
Thermal power installed capacity = 2200 Mwh	Electricity supply outside the area = 56,927.5 million Kwh
Power generation in the region = 145.634 billion kwh	Hydropower generation = 44.19 billion kwh
Coal-fired power generation ratio = 97.5%	Predicted thermal power generation = 86,465,600,000 Kwh
Biomass blended fuel power generation ratio = 1%	Thermal power installed capacity = 2200 Mwh
Natural Gas Power Generation Ratio = 0	Intraregional electricity generation = 132,281 million kwh
Fuel to power ratio = 0	Coal-fired power generation ratio = 97%
Actual thermal power generation = 107.688 billion Kwh	Biomass blended fuel power generation ratio = 1%
Threshold = 0 billion Kwh	Gas to power ratio = 0
Electricity supply = 190,633 million kwh	Fuel to power ratio = 0
Electricity demand from outside the region = 65,932.2 million kwh	Actual thermal power generation = 86,465,600,000 Kwh
Other clean energy power generation = 885 million Kwh	Other clean energy power generation = 1.621 billion Kwh
Expected power generation = 124.7 billion kwh	Pre-capacity = 124.7 billion Kwh
The average generating time of thermal power = 5000 h	Average thermal power generation time = 5000h
109.994 billion Kwh of thermal power capacity	Thermal power capacity = 109,994 million Kwh
Coal-fired power generation = 104.996 billion kwh	Coal-fired electricity generation = 83,871.6 million Kwh
Power generation from biomass fuel blends = 1,076.88 million kwh	Electricity generation from biomass blends = 864.656 million Kwh
Natural gas power generation = 0 billion kwh	Natural gas power generation = 0 billion kwh
Fuel-fired power generation = 0 billion kwh	Fuel Electricity Generation = 0 billion kwh

$$\mathit{Car\ sharing\ rate} = \mathit{car\ trips}/\mathit{city\ trips} \tag{E.11}$$

$$\mathit{Car\ carbon\ emissions} = \mathit{car\ passenger\ turnover} * \mathit{car\ carbon\ emission\ factor}/100 \tag{E.12}$$

$$\mathit{Car\ energy\ consumption} = \mathit{car\ passenger\ turnover} * \mathit{car\ energy\ consumption\ factor} \tag{E.13}$$

$$\mathit{Car\ passenger\ traffic} = \mathit{car\ passenger\ traffic} * \mathit{car\ average\ distance} \tag{E.14}$$

$$\mathit{Car\ passenger\ volume} = \mathit{car\ ownership} * \mathit{number\ of\ car\ trips} * \mathit{number\ of\ car\ passengers\ per\ capita} \tag{E.15}$$

$$\mathit{Car\ Increment} = \mathit{Car\ Ownership} * \mathit{Car\ Growth\ Rate} \tag{E.16}$$

Table D.3
Parameter Settings of 2020 for Power Industry: CO$_2$ Emission subsystem.

Baseline scenario	Low-carbon scenario
Unit coal consumption rate = 31% kgce/kwh	Unit coal consumption rate = 0.305 kgce/kwh
Coal consumption = 32.548,800 tons	Coal consumption = 25.5808 million tons
Coal carbon emissions = 87 million 468 thousand and 500 tons	Carbon emissions from coal = 68,743,400 tons
The demand for desulfurizer = 10.4996 million tons	Desulfurizer demand = 8.38716 million tons
The carbon emission of desulfurizer = 10 million 499 thousand and 700 tons	Carbon emission of desulfurizer = 8.38721 million tons
Natural gas consumption rate = 0 m3/kwh	Natural gas consumption rate = 0 m3/kwh
Natural gas emission factor = 32.5918 tCO$_2$/10000 m3	Natural gas emission factor = 32.5918 tco2/10000 m3
Fuel-fired power generation = 0 billion kwh	Fuel Electricity Generation = 0 billion kwh
Fuel consumption = 0 tons	Fuel consumption = 0 million tons
Fuel carbon emissions = 0 million tons	Carbon emissions from fuel oil = 0 million tons
Biomass consumption rate = 0 kg/kwh	Biomass consumption rate = 0 kg/kwh
Emission factor of biomass fuel = 0tco2/t	Emission factor for biomass fuel = 0 tco2/ton
Total carbon emission of thermal power = 97 million 968200 tons	Total carbon emissions from thermal power = 77.1306 million tons
Coal-fired power generation = 104.996 billion kwh	Coal-fired electricity generation = 83,871.6 million Kwh
Coal emission factor = 2.6873 kgco2/kg	Coal emission factor = 2.6873 kgco2/kg
Desulfurizer consumption rate = 0 kg/kwh	Desulfurizer consumption rate = 0 kg/kwh
Desulfurizer emission factor = 0.0044 kgco2/kg	Desulfurizer emission factor = 0.0044 kgco2/kg
Natural gas power generation = 0 billion kwh	Natural gas power generation = 0 billion kwh
Consumption of natural gas = 0 m3	Natural gas consumption = million m3
Natural gas carbon emissions = 0 million tons	Natural gas carbon emissions = 0 million tons
Fuel consumption rate = 0 kg/kwh	Fuel consumption rate = 0 kg/kwh
Fuel emission factor = 3.8344 tco2/ton	Fuel emission factor = 3.8344 tco2/ton
Power generation from biomass fuel blends = 1,076.88 million kwh	Electricity generation from biomass blends = 864.656 million Kwh
Biomass consumption = 0 million tons	Biomass consumption = 0, 000 tons
Biomass combustion emissions = 0 million tons	Biomass combustion emissions = 0, 000 tons
Carbon capture and storage = 0 million tons	Carbon capture and storage = 0, 000 tonnes

$$\mathit{Bus\ Route\ Increment} = \mathit{Bus\ Route\ Length} * \mathit{Bus\ Route\ Growth\ Rate} \tag{E.17}$$

$$\mathit{Bus\ ownership} = \mathit{length\ of\ bus\ line} * \mathit{growth\ rate\ of\ bus\ line} \tag{E.18}$$

$$\mathit{Bus\ passenger\ traffic} = \mathit{bus\ ownership} * \mathit{average\ number\ of\ bus\ trips} * \mathit{average\ number\ of\ passengers\ on\ buses} \tag{E.19}$$

$$\mathit{Bus\ passenger\ turnover} = \mathit{bus\ passenger\ volume} * \mathit{average\ bus\ ride\ distance} \tag{E.20}$$

$$\mathit{Bus\ Energy\ Consumption} = \mathit{Bus\ Passenger\ Turnover} * \mathit{Bus\ Energy\ Consumption\ Factor}/100 \tag{E.21}$$

$$\mathit{Bus\ Carbon\ Emission} = \mathit{Bus\ Passenger\ Turnover} * \mathit{Bus\ Carbon\ Emission\ Factor}/100 \tag{E.22}$$

$$\mathit{Bus\ sharing\ rate} = \mathit{bus\ trip\ volume}/\mathit{urban\ resident\ trip\ volume} \tag{E.23}$$

$$\mathit{Taxi\ sharing\ rate} = \mathit{taxi\ trip\ volume}/\mathit{city\ resident\ trip\ volume} \tag{E.24}$$

$$\mathit{Taxi\ passenger\ volume} = \mathit{taxi\ ownership} * \mathit{average\ taxi\ passenger\ volume} * \mathit{number\ of\ taxi\ services} \tag{E.25}$$

$$\mathit{Taxi\ increment} = \mathit{taxi\ ownership} * \mathit{taxi\ growth\ rate} \tag{E.26}$$

$$\mathit{Taxi\ passenger\ traffic} = \mathit{taxi\ average\ passenger\ distance} * \mathit{taxi\ passenger\ traffic} \tag{E.27}$$

$$\mathit{Taxi\ carbon\ emissions} = \mathit{taxi\ passenger\ turnover} * \mathit{taxi\ carbon\ emission\ factor}/100 \tag{E.28}$$

$$\mathit{Taxi\ Energy\ Consumption} = \mathit{Taxi\ Passenger\ Turnover} * \mathit{Taxi\ Energy\ Consumption\ Factor} \tag{E.29}$$

CO$_2$ **Emission Subsystem**

$$\mathit{Fuel\ car} = \mathit{car\ ownership} * \mathit{fuel\ car\ ratio} \tag{E.30}$$

$$\mathit{Electric\ car} = \mathit{car\ ownership} * \mathit{electric\ car\ ratio} \tag{E.31}$$

$$\mathit{Natural\ gas\ car} = \mathit{car\ ownership} * \mathit{natural\ gas\ car\ ratio} \tag{E.32}$$

$$\mathit{Car\ carbon\ emission\ factor} = \mathit{natural\ gas\ car\ ratio} * \mathit{natural\ gas\ car\ carbon\ emission\ factor} + \mathit{fuel\ car\ ratio} * \mathit{fuel\ car\ carbon\ emission\ factor} + \mathit{electric\ car\ ratio} * \mathit{electric\ car\ carbon\ emissions\ factor} \tag{E.33}$$

$$\mathit{Energy\ consumption\ factor\ of\ car} = \mathit{ratio\ of\ natural\ gas\ to\ car} * \mathit{energy\ consumption\ factor\ of\ natural\ gas\ to\ car} + \mathit{ratio\ of\ fuel\ to\ car} * \mathit{energy\ consumption\ factor\ of\ fuel\ to\ car} + \mathit{ratio\ of\ electric\ car} * \mathit{factor\ of\ energy\ consumption\ of\ electric\ car} \tag{E.34}$$

$$\mathit{Fuel\ taxi} = \mathit{taxi\ ownership} * \mathit{fuel\ taxi\ ratio} \tag{E.35}$$

$$\mathit{Gas\ taxi} = \mathit{number\ of\ taxis} * \mathit{gas\ taxi\ ratio} \tag{E.36}$$

$$\mathit{Electric\ taxi} = \mathit{taxi\ ownership} * \mathit{electric\ taxi\ ratio} \tag{E.37}$$

Table F.1
Parameter settings of 2020 for transportation industry-1.

Baseline scenario	Low-carbon scenario
GDP growth rate = 0.1267	GDP growth rate = 0.07
GDP increment = 192 billion 920 million yuan	GDP increment = 192 billion 920 million yuan
Travel volume of urban residents = 28.037 million person-times/day	Travel volume of urban residents = 28.037 million person-times/day
Total annual carbon emissions from urban passenger transport = 34.9289 million tons	Total annual carbon emissions from urban passenger transport = 29.8478 million tons
Daily carbon emissions from urban passenger transport = 9569.56 tons	Urban passenger daily carbon emissions = 8177.49 tons
Urban population = 11,201,500	Urban population = 11,201,500
Urban population growth rate = 0.039	Urban population growth rate = 0.0391
Urban population growth = 437,978	Urban population growth = 437,978
Taxi fleet = 16,183.2 vehicles	Taxi fleet = 16,183.2 vehicles
Taxi trips = 1,999,470	Taxi trips = 1,999,470
Taxi sharing rate = 0.071	Taxi sharing rate = 0.0714
Number of taxi services = 54.35	Number of taxi services = 54.35
Taxi passenger traffic = 2,198,900	Taxi passenger traffic = 2,198,900
Taxi passenger traffic = 17.4232 million person-kilometers	Taxi passenger traffic = 16,163,700 person-kilometers
Taxi energy consumption = 621.852 tons	Taxi energy consumption = 524.193 tons
Taxi energy consumption factor = 35.691 G/person/km	Taxi energy consumption factor = 32.4303 G/person/km
Average taxi ride = 8.3 km	Average taxi ride = 7.7 km
Average number of passengers carried by taxis = 2.5 persons/vehicle	Average number of passengers carried by taxis = 2.5 persons/vehicle
Taxi carbon emissions = 1884.46 tons	Taxi carbon emissions = 1638.12 tons
Taxi carbon emission factor = 108.158 G/person/km	Taxi carbon emission factor = 101.346 G/person/km
Taxi growth rate = 0.051	Taxi growth = 0.0506
Taxi increment = 818.872	Taxi increment = 818.872
Carbon emission per trip = 3.41725 tons/day/10000 person-times	Carbon emissions per unit of travel = 2.92014
Number of electric taxis = 0	Number of electric taxis = 1294.66
Electric taxi ratio = 0	Electric taxi ratio = 0.08
Electric taxi energy consumption factor = 0 G/person/km	Electric taxi energy consumption factor = 0 G/person/km
Electric taxi carbon emission factor = 37.57 G/person/km	Electric taxi carbon emission factor = 37.57 G/person/km
Number of electric buses = 0	Number of electric buses = 1710.95
Electric bus ratio = 0	Electric bus ratio = 0.1
Energy consumption factor of electric bus = 0 G/person/km	Energy consumption factor of electric bus = 0 G/person/km
Carbon emission factor of electric bus = 00 G/person/km	Electric bus carbon emission factor = 7.81 G/person/km
Number of electric cars = 0. 000000	Electric car ownership = 382210
Electric car ratio = 0	Electric car ratio = 0.03
Electric car energy consumption factor = 0 G/person/km	Electric car energy consumption factor = 0 G/person/km
Carbon emission factor of electric car = 0 G/man/km	Carbon emission factor of electric car = 46.96 G/man/km
Electricity indirect emission factor = 1.12 t/MWH	Electricity indirect emission factor = 1.12 t/MWh
Bus ownership = 17,109.5 vehicles	Bus ownership = 17,109.5 vehicles
Bus trips = 7,558,200	Bus trips = 7,054,130
Bus unit mileage configuration = 1.48 vehicles/km	Bus unit mileage configuration = 1.48 vehicles/km
Bus share = 0.27	Bus share = 0.2519
Bus passenger traffic = 8.86272 million passengers	Bus passenger traffic = 10,299,900 passengers
Bus passenger traffic = 70.61 million person-kilometers	Bus passenger traffic = 69,416,200 person-kilometers
Bus energy consumption = 411.582 tons	Bus energy consumption = 418.773 tons
Bus energy factor = 5.8 28960/Man Km	Bus energy factor = 6.03279 G/person/km
Average bus ride = 8.6 km	Average bus ride = 8 km
Average number of bus trips = 14	Average number of bus trips = 14
Average number of passengers per bus = 37	Average number of passengers per bus = 43
Bus carbon emissions = 1710.2 tons	Bus carbon emissions = 1407.57 tons
Bus carbon emission factor = 24.22040 G/man/km	Bus carbon emission factor = 20.2772 G/man/km
Bus route length = 11560.5 km	Bus route length = 11560.5 km
Bus Line Growth Rate = 0.0116	Bus Line Growth Rate = 0.0116
Increment of bus routes = 134.101 km	Increment of bus routes = 134.101 km
Average trips of rail vehicles = 12	Average trips of rail vehicles = 12
Power consumption of rail transit unit operation mileage = 4.404 kwh/vehicle kilometer	Rail transit unit mileage allocation vehicles = 8.8 vehicles/km
Rail transit share = 0.22	Electricity consumption per operating mileage of rail transit unit = 4.40357 kwh/car km

$$\text{Taxi energy consumption factor} = \text{gas taxi ratio} \ast \text{Gas Taxi Energy Consumption Factor} + \text{fuel taxi ratio} \ast \text{fuel taxi energy consumption factor} + \text{electric taxi ratio} \ast \text{Electric Taxi Energy Consumption Factor} \tag{E.38}$$

$$\text{Taxi carbon emission factor} = \text{gas taxi ratio} \ast \text{gas taxi carbon emission factor} + \text{fuel taxi ratio} \ast \text{fuel taxi carbon emissions factor} + \text{electric taxi ratio} \ast \text{electric taxi carbon emissions factor} \tag{E.39}$$

$$\text{Fuel bus} = \text{number of buses} \ast \text{fuel bus ratio} \tag{E.40}$$

$$\text{Electric bus} = \text{number of buses} \ast \text{ratio of electric buses} \tag{E.41}$$

$$\text{Natural gas buses} = \text{number of buses} \ast \text{ratio of natural gas buses} \tag{E.42}$$

$$\text{Bus energy consumption factor} = \text{ratio of natural gas to bus} \ast \text{ratio of natural gas to bus} + \text{ratio of fuel to bus} \ast \text{ratio of fuel to bus} + \text{ratio of electric bus} \ast \text{factor of energy consumption of electric bus} \tag{E.43}$$

Table F.2
Parameter settings of 2020 for transportation industry-2.

Baseline scenario	Low-carbon scenario
Rail transit vehicles = 4249.72	Average number of passengers carried by rail vehicles = 125
Rail transit trips = 6.16082 million person-times/day	Rail transit vehicles = 4249.72
Rail transit unit mileage allocation vehicles = 8.8 vehicles/km	Rail transit trips = 8,401,100 person-times/day
Rail transit passenger volume = 6.37458 million passengers	Rail transit share = 0.3
Energy consumption of rail transit = 254.218 tons	Rail transit passenger volume = 6.37458 million passengers
Energy consumption factor of rail transit = 2.6 G/person/km	Energy consumption of rail transit = 299.651 tons
Average multiplication distance of rail transit = 7.8 km	Energy consumption factor of rail transit = 2.6 G/person/km
Average number of passengers carried by rail transit = 125	Average multiplication distance of rail transit = 7.8 km
Rail transit carbon emissions = 837.086 tons	Carbon emissions from rail transit = 878.151 tons
Carbon emission factor of rail transit = 4.7 G/man-kilometer	Carbon emission factor of rail transit = 4.7 G/man-kilometer
Rail transit line length = 482.923 km	Rail transit line length = 19.2 km
Rail transit line growth rate = 0.0628	Rail transit line growth rate = 0.0628
Increment of rail transit line = 30.2202 km	Increment of rail transit line = 30.3275 km
Electricity consumption of rail transit = 108,449,000 KWH	Electricity consumption of rail transit = 108,449,000 kwh
Carbon emissions from rail transit = 1,214.62 tons	Carbon emissions from rail transit = 1,214.62 tons
Rail transit operation mileage = 24 million 627 thousand and 400 vehicle kilometers	Rail transit operation mileage = 24 million 627 thousand and 400 vehicle kilometers
Rail transit operation turnover = 97.7761 million person-kilometers	Rail transit operation turnover = 115.25 million person-kilometers
Rail passenger turnover carbon emissions = 459.548 tons	Carbon emissions from rail passenger turnover = 541.677 tons
Transportation GDP = 17.1659 billion yuan	Transportation GDP = 17.1659 billion yuan
Carbon emission intensity of GDP in transportation industry = 20.3478 tons of CO_2/10000 yuan	Carbon emission intensity of GDP in transportation industry = 17.3878 tco2/10000 yuan
GDP share of transportation industry = 0.0218	GDP share of transportation industry = 0.0218
GDP in the region = 2756 billion yuan	GDP in the region = 2756 billion yuan
Gas taxi fleet = 16036.1 vehicles	Gas taxi fleet = 14564.9 vehicles
Gas taxi ratio = 0.99	Gas to taxi ratio = 0.9
Gas taxi energy consumption factor = 35.87 G/person/km	Gas taxi energy consumption factor = 35.868 G/person/km
Gas taxi carbon emission factor = 108 g/person/km	Gas taxi carbon emission factor = 108 g/person/km
Number of fuel taxis = 147.12	Number of fuel taxis = 147.12
Fuel to taxi ratio = 0.008	Fuel to taxi ratio = 0.0316
Fuel taxi energy consumption factor = 16.4 G/person/km	Fuel taxi energy consumption factor = 16.4 G/person/km
Fuel taxi carbon emission factor = 125.4 G/person km	Fuel taxi carbon emission factor = 125.4 G/person km
Fuel bus ownership = 371.946	Fuel bus ownership = 371.946
Fuel to bus ratio = 0.0307	Fuel to bus ratio = 0.02632
Fuel bus energy consumption factor = 0.832 G/person/km	Fuel bus energy consumption factor = 0.97 G/person/km
Fuel bus carbon emission factor = 26.49 G/person/km	Fuel bus carbon emission factor 22.79 G/person/km
Fuel car ownership = 124855 vehicles	Fuel car ownership = 12103300 vehicles
Fuel car ratio = 0.98	Fuel car ratio = 0.95
Fuel consumption factor of fuel car = 24.6 G/person/km	Fuel consumption factor of fuel car = 24.6 G/person/km
Fuel car carbon emission factor = 137.05 G/man/km	Fuel car carbon emission factor = 137.05 G/man/km
Number of trips per capita = 2.5 trips/day	Number of trips per person = 2.5 person/day
Carbon emissions per capita = 8.54312	Carbon emissions per capita = 7.30036
Number of natural gas buses = 16737.6	Number of Natural Gas Buses = 14885.3
Natural gas bus ratio = 0.98	Natural gas bus ratio = 0.87
Natural gas bus energy consumption factor = 5.94 G/person/km	Natural gas bus energy consumption factor = 6.91 G/person/km
Carbon emission factor for natural gas buses = 24.17 G/man-km	Carbon emission factor for natural gas buses = 21.84 G/man-km
Natural gas car ownership = 254,807 vehicles	Natural gas car ownership = 254,807 vehicles
Natural gas to car ratio 0.02	Gas to car ratio = 0.02
Natural gas car energy consumption factor = 44.83 G/man-kilometer	Natural gas car energy consumption factor = 44.835 G/man-kilometer
Carbon emission factor of natural gas car = 135 G/man-kilometer	Carbon emission factor of natural gas car = 135 G/man-kilometer
Car ownership = 1.27403 million vehicles	Car ownership = 1.27403 million vehicles
Car trips = 2.3	Car trips = 2.3
Car trips = 2,472,730	Number of car trips = 1.68022 million
Car share = 0.088	Car share = 0.06
Passenger traffic by car = 5,860,560	Passenger traffic by car = 5,860,560
Car energy consumption = 937.671 tons	Car passenger traffic = 31.6713 million person-kilometers
Car energy consumption factor = 25.0047 g/person/km	Car energy consumption = 768.557 tons
Average distance of cars = 9	Car energy consumption factor = 24.2667 g/person/km
Average number of passengers per car = 2	Average distance of cars = 8.4
Carbon emissions from cars = 5137.81 tons	Average number of passengers per car = 2
Car carbon emission factor = 137.009 G/man/km	Carbon emissions from cars = 4253.65 tons
Car growth = 0.0679	Carbon emission factor for cars = 134.306 G/man-km
Car Increment = 8.65069	Car growth = 0.0679
Car turnover = 37,493,800 person-kilometers	Increment of cars = 865069

$$\textit{Bus carbon emission factor} = \textit{natural gas bus ratio} * \textit{natural gas bus carbon emission factor} + \textit{fuel bus ratio} * \textit{fuel bus carbon emission factor} + \textit{electric bus ratio} * \textit{electric bus carbon emissions factor} \tag{E.44}$$

$$\textit{Urban passenger carbon emissions} = \textit{bus carbon emissions} + \textit{taxi carbon emissions} + \textit{car carbon emissions} + \textit{rail transit carbon emissions} \tag{E.45}$$

Appendix F. Parameter settings of 2020 or transportation industry

See Tables F.1 and F.2.

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